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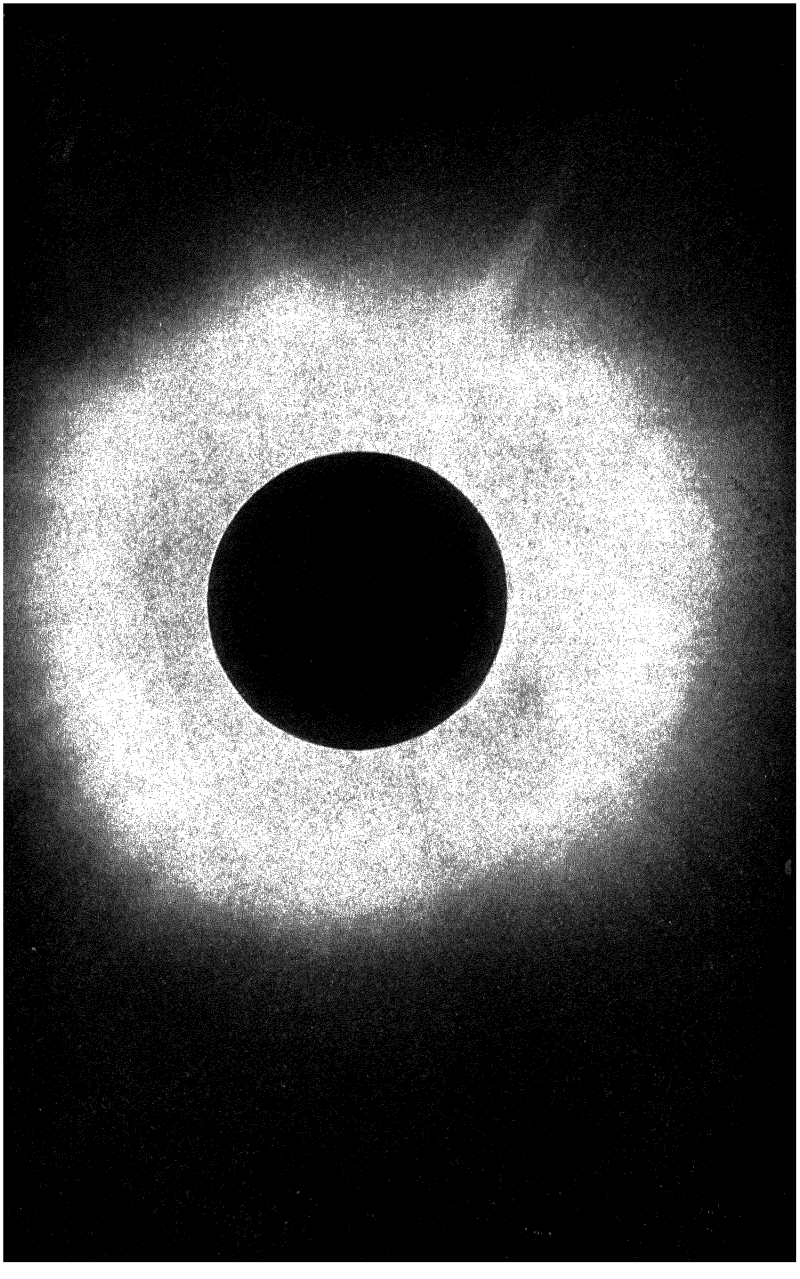
THE FUNDAMENTALS OF ASTRONOMY



THE TOTAL ECLIPSE OF 1926.

THE FUNDAMENTALS OF ASTRONOMY

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PREFACE

It is unquestionable that a knowledge of astronomy is of great cultural value. No science has done more to broaden the outlook and uplift the mind above superstition and bigotry, nor has any science contributed more to the satisfactions of a wide mental horizon.

If this book will assist to enlarge the circle of those who elect astronomy as a general study and thus will multiply the number of people who appreciate the wonders of the universe, it will have fulfilled its purpose.

This textbook, though based on "The Earth and the Stars," which was published recently by one of the present authors, has been so modified, corrected, modernized and amplified, that it is practically a new work. However, the authors have attempted to retain the non-technical character of the original and to relieve the tedium of the ordinary textbook by anecdotes and historical allusions and thus to stimulate the interest of the student.

It is felt that the book is suitable for elementary courses as given in the average university and college. Those details of practical astronomy which the student ought to know are a part of the book and no little astrophysical data is included. The fact that each of the authors has had a wide experience in modern astronomical research as a director of an observatory should tend to interest the student by close association with original sources.

The charts of the constellations are copyrighted and are printed through the kind permission of the Eastern Science Supply Company.

S. A. Mitchell
C. G. Abbot

May 15, 1927.

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FUNDAMENTALS OF ASTRONOMY

CHAPTER I

HOW TO KNOW THE STARS

In order to know and love " the silence that is in the starry skies," one should follow the advice of the famous American astronomer, the late Professor Simon Newcomb, who recommended everyone to go alone on a clear, sparkling, moonless night to a hill in the country where there is a wide horizon. Let us suppose that we follow his advice in the month of October and watch the slow majestic march of the stars as one by one they rise, cross the sky, and set. Soon after sunset, we take our place to watch the sky unaided by other instruments than our eyes, like the Magi who followed the star of Bethlehem.

Let us look first towards the western sky, before its stars are set. The twilight still shows a dusky sunset glow far down next the horizon. In October of each of the years 1925 to 1929, and in the sixth year after each of these, the little planet Mercury, our sun's nearest neighbor, is evening star, and on clear nights can be seen for a half hour or more after sunset, very near the spot on the western horizon where the sun went down. Similarly in October of the years 1928, 1930, 1931, 1933, and on the eighth year after each of these, the planet Venus, our nearest neighbor after the moon, is evening star. Being farther from the sun than Mercury, she often reaches a much higher standing in the western sky after sunset, and may sometimes be followed for three hours before she sets. Venus, albeit not equally brilliant in each of the above years, is the brightest of all the heavenly bodies except the sun and moon.

Every October in the years 1923 to 1927, the great planet Jupiter is visible in the evening hours, and in the years 1923 to 1933 Saturn also. If we had a telescope we should see the wonderful rings of Saturn, perhaps the most beautiful of all celestial sights. Mars, the fiery red planet, is evening star in October of the years 1929, 1931, and every second year thereafter till 1939. All of these

five bright planets, and Uranus and Neptune also, which can not be distinguished without a telescope because they are far away and faint, follow nearly the path of the sun, and are therefore never far away from the plane of the ecliptic. Although we loosely speak of them as morning or evening stars, the planets are not stars at all. They belong to the family of our sun, and shine by reflecting his light. Stars, on the contrary, are other suns, immensely distant and shine by their own light. Planets appear to wander about among the stars. Stars retain their relative places with slight change from year to year.

It makes a great difference in the face of the starry sky how far to the north or the south one lives. The Southern Cross, for instance, is never visible north of Florida, nor the Great Dipper in Patagonia. For people in the United States and Southern Europe, the October evening sky presents its brighter stars about as follows: In the northwest the glowing Arcturus is about to set, while in the southwest the duskier red Antares in the constellation of the Scorpion is also nearly setting. Somewhat west of the zenith stands the brilliant white star Vega, and towards the east and south from Vega, in the embrace of the Milky Way, lies the slightly fainter white star Altair. Farther east, somewhat farther north than Vega, and in brightness half-way between Altair and the pole star, is Deneb, another white one. A very brilliant far-northern star is the yellowish Capella, seen a good way to the northeast of Deneb. Of all the bright northern stars, Capella is most like our sun.

Towards the southeast and not well seen early in the October evening lies a field of bright gems. Aldebaran, which is the red star in the V-shaped group, rises earliest of them, and has gotten well up in the eastern sky. Southeast of him lies the great group of Orion whose central figure is like a square with the giant red star Betelgeuse to the north, and the giant blue star Rigel to the south of it. Farther south and later rising is the white Sirius, brightest of all the stars of the entire heavens. Rising still later, and about as far north as Betelgeuse, comes Procyon, slightly yellowish of tinge. Rising soon after Procyon but farther north, comes the reddish Pollux, the brighter of the twins Castor and Pollux. Last of all of the first magnitude stars of our northern October sky to rise is Regulus, in the constellation of the Lion, which comes up a little north of east at about two o'clock in the morning on October 15.

Had we traveled in the southern Hemisphere, for instance in South Australia or New Zealand, Deneb and Capella must have been dropped from our list of bright stars, along with the pole star, as too northerly for observation. But the yellow Alpha Centauri, the nearest of all the stars and very like our sun, would replace Capella. In the early evening it would lie in the southwest. Its blue companion, Beta Centauri, would lie still nearer the horizon and farther south. Nearly overhead would be the white star Fomalhaut, as bright as Deneb. The brilliant blue Achernar would be directly south at midnight, and following it five hours later, a little farther north, would come Canopus, next to Sirius the brightest star of all. The Orion stars would have moved to the northeastern quarter. We should see at this time of the year the two bright bluish stars, Alpha Crucis and Beta Crucis, of the constellation Southern Cross, far down near the southwest horizon in the evening and in the southeast several hours before sunrise. In October, Spica, alone of all the first magnitude stars, would be too near the sun and lost in the morning or evening twilight.

These twenty-one brightest stars and the five brightest planets which we have named should be well known to everybody. A table will be found in the Appendix which gives various facts about them.

Stretching diagonally across the sky from northeast to southwest, and passing almost directly overhead in the October evenings, lies the Milky Way. Like the bright stars, it marches from east to west throughout the night, but some parts of it are always in view, for it is a belt that completely encircles the heavens.

As we watch the stars moving through the night, we see that they move by less and less distances and more and more aslant to the horizon, as we look farther and farther north, till presently we find some that neither rise nor set, but describe large circles in the northern sky. Looking towards the center of these circles, we find the stars moving less and less till finally, at the pole star, the eye can scarcely see motion at all, unless we guide our view very accurately by some fixed objects in a line, such as stones or houses.

So the sun and all the stars move across our sky from east to west, or from west to east, according as they are south or north of the pole star. The reason for it is that our round earth is itself rotating eastwardly, one rotation in twenty-four hours, about its axis which points nearly towards the pole star. Of course we know that the

earth has no real solid axis, with bearings, like a bicycle wheel. It rests upon nothing, and spins thereon without ever losing its place!

As we watch the stars going by over our heads, they seem innumerable. But every one of them that the eye can see has long ago been numbered and given a place, each with its identifications and many descriptive annotations, in the astronomical catalogues. The naked-eye stars that can be seen in one view of the heavens are, in fact, hardly more numerous than the people in a large full theatre. All of them that the sharpest eye can see unaided in both the northern and southern hemispheres, and in the dark and daylight sides of the earth combined, hardly exceed five thousand.

But it is far otherwise when we search the sky with a giant telescope and photography. For the Milky Way, that looks like a dim cloud, resolves itself into a perfect host of individual stars. It has been computed, for of course no one's life-time would be long enough to examine them every one, that all of the stars which could be photographed with our largest instruments would be nearly as many as the human inhabitants of our earth, or perhaps a thousand millions. Occasionally, as we watch, we see what appear to be little stars dart out from among their neighbors, rush a long way through the sky and disappear, sometimes leaving behind a short-lived train of light. These shooting stars, or meteors, are not really stars at all, but are little cold bits of dust or metal which belong, at least temporarily, not among the stars, but among the planets. They are attached to the family of our sun, and happen, in their courses, to overtake or be overtaken by our earth's atmosphere. Rushing through the air with enormous speeds, they quickly become white hot, and burn up like iron heated too hot in the blacksmith's forge. Most of them are quite consumed in the upper air, but some very large ones reach the earth. Admiral Peary even found one of many tons weight on one of his Greenland expeditions, and brought it to the American Museum of Natural History in New York. Here, like a wild animal of the jungle caged in a zoölogical garden, this captured free tenant of boundless outer space is housed up to amuse and instruct the people.

Thousands of years have passed since men first looked upon the stars. Yet we know that their order has apparently changed but little in all that time. Probably there would be little of change of any kind among them that the sharpest naked-eye observer could

note if, like the legendary Wandering Jew, he had lived from the time of Christ until now. Stars that were brightest then are brightest now, as we know on the best of grounds.

It is true that once every few years there comes to view what astronomers call a new star. Thus, in February, 1901, there blazed up in the northern constellation of Perseus a star, till then obscure, which for a few days rivaled all but the very brightest of our list of twenty-one. But it soon faded and is now visible only to fair-sized telescopes. Again, in June, 1918, a new star arose near Altair, in the constellation Aquila, which briefly surpassed all but Sirius in brightness. But this also has faded to dimness. It is a curious thought that these new stars of the twentieth century are really so far away that their light, our swiftest messenger, traveling 186,000 miles each second, had been on the way some centuries. These stars had really flashed forth and faded back to insignificance before Cromwell was Lord Protector of England.

Before leaving our lonely hill of observation we shall probably ask ourselves the question whether among this myriad of objects which are within the visible creation, there is not, besides our world, some other, or perhaps many other abodes of thoughtful life similar to ours. Were there but beings like ourselves on other worlds, and could there be some wireless communication established between us and them, what a breathless interest we should have in learning from them of their forms of society, their governments, their religions, the scenes with which they are surrounded, and, in a word, the whole conditions of races of intelligent beings developed independently from ourselves!

CHAPTER II

SOME FAMOUS ASTRONOMERS AND FAMOUS INSTRUMENTS

The ancient astronomers looked upon the stars as if they were diamond-like gleams of light fixed on the inside of a hollow azure sphere. After astronomy became a science it was necessary to take a census of the sky by enumerating in catalogues the positions and magnitudes of the stars. The fascinating aim of modern astronomy is to give life to this flat picture by applying the latest discoveries in physics and chemistry, to discover what the stars are, how they took their origin, and what are their motions and what these signify, in short to solve the riddle of the universe. The earth is small and insignificant when compared with the colossal dimensions of the universe.

Hipparchus. — There is no more fascinating study in the whole of science than to trace the history of astronomy from the time of the early Babylonians and to watch the torch of knowledge, sometimes waning, but on the whole glowing ever more and more brightly as it was passed from one generation of astronomers to the succeeding one. The greatest observer among the early astronomers was Hipparchus who worked about 150 to 125 B.C. He catalogued 1026 stars, founded the science of trigonometry, fixed positions on the earth by latitude and longitude, determined the length of the year, the periods of revolution of the five great planets around the sun, and the obliquity of the ecliptic, that is, the inclination of the earth's equator to its plane of revolution about the sun. He found the eccentricity of the earth's orbit, or in other words how far it is from being circular; measured the distance of the moon roughly, and discovered the precession of the equinoxes. The intersection of the celestial equator and the ecliptic (in the plane of which the sun moves) is shifting constantly to meet the sun as it moves eastward in its annual journey among the stars. This last discovery of his waited two thousand years for its explanation.

Ptolemy. — Nearly three centuries went by from Hipparchus to Ptolemy of Alexandria, who flourished 127 to 151 A.D. He

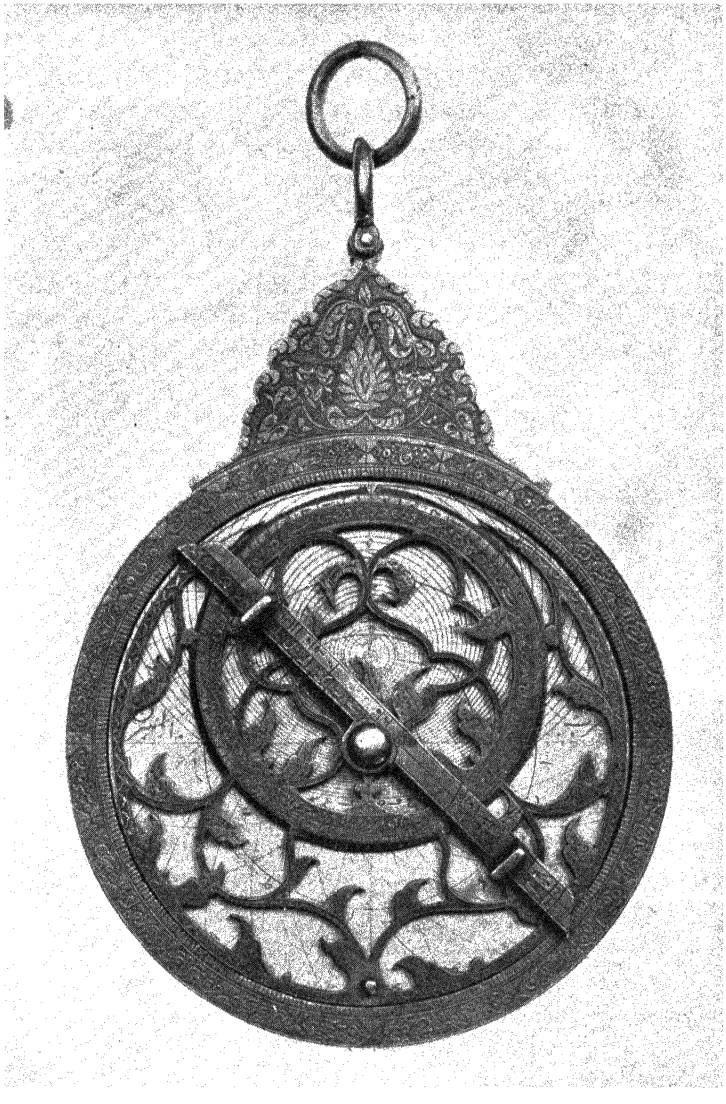

PLATE I. A PERSIAN ASTROLABE.

was not as great an observer as Hipparchus, but he collected all knowledge in the famous work which the Arabs called " Almagest." He describes the earth as a sphere in the center of the heavens, which he assumes are very far away compared to the size of the earth. " Though some say the earth turns on its axis, and truly this simplifies theory, yet," says Ptolemy, " it is ridiculous." The heavens, he points out, have two principal motions. One carries them around the earth uniformly from east to west each day, the other is peculiar to some stars only (he means the planets, of course) and is contrary to the first and about different axes. Ptolemy gives mathematical tables useful for trigonometry which he computed by an elegant method, and goes on with a great number of facts such as the obliquity of the ecliptic, the length of day and height of the sun at different times and places. Recognizing the earth as the center of things and immovable, he was at pains to work out an elaborate theory of epicycles and eccentrics to explain the apparent motions of the sun, moon and planets. He discusses the eclipse observations of the Chaldeans and his own, and sums up the knowledge of how to calculate eclipses. Ptolemy has preserved for us the catalogue of Hipparchus, giving the positions of the fixed stars, their arrangement in constellations, and their brightness.

Ptolemy's " Almagest " ruled the astronomical thought of the next thousand years and more, till there came the century of the geniuses. Where else can we find within a single century another such group of men of accomplishment as this! Gutenberg (1398–1468) who invented printing; Columbus (1446–1506) who discovered a new world; Copernicus (1473–1543) who reconceived the place of the earth in the universe; Leonardo da Vinci (1452–1519), Michelangelo (1475–1564), Titian (1477–1576), and Raphael (1483–1520), a quartet whose achievements it is unnecessary to rehearse, and Martin Luther (1483–1546) the apostle of the Reformation.

Copernicus, a physician and priest of a small place in Poland, spent his life in ministering to the poor and thinking of great things. He conceived that the rising and setting of the sun and stars are the consequence of a daily rotation of our earth upon an axis inclined toward the polar star, and that the earth and the great planets, Mercury, Venus, Mars, Jupiter, and Saturn (all that were

known in his day) revolve about the sun. So great a derogation as this of the majesty of the earth, and consequently of man, its chief citizen, seemed impious in the eyes of most of Copernicus' contemporaries and successors for a century and more; so that we find the immortal Galileo (1564–1642) suffering persecution in his old age for holding to this heresy.

Kepler. — The instruments of the ancient astronomers were very crude and permitted observations of small accuracy only. As astronomy progressed, better and better instruments were made. Before the invention of the telescope, the astronomers had to be content with sighting vanes, devices somewhat like gun-sights, for fixing accurately the directions of the celestial objects. These were mounted with reference to circles divided into degrees, as in the armilla and the astrolabe. With such instruments, the Greek astronomers Eratosthenes and Hipparchus, and the Egyptian Ptolemy made many discoveries and valuable measurements. Columbus did his navigation by means of the astrolabe. Up to the end of the sixteenth century, the best instruments were those of Tycho Brahe (1546–1601). He was an indefatigable worker. He constructed his own observatory, made his own instruments, and collected an enormous mass of observations of an accuracy superior to anything that had been done before. The records of these observations were given to his friend and pupil John Kepler (1571–1630). The observations of the planets, particularly those of Mars, permitted Kepler to establish the three famous laws of motion that bear his name. Until his time it was universally assumed that the circle was the only perfect curve, and with this idea of perfection it was unthinkable that the heavenly bodies could move otherwise than uniformly in circular orbits. It was not until after many years of weary trial that Kepler discarded the circle. When he had fully verified that the planets move in elliptical orbits about the sun, and with the sun not in the center of the ellipse but at one focus, he declared in a burst of enthusiasm: "What I prophesied twenty-two years ago . . . what I promised my friends . . . what sixteen years ago I urged as a thing to be sought, that for which I joined Tycho Brahe . . . for which I have devoted the best part of my life to astronomical contemplations, at length I have brought to light . . . It is now eighteen months since I got the first glimpse of light, three months since the dawn, very few

days since the unveiled sun, most admirable to gaze on, burst out on me. Nothing holds me! I will indulge my sacred fury . . . If you forgive me, I rejoice; if you are angry, I can bear it; the die is cast, the book is written . . . it may well wait a century for a reader, as God has waited six thousand years for an interpreter of his works."

Galileo. — The early years of the seventeenth century likewise witnessed one of the most important steps forward in the whole history of astronomy, the invention of the telescope by Lippershey of Magdeburg about the year 1600. Immediately the new instrument became popular in Holland. Galileo in Italy (1564–1642), hearing of it, reinvented it for himself; and constructing several telescopes with his own hands, made one in 1610 which magnified 33 diameters and multiplied enormously the number of the stars visible. With this famous instrument, he observed the sun-spots, noted the rotation of the sun, described the contour of the moon's surface, with its mountains, valleys and plains, discovered Jupiter's satellites and their revolution, observed the moonlike changing crescent of Venus, and discerned appendages to Saturn which Huyghens found later to be rings.

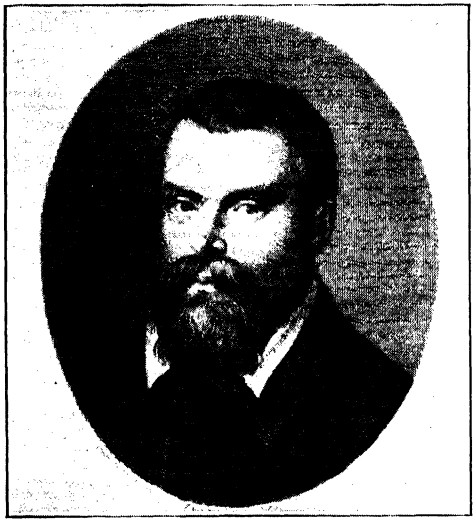

PLATE 2. GALILEO GALILEI.
Inventor, observer, philosopher.

Galileo's telescope was like a modern opera glass, with a convex lens in front, a concave one behind. With the simple lenses of the telescope of his time and much later, it was found to be useless to attempt to increase the power beyond Galileo's limit of 33 without greatly increasing the focal length. The simple lenses gave stellar images surrounded by color, "chromatic aberration," it is now called. Moreover, the art of glass-making was in a very crude state and the lenses were poor in quality and small in size. The

color surrounding the star images was very bothersome and there was no method then known for correcting it other than that of greatly increasing the focal length. Thus it came about that telescopes of a hundred, some even of six hundred feet in focal length were constructed. There was no tube to such instruments, and no clockwork to drive them, so that the difficulty of using them was enormous.

Newton. — These defects led the great Sir Isaac Newton (1642 1727) to declare that the lens or refracting telescope was in a deplorable condition. He therefore discarded the refracting telescope and devised the mirror or reflecting telescope. The Royal Society has preserved in its rooms in London, Newton's model of the reflecting telescope made by his own hands.

Newton is generally regarded as the greatest scientist that ever lived. It would be futile to attempt here even a bare mention of all that he has accomplished, but we must not fail to note one great discovery which is the basis of modern astronomy. His famous law of gravitation — all particles in the universe act as if attracted each to each by a force proportional to the product of their masses and inversely as the square of the distance between them — holds equally true for experimental masses in the laboratory, for the solar system which extends three billion miles to Neptune, and for the stars, enormously more distant still, which include thousands and thousands of systems in revolution according to Newton's law. By means of this law it is possible to weigh distant stars in terms of our sun by observing carefully the motions which by gravitation a star imparts to its companion. Newton's law makes even the dark stars yield up the secrets of their times of revolution and their masses.

Kepler could offer no explanation for his three laws but it was soon shown that from the principles of mechanics they follow as a direct consequence of the law of gravitation.

It is interesting to note that Newton, in his cautious habit of proving all things, withheld from publishing his law until after it had been well tested on the planets. He first tried it on the moon, but unfortunately, for lack of knowledge of the size of the earth, the distance that the moon fell towards the earth in one second of time differed sixteen per cent from that calculated from the law. He had adopted the value then accepted that one degree of latitude

on the earth was exactly equal to sixty miles. It is told of Newton that when he learned that Picard in Northern France had measured an arc of the earth's circumference and had found that one degree was equal to 69 miles, he saw at a glance that the increased length would completely verify his law, but was so excited that he was unable at the time to work out the simple mathematical problem. He then resumed his unfinished work and published it.

Calculus. — We have noted that Hipparchus developed the theory of trigonometry, the sicence of angles, and that Ptolemy worked out some of its important tables for application to the form of the earth and the motions of the planets. Newton, in his more advanced problems, similarly found the mathematics of his time inadequate, and invented what he called " fluxions," but now we call the " calculus," or the science of infinitesimal changes, to enable him to solve some of them. Even with Newton's additions, the mathematics of his time was so very far below its present state that his genius could not entirely overcome the difficulties in applying the law of attraction to the motions of the moon and planets. Nevertheless, he was able to make tremendous progress even in the difficult theory of the moon's motion, a subject which has engrossed the attention of the ablest mathematicians to the present day. Another of Newton's triumphs was his explanation of the precession of the equinoxes, that constant westward march of the sun's place among the stars at the times of equal day and night, which had been a complete enigma for two thousand years. He pointed out that it was due to the protuberance of the earth's equator, on which the attractions of the sun and moon produce this puzzling effect. He investigated the shape of the earth, and the cause of the tides. Not confined to mathematical astronomy, Newton experimented and meditated profoundly on the nature of light.

Solar spectrum discovered. — He allowed sunlight to pass into a darkened room through a hole in a shutter and to fall on a glass prism, and he found a colored ribbon of light, an impure spectrum. His books on optics are marvels of clearness of exposition, and his fundamental experiments have come down to us almost unchanged. The significant result of Newton's work is that the pure colors, and not white light, occupy the primordial position of importance, since it is possible to form all conceivable colors

including white light from a mixture of the pure colors. He investigated also the colors of thin plates. These colors we see displayed on rainy days where oil has dripped into the street, and they also come and go in soap-bubbles.

The grandeur of his accomplishments can hardly be understood by one not a mathematician, but the great Laplace says of Newton's famous work, the "Principia": "The number and generality of his discoveries relative to the system of the world . . . the multitude of original and profound views which have been the germ of the most brilliant theories of geometers . . . will assure the Principia a preëminence above all the other productions of the human intellect."

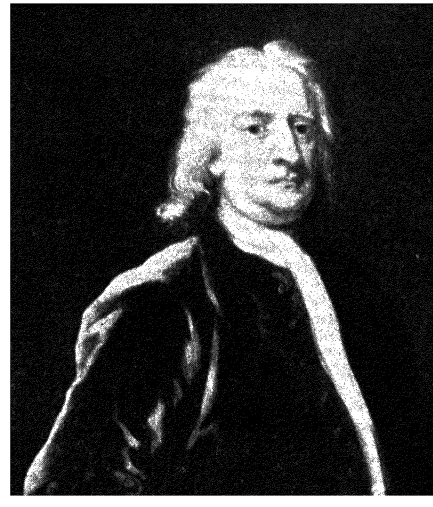

PLATE 3. SIR ISAAC NEWTON.
(From portrait at the Royal Society.)

So absorbed was Newton in his investigations, that at times he acted unconsciously, taking no cognizance of the ordinary concerns of life. Frequently on rising he would be seized by some new conception and remain for hours seated on his bedside in complete abstraction. Others had to remind him even to take nourishment. Yet he said, "I know not what the world will think of my labors, but to myself it seems to me that I have been but as a child playing on the seashore; now finding some pebble rather more polished, and now some shell more agreeably variegated than another, while the immense ocean of truth extended itself unexplained before me."

Sir Isaac Newton was buried in Westminster Abbey with royal honors. His pall was bourne by six peers of the realm. Upon his monument is inscribed, in Latin, "Let mortals congratulate themselves that so great an ornament of the human race has existed."

Bradley. — Though great progress had been made in the

astronomy of the solar system, systematic observations of the stars remained backward till long after the time of Newton. Knowledge of the stars was limited to the following facts: (1) The stars are not fixed, but they have " proper motions," or they change their positions perceptibly in long periods of time. (2) They are so remote that all attempts to measure their distances failed. (3) Some of them are brighter at times than at others, the light varying periodically. Astronomy owes much to two great men who arose at this stage: James Bradley (1692–1762), Astronomer Royal of England from 1742 to 1761; and Sir William Herschel (1738–1822), sometimes called the Founder of Sidereal Astronomy.

Bradley's exact observations of the places of stars laid the indispensable foundation for many of the discoveries of the nineteenth and twentieth centuries. His precious measurements of places for 3222 stars, reduced systematically by Bessel about 1813, provide trustworthy information of the state of the heavens in 1755. When compared with modern observations, they reveal for these stars the angular motions which have taken place in the past century and a half. But Bradley's great effort was made in the attempt to measure the distances to the stars, or in other words to determine their parallaxes. When Copernicus maintained that the earth revolves about the sun each year, he required us to believe that such changes as the earth's motion from one side to another of its orbit (a displacement of 186,000,000 miles) make no sensible change in the positions of the stars, so that the stars are either all equidistant, or else so immensely distant that this 186,000,000 miles change of the observer's standpoint does not appear to make the nearer stars alter their positions with respect to the farther ones. As everybody knows, the nearer trees of a forest do seem to cross over the farther ones when we ride swiftly by in an auto. But even Bradley with his great skill could not detect such changes among the stars. However, in attempting it he discovered the " aberration of light " and the " nutation of the earth's axis," both of which are not only highly interesting in themselves, but absolutely essential to be allowed for in all exact star positions. The aberration of light is the small displacement which a distant luminary shows on account of the advance of the observer, who travels with the earth on which he stands, while the light is on the way. Nutation is a small modification of the precession of the

equinoxes, caused by the moon's changing place in its orbit. (See Chapter IV.)

Herschel. — The genius of Sir William Herschel was of another sort. Son of a band-player in Hanover, he made music his profession for many years, and attained great success with it at the English watering place of Bath. But his mind was ever drawn to the mystery and grandeur of the starry heavens. Wishing to possess a good-sized telescope, he undertook to make one, and lenses being impracticable for him to make, he mastered the art of casting metals and grinding and polishing optical mirrors. It is said that he made no less than 430 of these metallic mirrors. He sometimes spent sixteen hours at a stretch on grinding or polishing, without stopping for food except to eat morsels which his devoted sister, Caroline Herschel (herself later the recipient of the gold medal of the Royal Astronomical Society) put into his mouth. The most famous of Herschel's telescopes was 4 feet in diameter, but he did not use it so much as some of less size.

Star gauges. — Herschel was the great explorer of the heavens. He readily perceived that the number of the stars is so great that it is out of the question for mortals to enumerate them, much less to examine each one separately. But it is highly desirable to study the distribution of the curious objects like nebulæ, double stars, and star clusters which lie among them. So Herschel undertook his famous "star gauges," counting the stars in selected fields as samples of the whole. In these studies he counted the stars in 3400 gauge-fields, discovered 806 double stars, 2500 nebulæ, systematically measured the brightness, called "magnitudes," of the principal stars, and made numerous drawings of the stranger objects which he discovered.

He spent much time on the study of the sun and sun-spots, for he perceived clearly the importance of all knowledge of solar phenomena. In one of his papers he points out that humanity in general is as closely dependent on the sun as the Egyptians are on the overflow of the Nile, so that there can be no subject more deserving of our study. After describing in much detail various surface appearances of the sun and the changes in them, he gave some statistics, which he admitted were by no means convincing, in the attempt to find some relation between the prevalence of sun-spots and the price of wheat. He had a curious theory about

the sun which we know is certainly incorrect. He believed that the spots were holes in the outer envelope of the sun that permitted us to see through to the dark central globe which was so cool that it might even be habitable!

Uranus discovered. — Herschel's arduous time-consuming labors and investigations were carried on at first in addition to his professional life as musician. But when, on March 13, 1781, he discovered the planet Uranus, and thus added another major member to the sun's family, he sprang almost at once into such fame as an astronomer that the King made him a yearly grant of £200, and thereafter he withdrew from his musical profession, and devoted himself altogether to astronomy.

Herschel systematically observed the relative positions of double stars in the belief that he might find a close double star, one of whose members was nearer to us than the other. In this manner he hoped to detect the parallax of the stars, but was unsuccessful. None of the doubles measured returned to the same relative positions after the lapse of a year, which would be necessary if one of the components of the double was much closer to us than the other. Many doubles were measured which later proved to be physically connected systems in revolution about one another, and therefore at practically equal distances from the earth. Sir William Herschel was the first President of the Royal Astronomical Society and his son, Sir John Herschel, its first Foreign Secretary. His epitaph claims for him that " he burst the barriers of heaven."

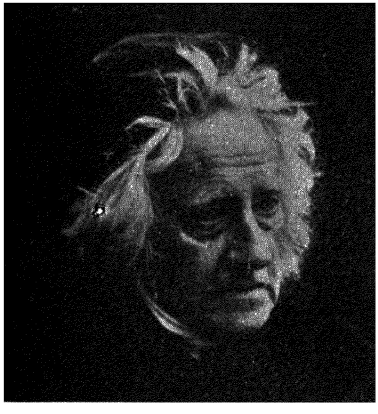

PLATE 4. SIR JOHN HERSCHEL.
(From photo by J. M. Cameron.)
The great son and successor of a famous astronomical father.

Double Stars. — Though in order of time we ought first to speak of Laplace, of Bessel and of Fraunhofer, we will go right on with the Herschel line, and speak of Sir John Herschel (1792–1871) who worthily upheld the glory of his father's name. He also made his own telescope of 18 inches diameter, and remeasured with it a

great number of his father's double stars. In this way, he noted the changes of their places which confirmed their mutual revolution, and in one case found that more than the entire orbit had been completed since discovery. The observations showed that the components of the doubles moved about each other in obedience to Newton's law of gravitation and thus extended its sway throughout the universe. Sir John Herschel confirmed his father's discoveries of nebulæ, added many new nebulæ and clusters, and found, besides, more than 3000 new double stars.

These studies lay in the northern sky. He felt the need of making similar surveys of the southern heavens, and made a famous expedition to the Cape of Good Hope (1834–1838). He made counts of 2299 gauge-fields, examined the remarkable " Magellanic Clouds," so rich in nebulæ and clusters, which he catalogued, measured over 2000 double stars and nearly 2000 nebulæ. How extraordinary are the results of such devotion as the Herschels, father and son, in those days before photography, when all the measuring had to be done at the telescope, and the telescope had no driving clock to keep it fixed upon its star!

Laplace. — And now we must turn back to Newton's great successor in physical astronomy, the Marquis de Laplace (1749–1827). In the century between these two great geniuses, who observed the heavens as fruitfully with mathematics as the Herschels observed them with the telescope, their chosen instrument, mathematical analysis, had received almost as great increase of power as had the telescope. Such masters as Leibnitz, Newton's contemporary and codiscoverer of the infinitesimal calculus, Euler, Clairault, d'Alembert, Lagrange, and Legendre had fashioned it and applied it with ever growing power to the problems of the motions of the sun, moon, and planets. And now arose Laplace, whose masterpiece, the " Mécanique céleste," brought together and amplified all that his predecessors and contemporaries had discovered and himself conceived.

Going up to Paris as a youth of eighteen, Laplace carried a letter of recommendation addressed to the great mathematican d'Alembert. But the master paid no attention to him. Then Laplace wrote him so profound a letter of his own on the principles of mechanics that the enthused d'Alembert responded: " You needed no introduction; you have recommended yourself! " Thereafter, he was Laplace's zealous supporter.

Then began a mathematical duel between Laplace and his great rival Lagrange on the inequalities of the motions of Jupiter and Saturn. The controversy brought out the most superlative brilliance on both sides, and led to the discovery of the causes of some of the most obscure peculiarities of planetary motion, as well as of the most fundamental principles which it obeys.

After this, Laplace devoted himself to his great treatise the " Mécanique céleste," second only as a work of genius to Newton's " Principia." It has been called " the 18th century Almagest," because like Ptolemy's masterpiece, it was the compendium of its subject. The five great volumes stretched out in their publication over the period 1799 to 1825. Even to experts it is not easy, partly on account of the brevity of its style. Laplace was accustomed to omit long passages of demonstration, saying merely " whence it is easy to see." But his colleague, Biot, remarks that sometimes Laplace himself could recover the omitted portion only by an hour's hard labor.

Before the publication of any part of the " Mécanique céleste," Laplace, in 1796, published a part of the pith of it more simply in " Exposition du système du monde." Here occurs the first expression of his famous " Nebular Hypothesis " of the origin of our solar system by condensation and division of a nebula which he assumed once filled the space to beyond the orbits of the outer planets.

Like Newton, Laplace gave attention to a wide range of subjects. The theory of probability, the foundations of the mathematical theories of heat, electricity and magnetism, the discussion of figures of equilibrium of rotating fluids, the gravitational attractions of bodies of different forms, and many other profound subjects were illuminated by the work of Laplace.

Bessel. — And now we may turn to several names that give glory to German astronomical science. First is Friedrich Wilhelm Bessel (1784–1846). At first a clerk in a Bremen mercantile house, but wishing to travel and seeing a possible opening as supercargo, he studied languages, geography, picked up all sorts of information on the habits of distant peoples, and learned something of navigation. From navigation, he was led on to astronomy and mathematics. He made for himself a sextant, and, observing, with the aid of a common clock, amused himself with determining the

longitude of Bremen. This fixed his career. Coming upon some old observations of Halley's comet, Bessel deduced from them so good an orbit as to charm the celebrated Olbers, who caused the work to be published. Still Bessel remained in the counting-house, but filled his leisure hours by mastering the calculus and the "Mécanique céleste," till Olbers secured for him the post of assistant in the observatory at Lilienthal with a salary of one hundred thalers a year. Olbers long after declared it was the greatest service he ever rendered astronomy when he induced Bessel to make it his profession. After four years, he was selected by the Prussian Government to be in charge of the new Observatory of Königsberg, where he remained for thirty-two years, until his death.

PLATE 5. FRIEDRICH WILHELM BESSEL
Pioneer in measuring star-distances.

His first great service to astronomy was to make patient, painstaking, exact reductions of the star places observed by such men as Bradley, applying the minute corrections for refraction, precession, aberration, nutation, and others which are indispensable to the detection of the small "proper motions" of the stars. Star rays are bent or "refracted" by our atmosphere; star places change owing to the westward march or "precession" of the equinox; they are affected by the relative motion of the earth and light which we call "aberration"; and by the moon's gravitational influence on "precession" which we call "nutation." All these effects have to be

removed before the star places become standard. Bessel's methods of reduction became classic, and were followed everywhere. It was, however, time to re-observe accurate places for the stars which Bradley and Piazzi had observed in the eighteenth century, and to add to their number, and this Bessel undertook, 1821–1833. His lists numbered 50,000. In these observations he was aided by Argelander, whom he drew away from the counting-house even as Olbers had drawn himself. This Argelander was the same who observed and published, about the year 1860, the great " Bonn Durchmusterung " and corresponding " Atlas " in which are found places and magnitudes of over 324,000 stars, including all in the northern heavens to the 9th magnitude, or some twenty times fainter than the eye can see.

Argelander. — Argelander's work made his Bonn telescope one of the famous instruments of the world. The " Durchmusterung," together with Gould's extension of it to the south pole of the heavens, is even yet, after the lapse of more than half a century, indispensable to the astronomer. But this famous telescope of Argelander's is only a simple little one about 3 inches in diameter, which shows that it is the man that counts much more than his instruments.

Stellar Distances Measured. — We have seen that both Bradley and Herschel failed in their attempts to measure the distances of the stars. Success attended the efforts of Bessel. The earlier attempts to measure distances had been made on bright stars, because it was thought that they must probably be the nearer ones. Bessel chose a new principle, and selected the star 61 Cygni which had *moved farthest of any* since Piazzi's measurements of 1792, and it therefore possessed the largest proper motion of any star then known. It was plain that the nearer a star the larger would appear to be its " proper motion," or angular displacement compared to neighboring stars. And so Bessel, from 1837 to 1840, measured from time to time the position of 61 Cygni among its neighbors. As early as the end of 1838, he was so sure of his observations that he ventured to publish the angular displacement of the star due to the earth's revolution. The astronomer calls the angle which the radius of the earth's orbit around the sun would subtend if viewed from the star, the " annual parallax " of the star, or more simply its parallax. Bessel's final value of the parallax of 61 Cygni

is 0.3483 seconds of arc, which is an angle about ten per cent greater than that given by modern determinations. One second of arc subtends an angle measured by the ratio of 1 : 206265, and is roughly one-third of an inch as seen at the distance of one mile. Consequently, if from a station on 61 Cygni we could observe the earth's orbit around the sun, the radius of it, 93,000,000 miles long, would fill just a little over one-third of a second of arc, or about the width of a telegraph wire seen at the distance of two miles.

Though Bessel was the first to publish the parallax of a star, Thomas Henderson had anticipated him in observing one, and published but two months after Bessel the parallax value of 1 second of arc for the brilliant southern star Alpha Centauri. Later measurements have reduced his value to 0.75 seconds, but it is still the largest parallax and therefore represents the least star distance known. But light, traveling 186,000 miles a second, requires 4.3 years to come from Alpha Centauri to the earth.

Fraunhofer. — On July 21, 1801, the Elector Maximilian Joseph happened to witness a sad accident when two alley houses in Munich tumbled down, and buried their occupants alive. Only one person was saved, and he a lad named Joseph Fraunhofer. The elector, moved by his distress, gave the boy eighteen ducats which the young Fraunhofer spent, part for books, part for a glass-polishing machine, and the remainder to purchase his freedom from the looking-glass maker to whom he was apprenticed.

Joseph Fraunhofer (1787-1826), though his life was lamentably short, was the father of the modern great refracting telescope, and of the still more fruitful modern spectroscope. From the time, in 1806, when he entered the optical department of von Reichenbach and Utschneider, he devoted himself to the improvement of the achromatic refracting telescope. He developed the theory of lenses and the art of glass making so far that in 1817 he perfected an object glass of finest quality, $9\frac{1}{2}$ inches in diameter. In those times, this was regarded as gigantic, for even in 1839, as Sir John Herschel tells us, a lens $7\frac{1}{2}$ inches in diameter, and perfect only to 6, was unique in the history of English glass making. Fraunhofer's $9\frac{1}{2}$ inch lens was secured by Struve for the Russian Government and installed, in 1824, as the "great Dorpat refractor." This famous instrument was used by Struve with the greatest success for the exact measurement of the angular separa-

tion and position of double stars. In these measurements Struve attained such celebrity that another European astronomer expressed the opinion that there was nothing more to do in that line of astronomy. He thought the art was "closed," as the patent men say, and that there were no more interesting doubles left for measurement. Needless to state he was mistaken, as we shall see later.

PLATE 6. JOSEPH FRAUNHOFER.
The father of modern spectroscopy.

Fraunhofer Lines in the Solar Spectrum. — It was Fraunhofer, too, who made the Königsberg heliometer, or divided-object-glass telescope, with which Bessel determined the parallax of 61 Cygni. But notwithstanding these triumphs of the optician, it is rather the spectroscopist Fraunhofer whom we are still more apt to remember. Newton, Wollaston, and others had done something in this branch of science, but Fraunhofer introduced the narrow slit to limit the entering beam of light which is indispensable to a suitable separation of the rays of the colors and shades of color found in the spectrum. When he had done so, he perceived with great distinctness many dark lines in the sun's spectrum. Wollaston indeed had observed some of them, but Fraunhofer was able to detect about 600 solar lines, to some of which he assigned the letters of the alphabet which we still employ. Among them are the heavy lines A, B, and C in the red, D in the orange-yellow, E in the green, F in the blue, G in the indigo, and H and K in the violet. But we honor their

discoverer still more by calling all dark spectrum lines, whether seen in sun- or star-light, " Fraunhofer lines." It was not, however, until after Kirchhoff's immortal discovery of 1859, that the illumination of Fraunhofer's dark lines began to dawn. From then till now they have been the master key which has unlocked, one by one, the secret storehouses of knowledge of the universe. We shall follow this wonderful story in later chapters, but in order to understand the work of Ångström, Janssen, Lockyer, Huggins, Young, Langley, Rowland, and Pickering, whose names are imperishably associated with " The New Astronomy," or " Astrophysics," we must tell briefly what it was that Kirchhoff found.

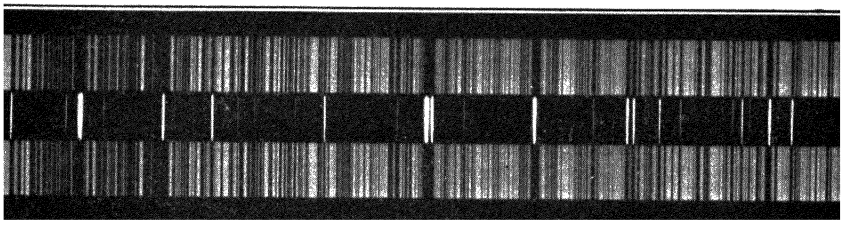

PLATE 7. EVIDENCE OF IRON IN THE SUN. (Mt. Wilson Observatory.)
The bright line spectrum is produced in the laboratory. The dark line spectrum above and below is solar. Note that every bright line has its dark solar counterpart. Many other dark solar lines appear also. These are produced by the existence in the sun of other vapors than iron.

Chemical Composition of the Sun Determined. — It was this: Every pure chemical element when heated to sufficient incandescence is a source of light which may be separated into elementary rays in the spectroscope. Unlike the hot stick of the ordinary electric arc lamp it gives out narrow bright rays in the spectrum, separated by wide dark spaces. With some elements, like iron, these are very numerous, while with others, like sodium, they are very few. But they fall almost precisely where Fraunhofer's dark lines do, and, still more suggestive, they may be " reversed," or changed from bright to dark lines if a hotter incandescent substance, like the calcium light which gives a continuous bright spectrum, is caused to shine through them. Here was proof positive that Fraunhofer's lines are produced by the existence of the ordinary chemical elements in the sun and stars. Fraunhofer's *D* line, for instance, is due to sodium. Astronomers no longer need wish that some angel would bring down star samples for analysis in the

chemical laboratory. The stars tell their own composition by the light they emit which reaches us very feebly across millions of millions of miles of space.

The Earl of Rosse. — The entrancing story of the spectroscope awaits and allures us. We must hasten through with our partial list of great position astronomers, and their works and instruments. The Herschels' greatest reflecting telescopes were eclipsed in size by the famous six-foot reflector of the Earl of Rosse (1800–1867). Sitting in Parliament as a representative Irish peer; President of the Royal Society, 1849 to 1854; President of the British Association, 1843; Vice Chancellor of Dublin University; a genial host and well-loved feudal lord of his tenantry — who would suppose that such a man would busy himself with the construction of the greatest telescope of his time?

James Short, at Edinburgh, had been the pioneer, and the elder Herschel, following after, had attained astonishing results in mirror making. But the secrets of these men died with them. Lord Rosse had to rediscover the proper proportions of copper and tin for the speculum metal, work out the process of casting, grinding, and polishing, and he did this and constructed and operated his great telescope with the aid of the Irish peasants of his estate whom he trained to this strange work. After successfully making smaller ones, his giant reflector of six feet diameter, fifty-four feet in focus, was finished, ready for observing, in February, 1845. It was mainly used for the study and drawing of the nebulæ. Many objects which had appeared nebulous to Herschel were found to be star clusters. But a new and highly important type was the spiral nebula, whose nature and relation to the stars is even yet not fully understood, though the spiral nebula forms are so remarkable and suggestive that we begin to look upon them as progenitors of star clusters.

Modern Telescopes. — Up to the time of Lord Rosse, four of the greatest aids to the modern telescope were not available. They are: Electricity, photography, exact driving mechanism, and mechanical revolving domes. The modern astronomer, sitting at his post, with eye following the guiding star, has his object kept almost exactly on cross-hairs by the automatic action of the self-winding clockwork, leaving him only the finest adjustments, to be made merely by pressing one or another of the electric buttons in his

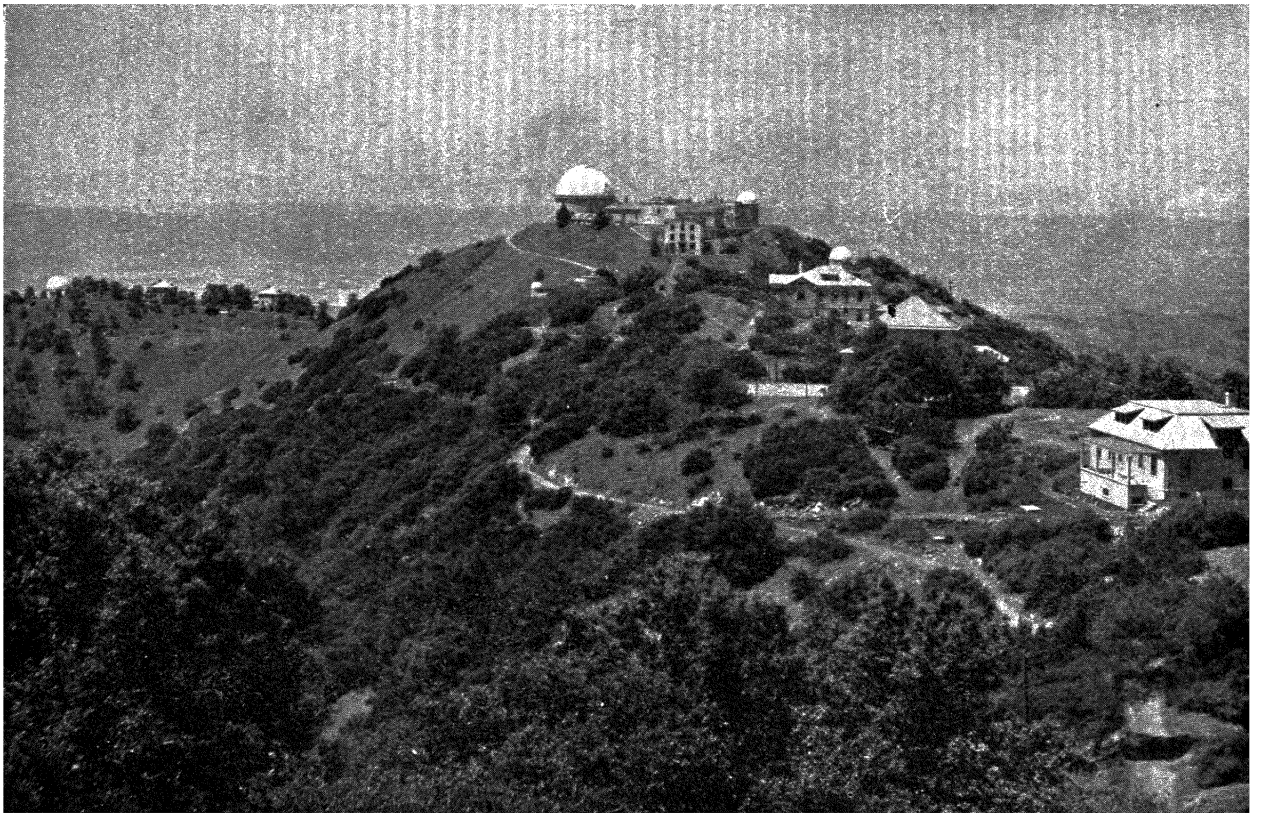

PLATE 8. THE LICK OBSERVATORY.

hand. Electric motors many yards away, responding instantly, obey his will, whether to shift the position of the star image, ever so slightly, to revolve the dome or move its shutter, or to raise or lower the platform on which the observer sits. And meanwhile the photographic plate, unwearied, constantly records an ever-gaining impression of the light which tells the secrets of the distant star. Observations which required the older astronomers to gaze hour after hour into the telescope itself, now are obtained in greater richness and accuracy, at convenience, by merely measuring in daylight the photographic records secured in a tenth or a hundredth of the time that the eye observations formerly required.

It will be well to close what we have to say about the telescope by describing two of the greatest modern instruments, the thirty-six-inch Lick refractor and the one-hundred-inch Mount Wilson reflector.

James Lick was an eccentric and wealthy Californian, who had settled there just before those known as the "forty-niners" rushed into California in the days of its gold discovery. Queer stories are told of him. In his younger days because of his poverty he had been rejected in love by the father of his intended, who was a wealthy miller. Lick vowed sometime to build a mill which should put to shame the one of his intended father-in-law, and this he did near San Jose, California, at a cost of $200,000. The interior was finished in highly polished California woods, so that it was the curiosity of the region till, unfortunately, it was burned.

As he approached old age, among many other great philanthropies, Lick formed the plan to perpetuate his memory by obtaining the most powerful telescope in the world. He appointed, in 1874, trustees, to whom he made over his whole fortune of $3,000,000 for philanthropy, and to carry out his purpose. They consulted the then foremost American astronomers, and by their advice fixed upon a great refractor, although it was out of the question to obtain one vying in size with Lord Rosse's reflector. Doubtless they reconciled their advice to Mr. Lick's desire by the consideration that with the four great aids we have just spoken of available, and with the larger field of good optical definition in which a refractor has the advantage, the proposed instrument would certainly fulfill the condition of being the most powerful telescope in the world.

The glass disks were made by the firm of Mantois in France. They were ground and polished by the firm of Alvan Clark and Sons, of Cambridge, Massachusetts, at that time the unrivalled big-lens makers of the world. The mounting, clockwork, and dome were by Warner and Swasey, of Cleveland, Ohio, since then the manufacturers of the similar parts for the great telescopes of the Yerkes and Dominion observatories. In the Lick telescope dome, for the first time, they introduced the rising floor, in order that the astronomer may conveniently do his observing with the telescope in many different positions.

It was felt not less important to select the proper site than to choose the best makers, for many of the finest telescopes of the world are placed where clouds and poor vision shamefully cut down the number of nights available for high class observation. Burnham, of Chicago, the great double star observer, tested the proposed site on Mount Hamilton, California, by observation with his own telescope. He found forty-two first-class nights and only seven that could be classed as low as medium during his stay. Nothing like such excellence of conditions had ever before been united in a site for a great telescope.

All these things took their time, and, sadly enough, James Lick died more than ten years before his great gift came into operation in 1888. His remains rest beneath the pier of the giant telescope.

There can be no question of its enormous success. With this instrument, Barnard discovered the fifth satellite of Jupiter which few men have seen, Aitken made his great series of observations of the closest of double stars, and Campbell did the classic spectroscopic work which will ever be associated with his name.

The hundred-inch reflector on Mount Wilson we owe also to the enthusiastic gifts of wealthy men. Mr. J. D. Hooker, a resident of Los Angeles, became extremely interested in the five-foot silver-on-glass reflector of the Mount Wilson Observatory. Seeing it frequently throughout its period of construction and erection on the mountain, under the design and supervision of Mr. G. W. Ritchey, he gave a sum of money to secure a larger disk of glass for the mammoth reflector of the world. There were nowhere, even in France, facilities to cast so enormous a block of glass, yet it was attempted

at the Saint Gobain glass works, which only a few years later were destroyed by the German invasion. Not being able to cast the great disk in one melting, a second lot was melted and poured upon the first before it cooled. The two lots did not thoroughly combine, so that the line of demarcation was obvious. For some years the compound disk remained in the observatory optical shop at Pasadena, while attempts were made at Saint Gobain, but unsuccessfully, to cast a better one. At length, when the failure was clear, the earlier disk was tested, and the blemish of its interior proved not to injure it for the purpose intended. But meanwhile, Mr. Hooker passed away. The subsequent preparation of the monster mirror and its mounting and dome were carried out by funds provided by Andrew Carnegie, the great steel manufacturer, through the Carnegie Institution of Washington.

Fully seven years the telescope and its smaller accessories were in building at the shops of the Mount Wilson Observatory in Pasadena, mainly according to designs of Mr. F. G. Pease. Meanwhile, the enormous excavation, and the pier of concrete almost rivaling the monster works of the old Egyptians, were being completed on Mount Wilson. Even the road up the mountain had to be widened and improved in preparation to transport the monster that was to come. The dome and larger telescope structures were at the same time being constructed by the Fore River Ship Building Company in Massachusetts, and were brought round Cape Horn and landed at the port of Los Angeles. The auto truck, without which the turns and doublings of the steep road could scarcely have been negotiated, and surely not with the long teams of oxen or horses of the old days, conveyed the immense parts to their final mountain home.

The mirror alone weighs fully four tons. With the large iron structures necessary to give it freedom of motion to follow any desired star, and to focus the starlight at the top of the tube 40 feet away, all this moving part, including mirror tube and mounting, amounts to no less than 100 tons. The problem of giving it perfect freedom in motion was solved by floating the moving part as if on a pair of ships and straddling between two miniature oceans of mercury. For at the upper and lower ends of the main polar axis are two great hollow cylinders, ten feet or more in diameter. These are enclosed by boxing which admits a film of quicksilver about a

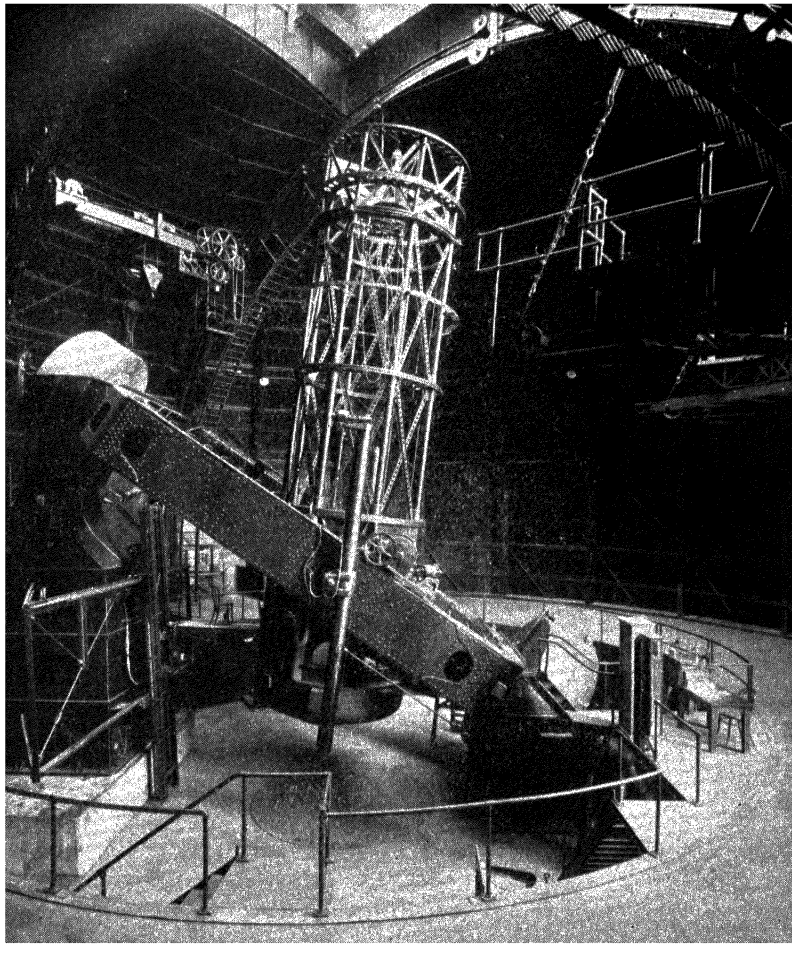

PLATE 9. THE 100-INCH TELESCOPE OF MT. WILSON OBSERVATORY.
The world's greatest telescope.

quarter inch thick on every side. As quicksilver weighs over thirteen times as much as water, these two little ships on their quicksilver seas are able to take the whole weight of the telescope off of its defining bearings. Like a canoe which rolls at slightest touch, this flotation bearing gives almost ideal freedom.

The telescope turns to follow the stars by means of a clock with a governor, something like a steam engine governor, whose two great balls rise and fall by trifling amounts, but in the mean keep the driving rate exact. This clock turns a screw which gears with a wheel, 17 feet in diameter, whose teeth are ground and polished to almost optical accuracy. Electric motors at all sorts of unexpected places enable the telescope to be moved quickly or slowly, up or down, right or left, or to slightly accelerate or retard the clock.

Provisions for all kinds of observing are there. One may sit upon a platform high up in the dome, after the Newtonian plan, or the rays may be brought down again and reflected out at the north side, close by the great mirror. Or by another scheme, called the Coudé, they are reflected southward, right down the hollow axis, and come to focus just at the south edge of the dome, as if they came from a mirror of 250 feet focal length. Photography, visual observing, heat measurements, spectrum photography, all are provided for under these several kinds of arrangements.

The telescope is housed in a dome over a hundred feet in height and diameter. Two immense shutters are run out by electric motors to right and left, and leave the telescope free to look out upon the stars from the zenith nearly to the horizon. The whole upper half of the dome revolves by electric trolleys on accurately ground tracks. The motion is so smooth that an observer standing on the dome floor cannot believe that it is himself and not the giant telescope that is in motion, unless he looks out upon the motionless stars or trees outside.

Though the demands of the great war invaded even the peaceful domain of astronomy, and laid hold of the astronomers and the observatory shop for warlike investigations, so that the telescope was delayed in its completion several years, already the Hundred-Inch Reflector has justified every hope, and has an enviable record of accomplishment that gives promise of wondrous things for the future.

First Asteroid Discovered. — As we stated above, the Marquis

de Laplace summed up all the knowledge of the motions of the solar system in the great " Mécanique céleste." But such knowledge did not halt, even with him. While Laplace was yet in the height of his powers, on the first evening of the nineteenth century, January 1, 1801, Piazzi discovered the minor planet Ceres. He continued to observe it till February 11 when a dangerous illness prevented him from going on. Not long after, the little planet became lost in twilight, and perhaps would long have remained lost, except for the brilliant work of the mathematician, Gauss, of Brunswick. He invented a new method of computing orbits, devised the system of getting the best result from observations called the " method of least squares," and from Piazzi's short series of position measures, actually predicted the location of Ceres for November so closely that the planet was readily picked up again.

Within a few months, Olbers discovered another little planet or " asteroid " which he called Pallas, and within five years more two others, Juno and Vesta, were found, all belonging to a family whose orbits lie between those of Mars and Jupiter. As time has gone on, nearly a thousand of these little planets have been discovered, so that it is difficult to name them, much more to work out their orbits so as to identify them. One of them, Eros, will deserve special mention later on, but perhaps their greatest value has been that they led Gauss into the line of study which culminated in his great work, " Theoria Motus," a worthy successor to the " Principia " and " Mécanique céleste."

Neptune Discovered. — One additional mathematical triumph remained for the astronomy of the first half of the nineteenth century. It was the independent determinations by J. C. Adams and U. J. J. Leverrier that the outstanding inequality of the orbit of Uranus could be attributed to the attraction of a major planet lying in a certain region of the heavens. This brought about the discovery of the planet Neptune, September 23, 1846. What a tribute to the human brain that, without a sight of Uranus, and merely by employing some tables of dry figures, it could call up from the depths of space another and greater planet, till then unseen, to take his place in the sun's family! Within three weeks there was also found with Neptune a moon, so that it became possible to fix accurately his mass. As it proved, Neptune is the third most massive of all the planets.

Lunar Tables. — It is our moon's motion which has given most trouble to the mathematical astronomers. Merely to print the algebraic terms representing the moon's motion requires a small quarto volume, and to compute tables from them so as to give accurately the moon's position over a long term of years is the work almost of a lifetime. This task of investigating the motion of the moon was undertaken by Peter Andreas Hansen, Director of the Ducal Observatory of Schleswig-Holstein. His daughter, Mrs. Bayard Taylor, tells in her delightful book [1] how, early in their married life, Hansen attended his sixteen-year old bride to a ball. She was dancing in her wedding gown of white satin, with a wreath of forget-me-nots in her hair, when suddenly she missed her husband. No one could tell her what had become of him. In her fear for him, she ran alone in her white satin slippers all the way from town up the steep height of the Seeberg, and found her bridegroom at his desk, deep in a problem. The idea had struck him in the midst of the dance, and, oblivious of everything, he had rushed home to put it on paper.

Hansen's " Tables of the Sun and Moon " were printed about 1860 by the English Government, which also awarded him a prize of £1000 for them. Of Hansen, Prof. Newcomb, in 1898, says: " He may now fairly be considered the greatest master of celestial mechanics since Laplace."

Even Hansen, however, did not quite succeed in smoothing out all the puzzles in the moon's motion, and something was left for our countrymen, Simon Newcomb and G. W. Hill, so well known for their labors at the Nautical Almanac Office in Washington. Finally, in this century, Professor E. W. Brown of Yale has carried Hill's methods to greater perfection, and, as it is believed, has finally laid the problem of the moon's motion to rest for many years to come.

Professor Newcomb (1835–1909) was a remarkable character. Lionlike in appearance, selfmade to be the leading American astronomer of his time, a prolific writer, with a delightful quiet humor, his " Reminiscences of an Astronomer " [2] are among the most enjoyable of biographies. He tells a story, substantially as follows, of a gravitation crank who came one day asking to see Professor

[1] "On Two Continents." Doubleday, Page, Co. 1905.
[2] Houghton, Mifflin & Co., 1903.

Newcomb. Said Newcomb, " I am he, what do you wish? " The visitor said he had called to tell him that he did not believe in Sir Isaac Newton's theory of gravitation. " Jump out of that window and be convinced, then," said Newcomb. That was not what the visitor meant, he did not believe gravitation extended to the moon. " But were you ever there to see? " asked Newcomb. " Of course not," replied the man. " Well, I never was either," answered Newcomb, " and I fear we cannot agree."

Helium Discovered. — The invention of spectroscopic chemical analysis by Kirchhoff, and its application to the sun by A. J. Ångström, about 1860, raised up a new type of astronomers. To J. Janssen and Sir Norman Lockyer belongs independently the honor of discovering the element helium spectroscopically in the sun, in the year 1868. It was nearly thirty years before this chemical element was detected on the earth, and only recently that it has been found in large quantities. The history of helium is indeed a romance in itself. Discovered in the sun and 30 years later on the earth, it combines with no other chemicals whatever.

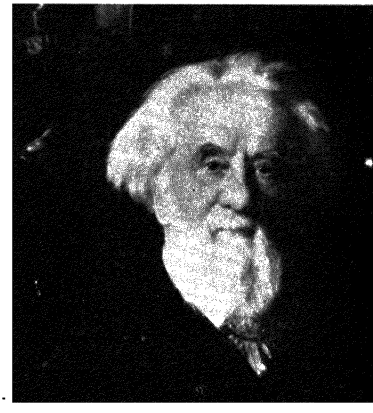

PLATE 10. SIR WILLIAM HUGGINS. (From portrait at the Royal Society.) A pioneer in Astrophysics.

Next lightest of all gases, its freezing temperature approximates absolute zero of cold. Lately found in certain gas wells in large quantities, helium being impossible to burn, makes balloons safe from fire.

Besides Kirchhoff and Ångström, Janssen and Lockyer, Sir William and Lady Huggins, who made numerous and interesting discoveries in the spectra of the stars and nebulæ at their private observatory of Tulse Hill near London, the pioneers of the new astronomy of the spectroscope are: Professor C. A. Young of Princeton, who discovered the yet unidentified " green ray " of the solar corona, who was the first to see a great storm on the sun associated with a powerful magnetic disturbance on the earth, and who wrote many choice books on astronomical subjects; Professor

S. P. Langley, late Secretary of the Smithsonian Institution, a master at visual telescopic work, who was the first to study extensively the solar and lunar spectra by the heat they produce, and who thereby traced out the invisible rays of the sun to wavelengths fully ten times greater than those of the deepest red; Professor H. A. Rowland of Baltimore, whose improvement of the accuracy of the screw led on to the ruling of very accurate reflecting gratings — polished metal surfaces ruled with a diamond to many thousand equally spaced lines per inch — with which wonderful instruments he himself made an epoch-making map of the solar spectrum, identified about fifty chemical elements in the sun, and made possible the solar and stellar work of a quarter-century; Professor E. C. Pickering, of Harvard College Observatory, who created the photographic library of the sky, wherein is daily recorded the brightness, spectrum, and places of thousands of stars, so that if at any time a new celestial object is discovered, the Harvard plates will furnish its previous history for many years.

We shall have occasion later to refer to other works of these and other remarkable astronomers. The purpose of this chapter is served if it gives the reader a bird's-eye view of astronomical history up to the beginning of the twentieth century, and some slight appreciation of those noble characters who, pursuing Truth for her own sake, have perceived her as the goddess of all countries alike, so that under her banners there can be no war.

CHAPTER III

THE EARTH

Are Other Worlds Inhabited? — The strangest thing about the earth is the people in it. Not that we are all strange people, but we do not positively know that there is another single orb in the heavens that boasts of any living inhabitants. Surely none of the visible stars, or the sun, are habitable, for they are all so hot that nothing could live there any more than in a blast furnace. As for the moon, it is a lifeless world, barren and desolate, without atmosphere or water. Only Venus, among the planets, seems a promising abode for life like ours, but it is too cloudy for us ever to see its surface. The rest of the planets surely seem very inhospitable. However, it is quite probable that among the thousands of millions of suns known to the astronomer there are many surrounded by solar systems similar to our own, and that some of these distant planets may be peopled by human beings. We shall never be able to observe any of these planets for the same reason that if we were on the nearest of the fixed stars and, armed with a great telescope, we looked at our own solar system, we could not see the earth nor even the much greater planet Jupiter. Both would be lost in the rays of the sun. Even if, in some far distant time, it should be proved that Venus is inhabited, we should have great difficulty to learn much concerning her civilization, for her tongue would be utterly unknown to us.

Influence of Temperature. — So the earth stands out because of its life, in air, on land, and in the waters. This leads us at once to think for a little of the conditions which make it habitable. One is temperature. All life depends on vegetation, and all vegetation languishes outside the temperature range + 55° to − 10° Centigrade (+ 132° to 14° Fahrenheit). These look like wide limits expressed in these terms, but let us refer them to the fundamental or absolute scale, which starts at absolute zero where molecular motion stops. We then express them as 328° to 263° Absolute Centigrade (591° to 473° Absolute Fahrenheit). Looked at in this way, we see that luxuriant vegetable life, and therefore all kinds

of life on earth, demands that the temperature shall not vary over 11 per cent either way from 296° Absolute Centigrade.

What prevents it? The sun, the air, and the water. If the sun shone as it does now, but on a cloudless earth without atmosphere, the earth's surface temperature would go to boiling by day and below frozen quicksilver by night in the United States as it does on the moon. Our equable climate is produced by the tempering effect of air, and the water vapor and clouds which it always contains.

A nice balancing of influences is in play. At prevailing temperatures, the earth radiates as much energy as it receives from the sun. We see sunlight, of course, which warms us. The sun has other powerful rays extending with great intensity beyond the red end of the spectrum to wave-lengths twice as great as the deepest red ones. Far beyond these, and wholly invisible to our eyes, are those powerful rays of the earth, the loss of which cools us. Their intensest wave-lengths are from ten to fifty times the wave-length of deep red. But these rays, through which the earth's surface is constantly cooling itself by sending them out in every direction, are cut off completely by thick clouds, and very largely by water vapor in the air.

In high-level deserts where clouds and moisture are well-nigh absent, the cooling by the earth's radiation is enormously greater than in the cloudy humid tropics, and there are, therefore, great temperature extremes between night and day, summer and winter, in such deserts. Everywhere the earth's actual temperature results from a balance between such of the incoming warmth-bringing sun rays as are able to pass the clouds and humidity, and the outgoing warmth-dissipating earth rays which escape through and from the atmosphere to space.

Life Depends on Sunlight. — In the next place, all life depends on the red, blue, and violet sun rays. For plants, which are food for other life, do not grow in darkness. There is an unknown process going on whenever sun rays of either of these three colors fall upon a plant-leaf, by means of which the plant takes in carbonic-acid gas from the air and builds it into the chemicals of life. Not only are these sun rays indispensable to all life on earth, but so, too, is carbonic-acid gas, which makes up only $\frac{1}{2\,5}$ of one per cent by weight of the earth's atmosphere.

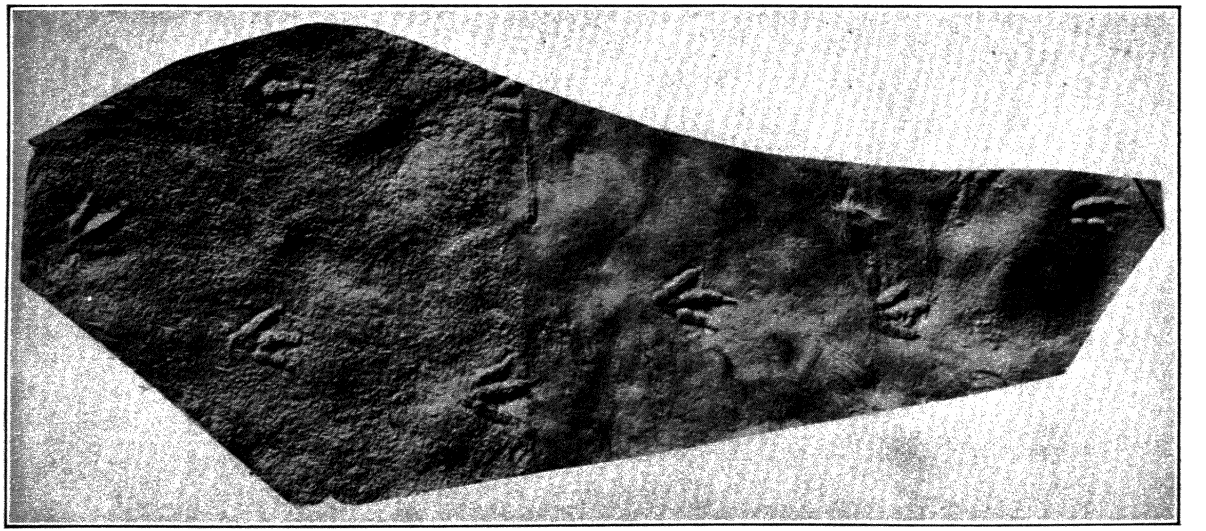

PLATE 11. FOSSIL FOOTPRINTS. (Amherst College Collection.)

The ancient creature (Anomeopus Curvatus) that walked upon a muddy shore has sent his mark to us across the great gulf of time no more convincingly than the chemical elements in distant stars are sending us the evidences of their presence in the spectral rays that bridge over chasms of both time and space equally stupendous.

In the next place, all life depends on water. Every living tissue, even bone, contains a large percentage of water, varying from 20 per cent in some kinds of bone to 95 per cent, or more, in some kinds of vegetation. Curiously enough, this indispensable liquid, water, is the only common liquid which exists naturally on the earth at the livable range of temperature, without being a product of life agencies. And this unique agency, whose properties are extraordinary among liquids, exists in perfectly prodigal profusion on the earth. For while the atmosphere weighs 5,000,000,000,000,000 tons, the water of the world weighs no less than 250 times as much.

All life depends on the extraordinary and unique chemical properties of carbon. Chemistry is, indeed, divided into two branches. Inorganic chemistry, the briefer branch, deals with *all the other* chemical elements except carbon. Organic chemistry is already far the more bulky of the two branches. Yet men are hardly more than beginning to explore its field, which deals solely with the compounds of carbon. It gets its name, organic, because it was once thought that all these compounds could be produced only by the agency of organic beings. But there is, at any rate, no other chemical element capable of combining in such a multitude of complex forms as are indispensable to the mystery we call life.

Finally, all animal life depends on the existence of free oxygen. Air is one-fifth oxygen diluted with four-fifths nitrogen, and containing some other gases in relatively trifling proportions. The oxygen which we inhale sustains a slow fireless combustion inside our bodies. It is this which keeps us alive and warm.

Thus, we see that it is no ordinary happening that life exists on our earth. Without the remarkable combination of conditions we have examined, we should perish. Some of them depend on the earth's size, and some on its rotation and distance from the sun. So we pass instantly from biology to astronomy.

Kinetic Theory. — About the beginning of this century, Professor Johnstone Stoney showed that for every planet there are some gases which must escape, others which must be retained, depending on the planet's mass, volume, and temperature. We all know how temperature affects water. The hotter it grows, the faster it evaporates, because some of the molecules, moving faster than the average, keep escaping from its surface. When hot enough, all the

water molecules move so fast that none remains, and the water becomes entirely steam.

In the atmosphere, something a little analogous goes on. Gravity tends to hold the gases down, but their flying molecules tend to escape. Very light molecules like hydrogen do escape. Probably there would be no hydrogen remaining uncombined in the earth's atmosphere, if it were not being slowly supplied, all the time, by chemical processes.

No Life on the Moon. — On the moon, gravity is so much less, because the moon has only 1/81.5 the mass of the earth, that all of our common atmospheric gases, as well as carbon dioxide and water-vapor, long ago escaped. This is why the moon is dead. So much for the influence of size and mass. But if the moon's atmosphere had always been exceedingly cold, as cold as it would have been if lying as far from the sun as Neptune, probably carbon dioxide, water, oxygen, and nitrogen would still be retained, because the molecules would not go fast enough to defy gravity to hold them.

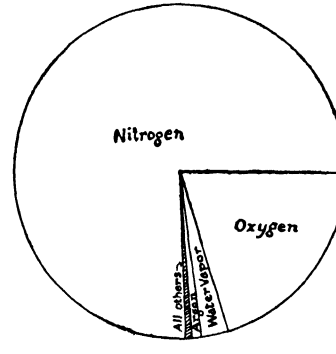

FIG. 1. COMPOSITION OF OUR ATMOSPHERE

The cross-hatched sector includes carbonic acid gas and a number of rare gases not named.

The Terrestrial Atmosphere. — About 70 per cent of the earth's surface is submerged in water, and to an average depth of 12,000 feet. The atmosphere stretches up and up, getting rarer and rarer, till at 15 miles above the earth's surface $\frac{24}{25}$ of it are left below. Yet there is air sufficient to produce by friction white heat in meteors, as they rush into it, as high up as 100 miles. At the earth's equator, the air is composed in percentage by volume roughly as follows:

	Nitrogen	Oxygen	Carbonic Acid	Water Vapor	Argon	Other Gases
Per cent	76.0	20.4	0.02	2.6	0.9	0.01

The water-vapor load varies from one-tenth per cent to four per cent of the weight of the permanent gases in different times and locations. At higher elevations, water-vapor rapidly grows less. Carbonic acid also diminishes, but not so fast. It is supposed that

at very high levels the composition of the atmosphere is utterly changed. Ozone (another form of oxygen) is there, as the spectroscope shows us, and it is supposed that finally helium (that interesting gas first found in the sun and now used to fill balloons) and other light gases become predominant.

Why are High Mountains Snow-capped? — Sometimes people express surprise that scientists assert that the earth's heat comes mainly from the sun. For, say they, the higher up towards the sun one goes on a mountain, or in an airship, the colder it is. The explanation of this paradox is easy. Sun rays heat only that which absorbs them. Perfectly transparent substances, if there were any, would not be warmed at all by transmitting sunlight. Thus a glass window-pane feels cold, though the hand grows warm inside the room when the sunlight falls upon it. So the air, being very transparent, is little warmed by sun rays, and a person on whom the cold air blows at high elevations is chilled also. But screen off the wind, and absorb the sun rays on a blackened receiver, and you will find it grows hotter at high altitudes than it does at sea-level, not because it is appreciably nearer the sun — what is a mile among 93,000,000 of them? — but because some sun rays are lost in passing through the air, even though it is very transparent.

The Approximate Shape of the Earth. — Although some people believe that the earth is flat, and others that we are living on the inside of a hollow sphere, yet it is easy to give many elementary proofs that our abode is on the convex side of the earth, which is approximately spherical, and about eight thousand miles in diameter. More than 200 years B.C., Eratosthenes and Aristotle each had a satisfactory proof that the earth is round. The former actually measured the size of the earth. It had been observed that on the day of the summer solstice (June 21) at Syene, a town up the Nile, the sun shone vertically down a well, while on the same day in Alexandria, at the mouth of the Nile, the shadow of a vertical rod cast by the sun at noon was found to subtend an angle of one-fiftieth of a circumference. Travelers said that the distance between the two places was 5000 stadia, so that the circumference of the earth is $5000 \times 50 = 250{,}000$ stadia. Aristotle had observed that at the time of the lunar eclipse, the shadow cast by the earth on the moon was circular in outline. Hence the earth must be circular in every section and must be a sphere.

PLATE 12. AN ANCIENT MAP OF THE AMERICAS.

Was California an island, or did the early navigators merely assume without proof a water connection from Puget Sound to the Gulf of Lower California? Almost certainly the latter.

In spite of these proofs, people throughout the middle ages generally believed the earth was flat, and it was not until Columbus had discovered America and later that the earth had been circumnavigated that it was generally accepted that the earth was round. Other proofs are: At sea, the horizon is everywhere circular in outline, and ships are seen "hull down." As we travel north, for each seventy miles traversed, the pole star increases its altitude one degree. Places east and west have different times; in London the time is 5^h faster than in New York and 8^h faster than in San Francisco. For ordinary purposes it is sufficiently accurate to regard the earth as a sphere of 7918 miles in diameter.

Figure of the Earth. — If the earth were a sphere, the length of one degree of arc measured along a meridian would be the same in all latitudes. This is found not to be the case. One degree of arc becomes greater and greater as we go from the equator to the poles. The determination of the exact shape and size of the earth represents the continued work of the geodesist and the astronomer in measuring the lengths of long arcs on the earth's surface. These arcs may be: (a) north and south along a meridian, (b) east and west along a parallel of latitude, or (c) oblique arcs. After the geodesist, or engineer, determines the lengths of these lines in miles with the highest degree of precision, the astronomer determines the position of the points on the earth's surface in order to find the length of arc in degrees subtended by the measured lines. The geodesist begins by measuring a base-line, from three to five miles in length and attains an accuracy of about one part in a million. Starting from this base-line, the country is covered with a series of triangles and quadrilaterals. By measuring the angles of the triangles very carefully, a triangulation is made and the lengths of all the sides of the triangles are found by trigonometry. Before the end of the eighteenth century, nine arcs had been measured. At the present time, many arcs have been measured in all of the civilized countries of the world. The arc across the United States, over 3000 miles long, is known to within a probable error of 85 feet. The determination of the exact shape and size of the earth is a problem of the very greatest difficulty.

For general studies we require not the detailed figure of the earth with its mountains and valleys, but rather the level at which water would stand if canals were driven through the continents

from ocean to ocean. This is known as the *geoid.* This has no regular figure but has bumps on it like a potato. The nearest regular figure is an oblate spheroid, shaped like an orange, bulged at the equator with a radius of 3963.3 miles, and flattened at the poles with a semidiameter of 3950.0 miles. The polar diameter is 26.6 miles shorter than the equatorial. The ellipticity, or flattening of the earth is $\frac{1}{297}$.

The shape of the earth, but not its size, can be ascertained by means of pendulum observations. Special pendulums are used which are caused to swing in vacuum enclosures for many hours, and these are employed at many points on the earth's surface. The time of vibration at each station gives a measure of the force of gravity there. After applying known corrections, the relative distance of the earth's center from all the pendulum stations becomes known. Certain astronomical observations are also utilized to determine the shape of the earth.

Foucault Pendulum. — It was not until 1851 that an experiment was performed by the French physicist Foucault giving ocular demonstration of the rotation of the earth. From the dome of the Pantheon in Paris a heavy iron ball was suspended by a wire more than 200 feet in length. This ball was free to swing in any plane, and it was accordingly a gigantic simple pendulum. The heavy ball was pulled aside from its position of rest and tied firmly by a string. After all motions had ceased, the string was burned and the pendulum was set swinging. The direction of the plane of motion must remain the same in space as there is no force acting on it tending to make it revolve. Consequently, if the earth were fixed in space, the pendulum would move back and forth in the same plane. Foucault found, from a marker placed below the ball, that the pendulum was apparently moving a little farther to the right (clockwise) at each end of its swing, and that the pendulum would have made a complete revolution at the end of 32 hours. As we have seen that there is nothing to make the pendulum alter the plane of its vibration, we must come to the conclusion that the apparent motion of the pendulum clockwise was actually caused by a shifting of the earth under the pendulum in a direction contra-clockwise.

If this experiment could be performed at the north pole of the earth, it would be found that there would be a complete revolution

in 24 hours, while at the equator there would be no rotation apparent at all. If we take a postage stamp and stick it on a terrestrial globe with one edge parallel to the meridian, then at the equator there is no rotation of the edge of the stamp with respect to the original direction of the meridian as the globe is turned. As the stamp is moved from the equator to the pole, the angle through which the edge of the stamp revolves with respect to the original meridian as the globe is rotated by a certain amount becomes greater and greater as the pole is approached.

Except for places at the equator, the meridians on the earth converge. By elementary trigonometry we derive a formula for the convergence of the meridians. This same formula is that for the rotation of the Foucault pendulum, which is 24 hours divided by the sine of the latitude.

The Rotation of the Earth. — Newton came to the conclusion that if the earth is rotating it must be flattened at the poles. Conversely, the shape of the earth is proof that the earth is rotating. The diurnal rotation of the sun, moon and stars can be explained either by supposing that the heavens revolve (as was thought before the time of Copernicus) or that the earth turns on its axis. Either explanation geometrically interprets the observed facts. However, now that the great range of distance of the sun and the stars is known, it would require an absurd adjustment of incredible speeds of revolution of all these heavenly bodies if we should conceive that they revolve daily about the earth. Hence, we must adopt the alternative hypothesis of Copernicus, namely that the earth is rotating on its axis once in 24 hours.

Other Proofs of the Earth's Rotation. — A gyroscope, which is a very heavy wheel carefully balanced and spinning rapidly, may be utilized to show a fixed plane by its rotation. If the gyroscope is set in rapid motion, the rotation of the earth will appear to make the gyroscope rotate, the theory being the same as for the Foucault pendulum.

The gyroscopic principle has recently been utilized to construct a compass whose position will be determined by the rotation of the earth on its axis. The gyroscopic compass points to the north pole of the earth, and gives the " true north " while the ordinary compass points to the " magnetic north." The difference between the two norths as given by the two compasses is called the

" deviation of the compass," a quantity difficult to determine, which varies from place to place, and must be allowed for when navigating by means of a magnetic compass.

The top of a high tower is carried by the rotation of the earth through a greater distance than the bottom of the tower. As the earth is rotating from west to east, a body let drop from a high tower should fall a little to the east of a point vertically beneath the point of projection. The experiment is difficult to carry out with accurate results because the deviation is small and currents of air are very troublesome.

In the northern hemisphere, projectiles are deviated to the right and in the southern hemisphere to the left. For this reason cyclones in the northern hemisphere have left-handed motions, and in the southern latitudes have right-handed or clockwise rotations. The Foucault pendulum may be regarded as a projectile, so that at each end of its swing it deviates to the right and consequently moves clockwise in the northern hemisphere. The trade winds are a consequence of the rotation of the earth.

Is the Rotation of the Earth Constant? — The earth is like a gigantic top spinning rapidly on its axis. Why does it not slow down and stop? If there were friction to overcome, as with a top, the earth would slow down. The earth in its rotation carries its atmosphere with it, otherwise there would be a wind of 1000 miles an hour at the equator. The rotation of the earth is the measurer of our time, and it is of the utmost importance to the astronomer to know whether the day is of constant length. The water flowing over the surface of the earth by tidal action causes friction which tends to slow down the earth, while the contraction of the earth by its cooling causes the earth to move more rapidly. Many millions of " shooting stars " are picked up by the earth each day which cause the earth to weigh more, and consequently to rotate more slowly. The various effects that would accelerate or retard the rotation of the earth appear to nearly compensate each other, so that the rotation is remarkably constant. Observations stretching over long periods of time, such as eclipses of the sun or moon, are utilized to check up the period of rotation. There are some indications that the length of the day has altered somewhat, and at the present is lengthening by one-hundredth of a second in a century. The change is small and we can not know whether the rate of change is temporary or permanent.

The Mass of the Earth. — The mass of the earth is the next most interesting quantity. To obtain it, we have to weigh the earth in terms of a standard weight. Several ways of doing this have been used. The most striking, perhaps, was among the first employed. In the year 1775, the Astronomer Royal Maskelyne, working under the auspices of the Royal Society of Great Britain, made the celebrated measurements of the deflection of the vertical, as indicated by a plumb line or a level, by the attraction of the mountain Schehallion in Scotland. The idea was thus to compare the attraction of the mountain to the attraction of the whole earth, and then, by taking samples and measurements, to find how many tons the mountain weighed. But the results were rather uncertain. Perhaps the best method is called the method of Cavendish, and was best employed by C. V. Boys in the year 1894. Two small balls on opposite ends of a rod, supported at its center by a fine-drawn fiber of quartz crystal, are attracted by large masses suitably placed so that the fiber is twisted through a measured angle. The force of the twisting, in terms of the earth's attraction, known as the "torsional constant," is measured by noting the time of swing of the rod; and hence the attraction of the large masses for the small ones is compared to the attraction of the earth for them. The earth's attraction for the balls is measured by weighing them in an ordinary balance, and thus the mass of the earth is obtained.

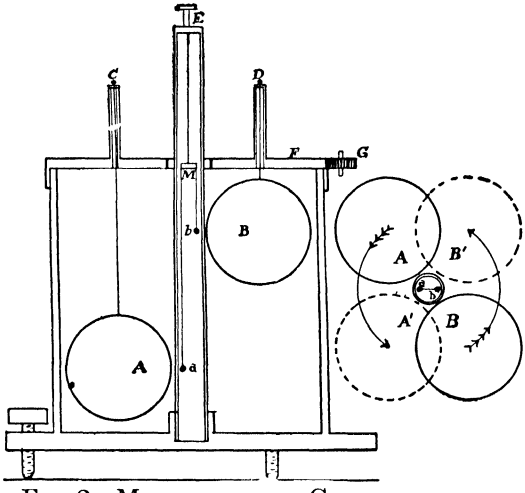

FIG. 2. MEASURING THE CONSTANT OF THE FORCE OF GRAVITY (Boys).

In order to weigh the earth against the large balls, A, B, the little suspended balls, a, b, whose time of circular vibration is observed, so as to measure the earth's attraction for them, are arranged to be attracted first in one direction, then in the other, by the balls, A, B.

As it comes out, the earth's mass is 5.997×10^{24} kilo-

grams[1] (1.320×10^{25} pounds). Compared to an equally-sized globe of water, the earth weighs 5.52 times as much. This also is very interesting, for earth and rocks, such as form all of the solid earth which we can ever explore, weigh, on the average only 2.8 times as much as equal volumes of water. Hence it is plain that down below these materials must be others very much heavier.

The Earth's Interior. — Calculations and experiments have been made which show that it is quite out of the question to assume that this increased density towards the earth's center comes merely from the enormous compression caused by the weight of the overhead layers. Yet when one considers that the pressure at a thousand miles depth is about 10,000,000 pounds on each square inch, this suggestion does not seem so foolish.

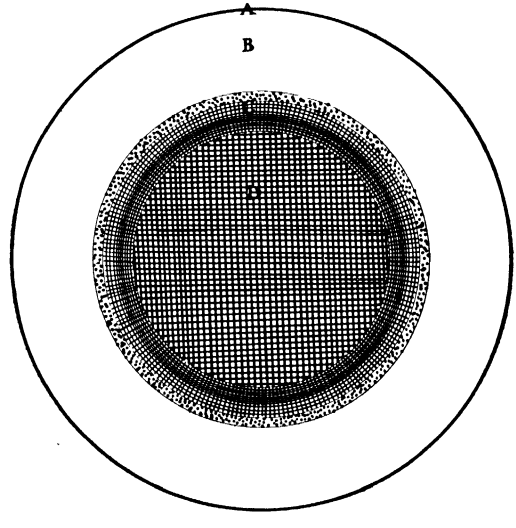

FIG. 3. THE EARTH'S INTERIOR (after Williamson and Adams).

A is the outer crust of granitic rocks 35 miles thick. *B* is a layer of silicates of iron and magnesium, about 1,000 miles thick. *C* is a layer in which the silicates gradually change to metallic iron 850 miles thick. *D* is a central core of nickel-iron.

Taking all known facts into consideration, such as the speed of earthquakes, the earth's moment of inertia, along with those we have spoken of, the best opinion is that the earth has a skin of ordinary earth and rock about 60 kilometers (37 miles) thick, then a shell 1600 kilometers (994 miles) thick of compounds of iron, magnesium, and silicon, then a shell 1400 kilometers (869 miles) thick in which iron begins to predominate, and finally a nickel-iron core something like a meteorite in make-up, 6800 kilometers (4225 miles) in diameter. The pressure at the center is something

[1] Which means 5997 followed by twenty-one ciphers!

like 50,000,000 pounds per square inch, and the material there is about 10 times as heavy as water. Of course, other substances like platinum, gold, silver, lead, copper, are scattered through the mass, but it is not supposed that they make up a very large proportion of the central core compared to nickel-iron. This view is taken partly on account of the well known composition of meteorites.

The Variation of Latitude. — We have likened the earth to a top spinning without friction on its axis. There is a small vagary connected with the earth's motion, a wobbling in its rotation. This is called the "variation of latitude," and was discovered by Chandler about 1890. He found that when the best sets of star observations ever made were cleared of all known defects, such as precession, aberration, and the others, there remained certain variations that were of a periodic nature, running a course in about 14 months. The nature of the variation was not constant, but in 1890 was as if the pole of the earth's rotation was wandering over the earth's surface in an orbit from west towards east, so that changes of latitude amounting in the aggregate to something like 30 feet actually occurred. From Bradley's observations, 160 years earlier, Chandler found the same type of polar wandering, but larger in amount, and taking place in little over a year instead of fourteen months.

This puzzling change was finally found to be due to the fact that the wandering of the pole is not a simple effect, but the combination of two, and possibly even three. The two principal ones have periods of 427 and 365 days, and of these the first is largest, but the second is variable in its magnitude. Sometimes the two conspire together and produce larger wanderings, while at other times they interfere and the wanderings are less. They go through the full cycle of these changes in 7 years.

The discovery appeared so important that six observatories were founded, located in the United States, Japan, Russia, and Italy, respectively, all at closely equal latitudes, for making the most accurate possible series of latitude determinations, so as to measure exactly the march of the pole. Their work was continued without interruption from about 1900 until the great war, when Russia fell out, and there has been some delay since in proper reduction and publication of the results, though the observations are still being continued at several stations.

The reason for the existence of the larger component part of the variation of latitude is too abstruse for a book of this kind, involving, as it does, principles of mechanics as applied to the rigidity

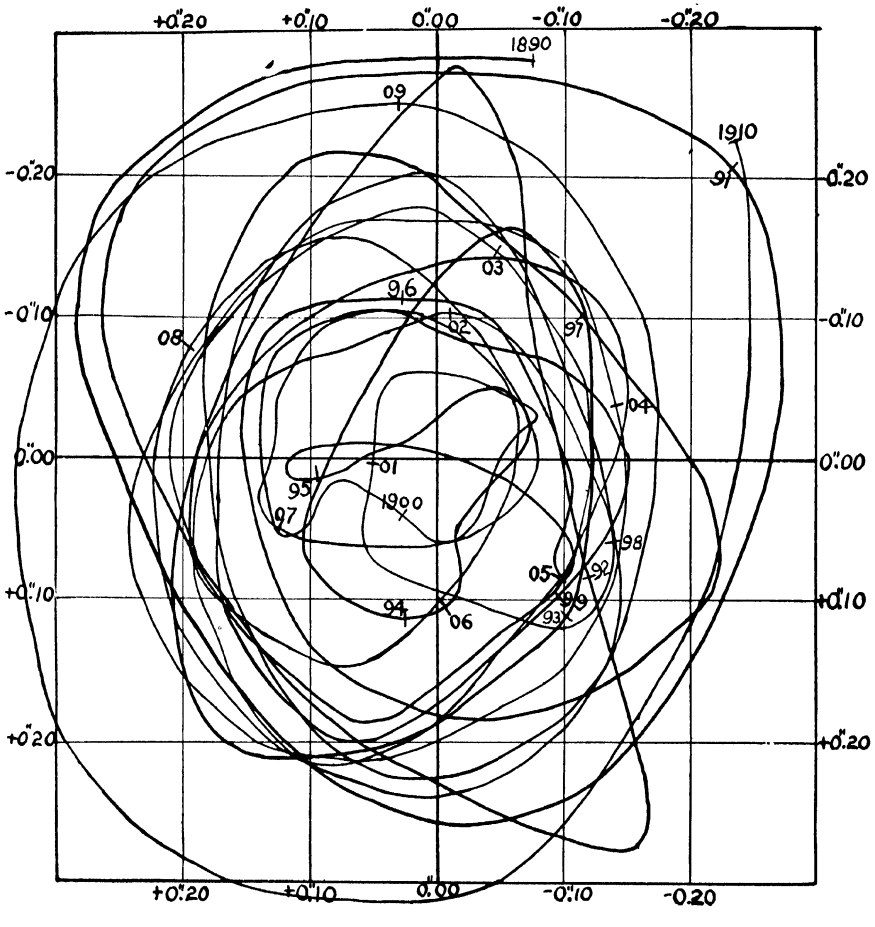

FIG. 4. Wanderings of the earth's pole from the year 1890 to 1910. The scale is in seconds of arc. The extreme diameter of the figure, about 0".6, corresponds to about 60 feet on the earth's surface. (After Albrecht.)

of the earth, and the relation of the axis of rotation to the axis of symmetry of figure. As for the second factor, whose period is a year, one might well expect some such thing, considering the unequal advance and retreat of the winter snow and ice, and other changes which attend the seasons. Without going further into causes, we must be glad that the discovery led to clearing up some

puzzling discrepancies in the work of several astronomers, which had hitherto cast some discredit on their reputations for accuracy, and on the excellence of their instruments. Now their work takes a rightful high standing.

Atmospheric Refraction. — One other thing which adds difficulty to accurate astronomical work is atmospheric refraction. We have all seen an oar looking like a broken stick in the still water. Light is like an army which marches along with even front until one wing comes to a difficult stretch of territory and lags behind, so that the average direction of the front swings through an angle. So it is with light from the submerged part of the oar. As it reaches the air-surface, where it travels easier, the light is turned (" refracted " is the technical word) in its course.

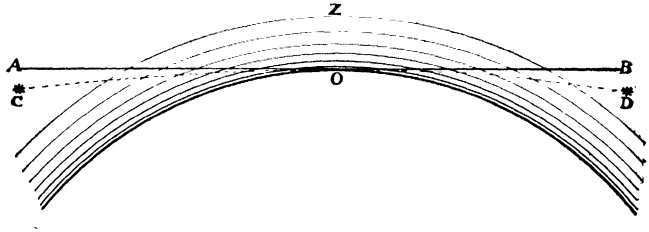

FIG. 5. ATMOSPHERIC REFRACTION.

The observer at *O* is beneath a sea of air *OZ*, which gradually grows less dense from the ground upwards, till at 100 miles elevation the atmospheric rarity rivals the best vacua. When the heavenly bodies are quite appreciably below the sensible horizon, *A O B*, they may still be seen owing to the curvature, called refraction, which their rays experience in passing obliquely through the gradually densifying air layers. This is indicated with exaggeration by the rays *OC*, *OD*.

This happens, too, in the lens and the prism, and also in the atmosphere. For the air next to the earth is denser than what is above, and light travels slower in it. Hence, the sun's rays at setting are bent around towards the earth, and therefore the sun can be seen after the clock says he should be below the horizon. Thus it is, too, with all stars, but to a less and less extent the nearer they are to the zenith, where the atmospheric refraction becomes zero. The refraction varies with altitude, barometric pressure, temperature, and differs for all different colors of light. Hence, it is very difficult to make a satisfactory allowance. It is very time-consuming, with this, and the other little corrections, to get exact results from star observations.

CHAPTER IV

THE MOTIONS OF THE EARTH

The Annual Motion of the Sun. — In the preceding chapter we have had certain proofs that the earth is rotating on an axis, thus causing the rising and setting of the sun, moon and stars. The earliest scientific observation ever made by man may well have been that of noting when the sun was at noon by placing vertically in the ground a straight stick, or gnomon, and watching the direction of the shadow as it progressed along the level ground.

Very early in the history of the human race it must have been noted that the length of the shadow at noon-mark varied during the progress of the year, being longer in winter (in the northern hemisphere) and shorter in summer. Likewise it was seen that the position of the point of sunrise changed along the eastern horizon. At the time of year of the longest daylight hours, the sun rose farthest north of east, and at the time in winter when the gnomon cast the longest shadow, the sun rose farthest south of east and set farthest south of west. The year, or the interval of time for the sun again to return to the same position was early found to be approximately 365 days.

It needed little of systematic observation to find that not only is the sun moving north and south in the sky, changing from the position of farthest south at the winter solstice on December 22, to that of farthest north at the summer solstice on June 22, but with respect to the stars the sun is found farther east each day, or with respect to the sun the stars are farther west each night. The plane in the sky in which the sun appears to move during the course of the year is known as the *ecliptic.*

The Annual Motion of the Earth. — The motion of the sun each year eastward in the plane of the ecliptic is only an apparent motion and not a real one. The moving body is the earth on which we live which once a year makes a journey about the sun in the plane of the ecliptic. As far as appearances go, it is immaterial whether we regard the sun or the earth as the moving body, but we shall later give reasons for believing the earth to move.

The Orbit of the Earth. — As the earth travels about the sun, it is easy to ascertain that the distance to the sun is not constant. This fact was known to Hipparchus over 2000 years ago. The angular diameter of the sun is observed to vary during the course of the year, being the greatest on January 1 and least on July 1. Of course it is improbable that the linear diameter of the sun would change so regularly each year. Just as a half-dollar looks much larger to the eye when close to us than when far away, so would the sun. Hence it must be closest to the earth on January 1 and farthest away on July 1. Here are the approximate semi-diameters of the sun;

January 1	16′ 17″.9	July 1	15′ 45″.7
April 1	16′ 2″.1	October 1	16′ 0″.4

The average value for the year is 15′ 59″.63. It is readily seen that the semidiameter on January 1 is approximately one-sixtieth greater than the average, and that on July 1 is one-sixtieth less than the average. Hence the distances from sun to earth vary by the same ratios. The sun is not in the center of the earth's orbit but is displaced from the center a million and a half miles towards the place where the earth is found on January 1. Obviously the sun is three million miles closer to us on January first than it is on July first.

Speed of the Earth in its Orbit. — By referring to the Government publication, the *Nautical Almanac*, published each year, it will be found that the motion of the earth in its orbit on January 1 is much faster than on July 1. Owing to the earth's motion, the sun changes its *celestial longitude*, or angle measured in the plane of the ecliptic. By means of drawing instruments, a protractor and a scale, it would be easy to make a diagram of the earth's orbit. If this were done, it would be found that the earth moves about the sun in an ellipse and with the sun in one focus of the ellipse. The average speed of the earth in its annual journey may be closely found by assuming the orbit a circle. The average speed is

$$\frac{2\,\pi \times \text{distance from earth to sun}}{\text{number of seconds in one year}}$$

This is 18.5 miles or 30 kilometers per second. This is a speed of 1100 miles per minute, a thousand times faster than an express train, and yet we have no sensations of our rapid flight.

The Distances from Earth to Sun. — By means of the refined researches of the mathematical astronomer an accurate plot can be drawn to scale of the orbits of all the planets and satellites of the solar system. The period of each of these bodies has been determined accurately and the shapes of their orbits. All of the planetary distances have been expressed by the astronomer by referring them to the *astronomical unit*, the distance from earth to sun. If we know accurately *one* distance in miles of this astronomical plan, either that of the earth to the sun, or of the earth to one of the planets, all distances will then be known. Celestial distances are usually found by the methods of the surveyor who wishes to ascertain the width of a river which he cannot traverse, by measuring a base-line and angles and solving by trigonometry. A civil engineer would be in a quandary if a base-line of only three inches in length was available for measurement on his side of the river, with the river a mile in width. This is exactly the problem that confronts the astronomer in attempting to measure directly the distance of the sun.

Solar Parallax. — Instead of expressing the distance to the sun in miles or kilometers, the astronomer replaces this unit ordinarily by means of the small angle at the sun (about 8.80 seconds of arc) subtended by the earth's radius, and this angle is called the solar parallax. As the earth is not a sphere and there are many different terrestrial radii, the equatorial radius is assumed. The distance to the sun when expressed in miles must therefore be subject, not only to all the errors of the astronomer in carrying out his measurements, but also to those due to the work of the geodesist in determining the size of the earth and in referring these measures to the standard yard or meter. It is a curious thing to consider that, if we should accept the sun's distance as now known, we could work backwards and ascertain the diameter of the earth without troubling a single surveyor. The result would be accurate within one part in a thousand.

Since the value of the solar parallax is so small and it is impossible to determine the angle with accuracy by direct measures from the earth, we must then measure the distance to some nearby object of the solar system where the value of the parallax is larger. The objects most frequently used in the past have been Venus, Mars and some of the minor planets.

In the years 1761, 1769, 1874 and 1882, the planet Venus moved across the face of the sun causing a *transit of Venus*. Many attempts were made at these transits to measure the solar parallax, but without very good results. There will not be another event of this nature until the year 2004.

Gill made some notable measures on Mars and the minor planets for determining the solar parallax. In 1898, the planetoid Eros was discovered which at intervals comes closer to the earth even than Mars. Although much was accomplished in 1900-01, when Eros at its nearest approach was 30,000,000 miles from the earth, much more will be expected in 1931 when the small planet comes to within half this distance.

The velocity of light can be utilized to find the distance to the sun by three different methods: (a) by the constant of aberration; (b) by the eclipse of Jupiter's satellites; and (c) by the velocity of the earth in its orbit, measured by the spectroscope.

The Velocity of Light. — This quantity has been measured very accurately by Michelson, Cornu, Fizeau, and others. Imagine a toothed wheel rapidly revolving, and a beam of light brought to focus just where it would meet either a tooth or a space in the rim of the wheel. Then let the ray pass out several miles to a mirror which reflects it straight back to the teeth again. You will see at once that at a certain speed of the wheel the ray would pass between two teeth, go out to the mirror, and on its return meet the adjacent tooth and be cut off, giving darkness. But at double this speed of the wheel, the ray would slip by between the next pair of teeth. So by increasing the speed gradually, and counting the alternations of light and darkness, one could get many teeth to pass, and obtain a high degree of accuracy in the measure of the time required by light to go out to the mirror and return.

Those interested may consult books of reference on light, and learn of other methods, but they all agree closely. By far the best value is the very recent one of Michelson 299,796 kilometers (186,285 miles) per second. Its probable error is less than 1 kilometer (0.6 mile). This being known, we have the sun's distance, if we can measure the time required for light to come to us from the sun. We saw in Chapter II that Galileo discovered the four moons of Jupiter with his telescope. These moons are frequently eclipsed by Jupiter's being between them and the sun in part of their revo-

lutions about him. As we watch these eclipses from the earth, they do not follow at perfectly regular intervals, because Jupiter and the earth are at different distances apart in their orbits from time to time. Thus, light has farther to go to us from Jupiter's moons when Jupiter is directly beyond the sun than when he is directly beyond the earth. The difference is just the diameter of the earth's orbit. Thus, by observing the times of the eclipses of Jupiter's satellites, and combining with the velocity of light, we find the double distance of the sun.

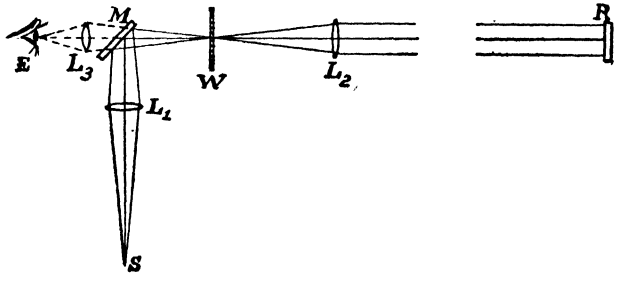

FIG. 6. TOOTHED-WHEEL METHOD FOR VELOCITY OF LIGHT.

From the bright source, S, a beam is focused by the lens L_1, and the thinly silvered mirror, M, upon the rim of the toothed wheel, W. Thence the light diverges to the lens L_2, which sends a parallel beam to the distant mirror, R, from which it returns through L_2, W, and M, and is focused by the lens, L_3, at the observer's eye. At great speeds, the teeth of the wheel, W, give alternately light and darkness, according as the returning beam strikes a tooth or a space. Knowing the speed of the wheel and the distance traveled, the velocity of light is calculated.

The present accepted value of the solar parallax is 8″.80, corresponding to a distance of 92,900,000 miles or 149,510,000 kilometers. To walk the distance from the earth to the sun at four miles per hour and ten hours a day, would take 68 years for the first million miles and 6300 years for the total distance. An airplane going at 60 miles per hour would take 175 years. Sunlight completes the distance in 499 seconds of time.

Torrid and Arctic Temperatures. — The changes of temperature from pole to pole of the earth are due to the fact that the earth is nearly spherical. For consider an open frame a yard square to be set up so that it is at right angles to the sun-

beam, and at noon on March 21 or September 23 carry it so from pole to pole. At the equator, the shadow of it will be of the same size as the frame, because, the sun being directly overhead, the frame is parallel to the earth's surface. But as we leave the equator in either direction, the earth's surface grows more and more oblique to the frame, and therefore the shadow of it gets bigger and bigger, till at the pole it becomes miles long. All of this time, the frame lets through just the same area of sun rays. Scattered over the larger area on which they fall, it is easy to see why they produce less warming.

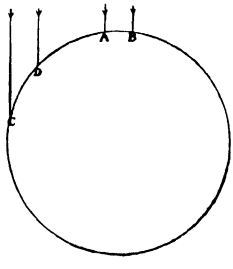

FIG. 7. COLD WEATHER AT THE POLES DUE TO THE OBLIQUITY OF SUN RAYS.

Compare the widths *AB* and *CD* over which the warmth of equal bundles of solar rays must be distributed at the equator and near the poles.

It is, of course, the same sort of proposition between noon, morning, and night, only that the atmosphere keeps the heat over night to a considerable degree, so that the extremes are much less than between the equator and the poles, where they have nights six months long. Also, the same sort of considerations show why mountains, broken by ravines, and with their steep slopes having so much exposed surface oblique to the sun's rays, are cooler.

The Seasons. — The seasons, which also occur because of change in the obliquity of sunbeams, depend on still another factor. Like a gyroscope, the spinning earth keeps its axis nearly in a fixed direction in space, pointing near the north star. But the ecliptic, or orbit in which the earth revolves about the sun, is inclined about $23\frac{1}{2}$ degrees from the earth's equatorial plane. Remember that the sun is practically unchanged in direction among the stars, no matter where you stand upon the earth. This is because the earth is so small, compared to the immense distance of the sun from us. To move clear from the south pole to the north would only displace the sun among the stars by 17.6 seconds of arc, or about as much as the width of a window seen six miles distant.

When the sun lies in the plane of the equator, it is neither winter nor summer anywhere, because then he is shining quite impartially upon the earth, and day equals night in length everywhere. But

since the plane of the equator is inclined to the plane of the ecliptic, this can only happen twice in a year. It is when the earth, in its revolution, reaches the line of intersection of the two planes. This occurs at the " equinoxes," March 21 and September 23. At all times between September and March, the sun is south of the

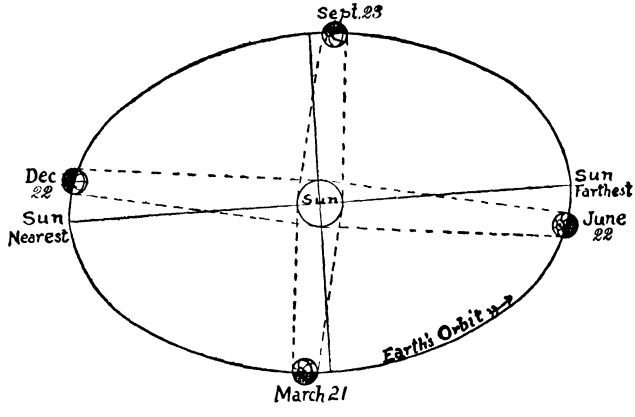

FIG. 8. CAUSE OF THE SEASONS.

The earth's equator is inclined about $23\frac{1}{2}°$ from the plane of its orbit, and the earth's axis always keeps in parallel positions as the earth revolves about the sun. Hence, part of the northern hemisphere is in shadow in the months near December, and part of the southern hemisphere in those near June. At the equinoxes, in March and September both hemispheres are fully illuminated. The sun is nearest in January so that the northern winters are warmer than otherwise they would be.

equator and favors the southern hemisphere, while between March and September, he favors the northern hemisphere. We reach the extreme positions at the " solstices," December 22 and June 22.

Precession of the Equinoxes. — We noticed in Chapter II that though Hipparchus discovered the " precession of the equinoxes," Newton, 2000 years later, explained it. Let us first state clearly what Hipparchus discovered. When the constellations were first named, the March equinox occurred when the sun was in the direction towards the constellation Aries. But as time went on this direction steadily changed until now the sun is in Pisces at the March equinox. That is to say there has been a " precession " of about 28 degrees towards the west. Newton showed that this was precisely the sort of thing which ought to happen because of the attraction of the sun and moon for the protuberance of the

earth's equator. The earth, indeed, can be looked upon as a monstrous gyroscope, and a force which pulls it in one direction starts a " precession " around an axis, so that the real motion which occurs is at right angles to the action of the force which produces it. You may see the same thing in a top, which is a kind of gyroscope. The pull of gravity which tends to tip the top over merely causes it to go round and round a conical figure. In consequence of the precession of the equinoxes, the pole of the earth, like the axis of a top, makes a swing among the stars. This takes 25,800 years. While now the pole points within $1\frac{1}{4}$ degrees of the north star, 12,000 years hence it will point close to the bright star Vega.

Nutation. — We saw that the Astronomer Royal, James Bradley, in seeking to detect " parallax," or the apparent motion of stars due to the real motion of the earth around the sun, failed therein but found instead " nutation " and " aberration." Nutation is but a sort of lunar excrescence to " precession." For since the gravitational pulls of the sun and moon on the protuberance of the earth's equator together produce precession, it is easy to believe that because the moon moves around the earth 12 times a year, marching very far to the north and south, and also very elliptically in her orbit, her attraction must be variable, and must give a nodding or wavy curve to the general circular march of the pole of the earth attending precession. This wavy motion is " nutation."

Aberration. — Bradley's " aberration " is quite of another sort. It is the result which comes to the apparent position of stars from the velocity of light not being infinitely great compared to the speed of the earth in its orbit. Bradley, indeed, was led to its explanation one day while boating on the river Thames. For he saw that the vane at the masthead pointed to a different quarter, depending on which way the vessel steered, and this without a change in the wind's direction. We are all familiar with a similar phenomenon when in the rain with an umbrella. If there is no wind and the rain is falling vertically, we hold the umbrella directly over our heads. When we walk, the umbrella has to be inclined forward, and the faster we walk the more has the umbrella to be tilted forward in order to keep ourselves dry. It is a question of relative motion.

Similarly with the stars. As the earth travels its orbit at, roughly, 18.6 miles per second, those stars lying over opposite to

the sun's direction in the plane of the ecliptic are apparently displaced by the angle whose measure is 18.6/186000 or 20 seconds of arc. Six months later, as the earth travels in the opposite direction, the same stars are displaced equally in the contrary direction. Clearly, if this angle can be accurately measured and then combined with the velocity of light, it will give the earth's velocity in its orbit, and so enable us to measure the orbit and determine the sun's distance. This is indeed one of the good methods of getting the distance of the sun. The "constant of aberration," as it is called, is usually taken at about 20.47 seconds.

Proofs of the Earth's Revolution. — The aberration of the stars is a necessary consequence of the earth's orbital motion, and thus may be regarded as a proof of its annual journey about the sun. The annual parallax of the stars is a second proof, and the motions of the stars in the line of sight observed by the spectroscope furnish a third proof of the earth's revolution about the sun. These matters will be treated more in detail in a later chapter.

CHAPTER V

TIME, THE CALENDAR, NAVIGATION

Time Measured by the Earth's Rotation. — The march of time is so important in human affairs that very great attention has always been given to it. By general consent, the unit of time is the day, measured by the rotation of the earth on its axis. Yet here the trouble begins. If we should define the day as the interval of time between two successive transits of the actual sun across the meridian, an accurate clock would soon show that the days so defined are quite unequal. In fact, the interval for the apparent sun to go from noon to noon at Christmas is over fifty seconds of time longer than at the middle of September. If instead of measuring by the sun, we should define the day by some star, or better still by the mean indication of many of them, our clock would have to be a very fine one, superior to any actually existing, to show the slightest inequalities. Yet our stellar days would be about 4 minutes shorter than our solar days.

Despite the inequality of apparent days, as measured by the sun's place in the sky, we must prefer solar time to stellar time because all of our concerns are controlled by sunlight. It would be highly inconvenient to have to shift the hours of all business steadily throughout the year to make them suit the sun's position. Imagine going to business sometimes at 1 o'clock in the morning, sometimes at 7 o'clock at night! This would happen if we should adopt the stars as our guide in regulating our daily life. Nevertheless, star time is continually employed by the astronomer to enable him to point his telescopes at the stars. This is called *sidereal* time. The time in ordinary use is *mean solar* time. The mean solar day is the average, or mean, of all the apparent solar days of the year. Mean solar days are each of constant length and thus a clock may be utilized, while the sun-dial which gives apparent solar time is sometimes ahead and sometimes behind the clock time. These differences may reach about 16 minutes each way. When we make use of a popular expression and state that

" this watch, or clock, regulates the sun," we should be careful that we refer to the mean sun, which has no actual existence, and not to the real sun.

Celestial Circles. — The *celestial sphere* we regard as of infinite radius with its center at the eye of the observer. Sun, moon, planets and stars are projected to the face of the celestial sphere. The earth in rotating keeps its axis always parallel to itself, and hence it points in a fixed direction. The earth's axis produced cuts the celestial sphere in the north and south poles of the sky. Near the north celestial pole is the pole star, or Polaris, which is about a degree away from the north pole in the sky. Since the earth's axis points in a fixed direction, the equator of the earth, being perpendicular to the axis, also has a fixed plane. The earth's equatorial plane produced outwards intersects the celestial sphere in a great circle called the *celestial equator*. The ecliptic intersects the celestial equator in two points called the *equinoxes*, because when the sun is at either equinox, there is equal day and night all over the world. On March 21, the sun is at the *vernal equinox*, and on September 23 it is at the *autumnal equinox*.

Celestial Coördinates. — The earth being regarded as a sphere, we fix the location of a city like New York, or that of a ship at sea, by two coördinates which we call *latitude* and *longitude*. Similarly the astronomer fixes the position of a point on the celestial sphere by two coördinates. He has a choice of what particular pair of coördinates he will use by his choice of his fundamental plane or great circle. If he utilizes the celestial equator to which to refer his coördinates, he measures the *declination* of a star as the angular distance north or south of the equator and measured along a circle which passes through the celestial poles. This is a similar process to the measurement of latitude on the earth. The angular distance measured on the celestial equator between the plane of the great circle, including the star and the celestial pole and a certain starting point, is called *right ascension* if the vernal equinox is used as the starting point, or *hour angle* if the meridian is utilized.

As the earth turns on its axis, it carries our meridian along (from west to east). The meridian passes over the heavenly bodies in succession, or they appear to transit across our meridian.

Time. — The time at any instant as kept by some clock, is the *hour angle* or some heavenly body measured westward from some

meridian. If the meridian passes through the observer we have *local time.* If the meridian is that of Greenwich (England) we have *Greenwich time,* and if the meridian is a standard one (such as that passing through the 75° meridian) we have *standard time.* The angle between the different meridians is fixed by the longitude, now universally measured from Greenwich.

Solar Time. — We might utilize the moon for a measurer of time, but there is no practical use for such time. We have to distinguish between two kinds of solar time. The west hour angle of the actual, or apparent, sun gives *apparent solar time,* and the west hour angle of the mean sun gives *mean solar time,* usually called *mean time.* The west hour angle of the mean sun from our local meridian is called *local mean time,* the west hour angle of the mean sun from the Greenwich meridian gives Greenwich mean time, or G. M. T.

Sidereal Time. — We might utilize any star, such as Sirius, for the determination of star time, but instead of any one particular star we employ the vernal equinox in the sky (the intersection of equator and ecliptic). When the vernal equinox is on our meridian, it is *local sidereal noon.* If the vernal equinox is four hours west of the meridian, it is sidereal time 4 hours. The *sidereal day* is the interval of time between two successive transits of the vernal equinox across the meridian. The most perfect clocks in the world are utilized by the astronomer to keep sidereal time. Such clocks are treated with the greatest care, being kept in a vault at constant temperature and atmospheric pressure, and are wound electrically about once a minute. Such refined clocks need no attention except periodically to be cleaned and oiled.

Different kinds of time. — The determination of time consists in finding how much fast or slow a particular clock or chronometer is at the instant. The relations between the different kinds of time may be visualized by referring to the diagram.

Let us make a projection of the celestial sphere at any instant on the plane of the equator. O is the north pole in the sky. OG is the meridian passing through Greenwich. OS is the meridian passing through the apparent sun, and OM is that passing through the mean sun. OV is the meridian passing through the vernal equinox (called the equinoctial colure). The angle GOW, measured in degrees, minutes and seconds, or in hours, minutes and seconds,

is the longitude. The angles of the diagram expressed in hours (15° = 1 hour) give the following times:

GOM = Greenwich mean time
GOS = Greenwich apparent solar time
WOM = local mean solar time
WOS = local apparent time
GOV = Greenwich sidereal time
WOV = local sidereal time
SOM = equation of time
VOS = right ascension of the apparent sun
VOM = right ascension of the mean sun

The conversion of one kind of time into another is a matter of great simplicity and is readily understood from the annexed diagram.

Equation of Time. — Time is determined by the rotation of the earth on its axis. Uniform time (which may be measured by a clock) is determined by any *fixed* point in the sky or by an object which apparently moves uniformly in a plane at right angles to the earth's axis, namely, in the celestial equator. Any heavenly body which apparently either moves in a plane oblique to the equator, or moves with a speed which is not uniform, can not furnish uniform time. We have already seen that the apparent sun moves in the plane of the ecliptic. Hence, it could not give uniform time. Moreover its speed in the ecliptic is not constant, moving fastest in its orbit on January 1 and slowest on July 1. On January 1, the earth must therefore turn more

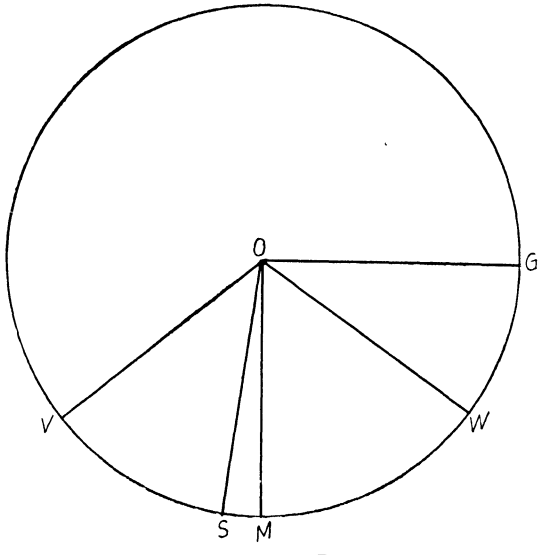

FIG. 9. TIME AND LONGITUDE.

than the average amount to overtake the sun, and the day, in consequence, is greater in length than the average. Hence, for two reasons, apparent solar days are of unequal length. The astronomer, in consequence, invented a fictitious sun which is supposed to move uniformly and in the plane of the celestial equator. This is called the *mean sun*. On or about March 21, the mean sun leaves the vernal equinox at the same time as the apparent sun. Both suns travel eastward in the sky and both return to the vernal equinox together at the end of the year. The mean sun travels uniformly in the equator, the apparent sun with variable motion in the ecliptic. The difference between mean and apparent time is the equation of time. The equation of time has the following values:

January 1	− 3^m 28^s	July 1	− 3^m 29^s
February 1	− 13 41	July 27	− 6 19
February 11	− 14 24	August 1	− 6 11
March 1	− 12 36	September 1	0 0
April 1	− 4 7	October 1	+ 10 7
April 16	0 0	November 1	+ 16 16
May 1	+ 2 54	November 4	+ 16 21
May 15	+ 3 49	December 1	+ 11 4
June 1	+ 2 29	December 25	0 0
June 15	0 0		

It will be seen that the equation of time vanishes four times a year. On November 4 the apparent sun is on the meridian 16^m 21^s before clock noon, while on February 11 the apparent sun is slow on clock time by more than fourteen minutes.

Mean and Sidereal Times. — Our diagram shows that GOV = GOM + MOV; and also WOV = WOM + MOV. The angle VOM is measured from the vernal equinox eastward in the plane of the equator to the position of the mean sun at the instant. By definition this is called the right ascension of the mean sun. This quantity may be taken directly from the Nautical Almanac. It may also readily be found with a fair degree of accuracy (as we shall show) by knowing the day of the year, or date. Hence we have a very simple rule: *Add the right ascension of the mean sun to the mean time and we shall obtain the sidereal time;* and also: Subtract the right ascension of the mean sun from the sidereal time and we obtain the mean solar time.

Length of the year. — The ordinary year on which the seasons depend is the interval of time it takes the sun to start from and

return to the vernal equinox. This is called the tropical year and its length is 365.2422 days. In a year, on account of its apparent motion eastward (caused by the actual motion of the earth) the sun crosses the meridian one time fewer than does the vernal equinox. Hence,

365.2422 mean solar days = 366.2422 sidereal days

1 mean solar day $= 1 + \frac{1}{365.2422}$ sidereal days

24 mean solar hours = $24^h\ 3^m\ 56^s.555$ of sidereal time

A year has one fewer mean solar days than sidereal days and hence each mean solar day must be longer than a sidereal day. Sidereal time gains on mean solar time by approximately four minutes per day. The gain is 24 hours, or one day in a year, or two hours a month.

How to Find Sidereal Time. — By definition it is evident that when the sun is at the vernal equinox on March 21, the right ascension of the mean sun is 0 hours and hence mean solar and sidereal time agree. On March 22, sidereal time has gained four minutes. On April 21, sidereal time has gained two hours. To find the sidereal time at 8:30 P. M. on September 1, we proceed as follows:

Sidereal time at noon on August 21 (five months after March 21)	$= 10^h\ 0^m$
August 21 to September 1 = 11 days; change	$= 44^m$
Right Ascension of the sun on September 1	$= 10^h\ 44^m$
Local Mean Time	$= 8^h\ 30^m$
Sidereal Time	$= 19^h\ 14^m$

Right Ascension and Sidereal Time. — The right ascension of the meridian, by definition, is the angular distance, measured in hours, from the vernal equinox eastward to the observer's meridian. The sidereal time, by definition, is the hour angle from the meridian westwards to the vernal equinox. Hence, the right ascension of the meridian is equal to the sidereal time at the instant. This time the astronomer can find immediately from his sidereal clock. Hence, suppose we wish to locate the bright star Vega on September 1. Its right ascension is $18^h\ 34^m$. We have seen above that the right ascension of the mean sun, which is the same thing as the sidereal time of mean noon, is $10^h\ 44^m$. Hence, Vega will be on our meridian at $18^h\ 34^m - 10^h\ 44^m$ or $7^h\ 50^m$ after noon, or at 7:50 P.M.

A change of latitude of the observer causes great changes in the appearance of the heavens, and particularly in the times of rising and setting of the sun and moon. The observer carries his horizon with him. It is the great circle of the celestial sphere passing through the eye of the observer and tangent to the earth's surface, or perpendicular to the plumb line. In Fig. 10 there is a projection of the celestial sphere on the plane of the meridian. We

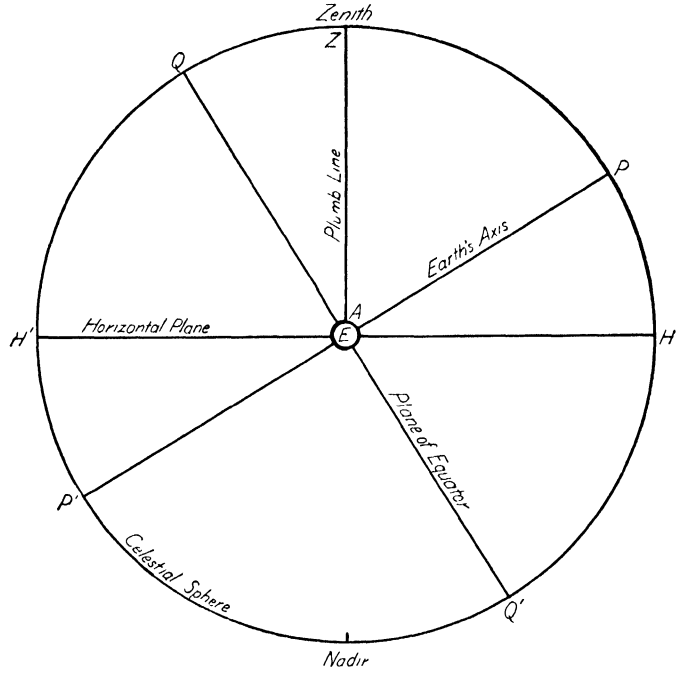

FIG. 10. CELESTIAL COÖRDINATES.

are able to see everything above the horizontal plane but nothing below it. If we live on the " top of the earth " at A, then the vertical line produced pierces the celestial sphere at the zenith, which is everywhere 90° from the horizon. The earth's equator produced to the celestial sphere gives the celestial equator. On the earth, the angle between the equator and plumb line is the latitude. The same angle on the celestial sphere is the declination of the zenith, the angle QEZ. This angle is equal to the elevation of the celestial pole above the northern horizon, the angle PEH. Hence, the latitude of the place is always equal to the elevation of the pole. Consequently, as we travel towards the north on the earth's surface

and increase our latitude, the pole star is found higher and higher above the northern horizon. Hence, when the sun or a star is on the meridian and we know the declination of the heavenly body, it is easy to find the angular distance of the object from the horizon or from the zenith.

Astronomical Time. — Astronomers for many years preferred to start their day at noon, so that the darkness, which is their time for observing the stars, would all fall in one day. They also count hours up to 24, instead of in two lots of 12 hours each, as most of us do, or in six " watches " each of 4 hours, as sailors do. For the same sort of reason that astronomers preferred to start the day at noon, people in general have agreed to start theirs at midnight. For their work comes in the daylight, and they prefer to have it during one calendar day. Very recently the astronomers have decided to follow the general public in this matter, and now the astronomical day also starts at midnight.

Beginning of the Day. — Some of the ancients used to begin the day with sunset, or with sunrise. This habit is still retained by certain sects in their observance of the Sabbath. The Greeks were accustomed to divide the day into two lots of 12 hours each, extending from sunrise to sunset, and from sunset to sunrise. Their night and day hours were therefore unequal, except at the times of the vernal and autumnal equinoxes. We should find it very difficult to adjust our clocks to this curious system, if it prevailed today.

The Week. — From time immemorial, the orientals have grouped the days into weeks of seven days. Only with the ancient Egyptians and in the modern period of the French Revolution was the attempt made to substitute another grouping. The French revolutionists employed a week of ten days. This arrangement lasted for some years in France. It is possible that the ancient ideas of the planets may have influenced the seven-day grouping. Regarding the earth as the center of all things, they considered that there were seven planets, namely, Sun, Moon, Mercury, Venus, Mars, Jupiter, Saturn. Our English names of the week-days come partly from the Saxon. Thus: Sun's day, Moon's day, Tiw's day, Woden's day, Thor's day, Frigg's day, Setern's day.

The Month. — Our months relate to the period of the moon's revolution about the earth. The " synodic " period of the moon's

revolution is just a little more than $29\frac{1}{2}$ days. This means the average time elapsing from new moon to new moon, or from full moon to full moon. If we consider the moon's place among the stars, without regard to the sun, we would have a shorter period for her rotation, namely 27 days, 7 hours. The advance of the earth in her own orbit around the sun makes the lunar month longer than it would be if the earth remained fixed.

The Calendar. — The tropical year of 365.2422 days is equal to 365 days, 5 hours, 48 minutes, 46 seconds. This time is no even multiple of the lunar month. Neither is it an even multiple of the week nor of the day. Yet it is very desirable that the months, at least, shall fall in the same seasons, year after year. The reconciliation of these odd intervals has cost a deal of study and heartburning, and even now the calendar is not regarded as satisfactory.

Twelve lunar months of $29\frac{1}{2}$ days count 354 days, leaving 11 days and a fraction to finish the year. The old Egyptians used 30-day months, with 5 supplementary days. Their year fell back a day every four years, so that the seasons would shift completely around in 1461 years. In ancient Rome the calendar was extremely confused. Their count of days in the months was especially curious. They fixed three points, the first day, or Calends, the middle day or Ides, and the ninth day before Ides, or Nones. Readers of Shakespeare's play "Julius Cæsar" will "remember the Ides of March." In March, May, July, and October, the Ides came on the 15th and the Nones on the 7th day. In other months these days were the 13th and the 5th. The Romans reckoned backwards instead of forwards from the Calends, Ides, and Nones. Always there were eight days before the Ides, but there might be three or five before Nones. Those before Calends might number as many as nineteen. The Romans began their year with March, so that September, October, November, and December got their names from being then the seventh, eighth, ninth and tenth months.

Julius Cæsar, with the advice of Sosigenes, reformed the Roman calendar. He decreed that common years should have 365 days, but every fourth year 366 days. In order to bring back the vernal equinox to the day of the year it had occupied at the time of Numa Pompilius, second king of Rome, Cæsar introduced two long extra months in the current year, making it 445 days. This is called

" the last year of confusion." The first reformed Julian year began with January 1 of the 46th year before Christ. Cæsar adopted the simple plan of making the 1st, 3d, 5th, 7th, 9th, and 11th months of 31 days, the others of 30 days each, excepting February which had usually 29, but 30 in leap years. The Emperor Augustus Cæsar, desiring to make his month August equal to Julius Cæsar's July, changed the lengths of the last five months of the year, and stole one day from February to add to August. However, he corrected one error. Julius Cæsar's decree had not been rightly followed as to the leap years, and every third instead of every fourth year had been given 366 days. This was rectified by Augustus.

Still the Julian year was imperfect, for it was too long by 11 minutes, 14 seconds, on the average. The vernal equinox had occurred on March 25 in Cæsar's time. When the famous Council of Nicæa was held in the year 325, A.D., the equinox had fallen back to March 21, and in the time of Pope Gregory XIII, ten days more to March 11. Hence, in the year 1582, this Pope ordered that 10 days should be suppressed from the calendar, and that thereafter no even century years should be leap years, as they would have been under the Julian system, unless divisible by 400.

The countries of Spain, Portugal, Italy, and France made the change in the same year, and the Catholic states of Germany the year following. In Protestant Germany it was delayed until the year 1700, and in England until 1750. Russia did not make the change from " Old Style " to " New Style " until February 14 of the year 1918, when, of course, she had to drop 13 days.

There naturally was much opposition to the change. Even yet in our own country there are some sections where " Old Christmas," as it is called, is celebrated with quiet reverence on January 6, while " New Christmas," on December 25, calls forth a noisy jollification with firecrackers and guns. It is said that a certain pious couple in England continued for many years to observe Good Friday Old Style. They would go to the church door with all decorum, the old gentleman would rap with his stick, and finding no admittance they would return and read service at home. On the New Style day, they took care to ignore it as conspicuously as their occupations could possibly justify, in order to show their disapproval of such irreligious tricks as changing the calendar.

The Gregorian Calendar. — From now on every year divisible

by four will be a leap year until the year 2100 which will contain 365 days only. The Gregorian arrangement is not quite perfect, for it leads to a retrograde departure of one day in 3323 years in the date of the vernal equinox. It has been suggested to prevent this by causing the year 4000 and all its multiples to be common years, but neither we nor our readers need be seriously concerned about this modification, which would preserve the present date of the vernal equinox for about 20,000 years. If Pope Gregory had ordained the dropping of the leap year on each year divisible by 128, there would have been no error amounting to a day in 100,000 years.

The Mohammedans do not try to maintain the date of the vernal equinox unchanged. Their calendar dates from the "Hegira," or first day of the month preceding the flight of Mohammed from Mecca to Medina. They reckon time by lunar months, which retrograde through all the seasons in about $32\frac{1}{2}$ years. They prevent much departure of the months from the phases of the moon by suitable extra days in certain months of certain years.

The Hebrew year purports to date from the Creation, said to have occurred 3760 years, 3 months prior to the Christian Era. Their year has elements weekly, lunar, and solar, for they modify the numbers of days slightly, and insert an extra month occasionally, so as to fit their festivals to chosen week days, and their months to chosen seasons.

The Christian festivals have a curious and highly complicated relation to the calendar. In order to understand the origin of these peculiarities, we must go back to the Council of Nicæa, in the year 325 A.D. Easter was the great moveable feast of the early church, as it is still. There were some who desired to celebrate Easter on Sunday, while others held to the 14th day of the moon's age as the proper time for its observance, agreeing with the Jewish custom of the Passover. As the latter believers were in the minority, they were called heretics.

In dealing with this question, the Council of Nicæa laid down the following propositions: Easter should be observed on the Sunday immediately following the full moon that happens upon or next after the vernal equinox. However, if the 14th day of the moon's age, which is to be regarded as full-moon day, occur on Sunday,

the celebration of Easter is to be postponed until the Sunday following, so as to avoid the practises of heretics and Jews. Probably the fathers who sat in council did not realize how stiff a problem they were proposing, in thus ordering the reconciliation of the solar year, the lunar month, and the Christian week. They evidently had an eye single to clearing themselves of all taint of heresy.

We shall not go into all the details of the matter, but we ought not to leave the subject without mention of a few of the famous expressions. Representing the days of the week by A, B, C, D, E, F, G, let A always come on January 1. Then Sunday, if it were January 4th, for example, would be represented by the letter D in that year. This contrivance is called the "Dominical Letter" or "Sunday Letter." In each century the succession of days in the year returns after 28 years. In another century it may fall differently, because of the Gregorian suppression of the extra day in years divisible by 400. However, it is possible to make a very compact table giving the "Sunday Letter" forever.

Another expression is the "Metonic Cycle." This is a period of 19 solar years, which is almost equal to 235 lunar months of $29\frac{1}{2}$ days each. Thus after a Metonic Cycle the new moons again occur on the same days of the year. The ancient church calendar was drawn up on the assumption that the length of the year is exactly $365\frac{1}{4}$ days and that 19 years exactly equals 235 lunations. Both assumptions are a little erroneous, so that it was not many centuries before there came trouble. In adapting the Metonic Cycle to their calendar, they assigned 29 and 30 days alternately to the lunar months, and as this makes in twelve months only 354 days, they added six extra months of 30 days and one of 29 to fill out the 19 years. There was some further difficulty about leap years, but we will not explain it here.

With these arrangements tabulated for a cycle of 19 years, the same dates of the moon's phases would occur in any subsequent cycle. It only needed to know the number of the year in the Metonic Cycle. This is called the "Golden Number." These artificial arrangements did not ever in actual fact indicate the moon's phases exactly as they came in astronomically. Differences of as much as two days sometimes occurred. However, when authorized by the proper officials, these arbitrary provisions

took the place of the actual events of the heavens in regulating Christian festivals.

After the reformation of the civil calendar by Pope Gregory XIII, it became necessary to reform the church calendar also. This was undertaken by Aloysius Lilius, a learned astronomer of Naples. Rather than merely revise the "Golden Numbers," Lilius introduced another conception called the "Epact." It signifies the moon's age at the beginning of the year. Taking into account all the complications of the problem, it is possible to construct what is called the "Extended Table of Epacts" by whose aid the "Golden Number" can be read off corresponding to any desired day. Besides the table of Epacts, there is another large table giving the arrangement of Golden Numbers, Epacts, and Dominical Letters in the Gregorian Calendar. Proceeding by certain complicated rules, and with attention to avoid certain pitfalls, these various tables can be employed to find the age of the ecclesiastical moon (which is not the true moon) at any date, or to fix the occurrence of Easter. It is not a pastime to be recommended to our readers unless they enjoy puzzles.

After all, the regulations of the Council of Nicæa are not in fact literally carried out. For the use of the exact instants of the vernal equinox and of the full moon as determined astronomically, would occasionally change the date of Easter by a week from that which is adopted by the church.

Reform of the Calendar. — In closing our remarks on the calendar, we may refer to some recent proposals to reconcile the week and month with the year in a more regular fashion. The purpose of these proposals is to avoid the need of new civil calendars for successive years, and to simplify the work of computing pay-rolls and other data in which the month figures. There are two schools of these calendar reformers, one desiring the greatest attainable uniformity, the other moderate improvement with a minimum of change. Both agree however in their reconciliation of the week to the year.

Fifty-two weeks make 364 days. In common years there is one day, and in leap years there are two days in excess. The proposal is to give the extra one or two days different names from ordinary days, so that when they occur there will be a break of one or two days in the consecutive naming of days of the week. Thus, all

years may begin on Sunday, if preferred, or on some other day of the week, chosen to suit better the general convenience regarding widely observed holidays, such as Christmas and New Year. Many persons who are attracted by the simplicity of this scheme would have a rude shock if it were legally enacted, and they came to fully realize its effect on the Fourth Commandment of the Decalogue.

The other reform, to which no one would see religious objection, is the modification of the months. One proposal is to have thirteen months of 28 days each, with the one or two days additional in common and leap years belonging to no month at all, and celbrated as holidays. A more moderate party, desiring less change, and also desiring a year easily separable into halves, thirds, fourths, and sixths, retains twelve months and suggests four groups of three months, each group containing ninety-one days. These reformers also would have one, or sometimes two, extra holidays belonging to no month at all. Their arrangement of months might be January, April, July, and October of 31 days each, the rest of 30.

Various organizations have passed votes of recommendation of some one or other of these proposed plans, but there is no general agreement as yet about the matter. Such votes are often carried without much consideration or interest, at meetings in which only a small minority of the organizations are in attendance. It may be suspected that, like the metric system, actual legal enactment would find but half-hearted support, and would develop vigorous opposition.

Standard Time. — Life has become very complicated since the coming of rapid transit and the electric telegraph. A half-century ago it became very inconvenient for Philadelphia to keep slower time than New York and for Washington to be even slower than Philadelphia. Now all three cities keep the same time, that of the 75th meridian, or 5 hours slow on Greenwich. In the United States there are four time zones, Eastern, Central, Mountain and Pacific standard time, keeping their clocks 5, 6, 7 and 8 hours slow on the time of England. The whole civilized world is now divided into time zones, differing whole numbers of hours (sometimes half-hours) from Greenwich.

Daylight Saving Time. — In recent years we have become accustomed to being requested to push our clocks forward one hour in certain months of the summer. If we were very reactionary

we would keep our former method of life and refuse to obey, but this would be very troublesome to us if the rest of the section of the country where we lived were getting up an hour earlier, correspondingly advancing business hours, and going to bed also an hour earlier. We might object for a little while,

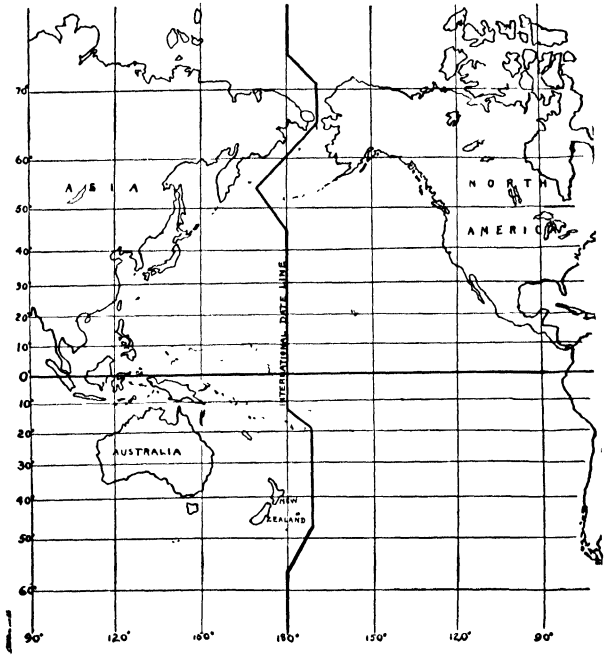

FIG. 11. THE INTERNATIONAL DATE LINE.
Lying near the 180th meridian from Greenwich, it is somewhat modified so that lands and island groups of similar conditions may use the same date.

but life would be very inconvenient and we would soon learn to follow the crowd.

International Date Line. — It is a curious thought that members of certain sects which regard it as conducive to salvation to celebrate the Sabbath on a particular day of the week, different from the common practise, are, nevertheless, content to adopt the determination of it which depends on the establishment by international treaties of a date line. This arbitrary date line lies in the Pacific Ocean at approximately 180° from Greenwich, but yet wanders irregularly so as to avoid separating certain island groups. Thus, it depends not only on the establishment of an observatory

at Greenwich, but on an arbitrary governmental convention, whether two members of such a sect, residing on two nearby islands, shall celebrate the same day, or two adjacent days, as the Sabbath.

Of course, it is too well known to need remark that ships sailing west omit a day, and ships sailing east repeat a day, when they cross the international date line. The reason is that when Greenwich sees the sun in the meridian at noon it is midnight on the 180th meridian, and either the same day or the preceding day, as we choose. If we imagine ourselves to be rapidly transported westwards, leaving Greenwich on Sunday noon, we should see the sun sinking back till it rose, and should fly to the 180th meridian supposing we were in earlier and earlier hours of Sunday morning. When we came to the date line, therefore, we should regard the hour as the midnight which separates Saturday from Sunday. On the other hand, if our flight had been eastward, we should have seen the sun set and disappear in the west, and arriving at the date line should suppose the midnight to be that which separates Sunday from Monday.

When the authors of this book crossed the 180th meridian on their voyage to Sumatra to observe a total eclipse of the sun, the day of March 4 was only 30 minutes in length. The ship captain said that we reached the 180th meridian, going westward, on March 3 at 11.30 P.M. The time immediately became March 4 at 11.30 P.M., and thirty minutes later the date changed to March 5. The battle of Manila Bay was fought on May 1, 1898. We read the news in the papers on April 30.

Navigation. — The accurate determination of time, precise surveying and map making, and navigation are some of the more important practical applications of astronomy. To navigate the great oceans with the greatest of safety, or to navigate the air when out of sight of land, observations of the heavenly bodies are necessary. In olden times, when the astronomical knowledge, imperfect as it was, resided altogether with the philosophers, and when there were no maps or charts worthy the name, or instruments of precision which could be used at sea, it was a venture even to cross the Mediterranean. Ships crept along shore from port to port, or from island to island. If driven far out of course, they were lost without means of regaining their desired haven.

The magnetic compass, it is true, helped greatly after its intro-

duction about the year 1400 A.D. Yet even Columbus, when he made his bold famous voyage of discovery, had no means at all of measuring longitude, and but the crudest for measuring latitude. The common instrument of that time for seamen was the cross-staff. With this, one could get roughly the altitude of the sun or stars above the horizon. In the northern hemisphere, where the pole star is available, it would be just possible with these rough means to know latitudes within a hundred miles.

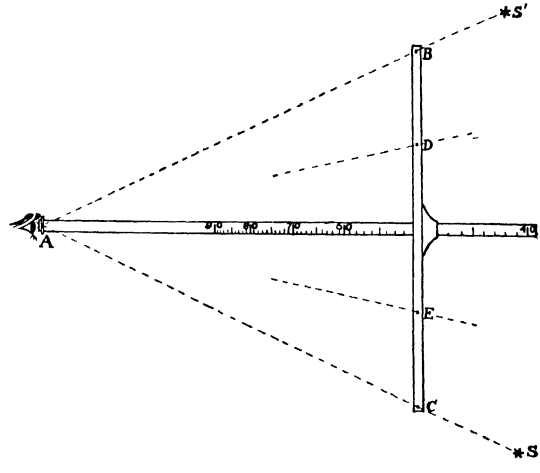

FIG. 12. THE CROSS-STAFF.

An ancient instrument for navigation. The observer sighted from A through B and C upon the celestial objects S, S'. The crossbar BC could be drawn nearer or pushed away till the adjustment was correct. Then the angle SAS' was read upon the scale. Other sights, D, E, were provided for smaller angles. The long bar was 36 inches, the short bar 26 inches.

There were no nautical almanacs, as in our own time, to indicate the precise places of the sun and stars, and the fact that they cross over the sky from east to west prevented much use of them even for latitudes. Time keeping was as crude as astronomy. Watches and clocks were unknown. The hours were observed by sandglasses or water clocks at sea, and by sundials on land.

Such were still the conditions when Magellan's ships sailed round the globe, when the Spanish and Portuguese were sending their argosies to the New World and the Spice Islands, and when Englishmen were seeking the Northeast and Northwest Passages in the frozen polar oceans. In a nautical book of the sixteenth century, about the time of the famous Spanish Armada, the writer says: "Now there be some that are very inquisitive to have a way to get the longitude, but that is too tedious for seamen, since it requireth deep knowledge of astronomy, wherefore I would not have any man think that the longitude is to be found at sea by any

instrument, so let no seamen trouble themselves with any such rule."

There are four great inventions which make modern navigation what it is. They are the mariner's compass, the flat representation in maps of the spherical earth, the sextant, and the chronometer. Two others might be added, though of less fundamental importance. They are the patent log and the patent sounding devices. Then there are the great national observatories and their publications which give the exact knowledge of the places of the heavenly bodies indispensable to the navigator far out at sea, and the accurate sounding and charting of the coast line of the whole world which keeps him from destruction at the shore. Finally, there is the thorough survey and charting of the magnetic conditions of the entire oceans, without which the compass would lose its value.

Determination of Latitude. — Our scope does not permit us to go deeply into this fascinating subject, but at least we must mention the principal uses of astronomy for the navigator. The simple method of determining the latitude of the place is to measure the altitude of the sun at apparent noon by means of the sextant. The upper or lower limb of the sun is made to appear tangent to the horizon as seen in the sextant. To the observed altitude, certain " corrections " are applied, for refraction, parallax, semi-diameter and dip of the horizon. The " true altitude " thus derived, subtracted from 90° gives the zenith distance. If the declination of the sun, taken from the Ephemeris, is added algebraically to the zenith distance, the latitude of the place is obtained, with no mathematics higher than addition and subtraction. It is important, however, to remember that north declinations are positive and southern declinations are negative.

If the sun is not on the meridian, the observations are reduced by trigonometry. The formulas are simple, but of course more difficult of application than addition and subtraction. These observations are called " ex-meridian " by the navigator.

We have seen from Fig. 10 that the latitude of a place always equals the altitude of the celestial pole. The north star, Polaris, visible over most of the northern hemisphere, lies within $1\frac{1}{4}$ degrees of the pole. Nautical almanacs indicate where at any time it lies in its small circuit around the true pole. Hence, by measuring with the sextant the altitude of the pole star, and applying the little

corrections necessary for its position in its circuit, and also for atmospheric refraction, the latitude is found most simply. Naturally many more observations of latitude are made on the sun than on the pole star.

Longitude. — The problem of longitude at sea was nearly hopeless until the invention of the chronometer by Harrison about the year 1760. It is true that the rapid change of position of the moon among the stars, and the rapid change of configuration of Jupiter's satellites had been suggested and used as means of fixing longitudes. But these methods depended for accuracy on astronomical observations and mathematical theory not yet in existence in Harrison's time. Even now, though these astronomical data are available, they cannot compete with the chronometer for giving exact longitudes at sea.

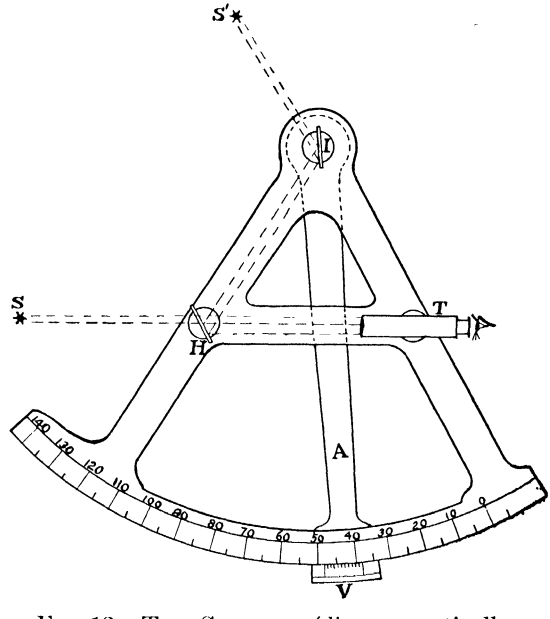

FIG. 13. THE SEXTANT (diagrammatically presented).

The telescope, T, observes the star, S, directly through the upper (clear) part of the horizon glass, H, while it also observes the star, S', by reflection from the lower (silvered) part of H and the mirror, I, which turns with the arm, A. The vernier, V, carried by the arm, A, reads off the angle between S and S' on the scale of the instrument.

In essence, the determination of the difference in longitude between any two places on the earth's surface consists in the determination of differences in time at any instant between the two places. The time utilized may be mean solar, apparent solar, or sidereal time. If we wish to know the longitude with respect to Greenwich, we must know the time in Greenwich at the instant when the observation was made at the observer's meridian. If, now, the

ship possesses a chronometer which is so accurate a timekeeper as to furnish him with the time at Greenwich, however long he may have been away from port, then the problem is solved.

It was John Harrison's invention that gave this great boon, for which the British Government granted him a prize of £20,000. An ordinary watch escapement prior to his improvements would change its rate of vibration with temperature. Harrison, by combining metals in the construction, succeeded in eliminating this temperature effect almost exactly. His son, William Harrison,

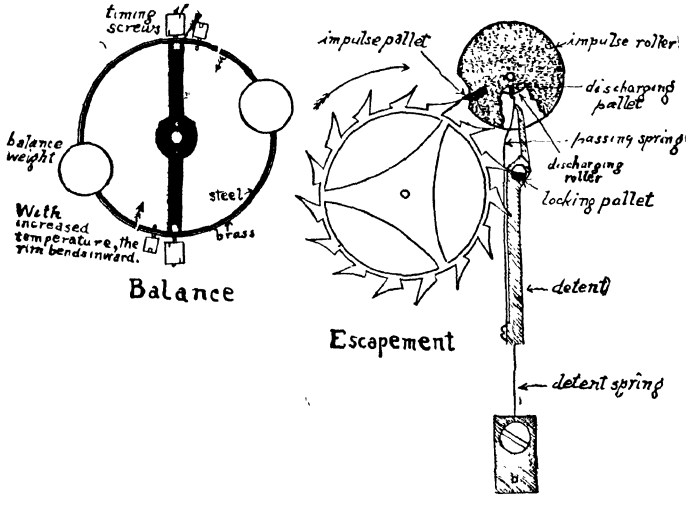

FIG. 14. PARTS OF THE MODERN MARINE CHRONOMETER.

made the testing voyage of the first Harrison chronometer to Barbadoes and return. On the voyage out, the chronometer lost only 5 seconds. On the return it lost $1^m\ 49^s$, for it was placed for dryness in the after part of the ship, where it was subject to much motion, which hindered its going. Even so, it determined the longitude of the home port, after 7 months' voyage, within 18 miles.

With later improvements, the chronometer has attained a perfectly marvelous accuracy. It is customary to carry three of these instruments in each very large ship. Voyages are recorded where the mean time by three chronometers, carried far across the equator and return, so that the range of temperature was very great, has varied less than 3 seconds in a hundred days. This error is but one part in three million of the total time elapsed.

Sumner's Method. — An American shipmaster, Captain Sumner, published in 1847 the celebrated device in navigation for getting both latitude and longitude, now called "Sumner's method." It depends in principle on the fact that the sun or a chosen star is vertically overhead at a given instant at some point on the earth's surface. By means of the tables and the chronometer, this point may be in fact definitely located. Suppose, now, for illustration, that two officers of the same ship observe the altitudes of two stars simultaneously, one being, let us say, 25°, and one 40°. If they should take compasses and draw circles on a globe, with centers on the spots where these two stars are known to be vertically overhead, and with radii equivalent to 90° − 25° and 90° − 40°, respectively, the ship must be at the instant of observation on the intersection of these circles.

In applying Sumner's method, the sun alone may be used, by allowing for the motion of the ship between two observations several hours apart. In place of a globe, the navigator uses a large-scale map of his region. There is no need of drawing full circles, for he knows within a few miles of where he is. On so large a scale as the map, the little arcs of circles which he requires will not differ sensibly from straight lines. The bearing of the sun is known, and he merely draws his lines on the chart at right angles to its bearing. Such are the simple elements of this masterly device called "Sumner's method." Its actual application in detail may be learned in works on navigation.

In the American and British navies, in the larger ships of the merchant marine, "old navigation," or the determination from observations of latitude and longitude, has been largely displaced by "new navigation," the method of Marcq St. Helaire.

The Mariner's Compass. — Another value of astronomy to navigation resides in the means which it affords to correct the compass. Cloudy weather forces the mariner to depend on "dead reckoning," which is a combination of the compass course steered and the distance run, as indicated by the patent log and the revolutions of the propeller. Almost all modern ships are made of steel, so that the compass has to be compensated for the magnetic material of the ship. But magnetism of steel changes with time and circumstance. Hence, it is necessary to test the compass often by comparing its indications with the true bearings of the heavenly

bodies. These comparisons are best made when the objects are known, from their " hour angles " and the nautical almanac, to be nearly east or nearly west.

Naturally, allowance is required for the " variation of the compass," the well-known departure which it has from the north and south, even when far separated from magnetic materials. It is a great boon which the Department of Terrestrial Magnetism of the Carnegie Institution has given to navigation recently, in constructing and equipping the non-magnetic yacht " Carnegie," and measing magnetic conditions of all the oceans. For the earth's magnetism varies continuously, so that the old magnetic charts, based on observations in wooden ships of the old days, have become obsolete. Chart errors of several degrees in the direction of a freely pointing magnet were disclosed by the " Carnegie " surveys. Thus a ship, sailing by dead reckoning for two days, might easily run from 30 to 50 miles out of her course, merely owing to the errors of the old magnetic charts, now fortunately displaced by modern ones.

Radio. — Wireless telegraphy has been a great boon to voyages by sea. Not only can ships talk to each other at sea and send out " SOS " when in distress, but problems of navigation are greatly simplified. A ship at sea, through its wireless apparatus, is always in communication with one of the powerful land stations which sends out accurate time each day. Greenwich time is always accurately known in consequence, and the constant rate of the ship's chronometer has become of little importance. By means of " directional wireless," and deep-sea sounding devices, a ship may find its way into ports in spite of thick weather and fog. The gyroscopic compass, already alluded to, gives always the true north and gets rid of the necessity of correcting the magnetic compass. All of these aids to navigation have greatly increased the safety of life while at sea.

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CHAPTER VI

THE MOON AND THE TIDES

The professional astronomer observing with a great telescope might possibly wish to banish the moon from the skies, for its light greatly interferes with the work of seeing or photographing faint stars. But what a dreary old world this would be, especially to poets and lovers, if the " fickle and inconstant moon " were forever blotted out of sight. It has seemed like a kind dispensation of Providence that in the short summer nights the full moon is low down in the southern skies while in the long winter nights, when we are in urgent need of light at night, the moon rides high in the sky and appears to give a very strong illumination, especially when reflected by the snow. We shall see that from the nature of things this could not have been otherwise. Besides giving light at night, the moon is of the greatest aid to commerce in that it regulates the tides. The moon owes its conspicuousness to the fact that it is the earth's nearest neighbor, our satellite, for after all it is a very insignificant object compared with the greater sun, the planets and the stars.

Motion of the Moon. — We have mentioned in Chapter II what a difficult field the theory of the moon's motion has proved, calling the greatest mathematicians to display in it all their powers. It is therefore very unsuitable to a book of this kind to venture far upon it. Still there are a few general facts that will interest us. First, as everybody knows, the moon is continually moving eastward among the stars. If we note the moon tonight near a bright star, it will not take long to observe that the moon moves through an angle equal to its diameter in one hour, and in 24 hours it has moved 13° eastward. In $27\frac{1}{3}$ days the moon has moved through a complete circuit of the sky and is back once more near the same bright star. The moon thus revolves about the earth while at the same time it accompanies the earth in its annual journey about the sun.

We have noted that, due to the earth's orbital motion, the sun appears to move eastward among the stars, completing a revo-

lution in the plane of the ecliptic in one year. The moon's orbit is *near* the plane of the ecliptic (but not *in* the ecliptic) and its motion eastward from a star back again to the same star is in a period called a *sidereal* month. Since the moon moves eastward among the stars so much more quickly than the sun, it overtakes and passes

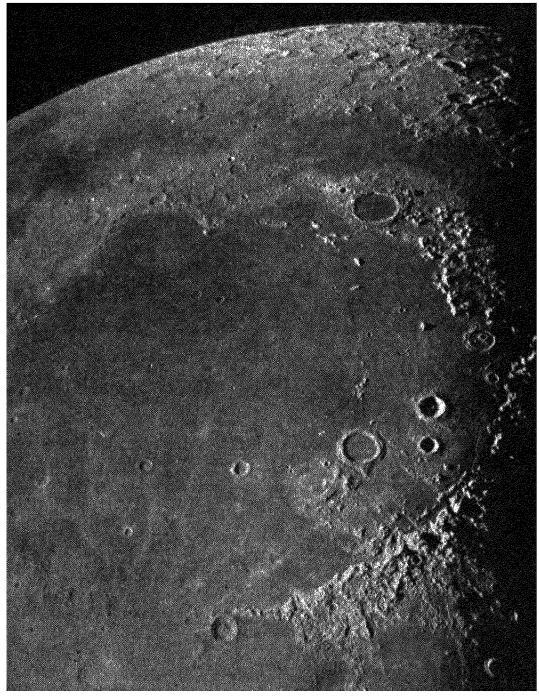


PLATE 13. A PART OF THE MOON'S SURFACE.
(Mt. Wilson Observatory.)

This desolation is matched by few large regions upon the earth. Some of the craters, as for instance the one with the dark rim-shadow, seem to be surely extinct volcanoes. Many of the little ones may possibly have been caused by meteorites falling with no air cushion upon the naked surface.

the sun at frequent and regular intervals. When the moon is almost directly between us and the sun, we call it *new moon*. The interval of time from new moon to new moon, or from full moon to full moon is called a *synodic month*. This is longer than the sidereal month and amounts to $29\frac{1}{2}$ days. In a sidereal month, the moon makes a complete circuit in the sky. But in this interval the sun has ap-

peared also to move and in the same direction, eastwards, that is taken by the moon. Hence the moon must go through more than a complete revolution to catch up to the sun.

Rotation Between Synodic and Sidereal Months. — The relative motions of sun, moon and stars are quite similar to the motions of the hands of a watch. The stars may be likened to the fixed numerals on the dial of the watch, the minute hand to a pointer towards the moon and the hour hand to another towards the sun. As we face south, the motions of the moon and sun are to the left across the face of the celestial dial and not to the right as with the hands of the watch. Moreover, the periods of sun and moon (the year and the sidereal month) have no integral ratio such as that of 1:12 in the case of the watch. These facts in nowise alter the fundamentals of the problem.

Let M, S, and E represent the number of days in a sidereal month, a synodic month and a year. In *one* day, with respect to the stars, the moon describes a portion of her revolution represented by $\frac{1}{M}$; in the same day the sun moves $\frac{1}{E}$. Since the motions are in the same direction, the amount the moon gains on the sun in a day is the difference of the two motions, $\frac{1}{M} - \frac{1}{E}$. But in a synodic month of S days, the moon gains a whole revolution on the sun and in each day must gain $\frac{1}{S}$ of a revolution. Hence we have the simple equation:

$$\frac{1}{S} = \frac{1}{M} - \frac{1}{E}$$

Another way of looking at the same problem is that in a year the sun makes a complete revolution among the stars, and hence the moon overtakes the sun exactly one time less than it overtakes a star. Or in other words, there is exactly one more sidereal month in a year than there are synodic months. Hence:

$13.269\ M = 12.269\ S$
M = sidereal month = $27^d\ 7^h\ 43^m\ 11.^s5 = 27^d.3217$
S = synodic month = $29^d\ 12^h\ 44^m\ 2.^s8 = 29^d.5306$
In a day the moon moves $360° \div 27.3217$, or $13°11'$.

The Phases of the Moon. — The moon has no light of its own and shines merely by reflected sunlight. The moon being a sphere,

we can see at any one time only that half that is turned towards the earth. At the time of *new moon* the illuminated portion of the moon is turned away from the earth and it is consequently invisible to us. A half month later the sun's light is shining full on the face of the moon and we see the full moon. When the sun and moon are 90° from each other, they are said to be in *quadrature*. One half of the face of the moon turned towards us is illuminated by sunshine, and we see one-quarter of the whole moon, either at *first quarter* or *last quarter*. Between new moon and first quarter we have the crescent moon, setting shortly after the sun; and between last quarter and new moon we again have the crescent moon, rising shortly before the sun.

The Moon's Path in the Sky. — The moon's orbit is inclined to the earth's orbit, the ecliptic, by a small angle, of a little more than 5°. The two points where the moon's path cuts the ecliptic are called the *nodes*, the *ascending node* when the moon passes to the north side of the ecliptic and the *descending node* when it passes to the south side. On account of perturbations of the moon's orbit, the moon never quite returns to the same point at the end of the month that it had at the beginning. The moon's nodes make a complete circuit of the ecliptic in a little over 19 years, the node moving westward. The interval of time between two successive returns to the node is called the *nodical* or *draconitic* month, an interval of time of great importance in the prediction of eclipses.

When the *ascending node* of the moon's orbit coincides with the vernal equinox, the inclination of the moon's path to the celestial equator is 23° 27′ + 5° 8′, or 28° 35′. This is the maximum declination of the moon. Under these conditions the moon's meridian altitude changes during the month through an angle of 57° 10′.

Moon Rises Later Each Night. — Since the moon moves eastward, it rises later each night, the average being fifty minutes. On one calendar day (midnight to midnight) during each month the moon does not rise, and on another day it does not set. If we call the interval between two transits of the moon a lunar day, then there is one less lunar day in each synodic month than there are mean solar days. Hence, each lunar day is equal to $24^h \times \frac{29.5306}{28.5306}$ $= 24^h\ 50^m.5$. Just as in the case of the sun, whose time of rising de-

pends on its declination, or distance north of the celestial equator, so it is equally true with the moon. Although on the average the moon rises 50 minutes later each night, the actual retardations of moonrise have a wide range. At 40° latitude the variation is from 13 minutes to 80 minutes. At higher latitudes the range is still greater. These variations in the time of moonrise take place each and every month, but it is only under special conditions (unless one is an astronomer) that they are readily noticeable.

Harvest and Hunter's Moon. — One notices the time of rising of the moon most easily when the moon is full. At the full moon nearest the autumnal equinox (September 23) the daily retardation of the moon's rising is the least, and averages 22 minutes in latitude 40°. Near this time the moon rises each night farther and farther north. This is known as the *Harvest Moon;* the next following one, the *Hunter's Moon.* It is easy to know the day on which the moon is full, without referring to the almanac for confirmation, by remembering that the full moon is rising at the time the sun is setting.

Distance to the Moon. — This is a problem in trigonometry similar in character to that of a surveyor who wishes to measure the distance across a river that cannot be traversed. The mean distance is 238,857 miles, or 60.267 times the earth's equatorial radius. The moon's orbit is elliptical and the distance between the centers of the earth and moon range between 252,710 miles and 221,463 miles.

Diameter and Volume. — The angular diameter is 31′ 5″, and the linear diameter 2160 miles, or 0.273 of the earth's diameter. The volume is $\frac{1}{49}$ of the earth's.

Mass and Superficial Gravity. — The mass of the earth is 81.5 times that of the moon. The attraction of gravity on the moon is only one-sixth of what it is on the earth. A man who could on the earth make a high jump of six feet, if transported to the moon, with the same energy could jump 36 feet.

Rotation of the Moon. — Take a ball in your hand, grasp it firmly and hold it at arm's length. As you look at the ball, slowly rotate yourself. In so doing, you see one side of the ball; but to the walls of the room or to any one else in the room, all sides of the ball are seen, and the ball thus rotates. So it is with the moon. The moon turns always the same face towards the earth, and hence the moon rotates on its axis once in a sidereal month, that is, in exactly the same time that it takes to revolve around the earth.

Librations of the Moon. — The moon, however, shows us more than half her figure. This is called "libration" and is of three kinds. First, *daily*, because the earth is larger than the moon, so that we see beyond her central plane at moon rising and setting. Second, *in latitude*, because the moon's orbit is inclined, and just as the sun shines beyond the north pole in summer and the south pole in winter, so the earth sees beyond the moon's poles. Third, *in longitude*, because the moon's motion in her orbit is not precisely uniform. Although at one time we see only half the moon, yet altogether we have seen seven-twelfths of its surface, a strip around the edge of the moon coming in and out of view from the librations. Forty-one per cent of the moon's surface is never seen by us. This has furnished to certain people with lively imaginations and who do not wish to stick to the facts, an opportunity to describe the interesting conditions on the side of the moon turned away from the earth.

The Moon Visible Though not Directly Illuminated by Sunlight. — During a total lunar eclipse, or when the moon presents only a thin bright crescent, the dusky part of the moon's surface can usually be seen very plainly, though faintly. This is because the earth helps to illuminate the moon, but differently in the two cases. When the moon is totally eclipsed, the sun rays are bent somewhat by refraction in the earth's atmosphere, and thereby reach the moon diffusely, and are reflected back to us.

But at new moon, the lunar inhabitants, if there were any, would see a glorious sight as they gazed on the earth. For, compared to the full moon, the earth would look four times the diameter, and would average nearly three times as bright, so that nearly fifty times as much sunlight would be reflected by the earth to an observer on the moon as is reflected by the full moon to an observer on the earth. The pale light we see at new moon is some of this glorious earth effulgence reflected back to us.

This is popularly known as "the old moon in the new moon's arms."

Atmosphere and Temperature of the Moon. — Neither the moon nor the earth sends out any visible rays of its own. But if our eyes were sensitive to rays of ten to twenty times the wave-length of red light, we should see the moon by her own rays, and find her sending several times as intense ones as she reflects from the sun.

By examining these lunar rays with the delicate electrical thermometer which he invented and called the bolometer, Langley and his colleague, Very, showed that the sunlit moon approaches boiling temperatures. But when a total lunar eclipse comes on, it takes only a few minutes, they found, for the moon's surface temperature to fall far below freezing, indeed so cold that they could no longer detect her rays. This is one proof that the moon has no such atmosphere as the earth has. But, more decisive, no clouds are ever seen there, and no bending of star rays occurs when the moon passes between stars and us. At such times, called " occultations," the stars are blotted out suddenly, as if they were instantly annihilated. If the moon had an atmosphere, the stars would disappear lingeringly, as the sun does when it sets.

If there is no atmosphere on the moon, there can be no water on its surface, for the water would immediately evaporate and form an atmosphere.

Conditions on the Moon. — Its surface is highly desolate, abounding in extinct volcanic craters, and level-looking deserts, probably the bottoms of long dried-up seas of past ages, and, like the nitrate and borax deserts of Chile and Bolivia, doubtless covered with a crust of chemical deposits. The atmosphere, if any is now remaining, is inadequate to support life unless of the most primitive cell-like types. There is no evidence that water remains on the moon now, though possibly deep in the ground there still may be moisture. Sir G. H. Darwin suggests that possibly the material which composes the moon separated from the earth owing to a condition of instability associated with the earth's former shape and motion, and that, as a consequence of tidal influence, the month, at first identical with the day, lengthened, the distance separating earth and moon increased, and in course of time (not less, he estimates, than 200,000,000 years) the present arrangement developed. Darwin investigated the subject with great care mathematically, and while nothing so remote from observation is certain, he shows much plausibility for this hypothesis of the origin of the moon.

The Tides. — As everybody knows who has ever lived by the ocean, the water rises and falls twice a day. Every two weeks there is a time when the range of the tide is unusually high, while a week later the range of tide is much lower. These are called spring and neap tides. As long ago as the times of the ancient

Greeks and Romans, they knew that these phenomena were connected with the motion of the moon, but the real explanation began to dawn when Newton discovered the law of gravitation. He discussed the cause of the tides in the " Principia," and determined the tide-generating forces of the sun and moon, but did not

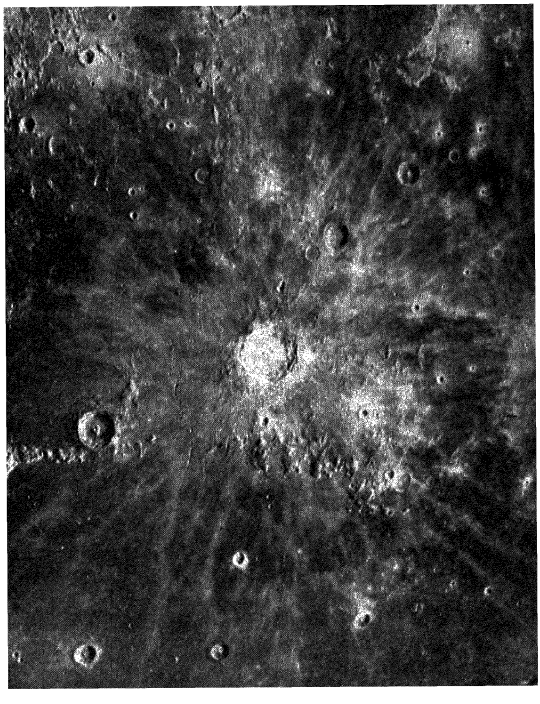


PLATE 14. THE LUNAR CRATER COPERNICUS AND SURROUNDING REGION.
(Mt. Wilson Observatory.)
The diameter of this crater is about 50 miles.

account fully satisfactorily for the lag of the tides behind these forces. As observation shows, the spring and neap tides arrive at a port about $1\frac{1}{2}$ days after the full and change of the moon.

Next to Newton, the greatest work on tides was done by Laplace in the " Mécanique céleste," and, after him, among the most fruitful tide students were Lord Kelvin, Sir George H. Darwin, S. S. Hough, and R. A. Harris. The subject is complex beyond all possibility of complete exposition here, but we may at least see

why it is that there are *two* tides formed at opposite ends of the earth's diameter, instead of merely one on the side towards the moon or the sun, whichever we are considering.

Tidal Theory. — Possibly it may seem simpler to the reader to consider first solar tides, for we are accustomed to think of the sun as central and fixed, with the earth revolving in a mighty orbit around it. Let us recall that Newton showed that all bodies behave as if every particle attracts every other particle with a force proportional to the product of the masses of the two, and inversely as the square of their distance apart. He also showed that for a spherical or ellipsoidal body the attraction of the whole system of particles which compose it, acting on every particle outside, is as if the body was reduced in size to a point, containing the whole of the mass, situated at the center of figure. Recall, also, that Kepler (page 86) discovered that the square of the period of revolution of a planet is proportional to the cube of its mean distance from the sun. Finally it is shown in works on mechanics that a body revolving in a curved orbit pulls away from the center with a force (called the centrifugal force) proportional to the square of the velocity divided by the radius of the orbit. In a steady state of orbital motion, the centrifugal pull is exactly balanced by the gravitational attraction towards the central body.

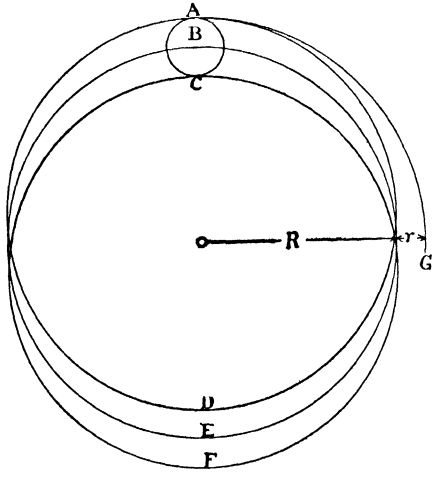


FIG. 15. TIDAL DIAGRAM.

Before going on with the tides, we may pause to note that the effect of centrifugal force due to the earth's daily rotation is seen in the heaping up of matter at the equator. There is no centrifugal force at the poles, due to the earth's rotation, because the speed there is zero, but at the equator the centrifugal force on the water is about $\frac{1}{5}$ pound per cubic foot, and therefore elevates the ocean level there until the height of the column of water is such that its weight balances the centrifugal force. On this ac-

count the polar diameter of the earth is $\frac{1}{297}$ part less than the mean equatorial diameter.

It is not necessary to take the earth's daily rotation into account to see why there is a tide-raising force, though if we should consider the actual tides produced it would be indispensable to do so. Hence, for simplicity, let us consider a spherical earth with a complete covering of ocean, and having no rotation on its axis, so that any equatorial diameter of it would point always to the same star. Referring to the figure, three equal particles at A, B, and C would all be revolving with equal velocities in equal orbits AD, BE, CF, respectively, because all the particles are under constraint to form a part of one body, which is the supposed non-rotating earth. The centrifugal forces of the three particles would, therefore, be equal, and equal to the centrifugal force on B, which is equal to the attraction $\frac{Mm}{R^2}$. But if the particle A had moved freely in an orbit AG of the radius $R + r$, the centrifugal force (equal to the attraction) would have been approximately $\frac{Mm}{(R+r)^2} = \frac{Mm}{R^2\left(1+\frac{r}{R}\right)^2} = \frac{Mm}{R^2}\left(1-\frac{2r}{R}\right)$. Hence, the actual centrifugal force of A, which we just showed was $\frac{Mm}{R^2}$, is too large for equilibrium by the amount $\frac{Mm}{R^2} - \frac{Mm}{R^2}\left(1-\frac{2r}{R}\right)$ or $\frac{2Mmr}{R^3}$. This is the tide-raising force on A and it is directed away from the central body. Similarly, the tide-raising force on C is $\frac{Mm}{R^2}\left(1+\frac{2r}{R}\right) - \frac{Mm}{R^2}$, and also approximately $\frac{2Mmr}{R^2}$. But it is directed towards the central body. So there are two equal tide-raising forces, oppositely directed, at the ends of the simplified earth's diameter. In the actual earth, the shape of the land, depth of the water, physical properties of water, rotation of the earth, inclination of the ecliptic, and other factors complicate the problem so exceedingly that Lord Kelvin, despairing of solving it from first principles, introduced the other procedure of working back from the actually observed tides to determine means of predicting them. This course is now universally adopted.

We have spoken of the solar tides as if they were simpler to un-

derstand than lunar ones. But if we adopt the modern conception that all motion is relative, it is just as easy to understand lunar tides, for we can think of the moon as stationary, and the earth revolving about it, just as we did for the sun. Lunar tide-raising forces are about two and a half times greater than solar, because although the moon's mass is only about $\frac{1}{81 \times 330{,}000}$ compared to the sun, yet the sun's distance cubed is about 60,000,000 compared to the moon's, which more than compensates.

Spring and Neap Tides. — At new and full moon, when sun, moon and earth are approximately in a straight line, the wave from the lunar tides adds its height to that from the solar tide. Under these conditions, the height of the tidal wave is the *sum* of the heights of the two waves produced by the sun and moon. These are called *spring tides.* When the moon is at first or third quarter, the sun and moon are 90° from each other, and the crest of the wave from the solar tide coincides with the trough of the wave from the lunar tide. The height of the tide is then the *difference* between the heights of the two waves produced by sun and moon. These latter are called *neap tides.* The lunar tide is of the greatest height when the moon is closest to the earth, at perigee; while the solar tides are greatest when the earth is closest to the sun, about January first.

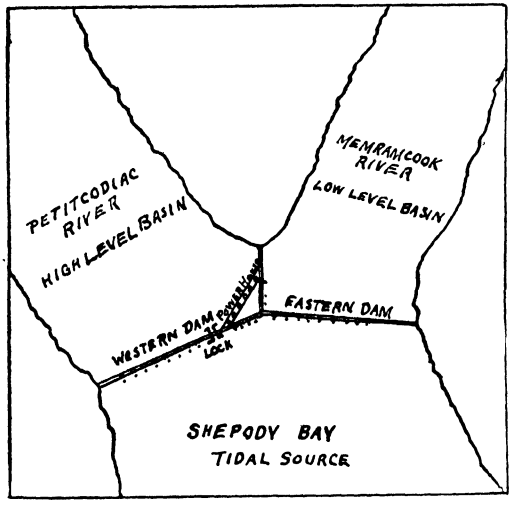


FIG. 16. HOPEWELL TIDAL POWER PROJECT.

The Petitcodiac River is to act as a tide-filled reservoir, discharging directly into Shepody Bay, or into the Memramcook River, according to the height of the tide. In this way a fairly steady head of water is to be maintained to operate turbines and so furnish power for electric distribution.

The highest tides of the year are possible in the winter season. When in addition there is a heavy wind on shore, blowing into the

mouth of a bay or river, the water may be backed up, or retarded from running out, with the consequent result of a very high tide.

Power Derived from Tides. — The height of the tides along the shore is determined by the configuration of the shore line. If the tidal wave runs into a funnel-shaped bay, then the tidal wave mounts very high when the wave reaches the narrow part of the funnel. Such is the case in the Bay of Fundy.

When one looks upon the great tidal flows in some rivers and inlets of the ocean, he is struck by the enormous energy displayed, and wonders if it could not be profitably used for power purposes. Tidal plants have been used for several centuries at various places, but none on a large scale. One of the most notable proposals is that at Hopewell, New Brunswick.

Hopewell stands at the head of an arm (Shepody Bay) of the Bay of Fundy, where the low-level neap tide seldom is less than 32 feet, and the high-level spring tide seldom exceeds 42 feet. Two little rivers, the smaller the Memramcook, the larger the Petitcodiac, empty into the bay at this point. The proposal is to run two dams across the arm of the bay just at the junction of these rivers, and to build a third short dam to separate the two rivers completely, so that they would form two independent basins. The eastern dam across the smaller river is to be so high that the tide can no longer enter it, while the western dam is especially constructed to permit the tide to back up into the larger river. The power plant is to be situated just across the junction of the western dam and the short separator dam, and is to be provided with turbines capable of operating at constant output under a moderate change of head of water.

In operation, the attendants would alter the gates of the dam at intervals predictable years in advance from the tide tables. Thus the flow of water would be either from the big reservoir into the bay, or from the big one to the smaller one, at pleasure, in either case operating the turbines. In this way they are to be kept running under a head which fluctuates only between about 27 and 15 feet, and most of the time much less. The power is to be generated continuously, owing to the large amount of water impounded, and is to be turned into electric power and transmitted throughout Nova Scotia and New Brunswick at costs ranging from $\frac{3}{4}$ cents per kilowatt hour, for large power users, up to 4 cents for small lighting service.

CHAPTER VII

THE SUN'S FAMILY, THE PLANETS

The Gigantic Sun. — To Maréchal Davout's men who marched the weary 90 miles from Vienna to the Pratzen Lakes in 48 hours, to join in the battle of Austerlitz, or to the " forty-niners " plodding their dreary journey, week after week, from the Mississippi to the Golden Gate, it would have seemed a mockery to describe our earth as a little planet. But yet, with its diameter of only about 8000 miles, it is so compared to Jupiter, Saturn, Uranus, and Neptune, with their diameters of 86,500, 70,000, 31,500, and 34,800 miles. Still more is it a puny object compared to the sun, whose diameter is 864,000 miles. The immensity of the sun is indeed overpowering. What the population of New York City is to that of an old-fashioned family, what the length of the Mississippi river is to that of the gutter spout of a roof, what the power of the " Mauretania " is to that of a row-boat, such is the mass of the sun compared to that of the earth. Even the immense planet Jupiter is swung by the sun's attraction over an orbit 3,000,000,000 miles in circumference, and, in retaliation, is only able to swing the sun through an orbit a thousand times smaller. Thus the sun is monarch of the solar system without a peer.

Kepler's and Newton's Laws. — The prime laws of the solar system are the three laws of Kepler and that of Newton. Kepler's three laws. — (1) The centers of the planets go in orbits which are ellipses with the center of the sun in one of the foci. (2) The line which joins the centers of the sun and planet (the radius vector) sweeps over equal areas in equal times. (3) The square of the period of revolution of a planet is proportional to the cube of its mean distance from the sun. (4) Newton's Law. — Every particle attracts every other with a force proportional to the product of their masses, and inversely to the square of their distance. Kepler's three laws, just stated, can be derived from it. When the separate attractions of all the particles of two separated spheres or spheroids are summed up, they prove to be the same as if the total mass of each was concentrated at a point in its center.

The Motions of the Planets. — Not only does the sun make the center of each planet move in an ellipse, but each planet makes the center of the sun move in a small ellipse. Each planet attracts the sun and also each of the other planets, with the result that the movements of a planet are subject to very many attractions. Hence, the motions of a planet cannot be determined by considering its relations to the sun alone. It is easy to see, therefore, that the problems which mathematicians have to solve in order to express planetary motion become very complicated, for the planets continually change their distances and directions from one another, so that their mutual attractive influences are always varying. The greatest masters of celestial mechanics have found the problem of planetary motion insoluble in absolute strictness, and have been obliged to resort to ingenious simplification and approximate methods, which can be repeatedly applied, with ever-growing accuracy of result, till a satisfactory degree of approximation is secured.

One great fact was proved long ago by Laplace. It is that the solar system is stable. One can conceive that, as ages pass, the mutual attractions of the planets might so alter each other's orbits that some catastrophe of collision among them would result. It is this which Laplace was able to show would never happen.

Bode's Law. — More than a century and a half ago, there was discovered that a curious approximate relation exists between the distances of the planets from the sun. All of the planets then known from Mercury to Uranus, agreed with the law, but when Neptune was discovered there was found to be a wide divergence from it. Bode's Law, which is useful in helping us to remember the distances of the planets, is obtained as follows: Write down the series of numbers which, after the second term, are found by multiplying each preceding term by 2:

0 3 6 12 24 48 96 192 384

add 4 to each number as follows:

4 7 10 16 28 52 100 196 388

Compare the distances of the planets from the sun on such a scale that the earth's distance is 10:

3.9	7.2	10.0	15.2	27.7	52.0	95 4	191.9	300.7
Mercury	Venus	Earth	Mars	Ceres	Jupiter	Saturn	Uranus	Neptune

Up to Uranus the agreement is close.

Kepler's Harmonic Law. — By aid of Kepler's third law, the known periods of revolution of the planets fix all the distances within the solar system in such a net that, if one of the distances becomes known, all others follow. For instance, the periods of Mercury and Mars are roughly 88 and 687 days, or nearly as 1 to 8. The squares of these numbers being as 1 to 64, and the cube root of 64 being 4, we should expect Mars to be about 4 times as far from the sun as Mercury. The actual distances are 36.0 and 141.5 millions of miles, almost as 1 to 4.

The Masses of the Planets. — Kepler's third law as it stands is not exactly true. It would be true only if the planets were particles of matter without sensible mass. For a massive body like Jupiter, it is true that the sun attracts the planet, which in consequence falls towards the sun, but the planet also attracts the sun, which therefore falls towards Jupiter. The relative motions of the sun and Jupiter depend on their relative masses. To express Kepler's third law so that it will correctly represent the planetary motions, a factor has to be introduced which includes the sums of the masses of the sun and the planet.

The " Harmonic " law, thus revised, has been of the greatest value, for it gives the means of deriving the mass of a planet which has a satellite. The revised harmonic law may be stated as follows: The combined mass of a body and its satellite is to the combined mass of another body and its satellite as the cube of the distance of the first satellite divided by the square of its period is to the cube of the distance of the second satellite divided by the square of its period. Or expressed as a mathematical formula this becomes:

$$M_1 + m_1 : M_2 + m_2 = \frac{r^3_1}{t^2_1} : \frac{r^3_2}{t^2_2}$$

where M and m are the masses of primary and satellite, r the distance apart and t the period.

Let us use this formula to find the mass of the sun with respect to the earth. Express the distances in miles and the periods in days. Hence:

$$(\text{S} + \text{earth}) : (\text{E} + \text{moon}) = \frac{(93000000)^3}{(365\frac{1}{4})^2} : \frac{(239000)}{(27.3)^2}$$

$$= 332000 \text{ (approximately).}$$

In the general formula, if the mass of the satellite is small compared to the mass of the primary body, then m_1 and m_2 may be neglected and the formula is simplified to become:

$$M_1 : M_2 = \frac{r^3_1}{t^2_1} : \frac{r^3_2}{t^2_2}$$

Our earth is not the only planet to have a moon. Most of the major planets, indeed, have more than one, as shown below:

Planet:	Mercury	Venus	Earth	Mars	Jupiter	Saturn	Uranus	Neptune
Moons:	0	0	1	2	9	9	4	1

What Makes the Planets Move? — People often ask what force it is which keeps the planets in motion. This question is natural enough because in our experience all machines stop running unless power is given to keep driving them. In the solar system, the case is different. There is neither resistance of the air nor friction to overcome. The planets swing along around the sun, age after age, without dissipating their energy, for the simple reason that there is absolutely nothing tending to stop them. It did take an enormous quantity of power sometime in the unknown past to put them into this state of motion, but, once done, it requires none whatever to maintain it. No one knows the character of the primeval forces which set the system in motion originally.

Periods. — We must distinguish between planetary periods of two different kinds, sidereal and synodic. The *sidereal* period is the time of the planet's revolution about the sun, from a star to the same star again, as seen *from the sun*. The *synodic* period is the interval of time required to bring the planet back to the same position with respect to the sun, but as seen *from the earth*. If E and P are the sidereal periods of the earth and planet, and S the planet's synodic period, then the same type of formula connects these three that was found for the moon. Since the planets all move about the sun in the same direction, the formula becomes

$$\frac{1}{S} = \frac{1}{P} - \frac{1}{E} \text{ for Mercury and Venus, and}$$

$$\frac{1}{S} = \frac{1}{E} - \frac{1}{P} \text{ for the exterior planets}$$

Planetary Distances and Periods. —

	Distance in Astron. Units	Distance in millions of miles	Sidereal Period	Synodic Period
Mercury	0 387	36 0	88 days	116 days
Venus	0 723	67 2	225 "	584 "
Earth	1.000	92.9	$365\frac{1}{4}$ "	— "
Mars	1 524	141.5	687 "	780 "
Jupiter	5 203	483.3	11 86 years	399 "
Saturn	9 539	886 0	29.5 "	378 "
Uranus	19.191	1782.8	84 0 "	370 "
Neptune	30.071	2793 4	164 8 "	$367\frac{1}{2}$ "

The appropriate distances in millions of miles of the four exterior planets may be easily remembered from the repeated recurrence of the figure 8: Jupiter, 480 million; Saturn, 880; Uranus, 1800; and Neptune, 2800 million miles. Note also that for the exterior planets, Mars, Jupiter, etc., the synodic periods become less and less, as the distance from the sun is increased and the planetary motion consequently decreased.

Apparent Motions of the Planets Projected on the Sky. — By means of the diagram, the reader may readily visualize the motions of the planets as projected among the stars. It is necessary to remember a few elementary facts: (1) The planets, including the earth, all move about the sun in the same direction, contra-clockwise. (2) The angular motions of the inferior planets, Mercury and Venus are greater than the earth's; while the earth moves faster about the sun than the exterior planets, Mars, Jupiter, Saturn, Uranus and Neptune.

The diagram is drawn approximately to scale to represent the motions of Venus and Mars. Face yourself towards the south. Hold the diagram in your hand with the line from earth to sun horizontal. If the sun is to the right of the earth, the position represents the sun in the west and in the horizon, and therefore in the act of setting. Turn the diagram through 180°. The sun is now to the east of the earth and represents the rising of the sun.

Hold the diagram in the hand with the sun to the right of the

earth. This is the evening sky. At superior conjunction, Venus is moving faster towards the east than the earth and will therefore emerge to the *east* of the sun and become the *evening* star. On the

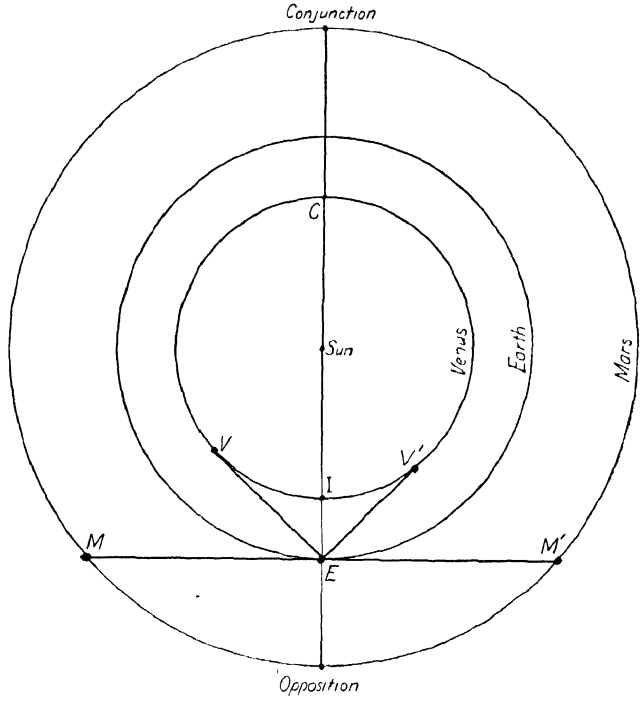


FIG. 17. PLANETARY MOTION.

other hand, Mars is moving to the east at a slower speed than the earth, and hence it emerges from the sun's rays to the *west* of the sun becoming a *morning* star.

Motion of Venus. — If you regard the earth as stationary, in the diagram, with Venus completing its orbit in a period of 584 days, then you can readily represent the motions of Venus. After passing superior conjunction at C and becoming an evening star, the planet slowly increases its angular distance from the sun, setting later each night. After 220 days it is at the position of "greatest eastern elongation" at V. This angle is 47° or 48°, the orbit of Venus departing little from a circle. From the position of greatest elongation, when Venus sets as late as possible after the sun, the planet begins to draw in towards the sun. After 72 days, Venus passes through inferior conjunction and becomes a morning star. Half

way between " greatest elongation " and " inferior conjunction " the planet is at its " greatest brilliancy." In the morning sky, the march of Venus is the same as in the evening sky but in the reverse order, that is, a quick separation from the sun to greatest elongation in 72 days, and then a slow drawing in towards the sun in 220 additional days.

The Motion of Mars. — As already stated, when Mars passes superior conjunction it becomes a morning star. After 390 days, it is at " opposition," or 180° from the sun, and is on the meridian at midnight. It then becomes an evening star. The planet comes to the meridian earlier and earlier each night by a clock that keeps solar time, and finally after another 390 days, the planet passes behind the sun at superior conjunction and again becomes a morning star.

Direct and Retrograde Motions. — With respect to the stars, the planets sometimes move towards the east, their motion being " direct," then they become " stationary," then reverse their motion to the west with " retrograde " motion, then again become stationary and again move to the east with direct motion. The projection of the planet's position on the sky results from the combination of the motion of the planet itself about the sun and the motion of the earth about the sun. We look out towards the planets from the earth which is itself in motion. The ancient astronomers explained the planetary motions by means of a system of cycles and epicycles. We explain these motions as a simple case of relative motion. Just as the sun appears to move eastward among the stars, due to the actual motion of the earth about the sun, so likewise the motion of the earth is superposed on the motion of the planet about the sun. If the planets all moved in the ecliptic the motions in the sky would all be in the plane of the ecliptic, so that in the direct and retrograde motions the planet would retrace its position in the sky. Since the planets move in orbits inclined to the ecliptic, their motions are projected against the sky in a series of loops. At each opposition when a superior planet is closest to the earth, it is at the middle of its retrograde motion in the loop.

All of the motions of the planets may be readily represented by an ingenious reader who will take the trouble of drawing to scale two planetary orbits. It is sufficiently accurate to represent the orbits as concentric circles with the sun in the center. If, now,

the positions of the earth and the planet are taken for equidistant intervals, e.g., once a month, the relative positions of earth and planet are found. By taking a fixed center apart from the first diagram, and by drawing from this central point a series of lines parallel to those on the first diagram and in length equal to the distances of earth to planet on the first diagram, their direct and retrograde motion, etc., can be readily represented. This is a simple case of epicyclic motion.

Physical Conditions of the Planets. — Let us now consider a little the physical state of the other seven great planets besides the earth. The major planets fall in two groups of very different types. There are the four smaller ones, Earth, Venus, Mars, Mercury, in order of descending mass, and the four greater ones, Jupiter, Saturn, Neptune and Uranus, similarly arranged. The first group is the inside, the second the outside group. The planets of the first group are all dense, with an average density nearly five times that of water, while the planets of the second group are all rare, with an average density only about 1.1 times that of water. These are very striking facts, which sometime will play a large part in the true theory of the origin of the solar system.

Mercury. — This little planet, only about one-twentieth of the mass of the earth, is so near the sun that it receives almost seven times as intense solar heat as the earth and moon do. Mercury reflects only about 7 per cent of the solar light, while the earth reflects 44 per cent, and Venus 59 per cent. The moon reflects about the same as Mercury. There is no reason to think Mercury has upon it either air or water, so that probably the full glare of the intense solar radiation falls upon its surface. This view agrees with the low reflecting power of the planet. Furthermore, it is believed, though not fully demonstrated, that just as the moon always presents the same face to the earth, so Mercury always presents the same face to the sun. If this is so, there is every reason to believe that the bright face of Mercury has a temperature almost hot enough to melt tin. Bread or biscuits would bake there in the open within a few minutes, and it would take a skillful baker to keep them from burning. By contrast, the perpetually dark side of the planet must be cold enough to freeze air, so that if there had ever been air and water on the bright side, they must now both be distilled around on to the dark side and congealed there. Such are the consequences

of the assumption that the day and the year of Mercury are of exactly equal length. Mercury, like Venus and the moon, presents its phases to our view, ranging from crescent to gibbous shapes, depending on whether it lies on this side or the farther side of the sun from us.

The orbit of Mercury is the most " eccentric," or elongated, of any in the system of the major planets, and it presents the perplexing feature that the orbit rotates so that the " perihelion," or point of nearest approach to the sun, travels around the sun faster by 43 seconds of arc per century than it should, so far as the attractions of all known members of the solar system would compel it. For a long time, it was supposed that an unknown planet called " Vulcan " existed between the sun and Mercury, and caused the discrepancy, but this idea is now given up. This is because many eclipse photographs, which included all stars near the sun to the 9th magnitude, have all failed to reveal " Vulcan." Seeliger, however, showed that perhaps the matter which sends us the so-called " zodiacal light " may be the disturber of Mercury's orbit. But many astronomers now accept the theory of " relativity," whose author, Einstein, proved that if " relativity " be true, the perihelion of Mercury should indeed rotate in accord with observation. One cannot say that this proves " relativity," for it might be that Seeliger's zodiacal light, or some other explanation, is valid. On the other hand, if there were no outstanding revolution of Mercury's orbit, it would be a severe blow to " relativity."

Venus. — Of all the planets, Venus is most like the earth. It is the one which comes nearest to us, excepting our moon and some of the little bodies called "asteroids" or minor planets. Eight-tenths as massive, more highly reflecting, and two-thirds as far from the sun as the earth, Venus seems more fit on many accounts than any other of the planets to support life similar to ours.

There is one obstacle to this view of which we shall have to take account. It rests on the uncertainty as to the time of the planet's rotation. There is no doubt at all about the approximate length of day of Earth, Mars, Jupiter, and Saturn, but with the other planets, including Venus, there are no plain markings to be seen telescopically. We know that the moon only rotates once a revolution. If Venus is of that class, and her day exactly equals her year, there would be a hot side and a frigid side, both unfavorable to living

conditions, and combining to distill over the water and atmosphere to be congealed on the dark surface.

The spectroscope has its word to say about this matter. It is easy to measure the rotation of the sun, because the one edge of it is coming towards us and the other receding, so that if the light from the east and west limbs is brought together in a spectroscope to give two bands of spectra superposed, the lines from the metals on the east limb are displaced towards the violet, compared to those arising on the west limb. The same thing has been done by Slipher for Uranus, and though the light does not arise there, but is reflected from the sun, yet the limbs of Uranus reflect solar rays whose spectra show the same sort of displacements of lines, and indicate that the planet rotates in 10 hours 50 minutes " retrograde," that is opposite to the prevailing direction for the other planets.

When this is applied to Venus, as has been done with extreme care by Slipher at the Lowell Observatory, and by St. John and Nicholson at Mt. Wilson Observatory, no decisive evidence of the planet's rotation is found. But the method is not sensitive enough to prove that the day of Venus is equal to its year, which is nearly 225 of our days. All that the spectroscope has yet been able to say is that the rotation of Venus occupies at least 10 days, and may possibly be equal to the revolution period of 225 days.

But this leaves the whole question of its habitability open. The direful consequences of distilling over the atmosphere and water to the dark side would occur only if the day and year were just equal. If the day is long, but not equal to the year, the consequences would not be disastrous to life. There is, moreover, another observation which seems to indicate that the day and year of Venus are not equal. It is this:

The reflecting powers of Venus, Earth, Mars and the moon are, respectively, 59, 44, 15, and 7 per cent. The moon is known not to have an atmosphere, Mars so little that he always shows his surface, while the earth is half cloudy. A fully cloudy planet would reflect 77 per cent, according to Aldrich's measures made from a balloon above a level sea of fog. Accordingly, it is natural to infer that Venus is nearly, but not quite, completely cloudy. If so, her atmosphere and moisture can not have distilled away to a frigid side never touched by sun rays. But there is still one more diffi-

culty. Slipher, and also St. John and Nicholson, observing carefully with the spectroscope, found no strengthening of water-vapor lines in the light reflected from Venus. If the planet is covered with clouds of water, how can this be? The explanation is, perhaps, that the clouds we see are very high ones, like our own cirrus clouds, which are composed of ice crystals, and that the light does not penetrate deeply enough into Venus' atmosphere to reach much water-vapor.

In the year 1924, conclusive indirect evidence of the moderately rapid rotation of Venus was obtained by Pettit and Nicholson. They observed that the *dark side* of the planet is nearly uniform in temperature from west to east, and nearly of the temperature that the earth would appear to be if viewed from another planet. Obviously this could not be so without fairly rapid rotation.

This being the true state of affairs on our sister planet, most of the essential conditions seem likely to be nearly as favorable for life there as on our earth. First, the clouds indicate abundant water. Second, the temperature should be suitable. For, on account of distance, the intensity of solar radiation should be just about twice what it is with us, but the greater reflecting power reduces the fraction absorbed in the ratio of $\frac{7}{10}$, so that the resulting solar heat absorbed on Venus averages about 1.4 times that upon the earth. This would tend to raise the mean temperature of Venus' surface to something like the temperature of our tropics, where life flourishes in greatest luxuriance.

Adams and St. John, on the other hand, can find no spectroscopic evidence of oxygen in the atmosphere of Venus. Yet, as the clouds render it impossible to see deep down, nearly to the surface, oxygen might still exist there plentifully enough to support life.

Of course, much of this is conjectural, but, so far as we can see, conditions on Venus may be favorable to life such as we know. But life was never known to start itself. Pasteur's experiments have discountenanced the supposed observed spontaneous generation of life. Its primeval origin is unknown, and the mere existence of favorable conditions is no warrant for the existence of life. We can not know in the case of Venus by telescopic examination, because apparently we are shut off by an impenetrable veil of clouds. Whether there are intelligent works of engineering there, we may never observe. Unless there should be wireless communication, we

probably never shall know whether we have intelligent neighbors on Venus or not.

But it makes the blood stir to imagine what might follow if ever our people could come into fluent communication by wireless with a race brought up completely separate, having their own systems of government, social usages, religions, and surrounded by vegetation and animals entirely unrelated to any here on earth. It would be a revelation far beyond the opening of Japan, or the discoveries of Egyptologists, or the adventures of travelers in the dark continent.

Mars. — There is a great popular interest in the possibility that Mars may be inhabited. At its mean distance, the planet is 141,500,000 miles from the sun, but owing to the eccentricity of its orbit this distance varies 13,000,000 miles. The sidereal period is 687 days, and synodic period 780 days. At opposition, the average distance from the earth is 141,500,000 minus 92,900,000, or 48,600,000 miles. When Mars is at perihelion, or least distance from the sun, the distance from the earth diminishes to 35,000,000 miles. This favorable opposition occurs always in the latter part of August at which time the earth passes the perihelion point of the orbit of Mars. The synodic period is 2 years 50 days. In the 2 years' interval, the earth naturally returns to the same place in its orbit, but in the extra 50 days it would describe about one-seventh of its orbital circumference. Every seventh opposition is therefore a favorable one, and these occur at intervals of 15, or sometimes 17 years. Favorable oppositions took place in 1877, 1892, 1907 and 1924.

The angular diameter of the planet varies from $3''.5$ at conjunction to $25''.1$ at a favorable opposition. In a telescope it takes a power of only 75 to cause Mars to look as large in the telescope as the moon appears to the naked eye. The linear diameter is 4215 miles, the mass is 0.1076 that of the earth's, and the superficial attraction of gravity 38 per cent that of the earth. Mars rotates on its axis. Its sidereal day according to Lowell is $24^h\ 37^m\ 22^s.58$. The inclination of the planet's equator to the plane of its orbit is $25°\ 10'$, according to H. Struve and $23°\ 30'$ according to Lowell. Hence, not only does the day of Mars differ little in length from that of the earth but it has seasons resembling those of the earth, though the year on Mars (687 days) is longer than that of the earth ($365\frac{1}{4}$ days).

Surface Features. — Even in a small telescope Mars presents a beautiful appearance, showing a surface with interesting markings, light and dark. Features of three different kinds are to be specially noticed. (1) Three-fifths of the planet is of a reddish or ochre color. This is the bare, almost featureless surface of the planet. (2) Two-fifths of the planet is of darker color showing a greenish tinge. (3) The polar ice caps, white in color, surround both the north and south poles. It is generally believed these are ice or snow. The south polar ice cap sometimes entirely disappears, but the northern one never quite vanishes.

Is Mars Inhabited? — It is rarely that the high powers of a great telescope can be utilized for a study of the planet. In fact

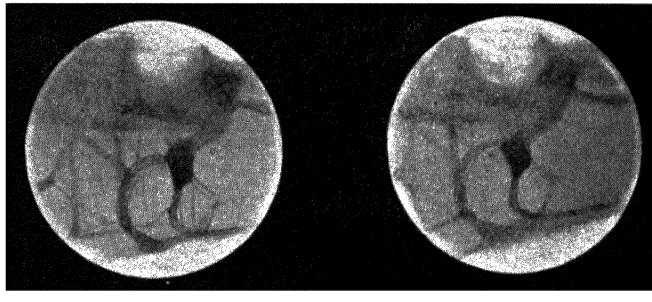


PLATE 15. MARS.

From drawings made June 17, 1922, one hour apart, by E. C. Slipher, Lowell Observatory.

it is even claimed by the experts that a telescope of moderate size (10 inches in aperture) exhibits the surface features of Mars to greater advantage than a larger telescope. Suppose, however, that it were possible to use a power of 1000 in a study of Mars, and suppose it were at its nearest approach to the earth of 35,000,000 miles. We would therefore be viewing the ruddy planet as if we were looking at it with the naked eye, with the planet at a distance of 35,000 miles. Now question yourself as to what you would see of the earth under these conditions. You would catch no glimpse of signs of habitation like the great cities of London or New York, there would be no signs of mighty rivers like the Mississippi or the Amazon. Now reserve your judgment a little and again survey the planet.

That Mars is inhabited by a race of human beings far more ad-

vanced in civilization than are we on earth (since Mars is smaller than the earth and has cooled off more rapidly) was the firm conviction of Percival Lowell. He based his belief on the appearance of the "canals." It is generally believed that there is little water on Mars, the only water observed being near the melting ice caps. As human life is impossible without water, the canals were believed by Lowell to be irrigation projects carried through the whole of the surface of the planet by a race of skillful engineers with wonderful mechanical appliances. In the "canals" themselves, as thus interpreted, we do not see the actual water surface but rather a strip of vegetation growing up along the main watercourse and its tributaries. On the advance of the spring season on Mars, the Lowell astronomers report that the canals actually grow, thus giving indication that vegetation then becomes more luxuriant. More than 400 canals and 200 oases have been observed and named at the Lowell Observatory. At least 50 of the canals are stated to be double.

At the opposite extreme in the interpretation of Mars was Barnard, generally regarded to have had one of the keenest eyes that ever looked through a telescope. Although he was an assiduous observer, and frequently saw the planet under splendid observing conditions, he never saw even a single canal. He did see a wealth of detail on Mars, and changes which were evidently seasonal, and was firmly convinced that at least there was vegetable life on Mars. The majority of competent astronomers who have made a study of Mars agree with the opinion of Barnard. When an astronomer observes a difficult object, it is impossible for him or anyone else to know whether he has made a drawing of what actually is seen to exist, or whether the mind has persuaded the observer quite unconsciously that he actually sees something a little different. The eye unconsciously may join disconnected patches into a continuous line. While driving through the Ardennes forest recently, one of the writers of this volume noticed that the ends of the pine branches appeared to lie in definite horizontal straight lines. This was all the more surprising seeing that the terrain was very hilly and that the trees and boughs grew at all angles.

It is now generally admitted that there exists much detail on the planet, probably in disconnected patches, but it is doubted

whether the canal system has an actual existence. If not, there is no "proof" that Mars is inhabited.

Unfortunately, photography cannot help in the problem. With the Lowell telescope, the direct photograph of Mars when closest to the earth is of the size of the head of an ordinary pin. Enlargement of the direct image, as is done in a telephoto camera, can never portray the fine details seen by a keen eye.

Atmosphere and Temperature. — Mars unquestionably has an atmosphere. As its gravity is only 0.38 that of the earth, its atmosphere must be rare, resembling the conditions on the tops of our high mountains. By spectroscopic methods, Adams and St. John

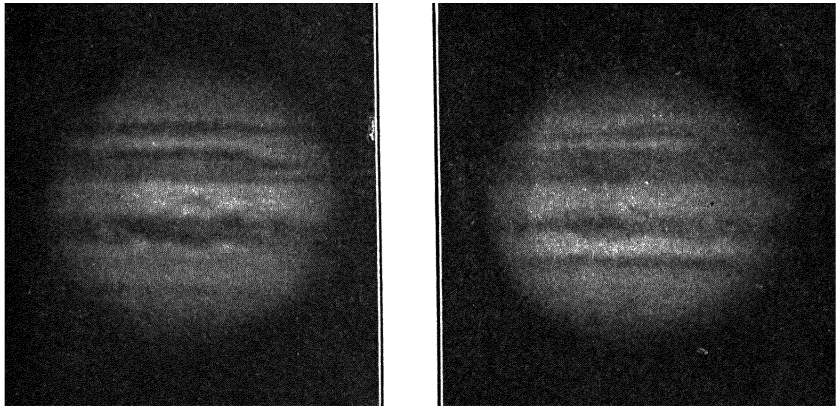


PLATE 16. JUPITER. (Photos by E. C. Slipher, Lowell Observatory.)
Left, October 19, 1915. Right, December 19, 1917.
The photographs show two different longitudes of the planet. The region of "the great red spot" is seen near the right edge of the left-hand view.

find that for equal areas Mars has 6 per cent of the water-vapor present in the atmosphere above Mount Wilson (5800 ft. elevation) and one-sixth the oxygen, or about two-thirds of that in the earth's atmosphere above Mount Everest (29,000 ft.)

Quite recently the observers at the Lowell and Mount Wilson Observatories have measured the temperature of the surface of Mars. They agree in stating that at noon at the equator the temperature may reach 10° C (50° F). At sunrise and sunset, the temperature has dropped to freezing, and each night it must be bitterly cold, something like – 50° F. The maximum temperature

comes at noon on the planet, and not in the afternoon as on the earth, again indicating that the atmosphere of Mars is practically devoid of water-vapor or other gases that absorb the planetary radiation. Probably the polar caps are of ice or snow, i. e., frozen water, though possibly of frozen carbonic acid.

The inhospitality of such conditions is apparent. We have, it is true, many evergreen trees, mosses, and other forms of vegetation which survive here in climates as rigorous as those at the Martian equator, but we cannot believe that Martian life braves out these conditions to be so abundant or advanced in type as some students of the subject would have us suppose. If animal life exists on Mars it must be of a very low order, somewhat akin to that of a jelly-fish.

Jupiter. — This is the giant planet. Of 10 times the earth's diameter, 317 times her mass, so far from the sun that the solar rays are only about one-thirtieth of their intensity here, blessed with a ten-hour day, composed of a material only a quarter as dense as that of the earth, surrounded by nine moons — surely a human would find extraordinary changes in his outlook if he awakened some morning on Jupiter! Labor unionists there would be adjusting their demands for a three-hour day for labor, and be in line with eight-hour practise upon Earth.

There are some very queer things about the rotation of Jupiter. He shows great reddish spots and belts upon his surface. It is by the march of these markings that the period of rotation is measured. It proves variable in the different Jovian latitudes. According to Williams, the rotation periods are as follows:

Latitude	+ 85° to + 28°	+ 28° to + 24°	+ 24° to + 20°	+ 20° to + 10°
Length of day	$9^h\ 55^m\ 37^s$	$9^h\ 55^m$	$9^h\ 49^m$	$9^h\ 55^m\ 34^s$

	+ 10° to − 12°	− 12° to − 18°	− 18° to − 37°	− 37° to − 55°
	$9^h\ 50^m\ 20^s$	$9^h\ 55^m\ 40^s$	$9^h\ 55^m\ 18^s$	$9^h\ 55^m\ 5^s$

These figures, some of them, rest on observations of as many as 60,000 revolutions of the planet. The irregularity of them is rather puzzling. It seems unlikely that it is a solid body that is being observed. And yet it is very hard to understand how a definite object could remain so long in a liquid or gaseous surface as these red spots do. They may be floating islands, it is true, like islands of seaweed, but the subject is certainly very obscure.

It has been thought by some that Jupiter is hot from his own

sources, even so hot as to give light of his own. But against this view is the fact that the satellites cast good dark shadows upon the planet's surface when they pass between Jupiter and the sun. Hence, Jupiter's light must at least be very feeble, compared to the weak sunlight there. Coblentz and Lampland, too, in recent observations with the thermopile, found evidence of very low surface temperatures for both Jupiter and Saturn.

The eclipses of Jupiter's four larger satellites (often called Galilean, because discovered by Galileo) give a means of determining the sun's distance from the earth, as has been described in Chapter IV. But this method is not the most accurate one. In old times, it was proposed to make use of the positions of these satellites to aid in navigation. For they are so many, and change their places so fast, that their appearance at any time, if compared to the

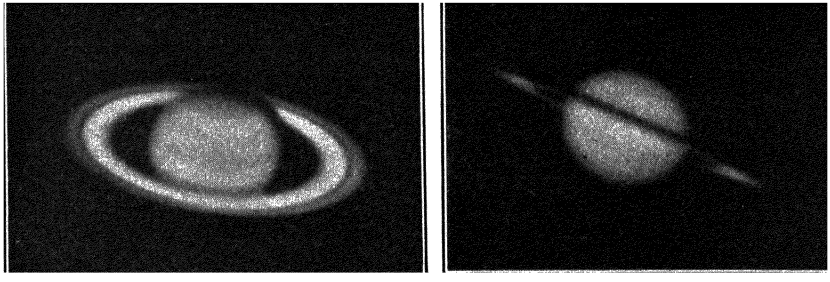


PLATE 17. SATURN. (Photos by E. C. Slipher, Lowell Observatory.)
Left, February 11, 1916. Right, May 24, 1922.
The bands upon the planet are perhaps of a cloudy nature. The rings are made up of meteoric particles rotating about the planet.

places given in the Nautical Almanac, is sufficient to give a fairly close value of the Greenwich time, and so of longitude at sea. This method cannot compete in accuracy in our day with a good chronometer.

Saturn. — Among all the beautiful and wonderful sights which the heavens afford, the four leading ones, perhaps, are the glories of the rising and setting sun, a total solar eclipse, the aurora with its weirdly dancing polar streamers, and the telescopic view of the planet Saturn. To see that silvery ball, so delicately poised within its wonderful rings, is a sight that never fails to charm, however familiar.

Like Jupiter, Saturn shows spots upon its surface occasionally, though far less conspicuously than Jupiter. From observing them, the time of rotation is known. It is $10^h\ 14^m$ at the equator and longer towards the poles, as with Jupiter and also with the sun. This planet is the least dense of any of them, indeed only 0.7 the density of water, and thus little more than half the density of Jupiter. It is as well provided with moons as Jupiter, for each has nine. The ninth satellite, discovered in 1898 by W. H. Pickering, makes its revolution in opposite direction to the others.

Far more remarkable, however, is the wonderful system of rings which has no fellow among all the heavenly bodies. Half the light the planet sends us is reflected by the rings. These are really a multitude of fine particles in procession around the planet. The rings are very thin compared to their total breadth, which amounts to 37,500 miles. Saturn itself is 70,000 miles, and the outer ring 167,000 miles in diameter. Because the rings are inclined 27° to the orbit of the planet about the sun, and this again is slightly inclined to the earth's orbit, they present themselves to us under very different aspects. Sometimes the rings come almost exactly in line with the earth and practically disappear, but at other times they open out widely and expose all their grandeur. Saturn lies so far away from the sun that it requires nearly 30 years to complete its orbit, so that it marches but little among the stars from month to month, and the changes in the aspect of its rings require the impatient observer to wait a long time. Owing to its great distance, sunlight at Saturn is less than $\frac{1}{80}$ of the intensity with us.

Uranus. — When Sir William Herschel discovered this planet, in 1781, he saw a round nebulous disk, which he supposed to be a comet, moving slowly among the stars. When its motion proved that it was really a planet, there was at first some disagreement among astronomers in selecting a name. Herschel's loyal preference for "Georgium Sidus," in honor of King George III, was supported officially in England till the year 1850.

Uranus, like the three other greater planets, is nearly of the density of water, and less than one-fourth that of the earth. Situated more than 18 times as far from the sun as the earth is, it receives only about $\frac{1}{400}$ as intense sunlight, and requires eighty-four years to make a revolution. The spectroscopic observations of Slipher indicate $10^h\ 50^m$ as the length of Uranus' day. It has four

moons, of which the outside one takes a little less than half the period of our moon to encircle its planet, while the inmost one goes round in $2\frac{1}{2}$ days. A curious thing about the satellites of Uranus is that they all go in orbits inclined nearly at right angles to the ecliptic. Thus it happened in 1882 and 1924 that their orbits were seen edgewise, and the satellites seemed to us to swing north and south on each side of the planet. In 1903 and 1945, on the other hand, the orbits of the satellites present their true circular form.

Neptune. — A most remarkable thing about this planet is the story of its discovery. John Couch Adams, just graduated from the University of Cambridge, began in 1844 to examine mathematically the problem of the size and position of a planet competent to produce by its attraction the disturbances which had been observed in the orbit of Uranus. By the autumn of 1845, he was ready to present his results for the inspection of the Astronomer Royal, Airy. He called at the Greenwich Observatory, but unfortunately missed seeing the Astronomer Royal because he was at dinner and his butler would not disturb him. So Adams left a paper for him which gave the computed place and elements of the supposed planet. This paper Airy acknowledged, but raised some further question, which for some reason Adams failed for some time to answer, perhaps because he thought that he had received a rather chilly welcome. So nothing towards looking for the planet was done in England for another year.

In the meantime, U. J. J. Leverrier, who had also attacked the problem in France about the same time as Adams in England, published his first results in October, 1845, and June, 1846. In a third paper, published August 31, 1846, Leverrier indicated that the planet would be large enough to show a disk which would distinguish it from a star. By this time, Airy had become more interested, and in July, 1846, recommended Professor Challis to undertake a search with Adams' positions. This search Challis began in August. But he had no star maps suitable for the purpose, and photography was not perfected, so that he got over the sky but slowly, and he did not immediately map his observations.

So it happened that Dr. Galle of Berlin, Germany, who had received from Leverrier a letter informing him where to look, and who fortunately had available a star chart of the region, recognized

the planet on September 23, 1846, and was the actual discoverer. Challis had really seen it 50 days earlier without knowing it. Nor was he the first, for when the orbit became known it was found that Lalande, at Paris, had recorded its place in May, 1795, over 50 years earlier. The mathematical work of Adams and Leverrier, who independently located very closely the unknown Neptune by its perturbing influence across the billions of miles to Uranus, is the feature of this old story which has always raised the admiration of mankind.

Neptune is the outermost known planet, 2,792,000,000 miles from the sun. He requires 165 years to complete his orbit, so that a large part of it is still to be traversed before the planet will return to the place where Lalande was the first man ever to see it. At this immense distance, the sun's rays are only $\frac{1}{900}$ the intensity of those that warm our earth, so that unless Neptune has stores of heat of his own, his temperature must be very low. Despite this low temperature and his large mass and gravity, the density of Neptune is only a fifth that of the earth, and not far from that of water.

We have little real knowledge of the physical state of what lies below the visible surfaces of the four great planets, Jupiter, Saturn, Uranus, and Neptune. But, from the low density, we suppose them to be largely gaseous, and from the low intensity of solar radiation at those immense distances, we see that they cannot be of temperatures fit for life unless their own activities provide other sources of heat than sun rays.

The Minor Planets. — Between the orbits of Mars and Jupiter lies a large gap of space, in which, according to Bode's law, should lie a planet 2.8 times as far from the sun as our earth. Beginning with the first night of the nineteenth century (January 1, 1801), when Piazzi discovered the first asteroid Ceres, astronomers have have been filling this gap with little planets, none of them nearly as big as our moon, and ranging from a diameter of 500 miles down to, comparatively speaking, mere rocks but a few miles in size. In all, nearly a thousand have already been discovered, and it seems probable that if we could detect every one, however small, the number would be almost countless. Now-a-days, they are discovered by photography. If a photographic telescope is set to follow the stars exactly, so that they appear as round dots on the

photograph, the minor planets will give elongated images, because of their motion, and this leads to their recognition. The difficulty comes in determining whether they have been seen before.

Some of these bodies are variable in their light, which means that one side is more reflecting than the other. This gives a chance to measure the time of rotation for a few of them.

Gauss suggested that these bodies might be fragments of a larger planet which exploded. But it is not now held that this was the case, because the character of the orbits does not seem to allow mathematically of this hypothesis. It is very interesting to note that the orbits lie in groups as indicated by the mean solar distances. In the accompanying diagram, the heights indicate numbers of planetoids, and horizontal positions indicate distances from the sun

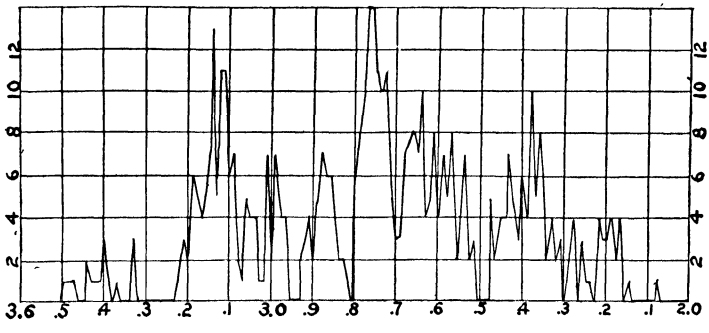


FIG. 18. Numbers of minor planets or asteroids, at solar distances between 2.0 and 3.6 times that of the earth. Note the gaps near 2.49, 2.81, and 3.24, which are points which require (by Kepler's law) 3, $\frac{5}{2}$, and 2 times Jupiter's mean angular motion respectively.

compared to the earth's distance. The curious feature has been pointed out that the groups tend to avoid distances in which the angular motion is in exact multiples of Jupiter's motion. Such points are 2.49, 2.81, 3.24, where the mean motion is 3, $\frac{5}{2}$, and 2 times that of Jupiter, respectively. There are a few of these little planets that have nearly the same mean distance as Jupiter, which is a very interesting coincidence.

Eros. — For astronomers, this planetoid is one of the most interesting objects in the sky in spite of its insignificant size. Discovered by photography in August, 1898, by Witt of Berlin, its orbit showed it to be a very remarkable object because it comes

closer to the earth (13,840,000 miles) than any celestial object except our own moon. Its sidereal period is 643.23 days, and its synodic period 845 days, the longest known. Its mean distance from the sun is 135,430,000 miles, but its orbit is very eccentric so that its perihelion distance is only 105,230,000 miles. At closest approach to the earth (which will always take place about January 22), it is at half the least distance of Venus from the earth. Under such conditions its horizontal parallax is nearly 60″. The accurate determination of its parallax affords the most accurate direct method for determining the scale of the whole solar system, including the earth's distance from the sun. Unfortunately these favorable oppositions are very rare, the most favorable one of our time taking place in the year 1894, when Eros had not yet been discovered. The nearest approach since then was in 1901, when the planet came within 30,000,000 miles of the earth. The next opportunity will come in 1931, when the least distance will be about 16,000,000 miles (on January 30). The orbit of the planet is exceedingly interesting on account of the fact that when at its least distance the perturbations of its orbit by the earth will be very great. This will permit a very accurate determination of the earth's mass with respect to the sun, and hence of the solar parallax. Eros is probably about 15 miles in diameter, and in a telescope it looks like a faint star.

The late Professor James Watson discovered a good many minor planets. He felt such a fatherly interest in them that he made provision in his will for a trust fund, called the Watson Fund, in the custody of the National Academy of Sciences, to be devoted to the promotion of knowledge of the Watson planets, and closely related subjects. Thus, among charitable homes for so many other things, we have something like a refuge for lost planets. There are, indeed, so many minor planets known, and so many being discovered, that the late Professor Weiss of Vienna used to speak of them as "those vermin of the skies." Without occasional reobservation and appropriate rectification of the data of their orbits, many of them would be lost. This has already happened with quite a number of them.

CHAPTER VIII

COMETS AND METEORS

In olden times the appearance of a comet was regarded with great horror as it was thought to forebode war, or pestilence, or the death of a favorite prince. Large comets are magnificent objects in the sky, often continuing to be visible for months at a time. In their physical characteristics comets differ greatly from stars and planets.

Discovery of Comets. — Up to the present we have records of 900 comets, of which number 400 were discovered before the invention of the telescope. Comets are now being discovered at the rate of half a dozen per year. Of these, 70 per cent are new comets, while 30 per cent are returns of comets already known. The new comets are usually picked up by observers who make a specialty of searching the heavens systematically with a telescope of low optical power. As a reward to the observer for his patience and zeal, the comet is usually known by the name of the discoverer. Recently several have been picked up accidentally by photography, the first instance being in 1892, the comet being found by Barnard on a plate exposed for some other purpose. Before periodic comets are observed visually, they are frequently picked up by photographs, taken at the time of their expected return.

Comets are known frequently by the name of the discoverer, or of some one who has made important researches in connection with them, as, for example, Halley's or Encke's comet. They are designated also by a small letter indicating the order of their discovery during the year, or by a Roman numeral showing the order of perihelion passage.

Brightness of Comets. — Occasionally brilliant comets appear, such as 1843 I, Donati's, 1882 II or 1910 I. Most of the comets discovered are visible only in a telescope. Some are visible only for a short time, while near the sun and the earth; some are observed for many months, Comet 1889 I having been followed in a telescope for more than two years.

Halley's Comet. — Many readers will recall the interest connected with the return of Halley's comet in 1910. This wanderer comes close to the sun once in 75 years. Halley was the friend of Newton who aided in the publication of the " Principia," and who used Newton's principles, then newly framed, to compute the orbit of this famous comet of 1682. Halley identified it with the comet observed by Apian in 1531 and by Kepler in 1607, and fixed its return for 1758–9. Sure enough, it reappeared on Christmas day,

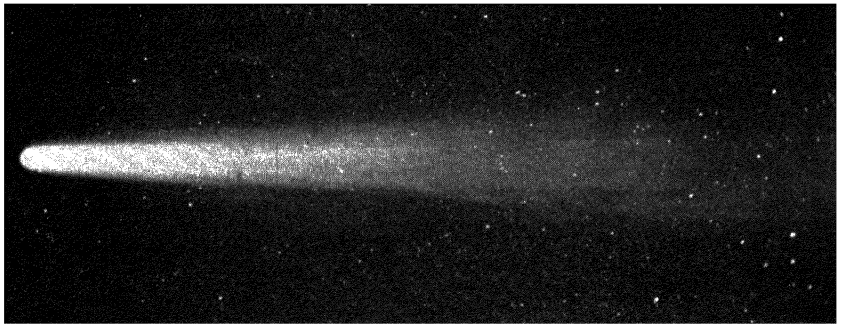


PLATE 18. HALLEY'S COMET OF 1910. (Photo by Ellerman.)
This famous comet, named for Newton's friend, Halley, who discovered its periodicity, revolves about the sun in about 76 years. Its orbit is very eccentric, so that at farthest it is about as far from the sun as the planet Neptune, and at nearest only about half as far as the earth.

1758. Since then it has been observed in 1835 and 1910. Careful computations of the orbit showed that it passed directly between the earth and the sun on May 18, 1910. Although very careful observations were made by astronomers spread throughout the world, no effects of this passage were observed in the diminution of the sun's effulgence or the curtailment of the sun's radiation.

The Comet of 1843. — One of the most brilliant comets of recent times blazed out suddenly in full daylight, on February 28, 1843. It was seen simultaneously in Mexico, the United States, and Southern Europe. On the steamer " Owen Glendower," off the Cape of Good Hope, the passengers were surprised to see a " short, dagger-like object " following the sun towards the western horizon. The head of the comet was then situated only 1° 23′, or a little over twice the sun's diameter, from the center of the sun itself, and observers in Italy were able to trace the tail four or five

degrees at midday. On March 3, the tail measured 25°, and on March 11, a second tail, twice as long as the first, shot out in a single day. The Russian, Boguslawski, estimated the length of tail at 581 million miles on March 21, or longer than the radius of Jupiter's orbit.

When the comet went closest to the sun, its center was but 78,000 miles outside the sun's surface. The comet went right round the sun through 180° of its path in 2 hours 11 minutes, at the rate of 366 miles a second. Not only so, but the *tail also swept round*, always streaming away from the sun. Had it been *the same tail*, and as long as Boguslawski observed it, the outer end must have traveled over 800 million miles in 131 minutes, or say 100,000 miles a second, approaching near the velocity of light.

Orbits of the Comets. — After the discovery of a comet, and when three independent observations are made of it, the orbit of a comet is calculated. On account of the greater simplicity of the computation, it is assumed that the comet moves in a parabola. When more observations are secured, and particularly when the observed arc is longer, a new orbit is calculated which may be an elliptic or hyperbolic orbit, if the observations can not be satisfied by a parabolic path.

Periodic Comets. — More than fifty comets are known with periods less than one hundred years. These move in elliptical orbits. The short-period comets are all inconspicuous, and some of them only telescopic. Two of the most celebrated of them are Encke's and Biela's. Encke's comet was discovered by Pons of Marseilles, November 26, 1818, but investigated by Encke, who found its period to be 1208 days, which is shorter than that of any other comet then known. He traced it back, and identified it with comets seen by various observers prior to 1800. After carefully investigating the perturbations it must suffer from the planets, Encke predicted the time and place of its return, and the event closely followed his prediction. The orbit lies altogether within that of Saturn, and is not extremely elongated. However, at "perihelion," or nearest approach to the sun, it goes inside the orbit of Mercury. This comet has served, by the perturbations it has experienced, to give some evidence on the mass of Mercury, as also that of Jupiter. On several occasions, the nucleus of Encke's comet (and indeed those of other comets) was observed to shrink in size as it

neared the sun. It is a curious effect, not perhaps quite understood, but may mean that the larger diameter represents an object shining by its own light too feebly to compete with sunlight on near approach to the sun. Encke's comet, for a number of revolutions, seemed to be falling nearer and nearer the sun, and shortening its period, as if it was encountering resistance to its flight. Later on, however, this tendency was reversed.

Biela's comet, discovered February 27, 1826, had a period of between six and seven years. It also was traced back into the eighteenth century. It returned several times, as predicted, but in 1845, after presenting first a pear-shaped form, it divided into two comets which gradually separated, thus perhaps showing in miniature the history of the earth and moon. On the return in 1852 the double form was recognizable, but the companions were over 1,200,000 miles apart. Both vanished shortly after their rediscovery, and have never been seen since.

The great planets, Jupiter and Saturn, are powerful disturbers of the comets. Occasionally a comet passes so near one of these great attracting bodies that the cometary orbit is changed altogether, sometimes to give it a planetary character, and sometimes perhaps to throw it out of our system altogether.

Dimensions of Comets. — The volume of a comet is sometimes enormous. Even a small comet may have a tail 5,000,000 or even 10,000,000 miles in length. The comet of 1882 had a tail 100,000,000 miles long. Cometary matter is exceedingly rare. Very faint stars have been observed many times right through the center of the nucleus of a comet thousands of miles in diameter, without perceptibly dimming the star's light. Lexell's comet approached the earth within 1,500,000 miles on July 1, 1770, and Laplace showed that had its mass been as much as $\frac{1}{5000}$ of that of the earth the year must have been lengthened appreciably, yet no such thing occurred. It has been stated that if all the material in a comet could be sufficiently compressed it would be possible to place it all in one small trunk. With such a colossal volume and small mass, the density, at least of the tail, must be considerably less than the best vacuum possible by mechanical means. The comet is therefore an "airy nothing." Even the head cannot be very dense, seeing that the 1882 comet and Halley's were absolutely invisible as they crossed the face of the sun. There must, however,

be a good deal of solid material in the head of a comet, but the diameters of the separate particles are small and with such large interspaces that the sun's light can filter through with little hindrance.

Physical Constitution of Comets. — Comets, as the spectroscope indicates, are composed in part of gaseous materials, mainly compounds of carbon, nitrogen, oxygen, and hydrogen. The tail always streams away from the sun, following behind the comet's head during the approach to the sun, but preceding the head when the comet is receding. This behavior of the tail of a comet forces us to the conclusion that the comet does not keep its same tail but is continuously forming a new tail. New matter is driven off from the head continuously by the pressure of the light of the sun. Clerk Maxwell predicted theoretically, and Lebedew, and Nichols and Hull, afterwards demonstrated experimentally that light exerts a pressure on small particles, which becomes enormous in such close proximity to the sun as was the case with the comet of March, 1843. It is easy to see that the position of the tail must depend jointly on the velocity of the head, the pressure and velocity of light, and the masses of the individual particles or molecules driven off. Hence, if there be several kinds of particles or molecules available, it is not strange that a comet may present two or even more tails, those materials which are driven faster streaming out more nearly directly away from the sun.

As an illustration of the zeal of astronomers in their search for comets, the following incident may be related of Messier, a devoted French observer of the eighteenth century.

"He is a very worthy man, with the simplicity of a baby. Some years ago, he lost his wife, and his attention to her prevented him from discovering a comet he was on the search for, and which Montaigne of Limoges got away from him. He was in despair. When he was condoled with on the loss he had met, he replied, with his head full of the comet, 'Oh, dear! to think that when I had discovered twelve, this Montaigne should have got my thirteenth,' and his eyes filled with tears, till, remembering what it was he ought to be weeping for, he moaned, 'Oh, my poor wife!' but went on crying for his comet."

Meteors and Meteorites. — What people speak of as "shooting stars" are not stars at all. They are bits of matter, varying in size

from dust particles up to bodies of many tons weight, that go coursing around the sun like planets. Some of the orbits which they occupy intersect the orbit of the earth, and thus it happens that we often fall in with them in our journey around the sun. When this happens, the energy of motion of the little body, entering the earth's atmosphere with immense speed, by friction with the air is converted into heat. This heat is generally sufficient to melt the outer part of the body. In this condition there is a union between its substance and the oxygen of the atmosphere, so that often the little wanderer is consumed in a blaze of light, and we see a *meteor*. Often the outer layer cracks off by expansion, and leaves its fragments behind as a meteor-train, lasting bright for several seconds.

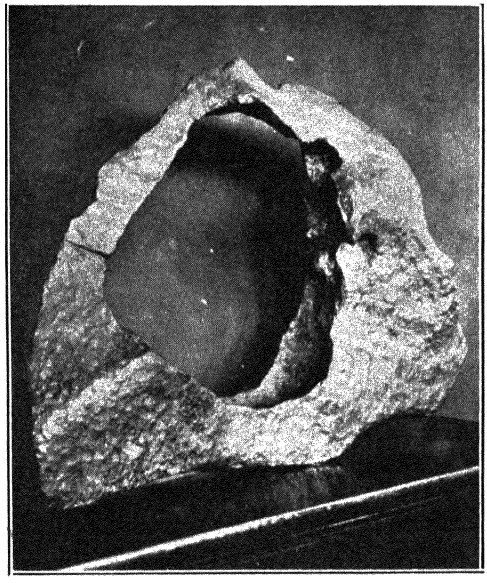


PLATE 19. THE TUCSON METEORITE.
This curiously shaped mass of nickel-iron weighs nearly 1400 pounds, and fell from the skies no one knows how long ago.

If the meteor is very large, it may go entirely through the atmosphere to the earth's surface, and then we speak of it as a *meteorite*. Thousands of them are now preserved in museums. The largest is one found in Bacubirito in Mexico, estimated to weigh 50 tons. The late Admiral Peary found one in Greenland which weighed $26\frac{1}{2}$ tons. He conveyed it to New York, where it now is deposited in the American Museum of Natural History. Although meteors enter the earth's atmosphere with velocities ranging from 10 to 45 miles a second, their speeds drop to very moderate values after they encounter the resistance of the air. Hence, it is very seldom that a meteorite makes itself a hole in the earth's surface as deep as 10 feet, and in one case a shower of them fell on ice and rebounded without breaking it.

Although the surface of a meteorite becomes very hot at its first

entrance into the atmosphere, it is cooled again in the lower air. If it reaches the earth, it is seldom hot enough to char wood, and often is merely a little warm to the touch. Very few fatalities have ever occurred by reason of persons being struck by meteorites. Several close escapes are on record, as when one fell between two carters on a road at Charsonville, throwing the ground up to a height of six feet, and when another broke through the roof of a cottage at Braunau. Human beings occupy so small a part of the earth's surface that the chance of a meteorite hitting one is very, very small.

Meteorites are of three classes. In one, they are composed mainly of metallic iron alloyed with nickel; in the second, these substances are mixed with stony matter; and in the third, they consist almost exclusively of stony matter. Altogether, about one-third of the most common chemical elements present on the earth have been found in meteorites, but no unknown ones. It seems probable that our earth is not very different in its make-up, both as regards elements and their proportions, from a mixture of all the meteoric specimens which have been collected.

Number of Meteors. — Multitudes of meteors fly in space. On dark, clear nights, nearly a dozen may usually be seen in an hour by one observer. Twice as many fall in morning hours as in evening ones, and more than twice as many in the last half of the year as in the first half. These peculiarities, of course, have to do with the direction the meteors go in their orbits, and the directions in which the earth is going with respect to them at different times. In the morning hours before sunrise, the observer is on the forefront of the earth as it careers through space at a speed of $18\frac{1}{2}$ miles per second on its annual journey about the sun. Successive meteors are separated on the average by 250 miles, but during the special showers, as that of November 1833, they come along as frequently as one for each 15 or 20 miles. It is estimated that as many as 20,000,000 meteors big enough to be visible, if it were always clear night-time, enter the earth's atmosphere every 24 hours. If telescopic meteors were included, the estimate would be hundreds of millions every day.

The Leonids. — The great showers of meteors come about $33\frac{1}{3}$ years apart, and have been noted in history since the tenth century. They are called the November meteor showers, and they

occur to a lesser extent on November 14 of every year. The next great November shower is due about 1932 or 1933. Since they radiate from a point within the Sickle of the star-constellation Leo, they are called the " Leonids."

The explanation is that there is a great stream or ring of meteors, extending all the way around their orbit about the sun, with condensed groups in certain parts of it. As the orbit is elliptical and intersects that of the earth but once, the earth falls into it only once each year. But once in $33\frac{1}{3}$ years the big group is encountered at the intersection.

The individual objects forming the shower are moving in parallel lines, and the paths through the earth's atmosphere are actually parallel. That they appear to radiate from a small area in the sky, is due to an effect of perspective. The eye of the observer sees the straight parallel paths projected back upon the face of the celestial sphere. The average person will readily admit that the rails of a railroad are actually parallel, even though they appear to meet at a distance, but it is very difficult for the same person to grasp the notion that the sun's rays shining through the clouds and " drawing water " are also parallel. The rays are seen to be projected on the celestial sphere like the spokes of an umbrella, but all of the rays are centered in the sun, and the sun is at such a great distance from the earth that the rays must be sensibly parallel. Similarly with a meteor shower, the meteors *appear* to radiate from a center, known as the radiant, but the paths of the individual meteors are *actually* parallel. The Leonids themselves travel through space at a speed of 26 miles per second. As their orbital motion is in a direction opposite to that of the earth, the speed with which the Leonids go through the earth's atmosphere is over 44 miles per second.

There are several other times of the year when it is worth while to look specially for meteors, notably for the Andromids, about November 20 to 24, whose principal showers are 6.7 years apart. Their orbit agrees with Biela's comet which was last seen in 1852. These meteors overtake the earth, and so seem to fly but slowly. Another great display is that of several weeks centering about August 10, when the Perseids come on. These seem to be nearly evenly distributed from year to year. Again, there are the April meteors, which radiate from near the bright star Alpha Lyræ (Vega) about April 19 to 21.

Connection Between Meteors and Comets. — On account of the common orbit, the Andromids are frequently called Bielids. The Leonids and Temple's comet of 1866 have the same orbit, the Perseids and Tuttle's comet of 1862 have identical orbits. The Aquariids of early May have an orbit parallel to Halley's comet. In 1916, a shower of meteors coincided with the orbit of the Pons-Winnecke comet. These coincidences of orbits could not happen by accident.

The Origin of Meteors. — Regularly recurring meteor swarms are moving in closed orbits about the sun. They are permanent members of our solar system. At successive returns, due to disturbances in their orbit, the meteors tend to spread out and eventually to form a continuous ring about the sun. Each year, as the orbits of earth and meteor swarm intersect, there will be a shower. The meteors are not uniformly distributed and the brilliancy of the shower may vary from year to year. We have a display of Perseids, each and every August. It is evident that the Perseids have been members of the solar system longer than the Leonids, even though the latter have been under observation for a thousand years. On account of the close connection between the paths of comets and meteors, it appears certain that meteor swarms are caused by the partial disintegration of comets.

Size of Meteors. — Since so many millions of " shooting stars " reach the earth's atmosphere each and every day, these bodies must add all of their mass to that of the earth. Even though consumed in the air and vaporized, we cannot neglect their mass since a gas has weight. Consequently the size of the average meteor must be very small or else the earth would be perceptibly increasing its mass, and as a result would rotate more slowly. The average " shooting star " is no bigger than a grain of sand. If the size were that of a marble we would have a very brilliant celestial object. Whether these objects come from the solar system or from without it is difficult to state with certainty. The crux of the problem lies in the difficulty of ascertaining with accuracy the speeds at which the meteors move. The best opinion seems to be that although the meteor swarms are members of the solar system, the sporadic meteors come to us from outside the solar system.

Height of Meteors. — Two observers at two different places

observing the same meteor and fixing accurately its position among the stars can determine its height in miles above the earth, at the beginning and at the end of its flight, and the velocity of motion through the earth's atmosphere. The " shooting stars " appear at an average height of 70 miles, and disappear at an average height of 50 miles above the earth's surface, after traveling a distance of 35 miles through the atmosphere. The larger objects, known as fire-balls, appear at an average height of 85 miles and the average path is something like 200 miles.

Observations of meteors are usually left to amateurs. Denning of England and Olivier in the United States have guided the work of the amateurs, with valuable results to astronomy.

The Zodiacal Light and the Gegenschein. — If one is in a favorable location, and the best is on a high mountain in or near the tropics, on a cloudless, moonless, night just a little while after sunset twilight ends, in the months January to April, or just before morning twilight begins, in the months September to December, he may see a faint illumination of the sky, stretching up from the direction of the sun towards the zenith. If his eyes are keen, and the conditions are right, he may even see the band of light stretch clear across the sky at midnight. But it is much brighter nearer the sun. This glow is called the " zodiacal light."

Just opposite the sun, at a proper interval of something less than two hours before sunrise, or after sunset, a still more delicate glow may sometimes be seen. It is not larger in diameter than the bowl of the Great Dipper. It is called the " gegenschein " or counter-glow. From its position it evidently relates closely to the zodiacal light.

The spectroscope has shown that these lights are reflected sunlight. But they are not, like twilight, caused by our own atmosphere. They seem to be due to a swarm of meteoric or possibly gaseous particles, encircling the sun in a great lens-shaped swarm extending out beyond the earth's orbit. In a way, it suggests the rings of Saturn, only that the zodiacal swarm is not thin as Saturn's rings are, but even spreads beyond the diameter of the sun. The plane of the lens does not lie exactly in the plane of the earth's orbit, but makes an angle of about 3° therewith.

Now we have called the roll of the sun's family, the solar system: Planets, satellites, minor planets, comets, meteors, zodiacal light,

and gegenschein. In the next chapter we must take a " close-up " of the sun himself, see what he is, how big, how hot, how composed, and in a word get acquainted with the immense globe which is at once our nearest star, the ruler of the solar system, and the fountain of influence which supports all life on the earth.

CHAPTER IX

THE SUN AND ITS SPECTRUM

Things are not what they seem. Stars look much like fireflies or like meteors. They are really white hot globes of gas. Many of them are so big that if the earth and sun were transported into one of them, the earth might circle round the sun at present distance, and always be submerged nearly a hundred million miles deep inside of the star. Again, the sun appears no larger than the moon. Really there are on its surface oftentimes sun-spots, too small to be seen with the naked eye, that are yet big enough to swallow up a dozen moons. Finally, the sun looks big enough to cover up all of the stars in the heavens, and bright enough to give a million times as much light as they all. In reality " the sun," as the late Professor Young used to say, " is only a private in the host of heaven." Betelgeuse is about three hundred times the sun's diameter. Rigel gives about 10,000 times the sun's light. It is distance that we have to allow for to correct these false appearances. Though it takes sunlight 8 minutes to come to earth, it takes the light of Rigel 400 years to come, and Rigel is by no means a distant star. There are many of them a hundred times farther off.

Our sun is an average star in several ways. No star could have obeyed better the spirit of the advice of Robinson Crusoe's father to stick to the middle class as the happiest. The sun's light is about 10,000 times less than the brightest, and about 10,000 times brighter than the faintest stars thus far observed. Its spectrum is about half way in character between the blue stars and the very red ones. Its mass is just about the average mass of all the known star masses. All that is peculiar about the sun as a star is that we know it has a family of planets, one of them the home of life. But because the sun is such a near star, we know a great deal about it that helps us to know the others.

Distance and Dimensions of the Sun. — The accepted value of the solar parallax is 8″.80, corresponding to a mean distance of 92,870,000 miles or 149,500,000 kilometers.

On account of the eccentricity of the earth's orbit, the sun is 3,000,000 miles closer to the earth on January 1 than on July 1. Assuming the orbit of the earth to be a circle, it is easy to find the distance in miles that the earth travels in its annual journey about the sun. Divide this distance by the number of seconds in a year and we find that the earth's orbital velocity is $18\frac{1}{2}$ miles per second, or more than a thousand miles per minute. We travel at this high rate of speed without experiencing any ill effects, for the reason that there is no friction, or resistance of the air, and that the motion is perfectly smooth.

The sun's mean angular diameter is 31′ 5.″93. Its linear diameter is 864,100 miles, or 109 times the diameter of the earth. The surface of the sun is $(109)^2$ times that of the earth, and the volume of the sun is $(109)^3$, or 1,300,000 times that of the earth.

The Mass of the Sun. — This quantity is determined by the force of gravitational attraction causing bodies to fall. If the earth had no orbital velocity it would fall into the sun from the sun's attraction. The motion of the earth does not destroy the power of the sun to make the earth " fall " towards it. If, therefore, we compare the distance that the earth falls towards the sun in one second of time with the distance that bodies fall towards the earth when let go, then the comparison of these distances gives the mass of the sun compared with that of the earth. This is found to be 332,000.

Density of the Sun. — We find the density of a body by dividing the mass by the volume. Compared with the earth, the density of the sun is 332,000 ÷ 1,300,000 or $\frac{1}{4}$ (approximately). Since we know the density of the earth, we know that the density of the sun is 1.4 times that of water. This is a very important fact.

The Sun a Gas. — What is the sun, then? A tremendous globe which, containing almost all the chemical elements that have been found on earth, is so hot that all of them are gaseous. In the foundry, we see iron poured like water in a white-hot stream, but the sun is far hotter than that. We see carbon dazzling hot in the crater of the electric arc light, but the sun is far hotter than that. The sun is so hot that if the carbon stick of the arc lamp was thrust into its depths, the carbon would burst into gas with an explosion. We stand upon the solid earth. There is no solid standing room upon the sun. We may float in boats upon a lake. The sun con-

contains no liquid to float upon. We fly in planes above the earth, but though the sun is gaseous like the atmosphere, no plane could navigate it for an instant, because the whole structure of the flying machine, pilot, engine and all, would explode into gas.

But though the sun is all gaseous, it averages 1.4 times heavier than water. This is partly because so large a proportion of the gas probably is of iron and other heavy elements. Still more, however, because the gas is under perfectly enormous compression. At the outer surface the pressure, of course, is very small. For just as in our atmosphere the density falls as we rise, and at a few miles high becomes vacuum-like in rareness, so the sun's gases merge into the vacuum of space. The sun, however, has over 330,000 times the mass of our earth, so that although its radius is 109 times the earth's, gravity at the surface is about 27 times what it is here. In other words, a man on the sun's surface would weigh two or three tons. Under this enormous attraction the pressure of the solar gas-globe increases rapidly downwards from the surface, so that only a tenth part of the way from surface towards center we may suppose the pressure to reach a thousand atmospheres at least.

On the other hand, there are perfectly enormous forces tending to drive outward the solar gases. The first is temperature. Eddington, whose work on the interior condition of the stars is epoch-making, shows that from 6000° Absolute Centigrade[1] at the surface, the solar temperature probably rises to the prodigious figure of 18,000,000° at the center. We know very well how steam pressure rises with temperatures in engines, usually not 70° above boiling. Imagine an engine run by the pressure effect of 18,000,000° !

But there is another disruptive force considerable in the sun, and in some greater stars quite formidable. It is the pressure of light. We saw how remarkably it forces out comets' tails as they near the sun's surface, even, it is said, driving out a tail 500,000,000 miles long from the comet of 1843. But within the sun such light-pressures as the comets meet with would sink into insignificance. Eddington has shown it to be probable that while light-pressure is not nearly as large as the gas-pressure due to temperature for stars of the mass of our sun, or smaller, it becomes the main disruptive agent for greater ones, and actually prevents the existence

[1] Reckoned from the absolute zero, – 273° Centigrade. In Fahrenheit the absolute zero is – 459° and the sun's surface temperature 10,800° Absolute.

of any stars many times more massive than the sun. These great stars cannot exist since they would fly asunder under the pressure of their own inner light.

The Heat of the Sun. — With these staggering figures before us, we can no longer be surprised that the sun's rays are warm, even on the earth, over 90,000,000 miles away. But in order to get a really vivid impression of what energy the sun rays carry, we should read pages 104 to 108 of Langley's " The New Astronomy." [1] He describes how he made an experiment to compare the rays of the molten steel poured from the Bessemer converter with those of the sun. Into the enormous converter-pot there streamed first some 15,000 pounds of molten iron loaded with half a ton of silicon and carbon. Then a blast of air was forced up through the glowing mass, and the chemical action set up a heat which so far surpassed mere iron-melting temperature that when another 15,000 pounds of molten iron was added it looked like " chocolate poured into a white cup." The cataract of liquid steel was then discharged, shooting showers of scintillations that seemed sunlike in their brilliancy, and spattering the surroundings for a hundred feet with little shooting stars. But there was nothing really sunlike at all in this fierce glare. For when Langley exposed an apparatus which took a balance between the brightness of the surface of the steel and an equal surface of the sun, the sun was found to send out at least 87 times as intense radiation, square foot against square foot, as the dazzling steel. This for the total rays, whether visible to the eye or not. But for the light rays only, the sun proved intrinsically not less than 5000 times the stronger source. And this was near Pittsburgh, where the sun's rays had already lost over half their intensity in the murk of the atmosphere.

So immense is our own distance from the sun, that we get no impression like this of his power from merely holding out our hand to his rays, but only when we try for even an instant to gaze at him. Plateau, the Belgian physicist, dared to look upon the sun for 20 seconds. He lost his sight thereby. However, the sun's heat, too, is enormous. If there was a shell of ice of the same radius as the earth's orbit, enclosing the sun, it would have to be nearly as thick as the Washington monument is high not to be all melted in a single year. It would weigh 4×10^{25} (4 followed by

[1] Houghton, Mifflin & Co., 1896.

25 ciphers) tons, and the complete melting of it would take as much heat as 4×10^{23} (4 followed by 23 ciphers) tons of anthracite coal would furnish. Such is the sun's yearly output of energy.

The Solar Energy, how Derived? — Of all this heat, the earth and all the planets gather only about $\frac{1}{200000000}$ part. The rest goes on and on, so far as we know, to infinite distances. But geology shows that plants and animals basked in sun rays about as intense as present ones apparently a hundred million years or more ago, and that during all the time since then, possibly, even, ever since a thousand million years ago, the sun has kept on flooding his rays throughout the universe about as fast as now. How is it possible that this can be? From what storehouse could energy so inexhaustible be delivered?

Energy Developed by Gravitation. — The answer was as unknown as the riddle of the Sphinx until a few years ago. To be sure, Helmholtz had pointed out that as the sun cooled he must shrink, and as he shrank, the energy of the fall of his material towards his center must be turned to heat. But it was shown that even if he once extended out to the orbit of Neptune, there could not be derived enough energy in this way to maintain radiation at present rates 25 million years. The great source was still a mystery. Now a gleam of light has come.

Atomic Energy. — Within the past few years scientists have learned that the atoms of all chemical elements are built of two kinds of "bricks" so to speak, the electrons and the protons. We do not find, either in our laboratories or in the gaseous nebulæ of the heavens, the conditions which build complex atoms from simple ones. In the laboratory, radium and other complex elements disintegrate, but none are formed into greater complexity. In the nebulæ, only the simpler elements, such as hydrogen, are found. Somewhere must have been the wonder-making laboratory of Nature, where the intricate structures of electrons and protons, composing the atoms of the metals, were framed together out of these two original and universal constituents. No place is more probable than the interiors of stars, where temperatures and pressures inexpressibly exalted prevail. If these are the crucibles of Nature, then it is here that hydrogen must take on complexities and become helium, oxygen, iron, gold, and all the rest.

This may be the source of heat. For the atomic weights of all

the elements but hydrogen are indistinguishable from whole numbers, when separated into their pure constituents, or "isotopes," as Aston has done. Hydrogen, however, is an exception, with its atomic weight of 1.008. When four atoms of hydrogen weighing 4.032 become one atom of helium of weight 4.000, the loss of weight represents, according to modern physical conceptions, a store of energy set free. Possibly similar stores are liberated less copiously when further complexities are introduced in forming heavier atoms. It is this sub-atomic storehouse to which we now look as the source of the all but inexhaustible radiation of the sun and stars. An even bolder suggestion is that matter, which is a passive form of energy, is changing into radiation, the active form, at these tremendous temperatures. If so, the stars continually lose mass as they grow older.

At the high temperature (6000° Absolute Centigrade) prevailing even at the sun's surface, and the far higher ones prevailing near the sun's center, we have said that nothing but gases can exist. But if this is so, says some reader, how can the edge of the sun look not fuzzy but sharp, as it certainly does? Ought we not to see right through the gases of the sun as we do through our own atmosphere?

Why the Sky is Blue. — To answer this question we must first refer to the late Lord Rayleigh's explanation of why our sky is blue. He investigated what happens to light when it enters an atmosphere of particles so small that even the waves of light are long compared to the diameters of the particles. Such an atmosphere is ours, for though the dust particles it carries are larger, the molecules of oxygen, nitrogen and other gases in it are very small indeed compared to wave-lengths. Lord Rayleigh found that such an atmosphere, and we may as well say at once any gas, scatters the beam of light in every direction. The scattering obeys certain perfectly definite laws which connect its amount to the angle the scattered ray makes with the original one, and to the wave-length of light. After working out these laws theoretically, he tested his results practically by observing the intensities of the various colors found in the light of the sky. His laws were verified. Later on, Schuster, Fowle, King and others tested them more rigorously against the accurate measurements of the transmission of sunlight by our atmosphere, which have been made on Mount Wilson and elsewhere by Smithsonian Institution observers. The agreement of theory

with observation is close. Fowle calculated the number of molecules in a cubic centimeter of atmosphere from Rayleigh's formulæ as applied to these observations. His value agreed within 1 per cent of the best results by wholly different electrical methods.

Why the Sun has a Sharp Edge. — So the light of the blue sky is sunlight scattered in every direction by the molecules of the gases of the atmosphere. The amount of yellow light scattered in passing vertically through the clear atmosphere to the level of Mount Wilson is about 6 per cent, and that of the blue over 20 per cent. A column of air containing 75 times as many molecules would scatter 99 per cent, even in the yellow. Now in the outer layers of the sun such a column would be made up by the solar gases within a path of 5000 miles. Hence, practically speaking, we cannot see more than 5000 miles deep down into the solar gases. For all visible rays which arise lower than that must be completely scattered before they can reach the surface. If this is so even at the center of the sun's disk, a far thinner layer, say 500 miles, must suffice near the edge of the visible disk, because we see into it obliquely. But such a layer is little more than $\frac{1}{10000}$ part of the sun's radius. Therefore, we must suppose that all of the fuzziness of the sun's outline must be confined within $\frac{1}{1000}$ of his radius. Evidently this is to all practical appearances sharpness of outline. Hence, we see that the mere scattering of light by the molecules of the solar gases (atoms, too, will do as well for this purpose) must suffice to give the sun's sharpness of outline. The recent researches of Lindblad and others seem to indicate that even this sufficient limitation is not the only one, but that actually the absorption of the gases, and not their scattering action, is the chief limiting agent to cut off the depth to which we see. This must, he thinks, act even quicker than scattering.

It is a curious consequence of these considerations that the edge of the sun's disk must appear less bright than the center, and that this contrast of edge and center brightness must be greater for violet and ultra-violet rays than for red and infra-red ones. For, as we have just said, the scattering, and absorption also, becomes complete in a much thinner layer of solar gases when viewed obliquely, as they are near the sun's edge. Therefore, we look there on more superficial, and consequently cooler, sources than when we look straight down deep at the sun's center. Besides, the effect is far

greater for short-wave rays than for longer ones, and so the violet and ultra-violet come from the most superficial layers of all, and show most contrast between edge and center. These results are confirmed by observation as shown in Figure 19.

The Solar Spectrum. — A hot body sends out light owing to the disturbances by heat of the outer electrons of its atoms. The frequency of the vibrations which the disturbance sets up in the ether fixes the color of the light. The quicker the vibrations, the shorter is the wave-length and the more the light tends towards the violet, and away from the red end of the spectrum. So each kind of an atom, having its own peculiar structure, sets up a different frequency of vibration, or a group of them. Incandescent iron differs from incandescent magnesium in the color of the several spectral rays it arouses, and so each chemical element has its own characteristic group of spectral rays.

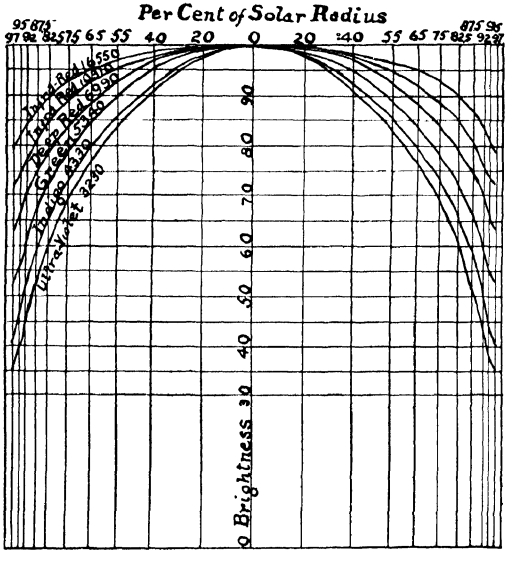


FIG. 19. Distribution of brightness along a diameter of the solar disk in various spectral colors. The sun is much fainter near the edges of its disk, and this contrast of brightness between edge and center is more marked for the violet end of the spectrum. (From Smithsonian observations.)

As was shown in Chapter II, each of the chemical elements when heated to incandescence gives out an emission spectrum of bright lines, the spectrum of every element differing from that of every other element. The spectrum of iron heated to a high temperature consists of thousands of bright lines in all colors of the spectrum. It was the great triumph of Kirchhoff in 1859, which laid the firm foundation of spectrum analysis, when he discovered that a bright-line emission spectrum may be changed into a dark-line absorption spectrum. This was shown in the following manner. If some hot

substance, like the limelight, gives a continous bright spectrum without displaying any special characteristic rays, while in front lies a gas at a lower temperature, then the resulting spectrum, after the rays pass through the cooler gas, will be a bright band crossed by dark lines at the very places where the gas alone would give bright ones. This effect is shown by the illustration in Plate 20. We are quite familiar with a similar process in the realm of sound. If a voice when singing sounds a note of certain pitch in a room where there is a piano, then one string of the piano will sound in unison with the voice. Similarly, a tuning fork in vibration will set in motion another tuning fork nearby which is tuned to the same pitch.

It is by this method that we find the chemical constitution of the sun and the stars. Their interiors present so complex a path to the rays which shoot hither and thither, back and forth, in every imaginable direction, that it would give a continuous band of spectrum, if it were not that the cooler gases lying at the surface

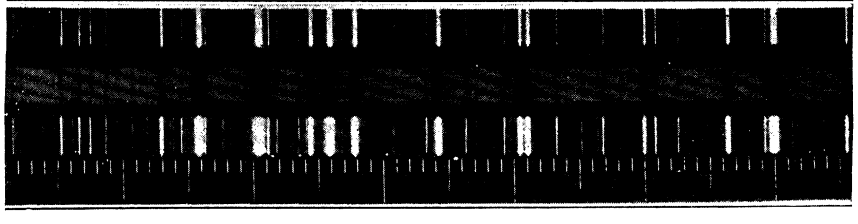


PLATE 20. THE BRIGHT AND DARK SPECTRUM OF IRON AS OBTAINED IN THE LABORATORY.

The violet region between wave-lengths 3800 and 3900 Angstroms. (Photographed by Anderson, Mt. Wilson Observatory.)

absorb their special rays, as the light escapes through them to us. So the solar and stellar spectra present bright bands of color crossed by dark lines of all the surface gases which are in position to produce their characteristic absorbing effects.

We have only to compare the dark-line spectra of the sun and stars with the bright-line spectra of the chemical elements, as we may easily produce them in the laboratory, to find, line for line, and in many cases even line-intensity for line-intensity, the evidences of the existence of these elements in sun and stars. This is shown in Plate 7. The laboratory spectrum we may compare to a photographic positive, the solar and stellar spectra to negatives of the

same subject. Yet though the reversal is unmistakable, there are small but highly significant differences in positions and intensities of the spectrum lines which add wonderful chapters to the story.

We shall see in the next chapter how the "flash spectrum" at the time of a total eclipse gives additional information regarding the constitution of the sun.

Doppler Effect. — Doubtless all have heard the change of pitch of a locomotive whistle as it passes a crossing, and noticed it higher as it comes, lower as it goes away, because more vibrations reach the ear per second while the locomotive approaches, and less while it recedes. The same sort of thing holds for light, except that since light travels so exceedingly fast, more than 700,000 times as fast as sound, it takes a very high velocity of a luminous body to make any effect of this kind that can be noticed.

Light is a wave motion. If light is coming from a distant source like a star, and if the star is moving towards us, we encounter more waves in a second of time than if the star were at rest. If more waves come into the eye in one second, then each wave is shorter in length from crest to crest. Shorter wave-length is towards the violet end of the spectrum. Hence, for a star moving towards us, any ray of given color or wave-length (represented by λ) is shifted towards the violet by an amount $d\lambda$. The Doppler formula is a very simple one. If V is the velocity of light, and v the velocity approach of the star:

$$\frac{d\lambda}{\lambda} = \frac{v}{V}$$

If the star is moving away from us, the shift of the spectral line is towards the red.

Rotation of the Sun. — As the sun rotates on its axis, its eastern edge is approaching us, and the western edge is receding from us at a speed of 1.2 miles per second. For many years a great campaign has been carried on by several observatories to measure the rotation of the sun by spectroscopic methods. This plan has distinct advantages over that of watching the time taken by sun-spots to cross the solar disk. Individual spots do not stay, as a mountain does on earth, exactly in the same places on the sun, but drift about a little both in latitude and longitude. Moreover, the spectroscope has the advantage that it can measure the sun's rotation at all latitudes, whereas the sun-spots only occur rather near the sun's

equator. The sun, like Jupiter, exhibits slower rotation towards the poles.

Many difficulties arose in the progress of the campaign. Although the work is still in progress, it seems rather certain now (1927) that there is little, if any, variation in the speed of rotation at the solar equator. According to these results, the sun's equator travels 14°.65 a day and requires $\frac{360}{14.65} = 24.6$ days for a complete rotation, while at other solar latitudes the times of rotation are 26.3 days at 30°, 31.2 days at 60°, and 35.3 days at 80°. These values hold for the average solar surface and furnish the times of the sidereal periods. (The synodic periods are found in the usual way and are about two days longer.)

These results are confirmed very closely by other methods of observing the sun's rotation, including observations of the march of sun-spots, faculæ and flocculi across the sun's disk, of which we shall speak in the next chapter. The spectral lines due to high-level hydrogen and calcium exhibit a faster rotation for the sun at all latitudes, and besides they show much less slowing up towards the sun's poles.

Zeeman Effect. — The great English physicist, Faraday, tried many experiments to find some connection between magnetism and light. But success was reserved for Zeeman of Holland, who discovered that in strong magnetic fields single spectrum lines are broken into two, or sometimes many, components, separated very distinctly in their spectrum places. The components, moreover, are of " polarized light," and the polarization is dependent on the direction of the magnetism. Hale used this effect of Zeeman's to discover and measure magnetism in the sun. He found that sun-spots go in pairs, of which one presents a north, the other a south magnetic polarity. Sometimes one of the spots is nearly invisible, though magnetically active. Furthermore, Hale found that the polarity of the pairs reversed itself between the northern and southern solar hemispheres, so that if the advance spot was a north pole in the southern hemisphere, it would be the following spot that was a north pole in the northern hemisphere. Still more curious, he found that though one arrangement of polarities persisted through a whole sun-spot cycle of 11.1 years, yet the new spots of the next sun-spot cycle showed the polarity reversed. This makes the full sun-spot cycle 22.2 years to bring everything, magnetic conditions

included, back to the original starting-point. We do not yet know the causes of these queer magnetic reversals, but doubtless they have something to do with the unequal rapidity of solar rotation in different latitudes.

Rowland showed many years ago that electrically charged particles in rotation behave like currents of electricity in loops of wire. As everybody knows, a current of electricity in a loop of wire makes of it a magnet. On this, of course, the electric telegraph depends. There are many electrons in a sun-spot. If they are in a whirl, as indeed the spectroscope shows them actually to be, the Rowland principle applies. Hence, probably, arises the magnetism of sun-spots. Hale, Ellerman, and van Maanen have found

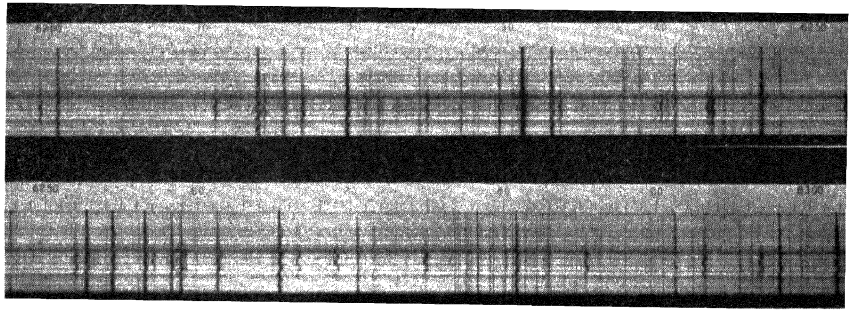


PLATE 21. PROOF OF MAGNETISM IN SUN-SPOTS.
(Hale, Mt. Wilson Observatory.)

The dark band which runs lengthwise through the centers of these solar spectra is caused by a sun-spot. The many dark lines caused by gaseous absorption show zigzag offsets where they cross the sun-spot. This is the Zeeman effect of magnetism disclosed by polarization apparatus. Many of the fainter lines show no zigzag bendings. These lines are produced by absorption in the earth's atmosphere, not in the sun. Many short lines appear in the sun-spot region alone. Such lines are due mainly to compounds which form in the relatively cool sun-spots, but break up and disappear over the hotter solar surfaces.

a weak magnetic field existing all over the sun's surface, and have been able to locate the sun's magnetic poles, a little removed from the poles of the sun's rotation, reminding us of the case of the earth's magnetism.

Pressure Effects. — Spectrum lines also give a measure of pressure. Humphreys and Mohler found displacements of spectrum lines depending on the pressure which the gas producing them is sustaining. It has recently been concluded from careful studies

of this indication that the pressures prevailing where solar spectrum lines are produced are but a small fraction, certainly less than $\frac{1}{10}$, of our atmospheric pressure. So the spectrum lines are of very superficial solar production, for as we saw above, the pressure increases enormously as we go down towards the sun's center.

Infra-Red Spectrum. — All these are minutiæ of spectroscopic study. But there is another branch of it much more impressionistic

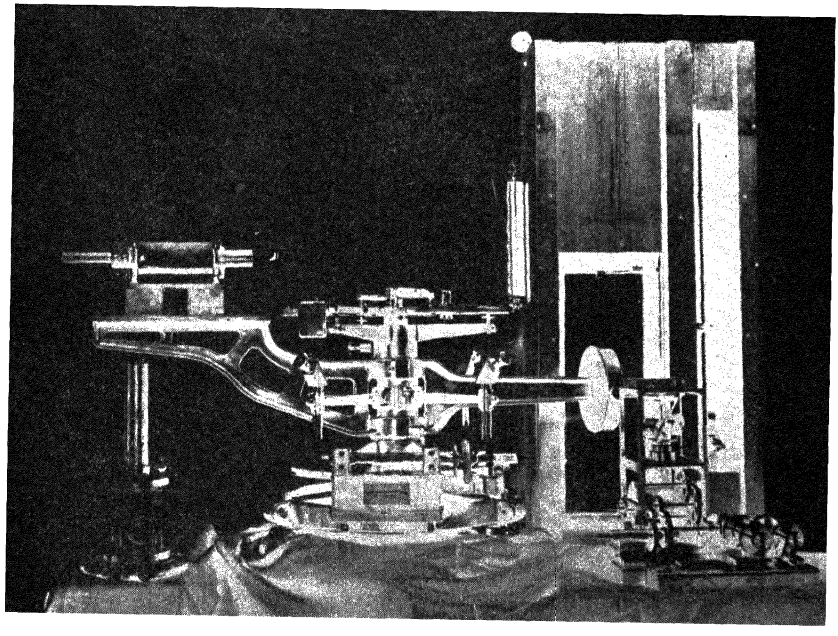


PLATE 22. A GROUP OF BOLOMETRIC APPARATUS.

The Langely bolometer, an electric thermometer sensitive to the millionth of a degree of temperature, is used in connection with a spectroscope, a galvanometer, an exact clockwork and a photographic recorder to produce automatically "bolographs" or curves of the distribution of heat in the rays of the solar spectrum.

(to borrow an art term) in its effects. The rays of sunlight heat whatever absorbs them. On lampblack, they produce nearly maximum heating. Dr. S. P. Langley invented an electrical thermometer which he named the " bolometer " for measuring the heat of the rays of the solar spectrum. The instrument has two hair-like ribbons of platinum, narrower than the strokes of the printed letters on this page, almost as thin as the ink which makes

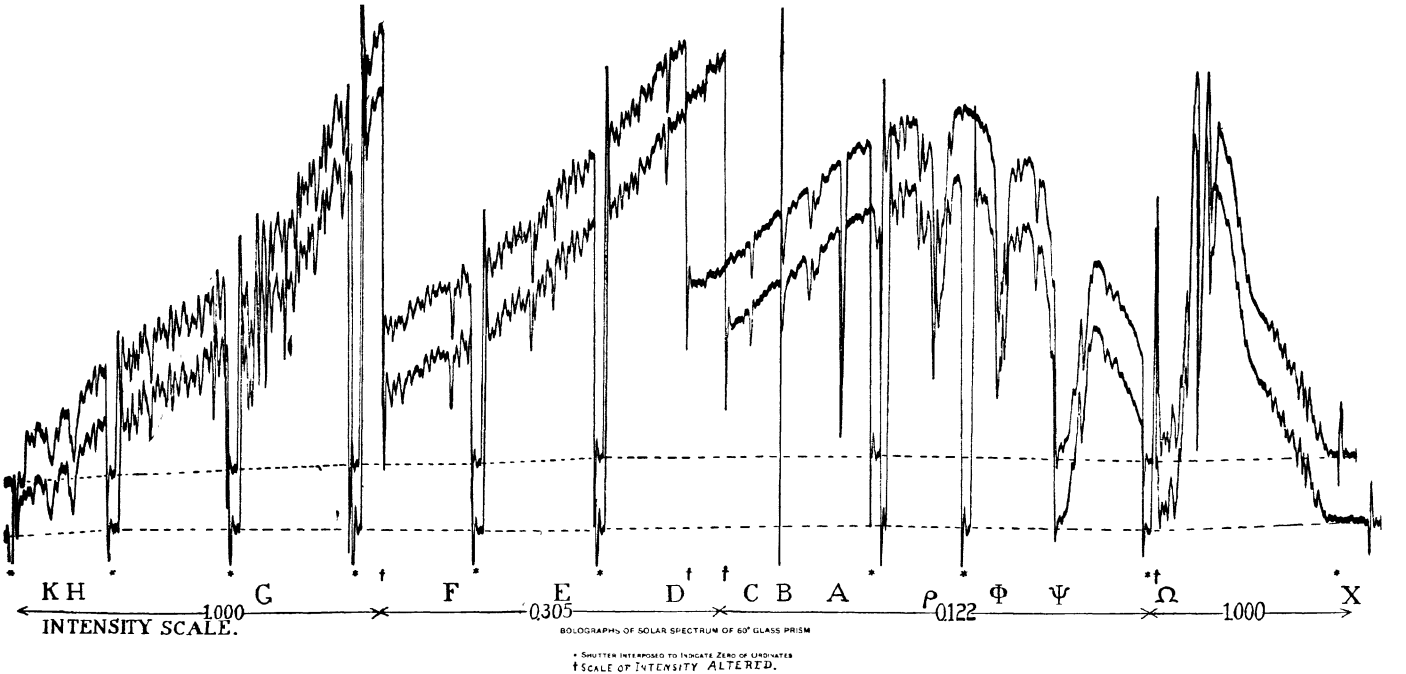


FIG. 20. BOLOGRAPHIC ENERGY CURVES OF THE SOLAR SPECTRUM.

The heat in the different colors and beyond the red where the eye sees nothing is here twice independently measured by the bolometer, an electrical thermometer sensitive to a millionth of a degree. The dark Fraunhofer lines cause the nicks and deep depressions in the curve. The rays are cut off at the starred places to indicate the zero of radiation, and the scale of intensity is altered at the dagger marks to keep the curves down to moderate height. In the infra-red spectrum (to the right of *A*) great absorption bands are shown due to water-vapor in our atmosphere. Nearly all of the nicks to the left of *B* are due to vapors of metals in the sun. (By permission, from "The Sun," D. Appleton & Co.)

them, and as long as one's finger nail. These tiny metallic ribbons are blackened with lampblack, and one of them is hidden behind a metal plate. As the rays of the solar spectrum fall upon the exposed one, they warm it above the temperature of its hidden neighbor. The tiny temperature difference, even if less than $\frac{1}{1000000}$ degree, suffices to alter the electric current balance of which the two ribbons form parts, and a little mirror, smaller than a pinhead, is turned by the electromagnetic impulse which the current-change produces. A tiny shaft of sunlight reflected by the mirror moves across a photographic plate, and so records the warming or cooling of the exposed ribbon of the bolometer.

A clockwork moves the solar spectrum over the bolometer ribbon, and moves the photographic plate at the same time. Thus, the warming and cooling of the ribbon is recorded as a jagged line, whose high spots show warm parts, and whose low ones show cool places in the solar spectrum. Such curves are reproduced in Figure 20. The dark spectrum lines of Fraunhofer, being cool, are depressions of the curve, which we call a "solar energy-spectrum curve" or "bolograph."

As Langley and his successors produced these curves, they found heat in the solar spectrum far beyond the ends of the spectrum visible to the eye. Beyond the violet lies the "ultra-violet," also observable by photography. Beyond the red lies the "infra-red," partly observable by special photography with dyed plates. In this infra-red region there are few Fraunhofer solar lines, but great wide deep bands of absorption by the oxygen, water-vapor and carbonic-acid gas of our own atmosphere.

The chief advantage of this method is not so much for showing details of invisible parts of the solar spectrum, as that it measures accurately the energy of all rays, whether they affect the eye or not. So we get a true picture of the distribution of energy in the spectrum of the sun. Recently the same thing has been done with the stars also.

We all know that as the blacksmith heats his iron, it produces heat at a distance, while not yet glowing red. Presently it becomes dull red, then yellow, finally white hot. If we should examine with the bolometer the spectrum of the rays sent out, we should find them at first only in the infra-red. But as the iron became very hot, the red, yellow, green and blue rays would grow more and more

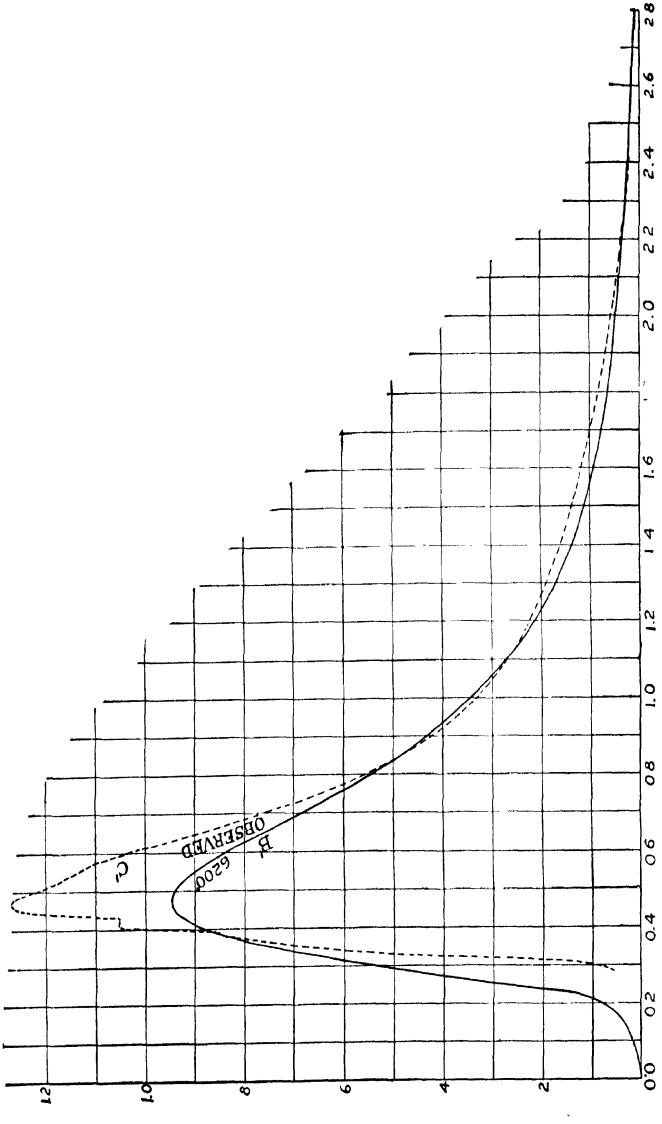


FIG. 21. CURVES INDICATING THE SUN'S TEMPERATURE.

From laboratory experiments we know that a perfectly radiating body at 6,200° of the absolute Centigrade scale (about 11,000° Fahrenheit Absolute) would give out radiations whose intensity in the spectrum appears in the heavy curve. From observations of the solar spectrum with the bolometer we find a fairly similar distribution as the dotted curve shows. A temperature of 6,200° Abs. C. is nearly twice that of the electric arc. It is but the superficial solar temperature. Deep down, the sun is doubtless at millions of degrees. (By permission, from "The Sun," D Appleton & Co.)

intense, so that the spectrum-energy curve would have its maximum continually shifting towards the violet, as the temperature rose higher.

There is a certain instrument, called the " perfect radiator " or " black body," that for any given temperature will give out more radiation of every wave-length than any other source at the same temperature. The laws of spectrum-energy distribution of this instrument are well known. So that if a body radiates nearly like a " perfect radiator " we have only to measure its energy-spectrum with the bolometer, and, from the form of distribution-curve

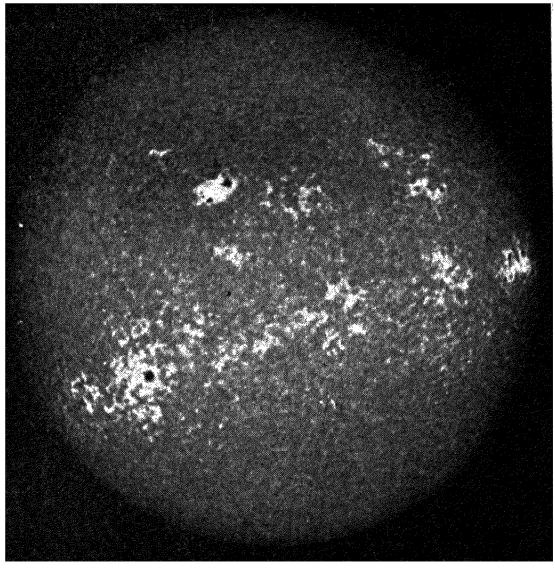


PLATE 23. THE SUN'S SURFACE PHOTOGRAPHED WITH THE SPECTROHELIOGRAPH IN CALCIUM LIGHT.
(Mt. Wilson Observatory.)
Note the sun-spot regions strongly marked by bright calcium flocculi.

resulting, we can tell the temperature of the body without the necessity of testing it with a thermometer.

Solar Temperature. — This is very important. For we can never go with our thermometer to the sun and stars, but it is easy enough to measure their energy-spectrum distribution-curves. In this way we find that the temperature of the sun is far above any that we can command continuously in the laboratory. Its

maximum occurs in the blue-green, corresponding to about 6200° Absolute Centigrade, nearly twice as hot as the electric arc light. Another method of measuring the solar temperature depends on measuring the sun's total heating effect on unit area just outside the earth's atmosphere. This turns out to be on the average 1.94 calories per square centimeter per minute, and indicates the sun's temperature as 5860°. We strike a mean of the two methods and call the temperature 6000° in round numbers.

Solar Constant. — The value 1.94 calories is called "the solar constant of radiation." Its importance is not only theoretical, but it gives a measure of the sun's energy available should we wish to run solar engines for power purposes. But of course we must make allowance for losses in our atmosphere and in the machinery, which indeed are very large. No one yet has succeeded in converting over 3 per cent of the solar radiant energy falling on his apparatus into useful work. The immensity of solar radiation we have already considered. The exact measure just given means that if the total energy of a ray 1 centimeter in cross-section (about $\frac{3}{8}$ inch square) should be totally absorbed and used without loss to heat one gram (about $\frac{1}{450}$ pound) of water, the water would rise in temperature 1°.94 Centigrade (3°.49 Fahrenheit) each minute. Expressed in other words, the solar energy outside our atmosphere is equivalent to about $1\frac{1}{2}$ horse power per square yard. (This subject will be treated more fully in Chapter XI.)

Spectroheliograph. — There is a special kind of spectroscope, called the spectroheliograph, whose principle was invented independently by Hale and Deslandres about the year 1890. Its purpose is to take pictures of the sun in the light of a simple chemical element. Most observers use the light of hydrogen or of calcium for these photographs. To do so, they form an image of the sun on a long slit and allow the narrow strip of the image, which the slit allows to pass, to form its spectrum. Somewhere in the spectrum will be a dark line, such as Fraunhofer's K line of calcium. This is really an image in calcium light of the bit of the sun's image which falls on the slit. A second slit just admitting this spectrum line is provided, and behind it a photographic plate. By exact mechanism either the sun's image or the whole spectroscope, it matters not which, is moved uniformly along till each part of the sun's image in succession has passed over the first slit. Meanwhile, the photo-

graphic plate has been moved along with the sun's image, if the spectroscope has been kept stationary, or has remained fixed if the whole spectroscope has been moved. Consequently, the whole sun's image has printed itself, bit after bit, in calcium light of Fraunhofer's *K* line on successive strips of the photographic plate,

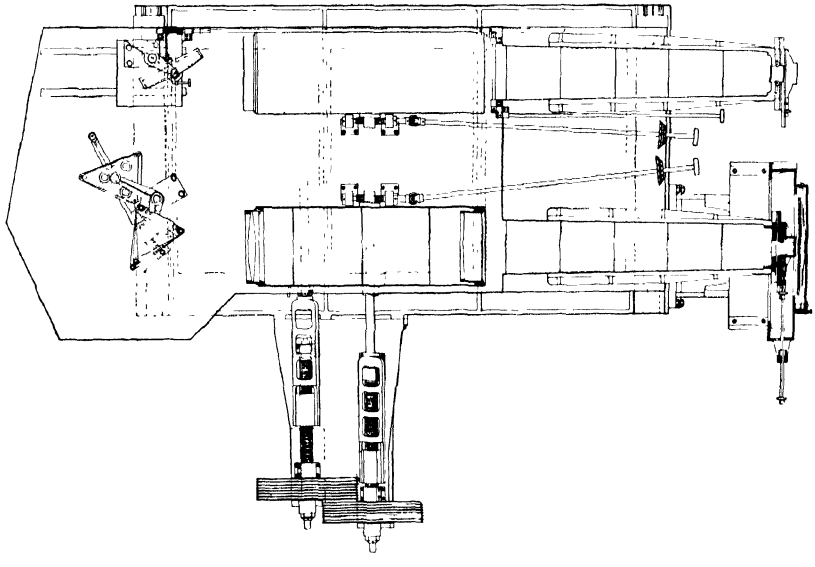


FIG. 22. THE FIVE-FOOT SPECTROHELIOGRAPH OF THE SNOW TELESCOPE (MT. WILSON OBSERVATORY).

An image of the sun falls upon a plate pierced with a long vertical slit (upper right corner). By means of the optical train, comprising lenses, mirror and prisms, the light which passes the slit comes to focus upon a second plate pierced with a second long vertical slit (lower right corner). This is slightly curved so as exactly to transmit the rays which fall in a single Fraunhofer line, such, for instance, as the *K* line of calcium in the violet. By means of the large grooved wheel and screw attached to it, the whole system is moved at a slow speed across the sun's image, so that a photograph may be secured behind the second slit showing the whole sun in *K* light of calcium.

so that we see a complete solar image photographed with that ray alone.

This ingenious device shows that the elements calcium and hydrogen take remarkable cloudlike forms called " flocculi " over the sun's surface. Of course the flocculi are *not* clouds, for it is far too hot where they lie to condense hydrogen! Rather, these appearances represent differences of temperature as the gases soar high above the solar surface at different levels. Occasionally such

forms take on snakelike shapes, twisting their contortions in rare cases over as much as half of the visible disk of the sun. St. John once was operating the spectroheliograph at a time when one of these snakelike wisps of hydrogen flocculus was sucked down into the center of a sun-spot and so disappeared.

This will bring us very naturally to discuss in the next chapter some of the telescopic features of the sun. Before doing so, let us sum up in a few words the remarkable service which the spectroscope affords to add to our knowledge of our splendid star.

Revelations of the Spectroscope. — Suppose we knew only the velocity of light, the angular width of the sun's disk, and had applied Kepler's law to map the solar system, but knew not its scale of miles. With the spectroscope, we could observe the shifting of positions of solar-spectrum lines in the rays reflected from the planets, as they move in their orbits, thereby measuring their relative velocities, and determining our actual solar distance, and the sun's diameter. The accuracy would rival the best measurements by other means. Secondly, we could measure the sun's rotation period by the opposite shifts of lines seen in rays from his east and west limbs. Similar studies would give us the rotation periods of the planets. Thirdly, we could determine, by observing the spectra of a large number of stars, that their spectrum lines showed displacements produced by the motion of the solar system, twelve miles a second, towards the constellation Hercules. Fourthly, we could discover the chemical elements in the sun and the stars. Fifthly, we could determine the minimum possible temperature of the sun's radiating surface by noting the distribution of energy in his spectrum. This would prove to us that the sun's material is wholly gaseous. Sixthly, we could discover that, like the earth, the sun has a magnetic field, and that in sun-spots this is particularly powerful, and has curious peculiarities. Seventhly, we could set a tenth of an atmosphere as the maximum limit to the pressure existing at the radiating surface of the sun. Eighthly, we could photograph the curious cloudlike forms of calcium and hydrogen streaming above the sun's general surface.

Indeed, as we go on to speak of the stars in later chapters, we shall come upon still other wonderful secrets that the spectroscope has told us of all the stars, our sun included. When all these mystery-fruits are heaped so profusely around the entrancing beauty of

the solar spectrum itself, we cannot sufficiently admire the powerful instrument which reveals so much to delight both the eye of the body and the eye of reason. In view of the luscious splendor of the spectrum, and the surprising revelation of the nature of light which it discloses, it is a very great pity that so few people have the opportunity to know it well; so that many are apt to regard it as something obscure and uninteresting.

CHAPTER X

THE FEATURES OF THE SUN AND SOLAR ECLIPSES

It is usually a great disappointment for one to look at the sun through a telescope for the first time. A bright disk of mottled aspect, resembling curdled milk at a distance, with perhaps a dark spot, or several of them, upon its surface — that seems to be all. Occasionally, at times of fine seeing, there is a wealth of detail shown on the face of the sun, reminding one of snowflakes sprinkled over a gray cloth. However, in the rare brief moments of a total solar eclipse, or when the spectroscope is added to the telescope to aid vision, the physical eye receives an impression of great beauty and grandeur. To the mind's eye, however, the stupendous scale of things on the sun, and the immensity of the forces that work in that great laboratory lend a different aspect to the phenomena. They are insignificant to our view only because of the enormous gulf of distance that separates us from them.

Solar Features. — The visible portion of the sun that we see is called the *photosphere*. As stated in the last chapter, it consists of gases at a high temperature of 6000° Absolute. There are no solids or liquids in the sun. The spectroscope shows that the sun is made up of the same materials that form the earth. Helium was discovered in the sun at the eclipse of 1868. It was not isolated in the laboratory as a chemical element until 1895.

Surrounding the photosphere is the sun's atmosphere called the *chromosphere*. It consists of gases at a high temperature, but at a cooler temperature than the photosphere. As the light from the photosphere passes out through the cooler gases of the chromosphere, the photospheric light is absorbed, giving rise to the Fraunhofer spectrum of dark lines on a bright background. Most of the absorption of the photospheric light takes place in the densest parts of the chromosphere lying closest to the sun's surface. This layer (about 1000 miles in thickness) is called the *reversing layer* because in it the bright spectral lines are " reversed " to black lines. The reversing layer is a portion of the chromosphere and has no separate existence.

We can never view the photosphere except through the gases of the chromosphere, but we can observe the chromosphere by itself. The best opportunity is afforded at a total eclipse of the sun when the spectrum of the chromosphere is called the *flash spectrum.*

Red flames, or prominences, take their rise in the chromosphere. Those that reach the greatest elevation consist principally of hydrogen, calcium and helium.

Observations made at total eclipses prove that the maximum

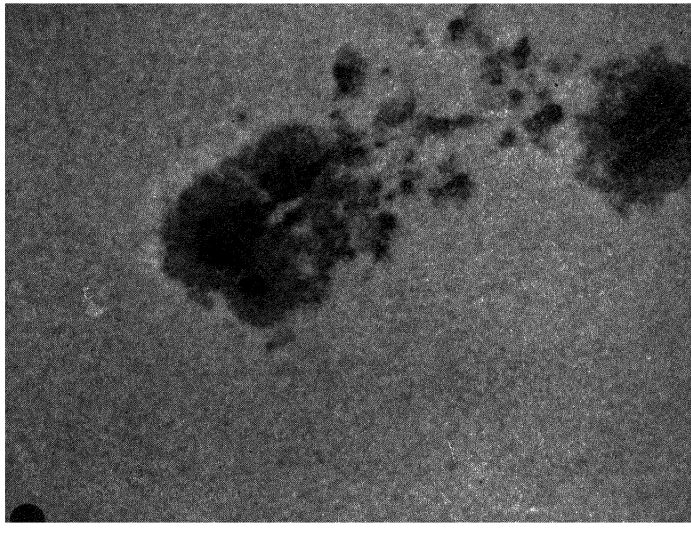


PLATE 24. A GREAT SUN-SPOT.
Enlarged from a direct photograph.
(Mt. Wilson Observatory.)
Notice that the whole solar surface shows a mottled appearance. The black circle in the corner shows the size of the earth on the same scale.

height to which the sun's atmosphere extends is 14,000 kilometers (8500 miles).

Outside the chromosphere extends the far-flung *corona,* visible only at total eclipses. It has been traced to a distance of ten million miles from the sun's surface.

Sun-Spots. — Spots frequently appear on the surface of the sun and are of great interest. As the diameter of the sun is more than a hundred times greater than the diameter of the earth, the apparently little dark spots on his surface are very often of a size to

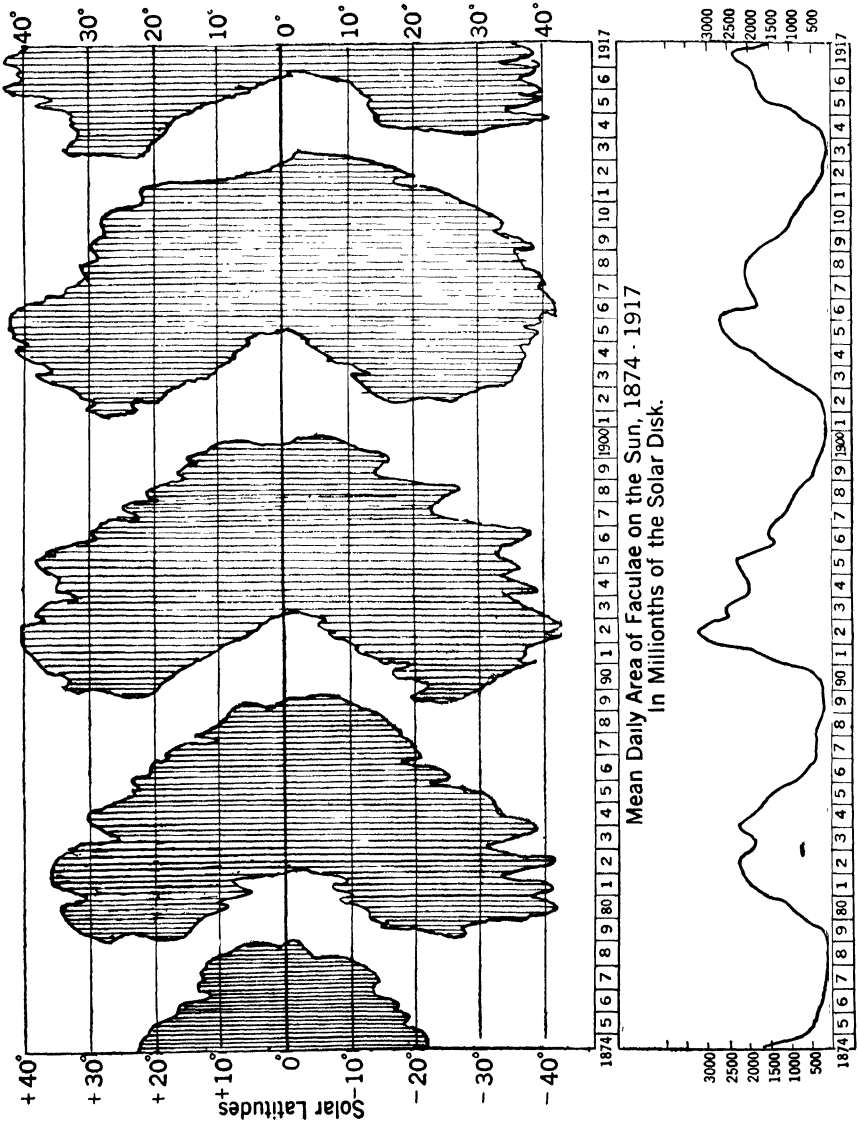


FIG. 23. THE BUTTERFLY DIAGRAM (from Greenwich Observations).

In the lower curve are plotted the mean daily areas of the solar disk covered by faculæ in the years 1874–1917. In the upper cross-hatched curves are indicated the latitudes where these solar faculæ prevailed. Towards the end of a sun-spot cycle of about 11 years average duration, the solar activity is confined near the sun's equator. When the next cycle begins, the activity starts up at some 30° to north and south of it.

engulf the world. Single spots sometimes exceed 30,000 miles in diameter, and spot groups often cover an area of several million square miles.

Sun-spots show distinctly two parts. The central dark region is called the *umbra* and the surrounding extension, less dense in shade, the *penumbra*. As all solar observers know, our atmosphere is much troubled by the heat of the sun's rays. Effects of the same kind as those to be noticed in looking over a hot stove, or a desert, tend to spoil the " seeing." On this account, it is seldom that one has a really satisfactory view of the structure of sun-spots. In the rare moments of fine seeing, solar features appear somewhat like those sketched by Langley, but seldom adequately photographed.

Sun-Spot Period. — The numbers of sun-spots wax and wane with a somewhat irregular periodicity averaging 11.1 years. This was first shown by Schwabe, in 1843, who had observed the sun-spots regularly for many years. Wolf of Zurich then collected all available statistics, and assigned a certain scale called " Wolf's sun-spot numbers " to indicate their frequency. His successor, Wolfer, has carried it out to this day, so that we have valuable records of the sun's spottedness from 1610 until now. The general results are given in Fig. 23 and Fig. 24.

Change in Solar Latitude. — Besides the change in sun-spot numbers, there is a strange shifting in prevailing latitude which must excite our interest. When the sun's surface is quiescent, the very rare spots that occur lie near the sun's equator. But as the quiescent period ends, and spots are about to become more prevalent, they appear at latitudes of 30° or so on either side of the sun's equator. With the progress of the new sun-spot period, which this outspread of position inaugurates, the belt of maximum spottedness slowly drifts back again. By plotting the numbers and latitudes of sun-spots on either side of the equator, Maunder has brought out the very curious figure called the " butterfly diagram " to illustrate this point.

Temperature of Spots. — By noting the intensities of the lines in the spectrum of sun-spots, and comparing them with the intensities of the same lines in the Fraunhofer spectrum, the spectroscope has proven conclusively that sun-spots are cooler than their surroundings. Evidence on this subject is very positive since chemical compounds, titanium oxide and others, form in the cooler tempera-

ture of the spots. The temperature of an average spot is about 4000° Absolute, 2000° below that of the photosphere. That is the reason why they look dark. No one should imagine, though, that they are really cool. If one could screen off all the rest of the sun and take light from the center of a big spot alone, it would be so dazzlingly bright that all electric lamps would look dim compared to it. Only because we see them against a tremendously brilliant background do the spots seem dark.

Sun-Spots are Whirlpools. — Compare them, if you please, to sand-whirls in a desert, or to waterspouts at sea. The central dark

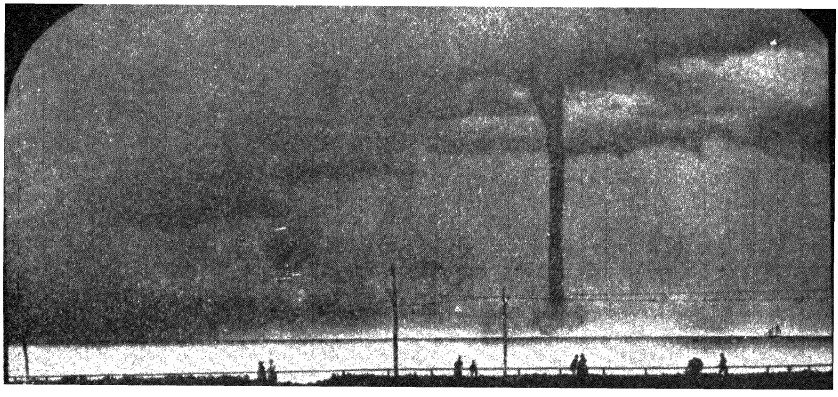


PLATE 25. WATERSPOUT, COTTAGE CITY, VINEYARD SOUND, MASS. AUGUST 19, 1893. (Photo by J. N. Chamberlain.)

umbra will be represented by the trunklike stem of the sand-whirl or waterspout, and the surrounding half-tone of the penumbra by the outspreading of the upper portion like a tree-top. In the sun-spot, gases from within are rising outward to the sun's surface. This upward motion towards a region of diminished pressure, of course, cools the gases by expansion, and makes the darkening. Arrived at the sun's surface, the gases spread abroad, making the penumbra. Centrifugal force tends to lower the pressure at the center, so that light gases from above are sucked back through the umbral region.

Sun-Spots Are Centers of Magnetic Disturbance. — By a brilliant application of Zeeman's discovery of the relations of magnetism and light, (page 127) Hale proved the existence of magnetism

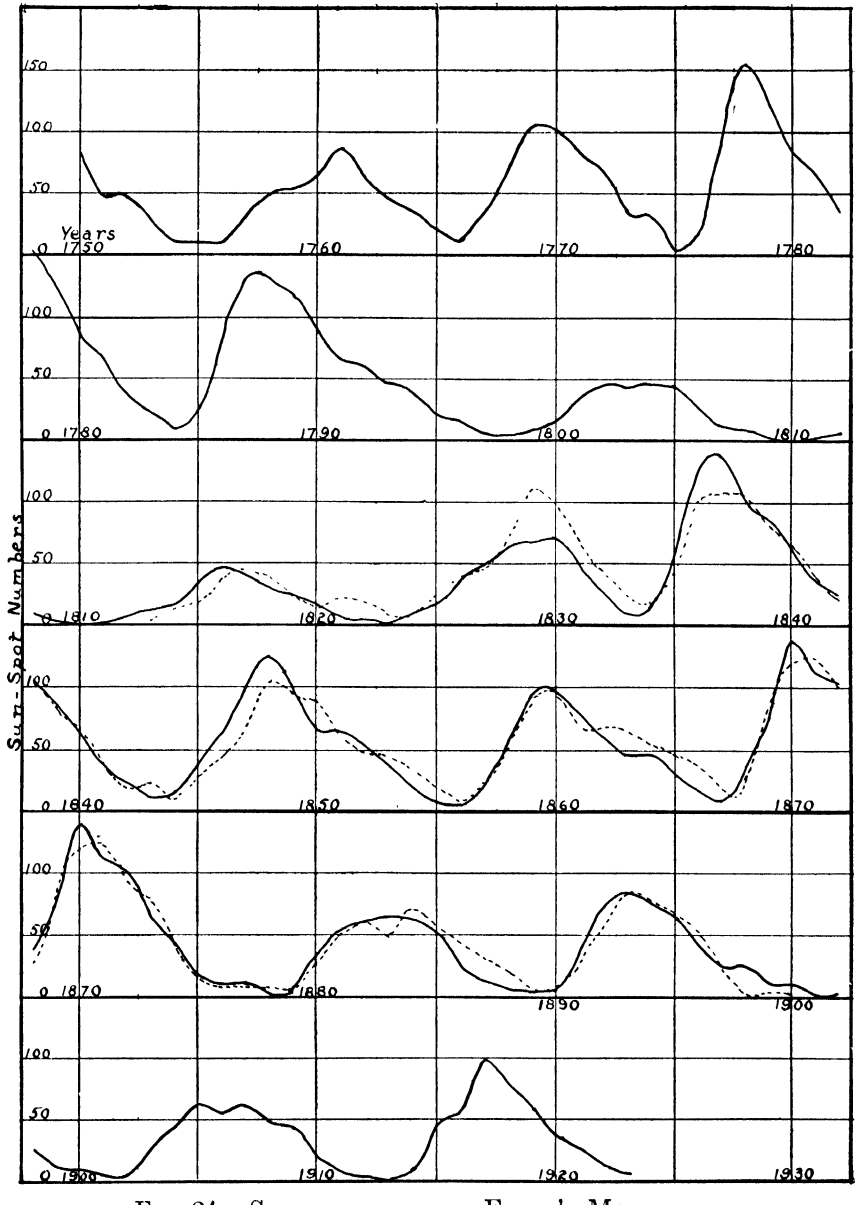


FIG. 24. SUN-SPOTS AND THE EARTH'S MAGNETISM.

The full curve represents the march of sun-spot numbers after Wolf and Wolfer from the year 1750 to 1923. The dotted curve shows the degree of variability of the magnetic declination as compiled from various sources. A tendency to 11-year periodicity, quick rise and slow decline, and greatly varying intensity of cycles are notable.

in sun-spots, and explained the widening and doubling of the spectrum lines therein. He was even able to measure the polarity and strength of the magnetic poles. A most curious result was found. For every north-polar spot, a south-polar spot lies nearby, at least incipiently. If the eastern one of the pair is north polar in the sun's northern hemisphere, it will be the western one which is north-polar in the southern hemisphere. Strangest of all, these conditions reverse as the sun-spot cycles change. That is, if the

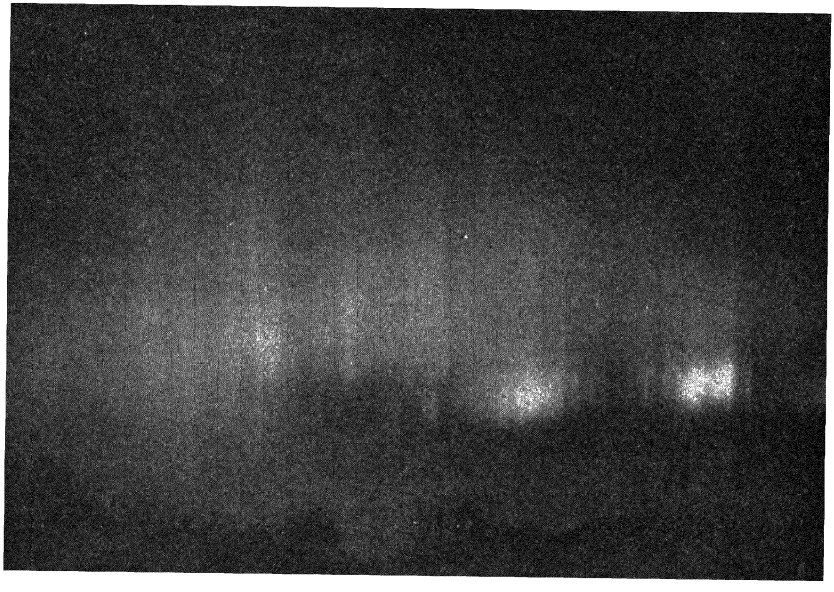


PLATE 26. AURORA BOREALIS, OR NORTHERN LIGHTS. (Photo by Störmer.)

eastern spot has been north-polar in the northern hemisphere through one sun-spot cycle, it will be the western spot that is so in that hemisphere in the next.

Not only is there magnetism in the sun-spots, but it exists all over the sun as well, though less intensely. Moreover, when sun-spots are plentiful there are often magnetic disturbances upon our earth. In Fig. 24 we may see how closely the magnetism of the earth depends on the spottedness of the sun. The electrical phenomenon in the upper air which is called *aurora borealis*, or northern lights, also shows a close relation to sun-spots. Sometimes when a very great group of spots passes the center of the sun, as for example on March 22, 1920, the northern lights become ex-

traordinarily brilliant, and magnetic storms, as they are called, interrupt telegraphic service. These magnetic storms have no connection whatever with thunderstorms. Whenever there is a display of northern lights, there is usually a spot to be found near the central meridian of the sun. Maunder has found that the magnetic storm occurs, on the average, about twenty-five hours after the spot has crossed the solar meridian. Frequently a magnetic storm again takes place when the spot again returns to the solar meridian by the rotation of the sun.

Sun-Spots and Weather Predictions. — Many and varied have been the attempts to connect the sun-spot period with such disconnected things as panics on Wall Street, famines in India, failure of the potato crop in Ireland, excessive heat (or cold) in one locality, excessive rain (or drought), etc., etc., etc. It has been said that "figures never lie." The figures themselves tell no falsehood but they may be manipulated to substantiate many different kinds of stories. Up to the present, no great success has attended the attempts on long-range weather forecasting based on the sun-spot period.

The sun sends out a little more radiation at times when the sun-spots are numerous. Of course there is a contrary tendency on account of the fact that spots are cooler than the sun as a whole. But they occupy so little area, hardly ever so much as $\frac{1}{500}$ of the sun's disk, that this tendency does not amount to much. On the other hand, the increased solar activity at times of many sun-spots may be likened to the stirring of an open fire which brings fresh coals to the front. So it is with the sun. When it is very active the radiating surface is a little hotter, and we may get as much as 3 per cent more solar heat at such times of maximum sun-spots.

Curiously, however, most of our world's land surface is a little cooler at sun-spot maximum. Possibly this may be caused by increased cloudiness at that time. For if it were more cloudy, more solar rays would be reflected away, and there would be fewer reaching the earth's surface to warm it. Decreased temperature at sun-spot maximum is not universal on the earth's surface. After all, the weather is very complicated, and the paradoxical observation of lower temperature when the sun is sending us more radiation, may have an explanation in the change of wind direc-

tions, due to the unequal effects of solar heat in clear and hazy regions.

Faculæ and Granulations. — Nearly all sun-spots are surrounded by patches of the sun's surface much brighter than the average. These are called "faculæ." They usually form just before spots are born, right where the spots are about to appear. Sometimes the spots fail to develop in regions of faculæ, but generally they do come soon after them. All over the sun's surface there is a

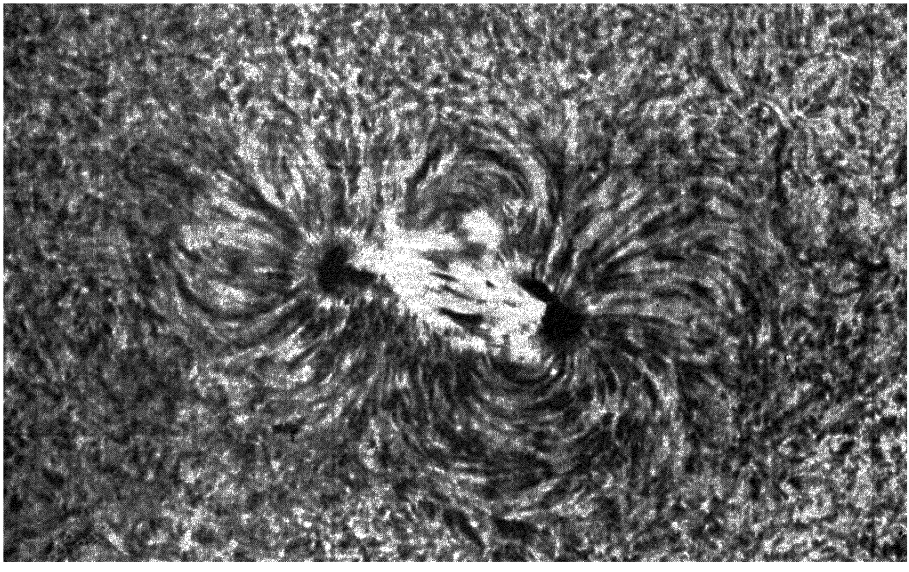


PLATE 27. SUN-SPOT GROUP, AUGUST 30, 1924.

Photographed in red hydrogen light with the 13-foot spectroheliograph and 60-foot tower telescope (Mt. Wilson Observatory). Note the ray structure, so like the lines of magnetic force revealed by sprinkling iron filings on a card over a magnet pole.

mottled appearance of difference in brightness, sometimes called "granulation." The apparently little patches of bright and darker solar surface are, as a matter of fact, hundreds of miles in extent. Most of these apparently insignificant solar features are really as large as the states of our Union. If one imagines them as New York dark, or Texas bright, they begin to assume more importance.

Sun-spots and all other solar features march across the disk in about two weeks because the sun rotates. Faculæ are more conspicuous when part way in from the edge of the sun's disk

than they are either at the edge or the center of it. This is readily understood. At the edge, we are looking very obliquely at the sun's spherical form, so that the objects there are greatly foreshortened. In this way, the faculæ, seen on edge, as it were, seem very small and indistinct. In the center of the sun's disk, though we see them broad-side on, we look straight down into the hotter interior. Against this brighter background the faculæ almost disappear. Faculæ and granulations are not to be regarded like mountains and lakes on the earth. They are not permanently placed objects, but merely regions which for a time are either hotter or cooler than adjacent regions, owing to processes of which we know little, which go on in that wonderful laboratory, the sun.

Prominences. — For the remaining features of the sun, we must either use the spectroscope or wait for a total solar eclipse. As these features, the prominences and the corona, are the most beautiful of all, much experimenting has been done to devise ways to observe them at all times, without eclipses. In this effort success has come so far as the prominences are concerned, but not for the corona. It happens that the prominences, which appear like flames leaping out to enormous distances beyond the sun's edge are composed of but a very few hot gases, mainly hydrogen, helium, and calcium. These gases give out their light in very narrow bright spectrum lines.

If the spectroscope is applied to study such lights as these, it does not spread them out in long continuous bands of color, but merely exhibits the few bright lines alone. If the scale of the spectrum is increased, for example, by the use of additional prisms, the lines of the prominence spectrum are spread out to greater distances from each other but the intensity of each line is unchanged. If we attempt to observe a prominence when an eclipse is not in progress, so that the bright glare of the sun is not darkened, it is impossible to keep stray sun light and sky light from shining down the tube of the telescope, giving a strong diffused glare all around the solar image. It is this strong light which obscures the prominences to naked-eye vision. The spectrum of the light of the sky is identical with the solar spectrum. By an increase in the dispersion of the spectroscope, this sky spectrum may be weakened at will, while (as above stated) the *bright* lines of the prominence spectrum remain without diminution in intensity. In this way,

the prominence lines, by contrast, may be made to predominate over the sky spectrum in brightness, and may become actually visible on the edge of the sun without waiting for an eclipse. The slit of the spectroscope may even be widened enough to exhibit the details of the prominence structure. When this is done, and the red line of hydrogen, the Fraunhofer C-line, is used for observation, the prominences then stand out in their feathery, flowery detail,

PLATE 28. A GREAT SOLAR PROMINENCE.
(Mt. Wilson Observatory.)

This photograph is taken spectroscopically, not during an eclipse. It shows one of the immense flamelike protuberances of hydrogen and calcium gases which frequently dash out from the sun's surface. In this case the extreme height is about 150,000 miles above the sun's surface.

and one can then get visually a charming sight of these *red flames.*

By means of the *spectroheliograph*, that special spectroscope which is able to photograph the whole sun and its surroundings with light of a single spectrum ray, the prominences may be beautifully photographed. Daily observations are made at great observatories, Mount Wilson, Kodaikanal, Yerkes, Meudon and

several others. The Mount Wilson spectroheliograph is shown in Fig. 22.

Prominences are seen every day surrounding the sun. At times they reach great activity and are shot out to great distances from the solar surface. A prominence 50,000 miles high is quite an ordinary affair. More rarely they reach elevations of 100,000 miles and have been detected to the enormous distance of 500,000 miles from the solar surface. These have the appearance of gigantic flames from the enormously hot solar furnace, but, as said above, there is no combustion going on there, only the phenomena of tremendous heat.

The eruptive prominences show high velocities and rapid changes in form. Velocities of more than 100 miles per second are frequently detected in the uprush of heated gases.

Flocculi. — The spectroheliograph also shows us the clouds of hydrogen or of calcium which lie above the sun's surface. Such pictures are in some respects like cloud pictures taken from above the earth in an airplane. They show in much more detailed structure than direct photographs do how the brightness changes from place to place in these gases. These changes are due, no doubt, to differences of temperature accompanying differences of level, as well as to other reactions going on in the sun. Hale has named these appearances seen in the spectroheliograph "flocculi," and speaks of hydrogen or of calcium flocculi, according to which gas is being photographed by the spectroheliograph.

Recently Hale has invented a new instrument, called the spectrohelioscope, for the visual observation of changes taking place in the solar features.

Eclipse Conditions. — If the moon's path were exactly in the plane of the ecliptic, there would be two eclipses each and every month. At the time of new moon, the moon would pass directly between the earth and the sun and there would be a solar eclipse; two weeks later, at its full, the moon would pass into the shadow cast by the earth, causing a lunar eclipse. But the moon's path is inclined over 5° to the plane of the ecliptic. At the time of new moon (when alone a solar eclipse can take place) it is only when the moon is near the plane of the ecliptic, or near its node, that an eclipse can take place. Whether the lunar and solar eclipses are total or partial depends on the angular distance that the moon is from the

node at time of full moon, or the sun is from the node at the time of new moon.

We have seen that the moon's node is moving in the direction to meet the oncoming sun. The interval of time that it takes the sun to move from the moon's node back again to the same node, is called the *eclipse year*. Its length is 346.62 days, or 18.62 days shorter than the calendar or tropical year.

Prediction of Eclipses. — If an eclipse takes place and we can calculate ahead that, after the lapse of a certain interval of time, the sun, moon and earth will return nearly to the same relative positions that they occupied during the eclipse, then we can be sure that an eclipse will again take place. If the conditions are very nearly the same as they were at the previous time, then the character of the eclipse will be nearly identical. That is, a total eclipse of the sun will be followed by a total eclipse of nearly the same duration of totality, etc. From the Chaldeans has descended to us the interval known as the *Saros*. The importance of this will be seen by the following values:

19 eclipse years	= 6585.7806 days
223 synodic months	= 6585.3211 "
247 nodical months	= 6585.3572 "
239 anomalistic months	= 6585.5374 "

The *anomalistic month* is the return of the moon to *perigee* or least distance from the earth. The *Saros* of 6585 days amounts to 18 years 11 days, if only four leap years intervene; or 18 years 10 days, if the 29th of February has come five times. After the lapse of a Saros, the sun, earth and moon have returned *very* nearly to the same positions they had previously occupied. (That the decimal parts of the above numbers are different have consequences that cannot be traced here.) A total eclipse of long duration of totality is followed at the expiration of a Saros by one of long totality, a partial eclipse by a partial eclipse, etc. Eclipses therefore occur in series, and it is possible to trace the conditions at each eclipse of the series. For solar eclipses, there are anywhere from 68 to 75 eclipses in such a series depending on conditions, and extending over some 1200 years. Of these, on the average, 25 are partial eclipses, 18 are total eclipses and 27 annular eclipses.

Oppolzer's *Canon der Finsternisse* contains the elements of all the eclipses (8000 solar and 5200 lunar) that come to pass between

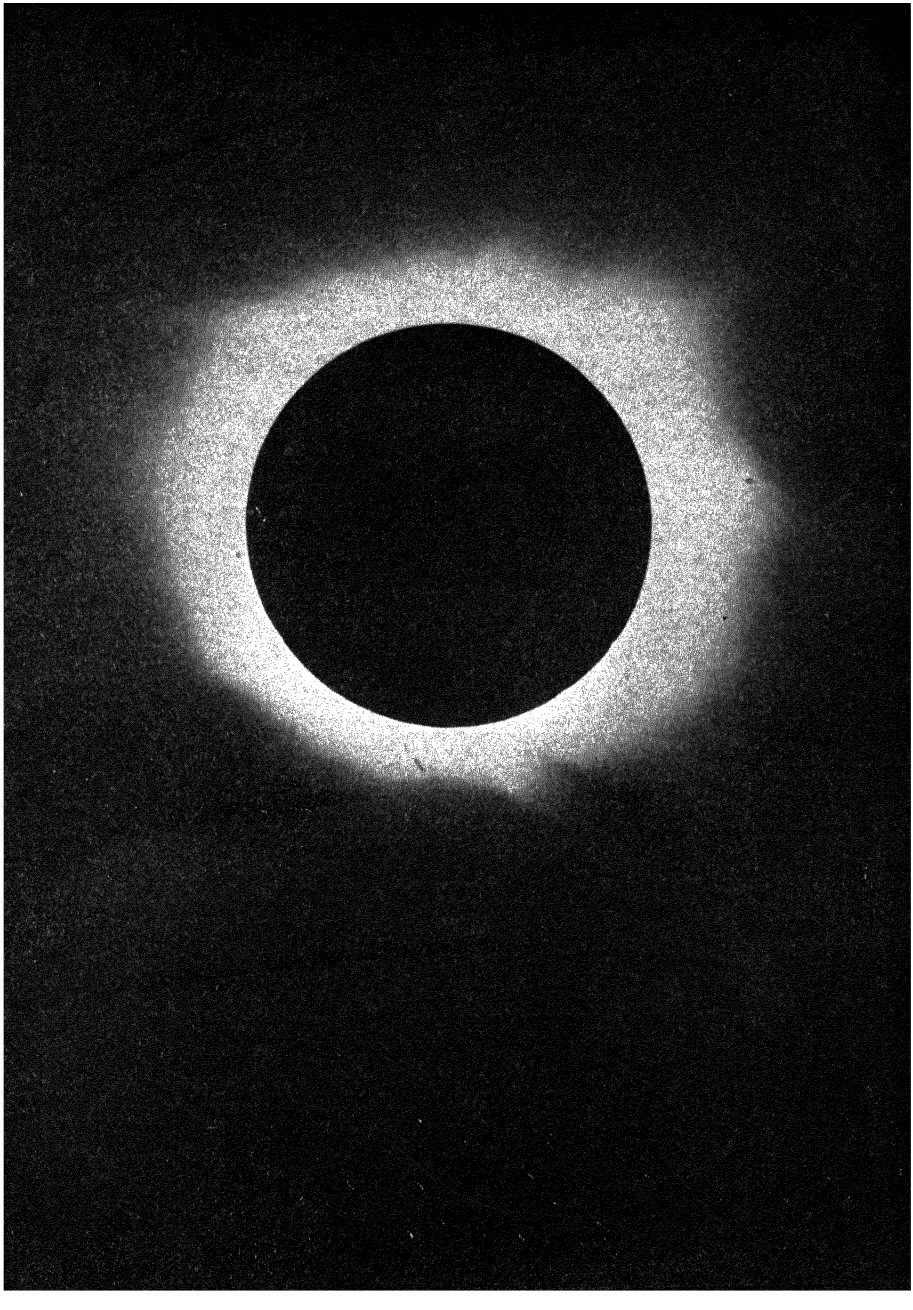


PLATE 29. TOTAL SOLAR ECLIPSE, JAN. 24, 1925. (Slocum.)

the dates 1208 B.C. and 2162 A.D. Charts are also given of the locations on the earth where total eclipses of the sun may be seen.

Number of Total Eclipses. — According to Oppolzer, on the average there are 66 total solar eclipses in a century, or two every three years. But fully half of these are unfavorable to observe for the reason that the eclipse tracks are in high northern or southern latitudes, or pass entirely across oceans, or lie in localities where the probabilities of good weather are unpromising. Consequently, on the average, about once in every three years a total eclipse somewhere on the earth is available for observation. As the duration of totality averages less than three minutes, we thus see that an eclipse observer may have an average of a minute per year for scientific work, provided he has financial backing to permit him to travel at times half way round the world, as was done by the authors of this book who went to Sumatra in 1901.

Number of Eclipses Each Year. — Eclipses are not of such rare occurrence as one might be led to expect from the above considerations. From the nature of things, there must be at least two solar eclipses, each and every year, and there may be as many as five solar eclipses in a single calendar year. In 1935 there will be two lunar eclipses and five solar eclipses. The maximum number of eclipses in a year is seven (there may be also four solar and three lunar) and the minimum number is two, both of the sun. Most of these eclipses are partial and present little of interest to the astronomer.

Duration of a Total Eclipse. — The moon is so small a body compared to the sun that its shadow tapers rapidly towards a point, and if the radius of the moon's orbit were but a little greater than it is, or the diameter of the moon a little smaller, there would be no total solar eclipses. Even as matters stand, the moon's shadow is not always long enough to reach the earth's surface. Under these circumstances the moon is not large enough to cover the whole sun, and at mid-eclipse there is a ring, or annulus, of light around the edge of the moon. This is called an *annular* eclipse.

At the time of a total solar eclipse, the maximum diameter of the shadow intercepted by the earth is 167 miles. Due to the fact that the moon is moving in her orbit in an easterly direction, and the earth is turning on its axis in the same direction, the moon's shadow will travel over the face of the earth. The orbital motion causes

the shadow to move 2100 miles per hour while the rotation of the earth at the equator is 1040 miles per hour. Hence, *at the equator*, the speed of the moon's shadow *eastward* is 1060 miles per hour (2100 – 1040). This is the minimum velocity, for with localities away from the equator and totality taking place in the morning or evening, the shadow may travel at 4000 or even 5000 miles per

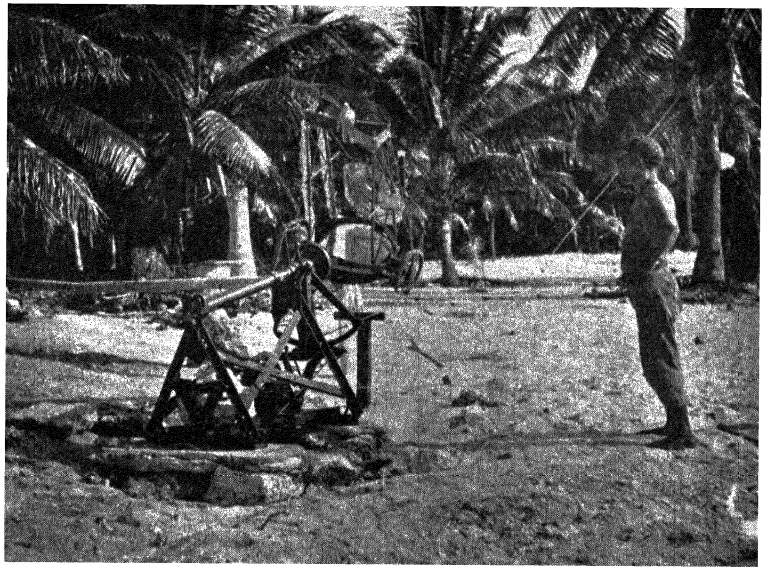


PLATE 30. APPARATUS OF SMITHSONIAN OBSERVERS AT THE FLINT ISLAND TOTAL ECLIPSE OF JANUARY 3, 1908.
A Samoan Marine is studying it out.

hour. The maximum duration of totality is about seven and a half minutes. Ordinarily a total eclipse of the sun may be seen as a partial one for a distance of 2000 miles on either side of the path of totality.

Frequency of Total Eclipses at One Locality. — Sometimes the path swept over by totality is as long as 5000 miles, so that as much as 1,000,000 square miles of the earth's surface may come within totality in one eclipse. However, as the earth's total surface is nearly 200 times as great, and as over 70 per cent of it is on the oceans, and a good deal more is inaccessible, it is clear enough that the chance is small of seeing a total eclipse in any given town. It has been estimated that on the average a stay-at-home would

see a total solar eclipse once in every 300 years. Not a single total eclipse was visible in London between 1140 and 1715. From the latter date up to June 29, 1927, no total eclipse has visited Great Britain. The United States has been visited by total solar eclipses

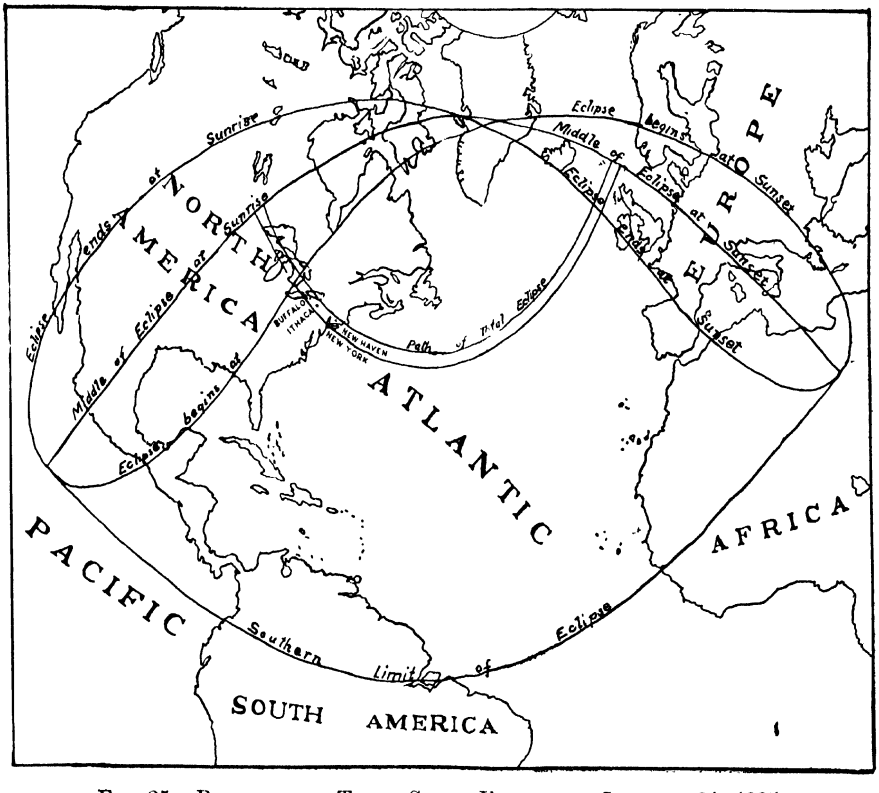


FIG. 25. PATH OF THE TOTAL SOLAR ECLIPSE OF JANUARY 24, 1925 (after the American Ephemeris).

in the years 1900, 1918, 1923 and 1925. After the eclipse of August 31, 1932, has passed into history, not a single total eclipse of the sun will visit the United States bringing conditions that promise successful observation until after the end of the twentieth century.

Figure 25 shows the path of totality and the area of partial eclipse of January 24, 1925.

Stars Visible During Totality. — The darkness which prevails during totality is not often highly intense. On most occasions it is possible to read by the light still remaining. Some of the light comes from the illuminated atmosphere outside of the shadow

path, some from the prominences, and some from the solar corona which we are about to describe. The planets Mercury and Venus are often seen near the sun, and sometimes others. At the eclipse of January 24, 1925, the planets Mercury, Venus and Jupiter, lying near together to the south and quite a distance west of the sun, were easily observed. Stars may be seen, too, during totality. During the eclipse just referred to, the stars Arcturus, Antares, Vega, and Altair could possibly be seen. With photographic telescopes guided by clockwork, stars as faint as the 10.5 magnitude, or about 100 times as faint as the eye can see at night, have been recorded during total eclipses.

Shadow Bands. — As the last thin crescent of the bright sun is about to vanish, it is often noticed that bands of alternately darker and lighter shade seem to dance along the ground. They are best seen by spreading white cloths, such as tablecloths or bed sheets on the ground. At the 1925 eclipse, Nature spread over the earth a white sheet of snow so that the shadow bands were seen by thousands of people. The bands may also be seen just after totality is over. They are caused by waves in the atmosphere a few hundred feet from the ground, and are therefore a meteorological and not an astronomical phenomenon.

The Coming of Totality. — To watch the coming of the moon's shadow, the observer should take his stand, if possible, on a little eminence where there is an unobstructed view towards the west, whence the shadow will come. It inspires a sensation very like fear to see the darkness approach with such appalling swiftness, as if it were a thing of evil, about to smite with a plague. The color of all things, too, is very ghastly, for the genial rays of the sun's central parts have long before been cut off, leaving only the dim reddish light of the thin crescent remaining.

The moment the shadow comes, the feeling of oppression and vague fear which we have described gives way to exultation as the beautiful glory of the solar corona bursts upon the eye. Streaming outwards for a long distance of one or more solar diameters, this pearly radiance, with its shapely curves and raylike structure, forms one of the greatest beauties of the heavens. As with the night-blooming cereus of the tropics, the rareness of one's opportunities to see a total eclipse greatly enhances the enjoyment of its loveliness.

Close up to the dark edge of the moon there lies a ring of crimson, with excrescences here and there, sometimes, as in the eclipse of 1919, extending out nearly the length of the solar radius. This is called the chromosphere, or colored atmosphere of the sun. At times of total solar eclipse the sight may be enjoyed in all its beauty, for we see it half or even all the way round the sun, depending on the length of totality. When the moon is but little above the angular diameter of the sun, so that the eclipse is very short, the chromosphere is seen to the best advantage. It is unnecessary to use a telescope in order to enjoy the entrancing beauty of a total eclipse.

Eclipse Problems. — (1) Determination of *times of contacts*, and photographing the partial phases in order to ascertain relative positions of sun and moon.

(2) *Direct photography* of corona and prominences with cameras large and small, for a historical record and for a study of motions of the coronal material.

(3) *The flash spectrum.* The dark lines of the solar spectrum appear as long as the photosphere is visible. At the beginning of totality the photosphere is covered by the moon, and the chromosphere, consisting of heated gases, gives its spectrum of bright lines, on a black background. The change is so sudden, the bright lines flashing out quickly, that Young at the eclipse of 1870 called it the "flash spectrum." It is a reversal of the ordinary solar spectrum but with remarkable changes in intensities, particularly in the *enhanced* lines, caused by the chemical atom having lost an external electron. The flash spectrum taken without slit furnishes a direct measure of the height in miles that the heated solar vapors extend above the surface of the sun.

(4) *The spectrum of the corona.* About forty bright lines appear in the spectrum of the corona, the brightest being in the green. They are due to a hypothetical element called coronium of which we know nothing but the wave-lengths of the lines.

(5) Measurement of the *intensity* of the light of the corona at different distances from the sun's edge.

(6) Observations of shadow bands, change of temperature, etc., as the eclipse is in progress, the effect on magnetic elements and the transmission of radio, etc.

Relativity. — It is only at times of total solar eclipses that stars close to the sun can be photographed, because the bright sky light

ordinarily overpowers them. Hence, there are two famous problems which could be attacked only at solar eclipses. First is that of the possible " inter-mercurial planet." While the law of Newton has been found to predict with almost complete accuracy the motions of the solar system, a slight departure from its theory occurs with the planet Mercury. Allowing for all attractions, there should be a slow rotation of the ellipse of Mercury's orbit, but the com-

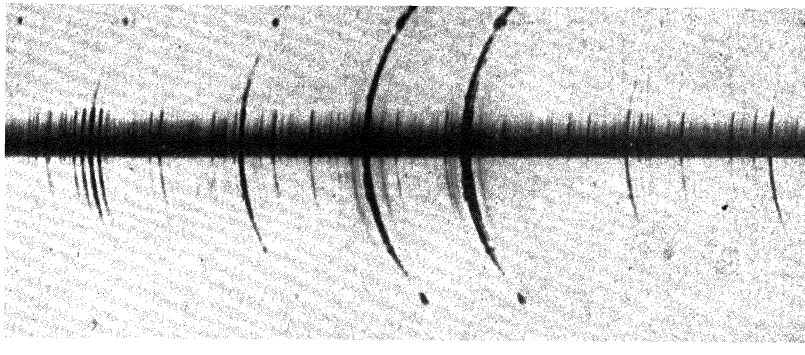


PLATE 31. A PORTION OF THE "FLASH" SPECTRUM OF THE TOTAL SOLAR ECLIPSE OF 1905. (Photograph by S. A. Mitchell.)

The spectral region is in the violet from 3800 to 4100 Angstroms in wavelength. The lengths of the lines give an indication of the heights to which the vapors which produce them rise above the solar disk. The two longest and heaviest lines are the H and K lines formed by mixed hydrogen and calcium, and by calcium vapors, respectively.

puted rate of its rotation disagrees by about 43 seconds of arc per century with the observed. Long ago it was suggested that there might be a little planet nearer than Mercury to the sun, whose attraction caused the unexplained discrepancy (page 102).

Several observers of the middle part of the nineteenth century thought they saw such a planet, or even several of them. A name, " Vulcan," was even assigned. At the eclipses of 1900, 1901, 1905, 1908, and 1922, cameras were employed especially successfully by the Lick Observatory expeditions. Though they photographed all stars to the ninth magnitude, Vulcan did not appear. Its existence is now disbelieved.

A totally different explanation of the rotation of Mercury's orbit is a feature of Einstein's theory of relativity. Einstein computed that there should be, in fact, a departure from Newton's law, just

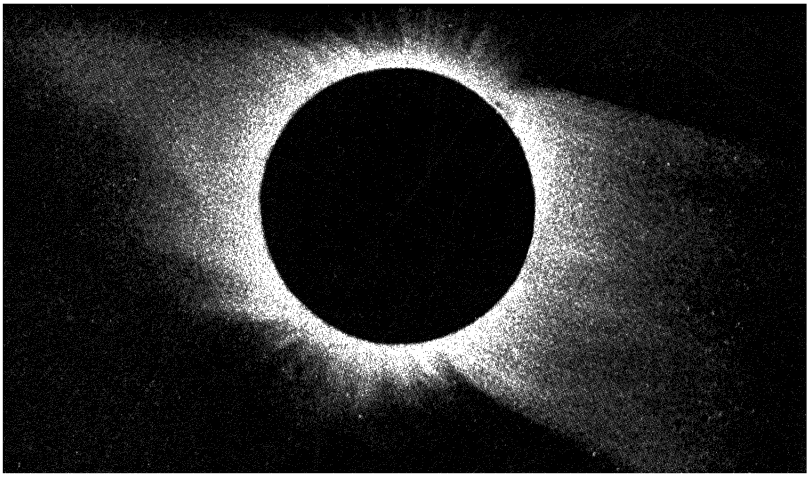
sufficient to make the observed discrepancy. Thus, this verification of the requirements of the theory of relativity is regarded as a strong support of it. Einstein predicted another small effect which up to that time was unsuspected. It is that rays from stars, as they pass close to the sun, must appear to be bent through a small angle which varies with the distance from the sun's center.

At the eclipse of May 29, 1919, English expeditions in Brazil and Africa sought for and found Einstein's predicted star displacement. There were many astronomers not entirely convinced, however. The circumstances of passing from bright warm day into eclipse night are so unusual and sudden that it was feared that some atmospheric or instrumental errors had caused the small star displacements found. Accordingly, at the Australian eclipse of 1922, the Lick Observatory expedition repeated the observation with all the precautions which experience and keen forethought could suggest. The result was even more conclusive. There can be no doubt that Einstein's prediction of star shifting is closely verified by observation. The observed deflection was 1″.72 at the edge of the sun, while 1″.75 was predicted by the theory of relativity.

The Corona. — The corona has been traced to a distance of ten million miles from the edge of the sun. The shape of the corona depends on the sun-spot period. At the time of minimum of spots, the corona extends far along the solar equator and has very pronounced polar brushes. At sun-spot maximum it is nearly circular in outline, "like a gigantic dahlia." Prominences are usually much more numerous at maximum of spots. The emission spectrum of coronium is brighter at maximum than at minimum of spots. Although the spectrum of the corona is mainly continuous, it exhibits faintly the dark lines of the ordinary solar spectrum.

The total light of the corona is about equal to the light of a standard candle at the distance of a meter, or about half that of the full moon at its average distance from the earth. The noon-day sun gives two million times more light than the corona. The surface brightness of the corona at the limb of the sun is about 1.4 times that of the full moon, and half the total light of the corona comes from a zone extending only 3′ from the edge of the sun.

So far it has been impossible to detect the corona without an



SOLAR CORONA OF MAY 28, 1900.

This drawing by P. R. Calvert from Yerkes Observatory photographs represents the form of the sun's corona at the 1900 total solar eclipse. The long equatorial arrow-shaped extensions are characteristic of a period of minimum sun-spots.

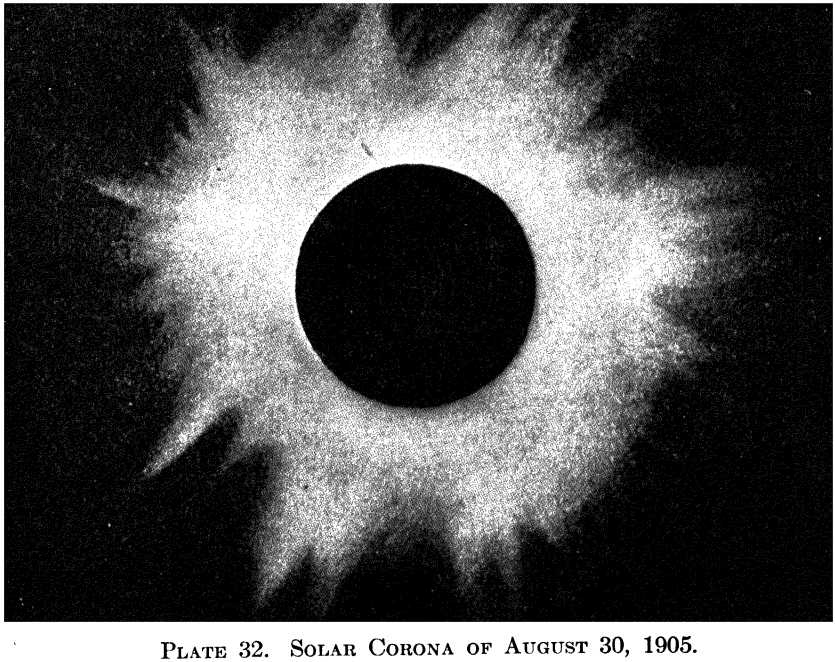


PLATE 32. SOLAR CORONA OF AUGUST 30, 1905.

This drawing by Mrs. C. G. Abbot from photographs by the United States Naval Observatory shows the irregular, but everywhere nearly equally extended, corona characteristic of the maximum period of sun-spots.

(These figures by permission from "The Sun," D. Appleton & Co.)

eclipse. The difficulty is that the coronal light has superimposed upon it the enormously greater illumination near the sun produced by the scattering of sunlight in our atmosphere and in the telescope. The effect of the illuminated atmosphere is ten thousand times more intense than the corona near the sun's limb, and hence astronomers hold out no hope of detecting the corona at any time other than at an eclipse. Coronal light is perhaps largely made up of radiation from the sun reflected by electrons.

The Sun's Atmosphere. — Observations made by the spectroscope, both when there is and when there is not an eclipse, have afforded so much positive knowledge that it is no exaggeration to state that we know vastly more of the chemical constitution and temperature at different distances from the surface than we know of the terrestrial atmosphere at its higher altitudes.

CHAPTER XI

HEAT, POWER, AND LIFE FROM SUN RAYS

How Solar Radiation is Measured. — Realizing, as every sensible person must, that our very lives depend on the sun's gift of heat and light, Sir John Herschel, and independently the French observer Pouillet, devised apparatus, about the year 1830, to enable them to measure the energy of the sun's rays. Pouillet's instrument was a flat box placed broadside towards the sun rays, filled with water and blackened on the sunward side. From the rear projected a thermometer designed to measure the change of temperature of the water-filled box. The device was alternately exposed to the sun and shaded, for equal intervals of time. During the shaded intervals, the influence of the surroundings was measured by the temperature change. These outside effects were added as a correction to the change brought about by exposure to the sun.

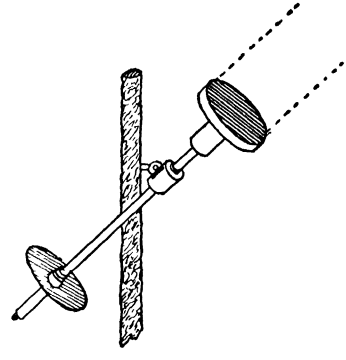


FIG. 26. POUILLET'S PYRHELIOMETER FOR MEASURING SOLAR HEAT.

The sun shines vertically on the blackened box which is filled with water. A thermometer inserted in the back of the box records the rate of rise of temperature. The instrument is kept accurately pointed by observing the shadow upon a disk near the rear end of the thermometer. Heating or cooling by the surroundings is eliminated by shading the instrument before and after exposures to the sun and noting the rates of cooling.

In this way the energy of the solar rays received on the whole area of the box was measured by the rise of temperature per minute of the box and the water it contained. The result was expressed in heat units, called " calories per square centimeter per minute." This formidable phrase is universally used to express measures of sun rays, but it needs explanation. Imagine a cube of water 1 cen-

timeter (about $\frac{3}{8}$ inch) on edge. It would be about as large as backgammon dice. If the water were well mixed with India ink, it would absorb the sun rays nearly completely. Suppose the absorption was really complete, and that the surroundings neither tended to warm nor cool our instrument. If such a cube of blackened water, contained in a little open dish, were exposed for 1 minute to the sun when vertically overhead, as it would be at noon in the tropics, the water would rise in temperature between 1° and 1°.6 C, depending on the clearness of the air. If it rose just 1° C, there would be just 1 calorie per square centimeter per minute of intensity in the sun's rays.

Effects of the Atmosphere on Solar Radiation. — The result, as we have said, would vary with the clearness of the air. It would also vary with the altitude of the observer above sea-level. Some readers, recalling how cold it is for those who fly in airplanes to great altitudes, and recalling the snow perpetually covering the peaks of the majestic Andes, even in the tropics, may jump to the conclusion that our cube of water would show most heat in the sun rays when at sea-level. This is not the case. The higher the station, the less loss of energy the sun rays suffer in the atmosphere, and the hotter they would heat our cube. If we were outside the atmosphere altogether, the intensity of sun rays would be almost 2 calories per square centimeter per minute, instead of only 1 calorie, as it often is found at sea-level.

It is very desirable to know the intensity of solar rays outside the atmosphere altogether. For this indicates how much energy the sun sends to warm the planet earth. It is also of great importance because we wish to know if the sun's radiation is constant or variable.

After Pouillet, other observers took up this kind of measurement. Forbes, Radau, and Langley deserve special mention. They showed that, since the influence of our atmosphere is different for different solar rays, letting some through almost unimpeded, cutting off some almost completely, and some partially, it is necessary to spread out the rays into the spectrum, and measure the change of intensity in each color, and of rays of no color, invisible to the eye, lying beyond the red and beyond the violet. For this purpose Langley invented the " bolometer," an excessively delicate electrical thermometer, which has been described in Chapter IX.

It measures as little as a millionth of a degree rise of temperature.

All the complexity of the bolometer and much more has to be endured in making the measurements of the sun's heat, for our atmosphere treats every ray differently, and we have to study each one by itself. The observations begin when the sun is low, while its rays pass obliquely in long atmospheric paths. They are carried on till the sun is high. From the changes of radiation attending the diminishing atmospheric paths, it can be computed what there would be if the measurements were made outside the air altogether.

Formula for Atmospheric Extinction. — Notwithstanding the great differences in the clearness of the air at different heights, allowance for atmospheric losses may be made for a homogeneous ray, that is, a ray of one color or, more exactly speaking, of a narrow range of wave-lengths, by employing the formula of Bouguer and Lambert. Referring to Fig 27, let AB represent the earth's surface, CD the upper limit of the appreciably absorbing atmosphere, and l_1, l_2, l_3 . . . . l_n represent equally massive layers of atmosphere, all so thin that they may be regarded each one as of sensibly homogeneous quality, though differing from one to another gradually in their transparency. Since the earth's radius is great compared to the atmospheric thickness (approximately as 4000 is to 40 for this purpose), the earth's surface may be regarded as plane, except for very greatly inclined sun rays. Let the observer, at O see the sun in the direction OS, making the angle Z with the vertical OV. Then $\frac{OS}{OV}$ = secant Z, and similarly in every layer, l_1 to l_n, the sun ray makes a path whose length is secant Z times what the length would be if the sun stood vertically overhead. The value secant Z (with slight corrections where Z exceeds 70°) is technically called the air-mass.

Now Bouguer and Lambert showed independently about two centuries ago that homogeneous light, traveling in a homogeneous medium, is continually diminished in its intensity at a rate which is ever proportional to the transparency of unit thickness raised to a power equal to the length of path. Applying this to our case, let us take in each atmospheric layer the unit thickness as the vertical thickness of the layer. Let i_0 be the intensity of the beam VO outside the atmosphere, and i its intensity at the surface of the earth.

Had it come vertically through the layer l_1, its intensity at the bottom of this layer would be, $i_0 a_1$, where a_1 is a fraction nearly equal to unity, representing the coefficient of vertical transmission for layer l_1. Similarly for l_2, except that we have a new coefficient, a_2, so that the intensity at the bottom of l_2 becomes $i_0 a_1 \times a_2$, and so

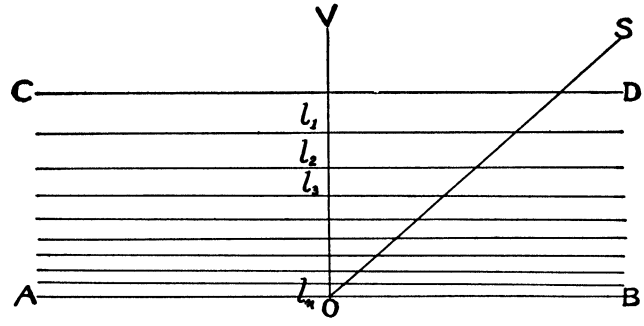


FIG. 27. ABSORPTION OF ATMOSPHERE FOR SOLAR RAYS.

on to l_n, with its coefficient a_n. The intensity at O for the vertical ray becomes, evidently, $i_0 (a_1 \times a_2 \times a_3 \times \ldots \times a_n)$. Let us call the continued product $(a_1 \times a_2 \times a_3 \times \ldots \times a_n) = a$, which is the vertical transmission coefficient for the entire atmosphere.

Let us examine now the ray SO. Applying the rule of Bouguer and Lambert, its intensity at the bottom of l_1 is $i_0 a_1^{\sec Z}$; at the bottom of l_2, it becomes $i_0 a_1^{\sec Z} \times a_2^{\sec Z}$. At O, it becomes $i_0 (a_1^{\sec Z} \times a_2^{\sec Z} \times a_3^{\sec Z} \times \ldots \times a_n^{\sec Z})$ or $i_0 (a_1 \times a_2 \times a_3 \times \ldots \times a_n)^{\sec Z} = i_0 a^{\sec Z}$. Thus, the great fundamental law of atmospheric transmission is: $i = i_0 a^{\sec Z}$, or $\log i = \sec Z \cdot \log a + \log i_0$.

Owing to curvature of the earth and other disturbing factors, it requires slight corrections where Z exceeds 70°. The law is applicable only to homogeneous rays, and fails for white light. Hence, in order to estimate the sun's radiation in free space, it is necessary to make spectrum observations, which greatly complicate determinations of the solar radiation at the upper limit of our atmosphere.

In applying the law, one observes with the bolometer the intensity, *i*, at various zenith angles *z*. By plotting logarithms of *i* against values of secant *z*, there results a straight line plot whose inclination gives logarithm *a*, and which cuts the axis

of logarithm i at the value logarithm i_0, where i_0 is the intensity outside the atmosphere. As remarked above, this is applicable only to individual spectrum rays, not to white light. Hence many rays of the spectrum must be measured separately and a summation of all of them computed. This result is reduced to calories by comparison with the total radiation separately measured as described below.

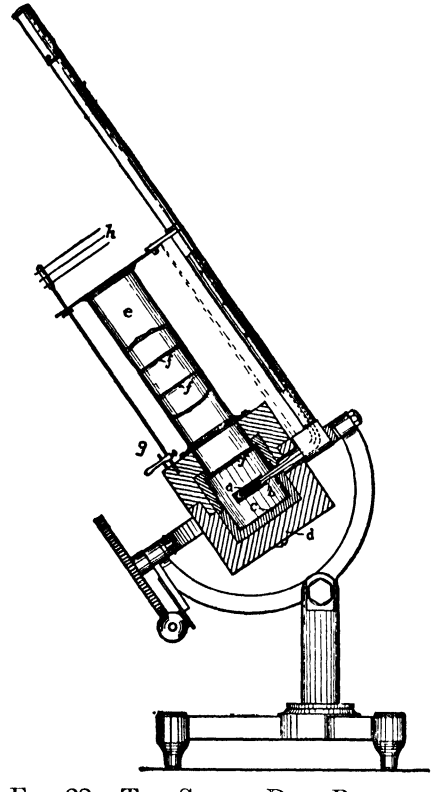


FIG. 28. THE SILVER DISK PYRHELIOMETER (Abbot's).

For measuring the total heat of solar rays, which enter through the vestibule, *e*, when the triple shutter, *gh*, is opened, and fall upon a blackened radiation-absorbing disk of silver, *a*, in which is inserted the bent-stem thermometer, *b*. The observer notes with his watch the rate of rise of temperature indicated by the thermometer, and corrects it by the average rate of cooling measured before and after the exposure to the sun.

Effect of Change of Solar Distance. — One other factor must be remembered. It is the alteration of the earth's solar distance. Owing to the ellipticity of her orbit, the earth is about 3,000,000 miles nearer the sun in January than in July. This leads to about 6 per cent greater intensity of solar rays in the depth of winter of the northern hemisphere than in midsummer. It is only because of the obliquity of the sun's rays, when coming to us from its far southerly winter pathway, that we have colder weather in winter than in summer. If we allow for this distance factor, and reduce to mean solar distance outside the atmosphere, we have what is called "the solar constant of radiation." It is the intensity of solar radiation outside the atmosphere at mean solar distance, expressed in calories per square centimeter per minute.

The Silver Disk Pyrheliometer. — For twenty years the observ-

ers of the Smithsonian Institution have been making measurements of this great constant of nature. They use to measure total radiation in the beam of white light a modification of Pouillet's blackened

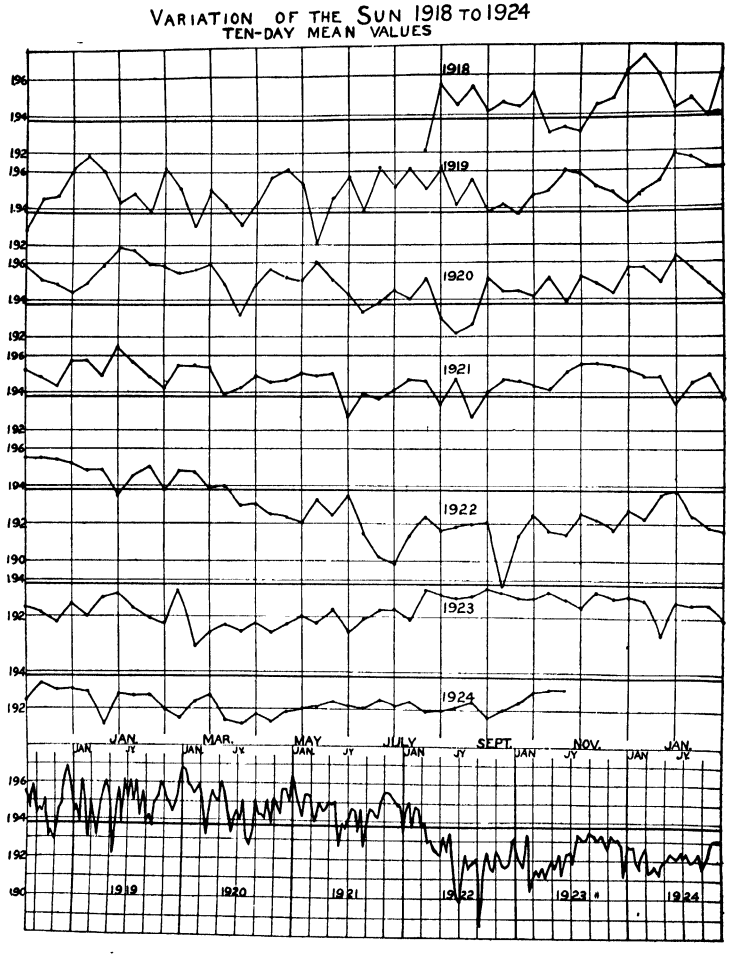


FIG. 29. VARIATIONS OF SOLAR RADIATION.

The curve shows the march from August, 1918, of ten-day mean values of the sun's heat as it is at the earth's average solar distance in free space. Note how deficient the solar radiation was from about March 1922 to March 1924. It would not seem remarkable if such long-continued changes produced notable modifications of climates.

box which he called the " pyrheliometer." This Greek expression means literally " heat of the sun measurer." The Smithsonian pyrheliometer has a blackened silver disk enclosed in a metal-and-

wood cavity having a vestibule with special contrivances to keep off air currents. The observer, with watch in hand, reads the rise and fall of an accurate thermometer which has a cylindrical bulb immersed in quicksilver in a steel-lined hole drilled radially in the disk of silver.

The Solar Constant of Radiation. — The mean value of several thousand measurements of the solar constant is 1.94 calories.

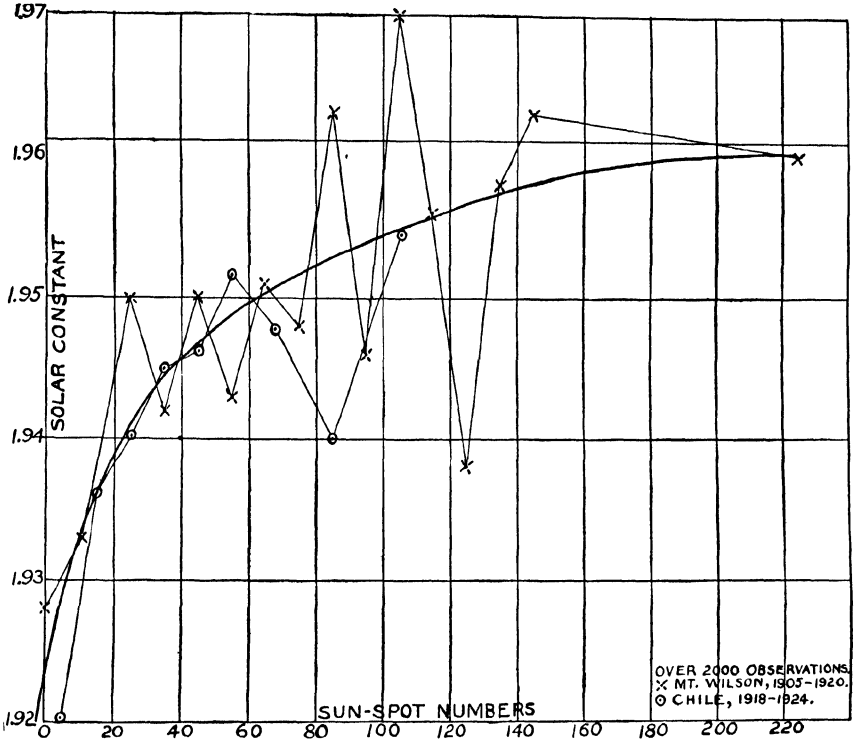


FIG. 30. VARIATIONS OF SOLAR RADIATION ASSOCIATED WITH SUN-SPOTS.

The curve shows that on the whole higher intensities of solar radiation accompany increased solar activity as shown in sun-spots.

However, the sun's output is not constant, but varies over an extreme range of nearly 10 per cent, between 1.82 and 2.02 calories. Variations so wide as this are not common, but values as far apart as 1.96 and 1.89 are not infrequent. The sun's variations are of two types. First, are those attending the march of the sun-spot cycle of 11.1 years average period. Values of the solar constant average 3 per cent higher at sun-spot maximum than at minimum.

However, if a large sun-spot, or group of spots, crosses centrally over the sun's disk, a low value of the solar radiation almost invariably occurs on the day after the central passage. Other irregular fluctuations occur from day to day and there have lately been discovered regular periodic fluctuations of $25\frac{2}{3}$, 15, and 11-month intervals.

Rapid Solar Changes. — Various evidences seem to show that the sun's rays are held back by raylike solar clouds connected to the sun's outer envelopes. When such a ray points towards the earth, our supply of solar radiation is reduced. As the sun rotates, these rays sweep by us, and so the changes go on, none of them lasting longer than a few days.

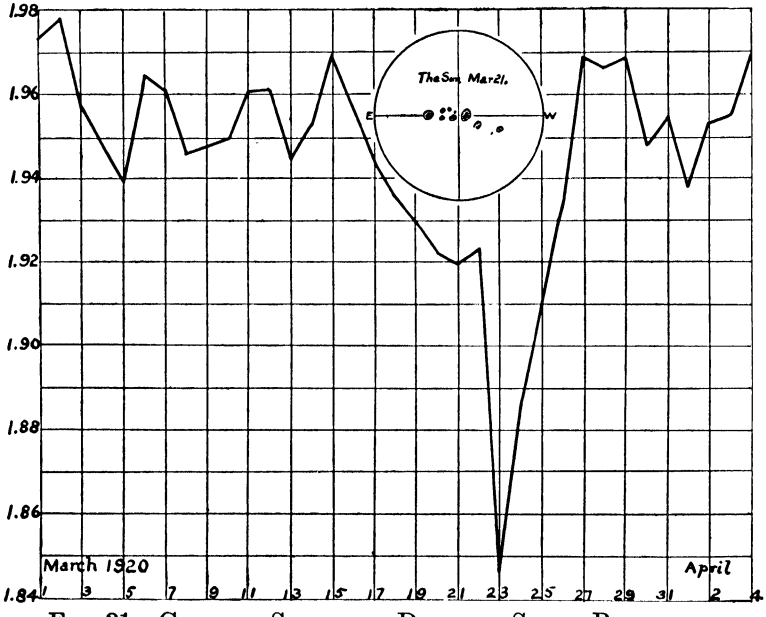


FIG. 31. CENTRAL SUN-SPOTS DIMINISH SOLAR RADIATION.

Note the large variation of solar radiation which attended the great sun-spot group of March, 1920. The minimum was observed just after the sun-spot group became central to our view, as it was carried along by the solar rotation. This sort of phenomenon (though seldom so strongly marked) almost invariably attends the passage of a sun-spot across the sun's disk.

Solar Power Plants. — The sun's rays have a genial warmth, but one is apt to be unprepared for the greatness of their possibilities as a source of power. It is a fact that if the solar heating that can be gathered on a square yard of surface could be transformed

without loss into mechanical work, it would exceed a horsepower. Many inventors have wrestled with the problem, but thus far none appears to have utilized over 3 per cent of available solar energy for mechanical work. This poor efficiency in solar engines increases the surface necessary per horsepower to something like a square of

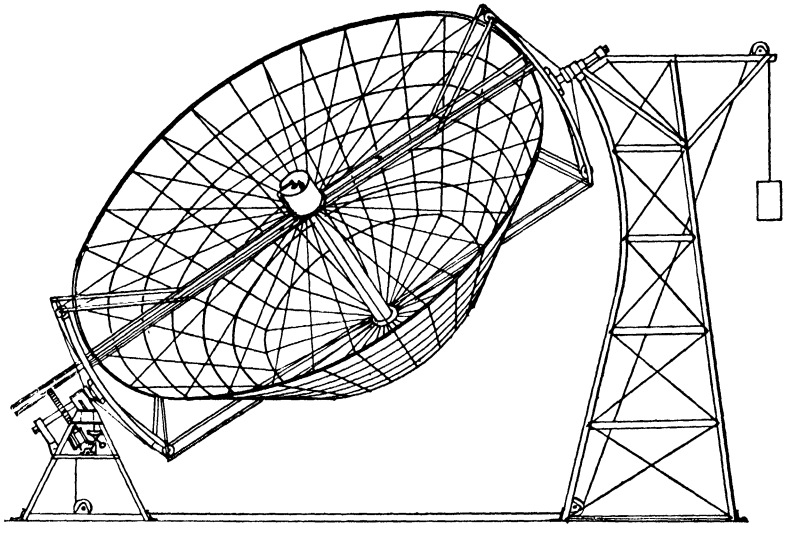


FIG. 32. THE SOLAR ENGINE OF ENEAS.

The great conical reflector concentrated rays upon a boiler connected by pipes to a steam engine. The power thus generated was employed to pump water. (By permission, from "The Sun," D. Appleton & Co.)

15 to 20 feet on a side, and thus the installation becomes both cumbrous and costly.

Three types of solar engines deserve mention. First is the type developed by Mr. A. G. Eneas and used for a time to pump water at the South Pasadena ostrich farm. As shown in the illustration, a great conical mirror concentrates the solar rays upon a tubular boiler which propels a steam engine. The instrument is moved by appropriate mechanism to face the sun all day.

A second type is the Shuman-Boys installation of cylindrical mirrors, shown in Plate 33, used in Egypt just before the world war for irrigation work. As the latitude of the place was small, the mirrors could be placed nearly horizontally. They were rotated so as to focus the sun rays upon a horizontal tubular boiler of rectangular section. Steam was thus raised to drive an engine. In

both the Eneas and the Shuman-Boys installations the boiler tube was protected by glass covers from loss of heat by air currents.

A third type of radically different design was that of Willsie and Boyle, used at Needles, California, about 1908. They employed a shallow pond of water, with blackened bottom and glass cover. The water grew hot, though by no means near boiling, by absorbing the solar rays. Its heat was employed to run a low-pressure engine, actuated by the vapor of sulphur dioxide, which boils at a much lower temperature than water. The efficiency of this device was much lower than that of the others, but by avoiding mirrors and means for turning them to face the sun, the inventors made a compensating saving in expense.

The promoters of both the second and third types of solar engine have claimed to reach the very verge of economical success in competition with coal or oil fuel in these desert localities. Mr.

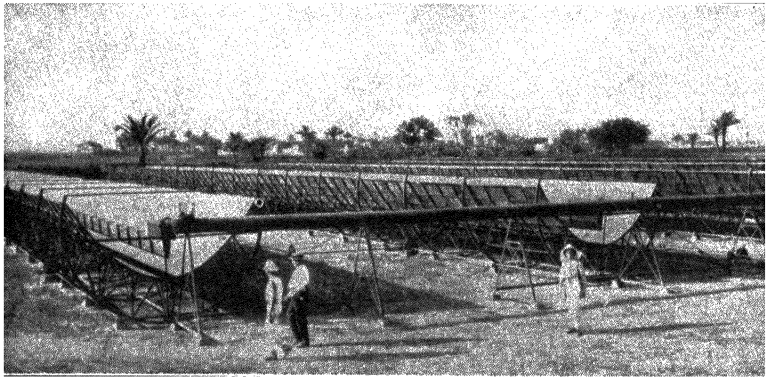


PLATE 33. THE SHUMAN-BOYS SOLAR ENGINE.
The gigantic mirrors here shown were employed in 1913 at Meadi, in Egypt, to collect solar heat for the purpose of driving a steam engine used for pumping water.

Eneas is inclined to think the methods of Willsie and Boyle most promising of any, but regards solar power as yet an unsolved problem.

Solar Cookers. — In another field, the solar heating has been used with partial success, namely that of cooking. There are two types of solar cooker. The simpler direct type was used with good success by Mr. W. Adams in India in the year 1878. He made an eight-sided conical reflector, within which was fixed, inside a glass

jar at the focus, the closed dish containing the food to be prepared. Meat and vegetables could be well cooked in this way within moderate lengths of time. However, cloudiness would stop the process.

The second type, shown in Plate 34, was employed in 1920 at the Smithsonian observing station on Mount Wilson, California. The whole cooking operations of a small family, including baking, boiling, stewing, and preserving, were done regularly with the solar

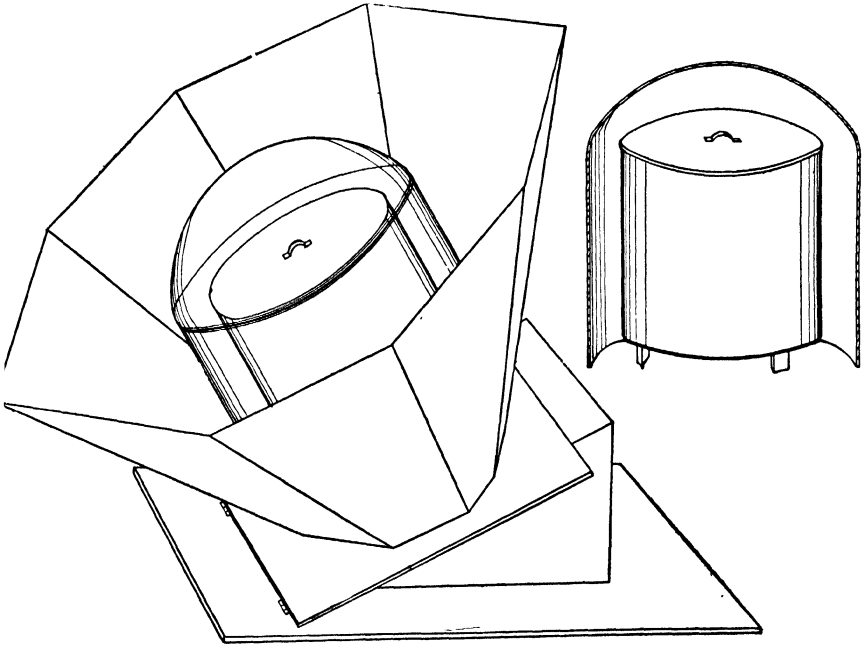


FIG. 33. THE SOLAR COOKER OF ADAMS.

An eight-sided conical wooden structure plated within with mirror glass concentrated the sun's heat upon a cooking utensil enclosed within a glass jar. Thus food was cooked by direct application of sun rays. Clouds, of course, if long continued, stopped the cooking. (By permission, from "The Sun," D. Appleton & Co.)

cooker. A cylindrical mirror focused the sun's rays upon a blackened tube, parallel to the earth's axis and containing engine cylinder oil. A simple clockwork kept the mirror facing the sun all day long. The oil, becoming hot, expanded, and thus maintained a gravity circulation through a reservoir above the level of the mirror. Two ovens inserted in this reservoir were bathed by the hot oil, and reached temperatures high enough to bake bread. Being well protected from losses of heat, the ovens kept hot over night, so that cooking

could go on at any time, despite occasional clouds. This device was interesting and worked well, but was too expensive for general use without modification.

From time to time, estimates are made of the probable duration of our supplies of coal and oil, which are the products of solar

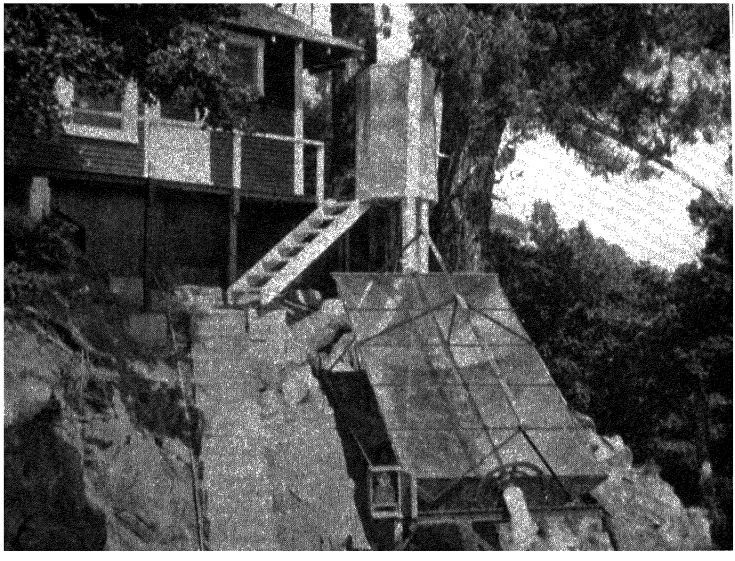


PLATE 34. ABBOT'S SOLAR COOKER.

The great cylindric mirror focuses 90 square feet of sun rays upon a tube $1\frac{1}{4}$ inches in diameter filled with engine cylinder oil. Hot oil rises up into the reservoir above, and cooler oil takes its place. In ovens inserted at the back of the reservoir, bread, meat, vegetables, etc., are well cooked. The ovens remain hot day and night.

rays of former ages. These estimates differ widely, but agree that these limited supplies of fuel will be exhausted within periods of time which are short compared to man's history on the earth. A partial substitute is already available in water power, and possibly the water power may be largely augmented by inventions for utilizing waves or tides. It is well worth while, however, to work earnestly towards the improvement of means for utilizing solar radiation for power purposes. There may be a great need of it sooner than we expect.

Plant Growth. — Sunlight of certain colors enables plants to

seize upon the carbonic acid gas of the air and absorb it through the immensely numerous tiny orifices, called stomata, which throng their leaf surfaces. Within the leaves the carbonic acid gas, in combination with other chemicals supplied through the roots in the sap, is transformed into the complex life-substances. This process, called " photosynthesis " is at the foundation of all life on the earth, for plants feed animals, and plants and animals feed man. The growth of plants requires a certain condition of temperature as well as light. The sun provides both.

Heretofore, these chemical processes which depend on sunlight have not been carried on without the aid of plant-life. It may be possible that laboratory investigation may devise a way to convert radiation into chemical energy without plant aid. If so, it may prove the key to the power sources of the future. At present, the outlook for artificial photosynthesis is not very bright.

While taking in carbonic acid gas, the plants give off oxygen, which is exactly opposite to the life process of animals. These creatures breathe in oxygen, and give out carbonic acid gas as a waste product. Thus, the two great kingdoms of life supplement each other. Some experimenters have utilized the evolution of oxygen to measure the effect of varying conditions on the rate of plant growth. To do this, they employ a water plant called *Elodea canadensis*, and allow its little oxygen bubbles to collect in an inverted tube, as they rise through the water.

The chemistry of plant growth is obscure. It seems to depend on the green coloring matter of the leaves which is called " chlorophyll." Yet artificial chlorophyll-bearing cells will not carry on carbon assimilation. Among the principal products of the plant's laboratory is glucose or starch. The rate of plant assimilation of carbon varies with temperature, with intensity of sunlight, and with concentration of carbonic acid gas in the air. The temperatures best fitted to promote growth vary considerably with different plants. This leads to the interesting diversification of plants over the earth's zones. But temperatures below 0° or above 50° Centigrade are highly unfavorable. As this range is but a sixth of the mean absolute temperature of the earth's surface, we easily see how necessary for life it is that the sun's radiation, on which the earth's temperature depends, should not change very widely. Geologists are of the opinion that it is fully a billion years that life

has gone on upon the earth. This shows how very long the sun must have maintained nearly its present supply of radiation.

Plants grow more and more luxuriantly under increased concentrations of carbonic acid gas, up to at least ten times the present proportions. Possibly those luxuriant jungles of the geological periods to which we owe our coal may have flourished during enrichment of the carbon contents of the air.

As for solar radiation, much investigation is needed on its relation to plant growth. Neither the actual wave-lengths nor the exact intensities most favorable to plants have been as fully determined as they should be in such fundamental matters. It is known, to be sure, that violet and red lights are useful, and green light useless, to promote carbon assimilation.

With deficient light, plants shoot up very tall. We see this illustrated by potato vines, by thick-growing forest trees, and by the vines which trail from the tree-tops of the dark jungles of the tropics. Curiously enough, red light, though effective to promote growth, acts also like darkness, for it has the tendency to cause excessive increase of stature in plants.

It has been proposed by some to employ plants as solar energy accumulators. For instance, they say, plants may be grown on waste land, their products may be distilled into alcohol and other chemicals, and these will store up the energy indefinitely in a highly concentrated form. While this is so, such quantitative investigations as have been made along this line are not encouraging. The cost is out of proportion to the result, and the available lands inadequate to satisfy large demands.

The efficiency of plants in the conversion of solar radiation into chemical energy has been roughly determined by several investigators. Their results differ widely, but seldom indicate values of the efficiency above 1.5 per cent. These rest on measures of actual leaf area. Inasmuch as plants do not fully occupy their ground, such values show maximum rather than average efficiencies.

There is, perhaps, no field where investigation is more needed, or more apt to produce useful results for mankind than that which is the subject of this chapter. Efficient devices for converting the energy of solar radiation into mechanical work, whether by heat engines or chemical or electrical means, would be a boon indeed. One can imagine a great shifting of population when the deserts,

PLATE 35, FIG. 1.

The Klondike Cosmos is a typical "short-day plant." The specimens on the right, exposed to full length Washington summer days were unable to flower. The specimen on the left, exposed to an 8-hour day, flowered at a height of a few inches.

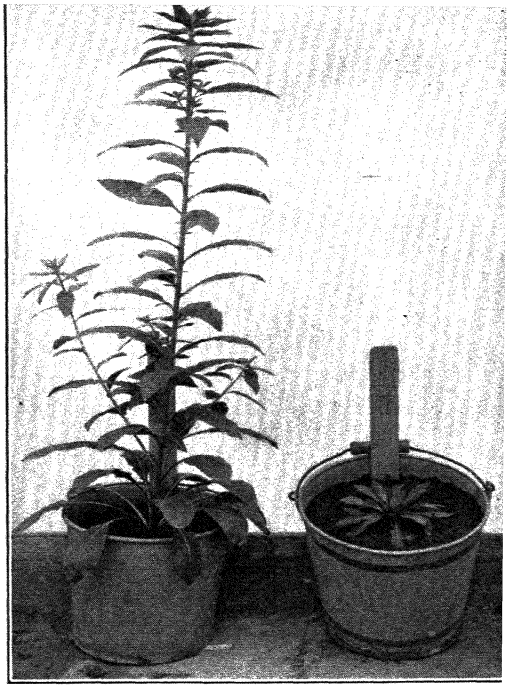


PLATE 35, FIG. 2.

The Evening Primrose is a typical "long-day plant." The specimen on the right, exposed to a 10-hour day, is unable to develop flowering stems. That on the left, exposed to the full length of a Washington summer day, is nearly ready to flower.

(Both figures from experiments of Garner, U. S. Department of Agriculture.)

where the sun shines almost continuously, become the power centers of the world. Hardly less fascinating is the possibility of new varieties and increased yields of useful plants, which may come from accurate knowledge of the relations of solar radiation to growth in plants.

CHAPTER XII

THE CONSTELLATIONS, STAR CHARTS AND CATALOGUES

Let us now leave the solar system and launch far out into the great universe. To the naked eye it is just an unorganized assemblage of big stars and little ones lying in all directions from the sun. City dwellers, among their gleaming lights, hardly even see the stars. Probably few of them realize that they rise and set like the sun. The Milky Way, which is the most outstanding feature of the whole celestial system, is unknown to a majority, perhaps, of our people.

All is changed as one seeks some open country-place with wide horizon on a crisp, clear, moonless night. The stars stand out like jewels, and among them stretches, like the rim of a gigantic wheel, the Milky Way, or " Galaxy," encircling the whole earth. From our earliest childhood we have been taught to believe that the terms " numberless as the sands of the seashore," and " countless as the stars " refer to numbers so great that it would be impossible to enumerate each individual object. The stars visible to the eye without telescopic aid are certainly not " countless " since all of the stars in the sky, from north pole to south pole of the heavens, altogether make up less than 6000 individual objects. One glances at the Milky Way and wonders what kind of a faintly glowing cloudy creation it may be, until he looks again with a small telescope, and lo! the gauzy cloud becomes a perfect host of stars, compared to which all other parts of the heavens look bare and deserted. It dominates the field of stars so masterfully, that astronomers often speak of the whole system of them, centering about the Milky Way, as the Galaxy.

The Constellations. — Long, long ago, the stars were grouped in constellations. It is hard to see why they are named, or separated by boundaries as they are drawn. A few of them, like Gemini, the Twins, Scorpio, the Scorpion, and Corona Borealis, the Northern Crown, really suggest their names by their configurations. Most of them, however, are like the rose which " by any

other name would smell as sweet," or like the child who was called John but might as well have been Samuel.

Nevertheless, some of the names are associated with fine old myths that deserve to be retold. The Queen of Ethiopia, Cassiopeia, and her husband, King Cepheus, had a daughter called Andromeda. Queen Cassiopeia boasted that she was as beautiful as the Nereids, and thereby provoked the vengeance of Poseidon. He sent a flood and a sea-monster who slew both man and beast. In this distress, the oracle of Ammon was consulted, and it gave the intelligence that the calamity could be removed only by exposing the King's daughter to the monster. Accordingly, Andromeda was chained to a rock on the shore.

Perseus, the hero, son of Danae and Zeus, returning from slaying the Gorgon Medusa, whose horrid head he carried in his wallet, found Andromeda, slew the monster, and released her. He married Andromeda in spite of Phineas to whom she had been promised. In a quarrel at their wedding, one glance at the Gorgon's head turned Phineas to stone. The pair returned to the native land of Perseus, where, after other adventures in which the Gorgon's head proved a highly useful weapon, they were the ancestors of the Perseidæ. Many other variations and additions to this famous old story may be found in books of mythology.

The four northern constellations of Cepheus, Cassiopeia, Perseus, and Andromeda, lie adjacently. Nearly everybody knows the Great Dipper in Ursa Major, the Great Bear. The two Pointers in the bowl of the Dipper show us the pole star in Ursa Minor, the Little Bear. If one carries the line of the Pointers just about as far on the other side of the pole, he comes to the two brightest stars of Cassiopeia. The configuration most conspicuously showing is called Cassiopeia's Chair. It also resembles a great capital W, if we omit one of the fainter stars which completes the chair-seat. Cassiopeia sits with her feet towards the bright star Arcturus.

Going on beyond Cassiopeia another length of the line from the Pointers to the pole star, we find Andromeda, whose brightest star forms one corner of the Great Square of Pegasus. From this brightest star we follow eastward in a circle round the pole to the other stars of Andromeda. The four principal ones form a line nearly as long as our measuring space, the polar distance of the

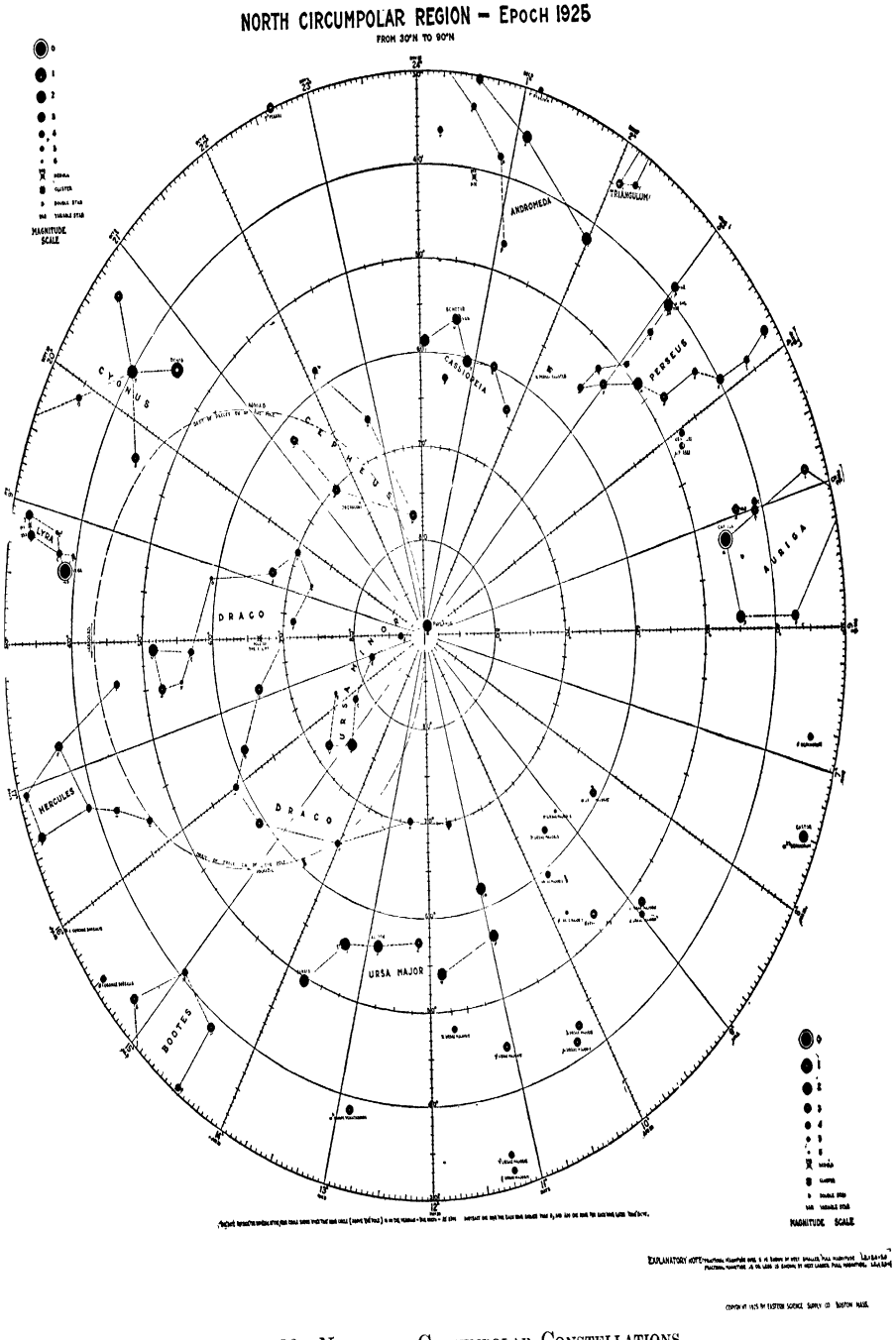


PLATE 36. NORTHERN CIRCUMPOLAR CONSTELLATIONS.

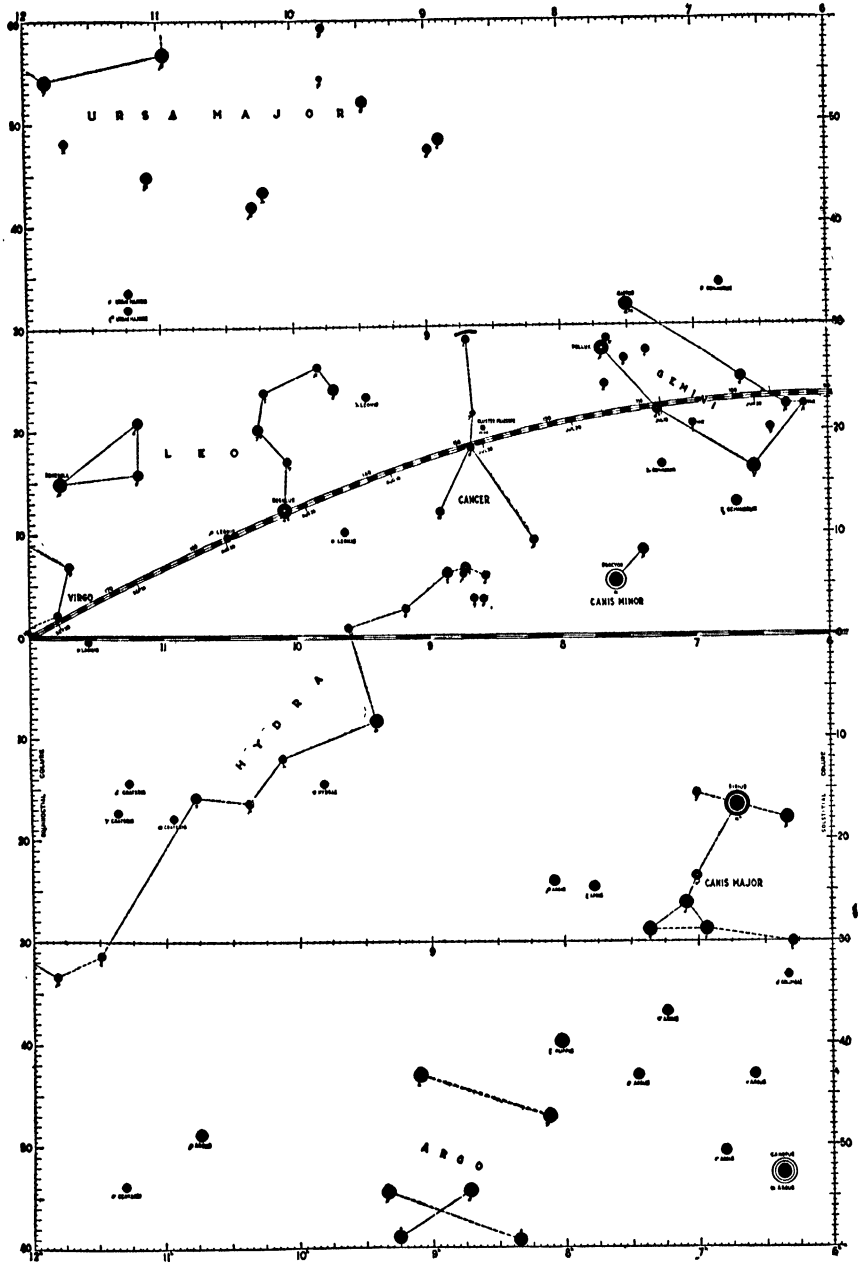


PLATE 37. EQUATORIAL CONSTELLATIONS, 6^h to 12^h.

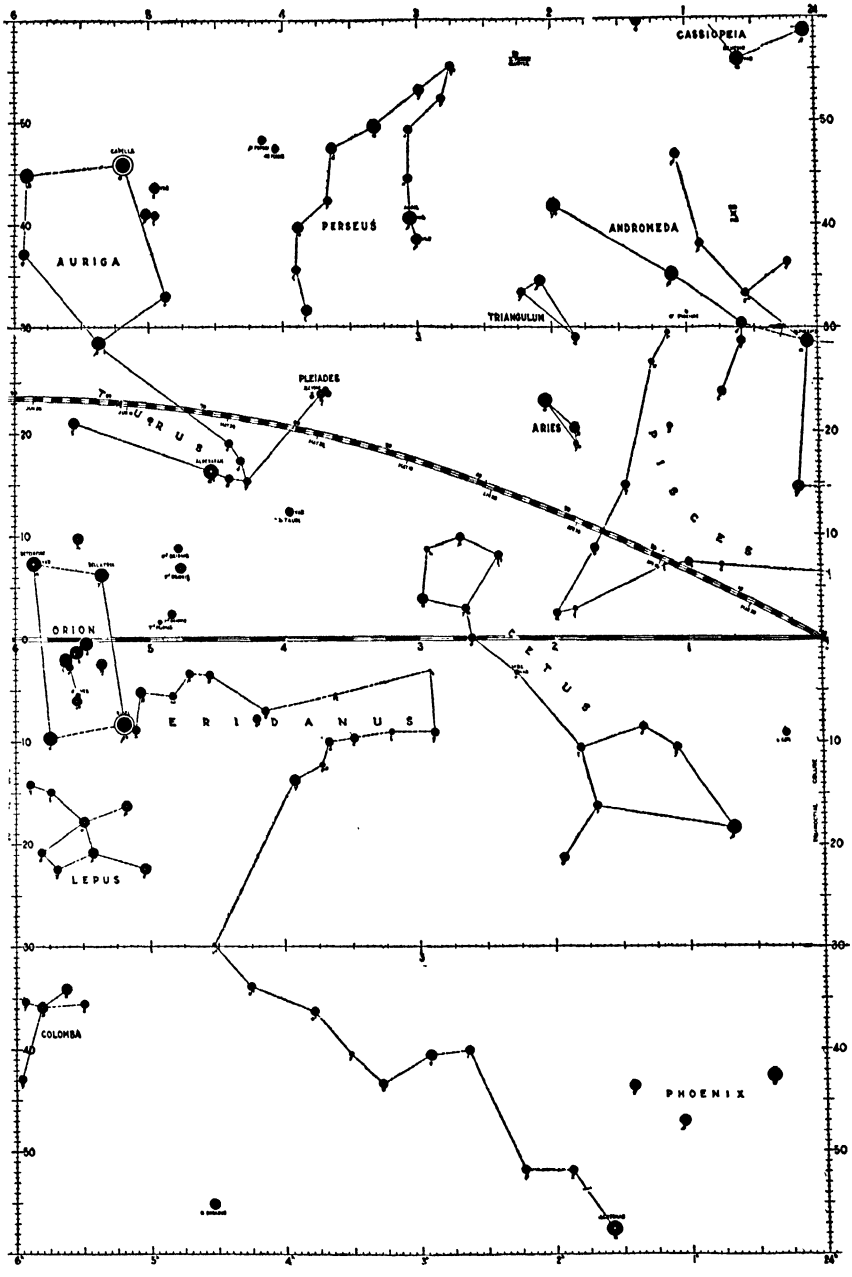


PLATE 38. EQUATORIAL CONSTELLATIONS, 0^h to 6^h.

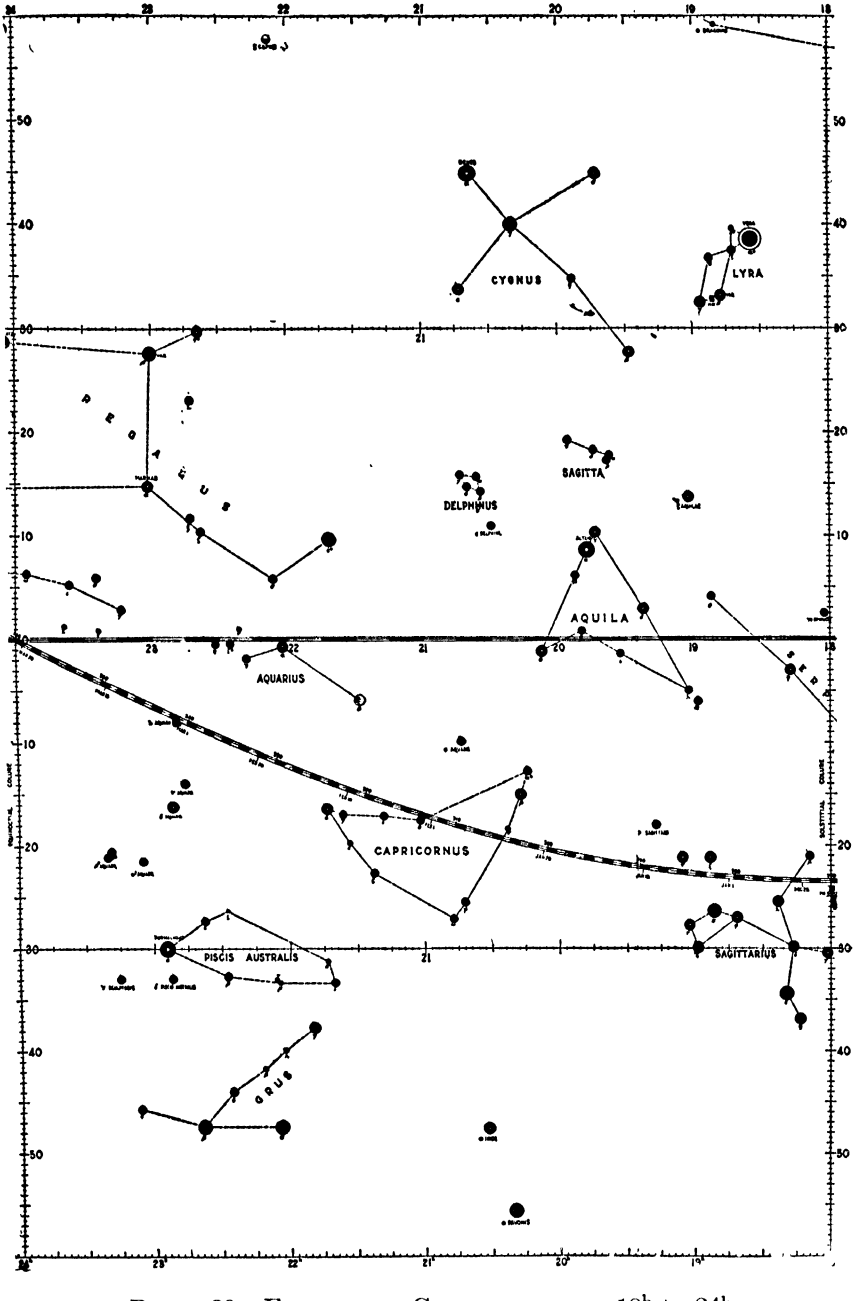


PLATE 39. EQUATORIAL CONSTELLATIONS, 18^h to 24^h.

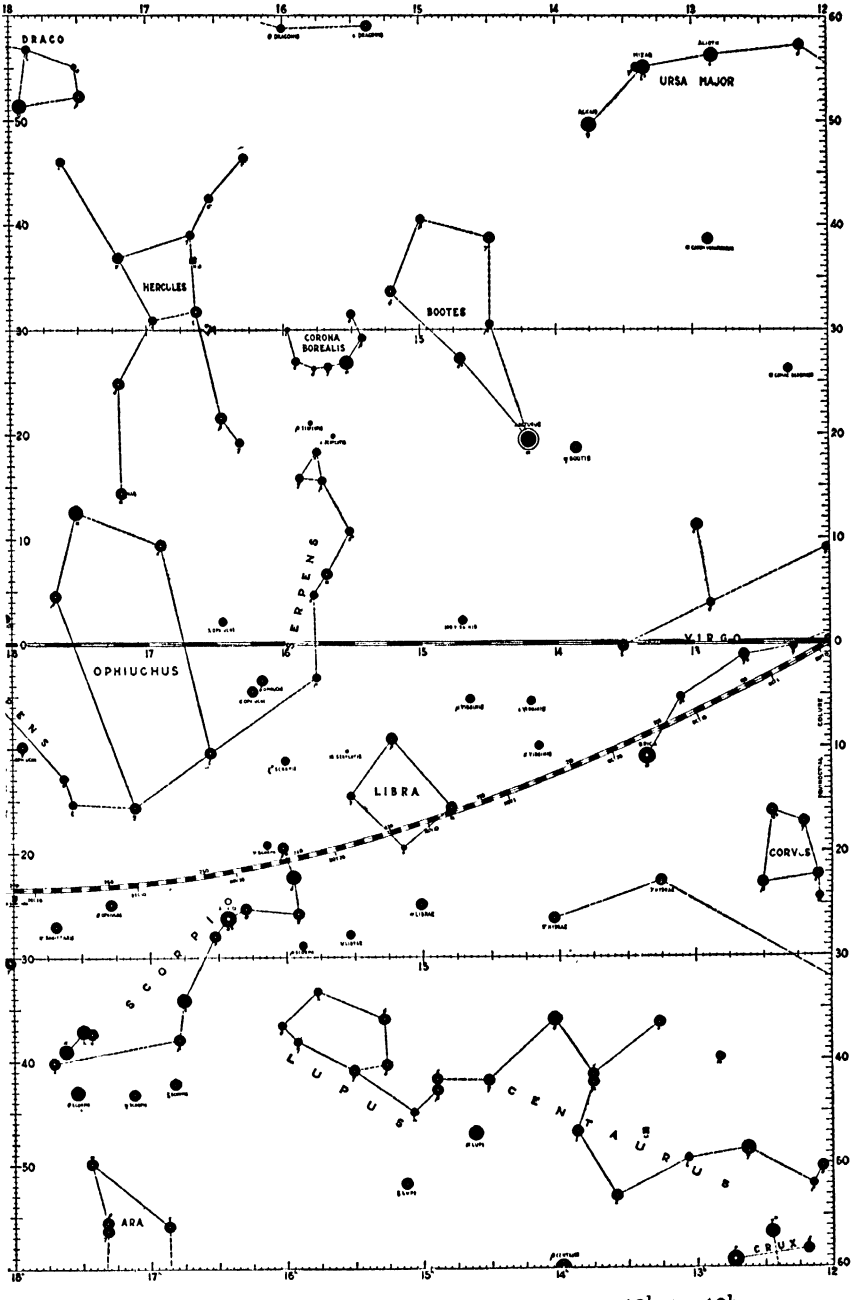


PLATE 40. EQUATORIAL CONSTELLATIONS, 12^h to 18^h

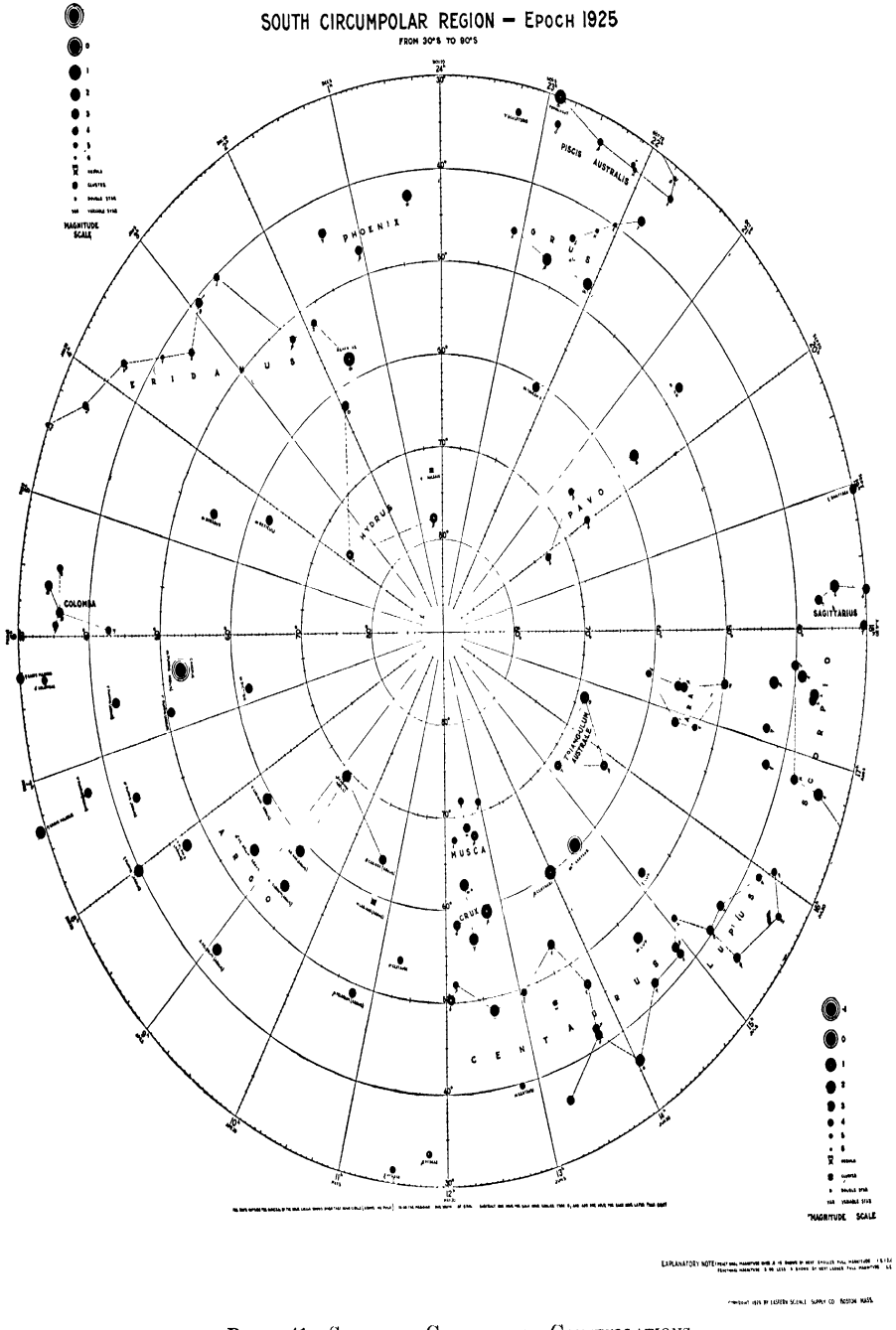


PLATE 41. SOUTHERN CIRCUMPOLAR CONSTELLATIONS.

Pointers. Still another length of it beyond, towards the east, and we arrive at the constellation Perseus. Its principal stars, seven in number, point roughly towards Cassiopeia, though straggling into several branches. What fixes Perseus more distinctly is that it lies about half-way between the eastern end of Andromeda and the brilliant star Capella in the constellation Auriga, the Charioteer.

The constellation Cepheus is not so conspicuous as the other three whose story we have joined with his. Cepheus lies a little west of a line from Andromeda to the pole, and a little nearer the pole than Cassiopeia. It has six principal stars.

Right across the pole from Capella, and about equally distant from it, we pass to Vega, that beautiful white star nearly overhead in the early evening in Autumn. Just west of Vega is a straggling collection of stars, of which eight are fairly bright. This is the constellation Hercules, named after the Latin form of Heracles, the great national hero of the Greeks. He led a very active life on account of the persecutions of Hera, Queen of the Olympian gods, the sister and wife of Zeus.

Hercules was related to Perseus both through his mother Alcmena, a Perseid, and his father Zeus, who appears to have been father to almost every hero in Greek mythology. Hera began her tricks even before his birth by causing Eurystheus to be born before him, so that Hercules should not rule the realm of Perseus. After killing his teacher of music, he had various adventures in exile. After his marriage and his killing of his own children in a frenzy induced by Hera, he was forced in expiation to serve Eurystheus, and began the celebrated twelve labors of Hercules. These were: (1) Wrestling with the Nemean lion. (2) Killing of the Lernean hydra. (3) Capture of the Arcadian hind. (4) Capture of the boar of Erymanthus. (5) Cleansing the Augean stables. (6) Shooting the Stymphalian birds. (7) Capture of the Cretan bull. (8) Capture of the man-eating mares. (9) Seizure of the girdle of Hippolyte, Queen of the Amazons. (10) Bringing off the oxen of Geryones, during which adventure he set up the "Pillars of Hercules" at the Strait of Gibraltar. (11) Bringing the golden apples from the garden of the Hesperides. (12) Conveying Cerberus from Hades to the upper world.

After accomplishing these feats, all of which led him into extra

adventures, Hercules engaged in a variety of extraordinary affairs, helped the gods in war, destroyed sea-monsters, set bound Prometheus free, wrestled with Antaeus, son of Poseidon and Ge (Earth), who had to be uplifted into the air to overcome him, because every time he touched mother earth he became stronger. We cannot even mention all of the encounters of Hercules, and must refer our readers to Greek mythology. Evidently he well deserves a constellation.

West of the constellation Hercules is the lovely Corona Borealis, or Northern Crown, and beyond that Boötes, the Ploughman, with its splendid reddish star Arcturus. Immediately south of Hercules are the two constellations Serpens, the serpent, and Serpentarius or Ophiuchus, the serpent-holder. To the east of Ophiuchus is Aquila, the Eagle, with its brilliant white star Altair, and north of Aquila and west of Hercules lies Cygnus, the Swan.

The remaining big northern constellation is Pegasus, the Winged Horse, which adjoins Andromeda lying east of Aquila. It is easily marked by what is called the Great Square of Pegasus, four fairly bright stars, not exactly forming a square, the northeastern one of which is Alpha Andromedæ. Pegasus, in mythology, was a very remarkable horse. He sprang from the trunk of the Gorgon Medusa after Perseus cut off her head. Bellerophon caught him as he drank of the spring Peirene, and mounted on Pegasus killed the Chimæra, and overcame the Solymi and the Amazons. Overconfident, Bellerophon tried to fly to heaven, but Pegasus threw him off and continued on riderless. In heaven, Pegasus served Zeus, fetching him his lightning and his thunder. When Mount Helicon, under enchantment by the song of the Muses, began to float towards heaven, Pegasus prevented it by stamping on the ground. The fountain of the Muses, Hippochrene, gushed out where his hoof fell. On account of his connection in this way with the Muses, Pegasus is referred to frequently in literature by authors who speak in a flowery way of " my Pegasus," meaning the inspiration of their writings.

Omitting mention of several minor northern constellations, and passing over the twelve signs of the Zodiac for the moment, let us now see about some of the mythological characters celebrated in the southern heavens. Foremost from every point of view is Orion. He was a mighty hunter of surpassing beauty and enor-

mous strength, son of Hyrieus or of Poseidon. Eos, the dawn-goddess, loved him, and carried him away to Delos. The gods were angry, and Artemis killed him with her arrows. In the lower world, Odysseus saw his shade driving the wild beasts in the hunt as he had done on earth. After death he was changed into the famous constellation, the grandest of the entire heavens. At its northern end is Betelgeuse, the red giant star, and at its southern end Rigel, the splendid blue one. Midway lie the belt and sword stars, themselves glorious in almost any company except that of Betelgeuse and Rigel.

To the east of Orion lie the two dogs, Canis Major with its wonderful star Sirius, brightest of the entire heavens, and farther north, Canis Minor, with Procyon. The great constellation Argo Navis, the Ship of the famous Argonauts of Greek mythology who sailed for The Golden Fleece, stretches east and south from Canis Major, well on towards the southern pole. Its brightest star, Canopus, second only to Sirius, lies just half way between Sirius and the south pole.

Beyond Argo Navis, the Ship, lies the famous constellation Southern Cross, disappointing perhaps from the unequal brightness of its four principal stars and the lack of one at the center, but yet very apt to bring a lump to the throat when one sees it after long absence, and remembers for what it stands. Half surrounding the Cross, and lying north of it, is Centaurus, the Centaur, with its two splendid stars Alpha and Beta Centauri, of which the first is our sun's nearest stellar neighbor.

In the Greek mythology, the Centaurs were half man and half horse, and not very highly recommended for their moral character. They attempted to carry off the bride Deidameia on the day of her marriage to Peirithous; but Theseus, who happened to be there, helped Peirithous to drive them off. They drew the car of Dionysus and carried Eros in some of his escapades.

North of Argo and east of Canis Minor is the long-stretching constellation Hydra, the Watersnake. This gigantic monster was the offspring of Typhon and Echidna, and possessed nine heads, of which the central one was immortal. Hercules slew the Hydra with the help of Iolus, as one of his twelve famous labors. As they cut off one head two grew in its place, but at length they burned out the roots with firebrands, and having cut off the immortal head,

buried it under a monstrous rock. Arrows dipped in the blood of the Hydra served Hercules for fatal weapons.

West and south of Orion is another very extended constellation called Eridanus, or the River. It ends not very far from the south pole in the bright star Achernar, or Alpha Eridani. North of Eridanus is Cetus, the Whale, which contains Mira, a noted star of irregularly varying brightness. There are quite a number of other smaller southern constellations, which we need not speak of individually here.

There remain the twelve well-known constellations called the Signs of the Zodiac; Aries, the Ram; Taurus, the Bull; Gemini, the Twins; Cancer, the Crab; Leo, the Lion; Virgo, the Virgin; Libra, the Balance; Scorpio, the Scorpion; Sagittarius, the Archer; Capricornus, the Goat; Aquarius, the Water-bearer; Pisces, the Fishes.

Polaris, little more than a degree from the pole, is Alpha Ursæ Minoris. A small telescope shows it double, and the brighter of its pair of stars is known by aid of the spectroscope to be triple. The telescope cannot show this. The brightest of the spectroscopically triple stars is a variable star of four days period. It is of the so-called Cepheid type which we shall explain in a later chapter.

In Ursa Major is the Great Dipper. The two stars at the end of the bowl are the Pointers which find for us Polaris. The star at the bend of the Dipper handle is Mizar, easily seen to have a smaller star, Alcor, close by. But Mizar itself is triple.

East of Ursa Major are two little constellations, Canes Venatici and Coma Berenices. In Canes Venatici is a wonderful spiral nebula. Coma Berenices, "The Hair of Berenice," is named for the great cluster of faint naked eye stars, which fancifully represent beautiful tresses.

In Boötes, east of these, the finest object is Arcturus, or Alpha Boötis. North of it lies a kite-shaped figure of five stars, the southern of which is the fine double, Epsilon Boötis.

Passing by the beautiful Corona Borealis, we come to Hercules. Its brightest star, Alpha Herculis, is a very red double of irregular variability. Though not very bright, Alpha Herculis gives us a great deal more heat than white stars much brighter. The constellation has several other double stars, but its greatest feature is the "Great Cluster in Hercules." This is a swarm of stars, shown

PLATE 42. THE GREAT STAR CLUSTER IN HERCULES. (Mt. Wilson Observatory.)

Over 50,000 stars have been counted in this cluster, but its distance is so great that doubtless many times this number exist there invisibly.

in Plate 42 which are very faint on account of their immense distance, though really very bright. There are perhaps millions of stars in this one cluster.

East of Hercules is Lyra, whose bright gem is Vega, or Alpha Lyræ. Our sun is travelling at 12 miles a second nearly towards Vega. Just east of Vega lie two little stars, Epsilon and Zeta Lyræ, which form with Vega a shapely little triangle. If one has sharp eyes, he can see Epsilon, the more northern of them, double. To a large telescope, each of the two visible stars in Epsilon Lyræ is also double. Zeta Lyræ is also a double star. A short distance south of them is Beta Lyræ, a double star whose components, revolving, partially hide each other alternately. Thus it is an eclipsing variable of about 13 days period. Southeast of Beta lies the famous "Ring Nebula in Lyra."

The principal stars of the constellation Cygnus, next east of Lyra, form what is sometimes called the Northern Cross. Its stars are not as bright as the finest ones of the Southern Cross, though in form the Northern Cross is perhaps superior. Yet Deneb at the head of the Cross, is very conspicuous. Albireo, at the foot, is a very fine double star for small telescopes. Southeast of Deneb is 61 Cygni, the first star whose distance was measured by Bessel, and one of the nearest stars to us. It is the western one of three little stars near together which form a nearly equal-sided triangle. The Milky Way is divided in Cygnus. It has some very interesting dark holes and rifts. There is also a very extensive nebula, shown in Plate 43, which in photographs appears much like a streaky, fine-spun, cirrus cloud.

East of Cygnus, in Cepheus, are some remarkable variable stars. Delta Cephei is the typical one. These stars are very massive, very blue, and vary regularly in periods of a few days. It is supposed that, like the heart, they are pulsating, and that this is the cause of their variation. Beyond Cepheus is Cassiopeia, in which constellation appeared, in 1582, Tycho Brahe's wonderful New Star, which for a time was brighter even than the planets.

Southeast of Cassiopeia lies brilliant Capella or Alpha Aurigae, a star called sometimes "the Goat." A little southwest of it lie three small stars called "The Kids." Capella is a spectroscopic double.

West of Auriga lies Perseus, from which direction come the

August meteors. In February, 1901, the brilliant new star, Nova Persei, for a few days rivalled the brightest stars of the heavens. A still more famous star is Beta Persei, or Algol, an eclipsing variable of three-days period.

West of Perseus, we find Andromeda, from whose direction come some of the November meteors. The Spiral Nebula of Andromeda is its greatest feature. Gamma Andromeda is a fine double. Next to the west comes Pegasus, notable for the Great Square, of which the northeast star is Alpha Andromeda. The northwest one of the square, Beta Pegasi, is very red, and, like Alpha Herculis, sends more heat to us than many brighter stars.

Much farther west is brilliant Altair, or Alpha Aquilæ, lying in the Milky Way. A few degrees west of Altair is Nova Aquilæ of June, 1918, which for a time outshone all the stars except Sirius.

We now turn to the Zodiacal constellations, beginning with Taurus, which contains the Pleiades and Hyades, and the fine bright-red star Aldebaran. It is very easy to find in the autumn and winter months, lying much south and a little east of Capella. The Pleiades, or "Seven Sisters," for most eyes are but six, forming a configuration like a little dipper. Carefully looking, we may see the seventh, Pleione, near the star at the end of the handle. Photographs show the stars of the Pleiades wrapped in nebulosity. The Hyades is the great V-shaped figure lying east of the Pleiades, and with Aldebaran near its point. The Hyades and the Pleiades are each really open clusters of stars having common motions in space.

Next east is Gemini, whose bright stars, Alpha and Beta, are named Castor and Pollux after the twin brothers of Helen of Troy. They went with the Argonauts for the Golden Fleece. On the return voyage there was a great storm, which immediately became calm when Orpheus, aided by Apollo, caused the two stars to shine above the heads of the twins. So Castor and Pollux became sailors' deities. As Castor is now fainter than Pollux, it seems likely that there has been a change of their relative brightness since the days of the ancients, who made Castor Alpha Geminorum. It is a double star, and each of its companions is also double.

The faint constellation of Cancer, the Crab, has within it the open cluster of Praesepe. Beyond Cancer is Leo, the Lion, whose gem is the fine star Regulus at the end of the handle of the "Sickle."

From the direction of Leo come November meteors. East of Leo comes Virgo, the Virgin, with the splendid star Spica. In Virgo are many spiral nebulæ, not visible except with great telescopes. At present, the autumnal equinox lies in Virgo. Libra, the Balance, contains no very remarkable objects.

Next comes Scorpio with the great red star Antares. There is a little companion to Antares which may be seen with a moderate-sized telescope. The Milky Way is very bright in Scorpio, and there have been several " new stars " in this region. Sagittarius, the Archer, also lies in the Milky Way, which has its most splendid and interesting region here. There are in its brightest parts great dark lanes and patches devoid even of little stars. They probably indicate dark nebulous matter nearer to us than the stars behind.

The constellation Capricornus is not very remarkable, though its brightest star Alpha is a naked-eye double. Aquarius, too, offers little of interest, and Pisces, also, is inconspicuous, but includes the present location of the vernal equinox. Finally, we come to Aries which was once the constellation of the vernal equinox, but now contains little remarkable.

Of the southern constellations, Orion is easily the most wonderful. The giant red variable star Betelgeuse, over 250,000,000 miles in diameter, is Alpha Orionis, but Rigel, Beta Orionis, is probably six times as hot, and so are the fine stars in Orion's belt. The central star of the sword, Theta Orionis, lies in the midst of the Great Nebula of Orion, and is really a multiple star of six companions. The whole constellation is enwrapped by nebulosity.

In Cetus, the Whale, is the star Omicron Ceti, or Mira, " the wonderful," which varies through a great range every eleven months. The cause of its variation is unknown. Each of the three little constellations, Dorado, Hydrus, and Tucana, which lie near the south pole, offers something interesting. In Dorado is the Greater Magellanic cloud, and in Hydrus, the Lesser. These luminous clouds of distant stars are like strayed bits of the Milky Way, but are in no sense a part of it. Tucana presents to us the fine globular star-cluster " 47 Tucanæ."

Canis Major, with Sirius our brightest star, and Canis Minor with Procyon, are both sufficiently striking. Each of these two surpassing brilliants is a double star to the largest telescopes. The great constellation Argo Navis presents our second brightest star,

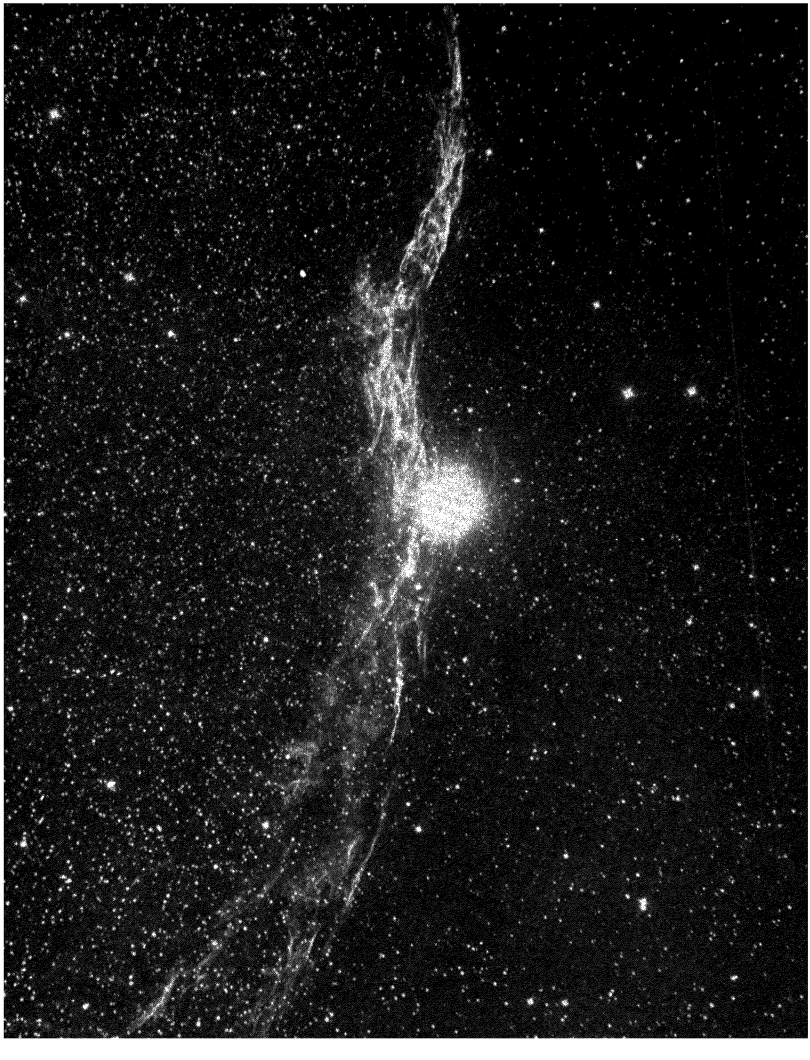


PLATE 43. THE VEIL NEBULA IN CYGNUS. (Mt. Wilson Observatory.)

Notice how few of the stars are on one side of the nebula compared to the other. Probably there is obscuring matter lying between us and the stars on the leaner side. A meteor trail appears on the photograph.

Canopus, and also the extraordinary red variable, Eta Argus. Within the past century, this star has sometimes been almost as bright as Sirius for years, though now it is beyond the range of the unaided eye. Adjacent to this star is the curious Keyhole Nebula. Near Eta Argus is the Southern Cross, whose brightest star, Alpha Crucis, is double. Surrounding the Cross is Centaurus with its splendid pair, Alpha and Beta Centauri.

The reader may locate the various interesting objects we have mentioned by consulting the accompanying charts. Below is given a list of the constellations, arranged in each group alphabetically. It includes many smaller ones which we have not thought necessary to speak of because they lack interesting features.

Northern (28)

Names of the Constellations. — Andromeda, Aquila, Auriga, Boötes, Camelopardus, Canes venatici, Cassiopeia, Cepheus, Coma Berenices, Corona borealis, Cygnus, Delphinus, Draco, Equuleus, Hercules, Lacerta, Leo minor, Lynx, Lyra, Ophiuchus or Serpentarius, Pegasus, Perseus, Sagitta, Serpens, Triangulum, Ursa major, Ursa minor, Vulpecula et Anser.

Zodiacal (12)

Aquarius, Aries, Cancer, Capricornus, Gemini, Leo, Libra, Pisces, Sagittarius, Scorpio, Taurus, Virgo.

Southern (49)

Antlia, Apus, Ara, Argo, Caela sculptoris, Canis major, Canis minor, Carina, Centaurus, Cetus, Chameleon, Circinus, Columba Noachi, Corona australis, Corvus, Crater, Crux, Dorado, Eridanus, Fornax chemica, Grus, Horologium, Hydra, Hydrus, Indus, Lepus, Lupus, Malus, Mons Mensæ, Microscopium, Monoceros, Musca australis, Norma, Octans, Orion, Pavo, Phoenix, Pictor, Piscis australis, Puppis, Recticulum, Sculptor, Scutum Sobieskii, Sextans, Telescopium, Tucana, Triangulum australe, Vela, Volans.

Designation of Bright Stars. — The borders of the constellations are defined arbitrarily in accordance with ancient custom. Within them the stars have received letters of the Greek alphabet, which generally run in the order of brightness, although there are a good many exceptions. Many of the stars named Alpha or Beta, and some fainter ones also, have special names, as, for instance,

Alpha Lyræ is Vega, Beta Orionis is Rigel, Omicron Ceti is Mira. Modern telescopes have revealed so many stars that Greek letters fail to suffice, and so the Arabic numerals have been added in many cases. Besides this expedient, one still more generally used is to give a star the number which it has in a certain star catalogue, as "Boss 3972" and the like. In star catalogues it is almost universal to arrange the stars in the order of increasing right ascension.

Star Catalogues. — The astronomer keeps track of the positions of the stars by means of the coördinates *right ascension* and *declination*. Observations are made for the determination of star places by a *meridian circle* and a refined clock keeping sidereal time. When the mean positions for the stars for the beginning of some given year are arranged in order of increasing right ascension, we then have a star catalogue. There are many catalogues and they are of many different types. Some of them give the positions of a great number of stars but with no high degree of precision. Such is the catalogue of Argelander listing 324,000 stars of the northern heavens as of date 1855.0. Then there are catalogues of great precision giving the positions of fewer stars, such as the catalogues from the Greenwich Observatory.

Star Charts. — For the purpose of identifying a star in the telescope, charts are of much greater use than star catalogues. Before the advent of photography, star charts were made by observing in a comparatively small telescope the relative positions of the stars. The most widely used star charts are known as the *Bonn Durchmusterung* from the observations of Argelander noted above. Similar charts have been made for the southern skies.

Nowadays by photography a permanent record of relative star positions is readily obtained. The positions of the stars may be measured from the photographic plates, thus giving a star catalogue. By an increase of exposure it is possible by photography to obtain a record of stars entirely invisible to the eye, even when the eye is aided by the most powerful telescope in existence. Forty years ago, a plan was inaugurated of photographing the whole sky by international coöperation with cameras known as *astrographic* telescopes. The scale of the photographs was such that one minute of arc was equal to one millimeter. The combined work, called the *Carte du Ciel*, is not yet completed.

Each star-place gives the position of the star *at the time* that the observation was made, each photograph portrays the relative positions of all the stars on a certain plate at the instant when the photograph was exposed. By comparing the star-places from observations made in different years, either from visual or photographic observations, it is possible to ascertain that the stars are not absolutely fixed but betray relative angular motions.

Proper Motions. — The change in the position of the star projected on the celestial sphere is called its proper motion. This quantity is usually measured in units of seconds of arc per year (or per century, if the motion is small.) To obtain proper motions with precision, it is necessary: (1) that the observations be as accurate and as numerous as possible, and (2) that the interval of time between the observations be as long as possible.

Proper Motions from Catalogues. — If we compare the catalogue position of a star, that is, its right ascension and declination, from observations made today with similar observations made a hundred years ago, we shall find that the right ascensions and declinations are vastly different. The chief causes of the difference are *precession and nutation.* On account of the shift in direction of the earth's axis, the fundamental plane in the sky, the *celestial equator,* shifts it position, and thus produces a change in right ascensions and declinations. These large apparent motions do not imply a real angular displacement of the star with reference to its neighbors. It is only after allowing for changes due to precession and nutation, and also for aberration, by methods thoroughly well known, that the actual angular shift in the star's position is ascertained. If, after eliminating precession and nutation, the positions from two catalogues are compared, and if we divide the total remaining change in position by the number of years of interval, we find the annual change in position, or proper motion. If many catalogues are used, with observations made at different times, we can then utilize the method of least squares to determine the most probable values of the annual proper motions in right ascension and declination, and can also fix the coördinates of the star for some fundamental or standard epoch.

The best definitive catalogue is the *Preliminary General Catalogue* of Lewis Boss, which gives the coördinates and proper motions of 6188 stars. The positions of these stars are derived from

a thorough study of observations stretching over an interval of nearly 150 years.

Proper Motions from Photographs. — By comparing two photographs of a region in the sky *made by the same telescope*, but at different times, the change in positions of the stars in the interval may be ascertained, and consequently the annual change. Precession, nutation and aberration are in this comparison eliminated, since all of the stars on one photographic plate are affected thereby alike, so that these influences do not alter the relative places of the stars. Thus we may confine our attention to the *differences* between the two photographic plates. These differences are obtained in either of two ways. First, the positions of the stars on each plate may be measured separately, and the changes in the positions found by taking differences, after allowing for certain quantities, well-known to every photographic astronomer. Second, the differences between the two photographs may be measured by the use of a special instrument called a *blink-microscope*. The two plates are mounted side by side. By means of an optical train, it is possible to look in an eye piece and see the star field of the left photograph, and then by turning a lever at the eyepiece, to view the right photograph. The two photographs can be adjusted so that the majority of the stars on one plate are exactly matched in position by the stars on the other plate. With plates so adjusted in the *blink* (as it is frequently called) it is possible to detect readily any changes in position of appreciable size of one of the stars, or any change in its brightness.

On account of the greater accuracy of photographic methods over visual observations, and the much larger telescopes that are used for the determination of star positions by photography, it is readily possible to attain a much higher degree of acurcacy in proper motions by photography. To attain a *given* accuracy, it is possible to get along with a much smaller time interval by photography. It has recently been demonstrated that photography by the McCormick telescope, with an interval of seven years, can attain as high an accuracy in proper motions as that found in the catalogue of Boss from observations stretching over an interval twenty times as great.

The star of greatest known proper motion was discovered by Barnard from photographs. It is called *Barnard's star*, and has a

proper motion of 10″.3 per year. Other rapidly moving stars, with their motions are: Cordoba 5^h243 (8″.7), 1830 Groombridge (7″.0), 9352 Lacaille (6″.9) and 61 Cygni (5″.2).

Real Motions of the Stars. — The spectroscope, by the Doppler principle, measures the motion of a star in the line of sight, towards or away from the observer, and gives the motion in units of miles or kilometers per second. To convert the proper motion, measured in angular units, into linear units of miles per second, it is necessary to know the distance of the star or, as we usually prefer to say, its *parallax*. We shall see in the following chapters that a great increase in precision in the determination of stellar parallaxes within the past two decades has revolutionized our ideas regarding the real motions of the stars.

CHAPTER XIII

THE LIGHT OF THE STARS AND THEIR DISTANCES

Stellar Magnitudes. — All that we know of the stars comes from the study of their light. Even without analyzing the quality of it, there are many interesting facts discoverable merely by measurements of brightness. This is closely associated, of course, with stellar distances, for we well know that lights fade rapidly as their sources grow more remote. Yet first of all it is necessary to establish a scale of exact measurements of *apparent* brightness, and to count the numbers of stars belonging to the several grades of brightness. The numbers of stars seen depend on the power of the telescope used, and on the clearness of the sky, and other factors. Evidently some standard conditions must be chosen. Astronomers use the term "magnitude," which is a very old one. The ancients used this classification, calling the brightest stars first magnitude, those about as bright as the pole star, second, and so on.

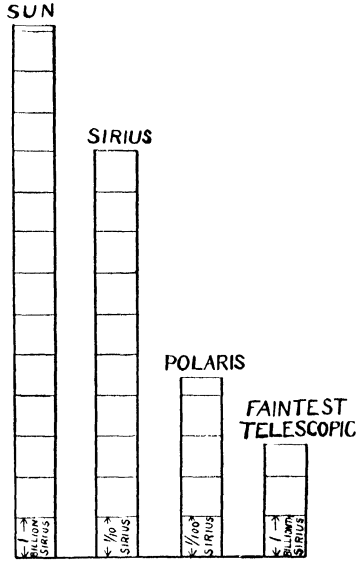


FIG. 34. The range of brightness of the heavenly bodies. In order to bring the diagrams within a page, the scales are altered, as shown by the arrows, from units of 1 billion times to units of 1 billionth times the brightness of Sirius.

In the nineteenth century, when greater accuracy was desired, the actual apparent brightness for average stars of the several magnitudes, already assigned roughly by common consent, was carefully measured. It proved that these conventional assignments could be nearly reproduced by making the exact rule that a difference of 5 magnitudes corresponds to exactly 100-fold in difference of

apparent brightness, and that each magnitude differs in brightness from the next by the fifth root of one hundred ($\sqrt[5]{100}$) fold in brightness.

This rule expresses itself very simply in logarithms. For the logarithm of 100 is 2, and the logarithm of $\sqrt[5]{100}$ is $\frac{2}{5} = 0.4$. Hence, to find the actual difference in brightness between two stars, multiply the difference in magnitudes by 0.4 and look up in a logarithm table the number corresponding. For example, the magnitudes of Vega and of Alcyone (in the Pleiades) are 0.1 and 3.0. The difference is 2.9. Multiplying by 0.4 we have 1.16, which is the logarithm of 14.5. Hence, Vega is 14.5 times as bright as Alcyone.

Conversely, we may express in magnitudes a known difference in brightness. For example, the sun gives us 57,600,000,000 times as much light as Capella. The logarithm is 10.76. Dividing this logarithm by 0.4, we find − 26.9 as the difference in magnitude between Capella and the sun. But since the magnitude of Capella is + 0.2, we can express that of the sun only by the *negative* quantity − 26.7. There are only two other stars, Sirius and Canopus, so bright that their assigned magnitudes are negative. They are − 1.6 and − 0.9, respectively. The moon, Venus, Jupiter, and Mercury, which all shine by reflected sunlight, also have negative magnitudes, changing in value from night to night, according to the positions of these bodies relative to the sun. We should always remember that the brighter a star, the less, speaking algebraically, is its magnitude.

Visual and Photographic Magnitudes. — The naked eye cannot see stars fainter than the sixth magnitude, but by increasing the aperture of the telescope the visual scale can be carried on to fainter stars. The eye is most sensitive to the green and yellow rays. The ordinary photographic plate responds most quickly to the blue and violet rays. It therefore makes a great difference in the star magnitudes which means of observing is used. We therefore have to distinguish between visual and photographic magnitudes. The former are frequently determined from measures made visually with a *photometer*, and the magnitudes are called *photometric*. By means of photography with a visual telescope (by a method which will be explained in connection with the subject of stellar parallaxes), magnitudes are obtained which agree closely with the visual

scale. These are called *photovisual* (*visual* magnitudes determined by *photography*).

Visual Magnitudes. — It is possible for an observer to arrange the stars visible in the field of view of a telescope in a sequence in decreasing order of brightness. A scale can then be formed of the numbers of *steps* between each star of the sequence. This method was devised by Argelander for the observation of variable stars. It gives roughly the relative brightness of the stars, but the observations cannot give an accurate valuation of the magnitudes until the step, or grade, of the individual observer becomes calibrated. Very fair results are reached by a skilled observer who after long continued observation, particularly on stars whose magnitudes are measured by instrumental means, has acquired habits of accuracy and constancy.

The Photometer. — In a work of this scope, it is impossible to go into the details. By means of polarizing prisms, or a graduated "wedge" which intercepts the light with steadily growing effect as it is moved along, stars of different magnitudes may be compared with each other or with the light of an artificial star or standard candle. The most complete work has been done by Pickering and his colleagues at Harvard College Observatory.

All work done visually depends on the peculiarities of the individual eye as well as on the judgment and training of the observer. Herein lies the great defect of the magnitudes determined visually. For this reason when great accuracy is required, photographic work has largely superseded observations made visually.

Stellar Magnitudes by Photography. — These include both photographic and photovisual magnitudes, the only difference in method takes place in the work at the telescope. There are a great variety of ways of deriving the magnitudes, chief among which may be noted: (1) Change in exposure times in definite ratios, (2) change in aperture of the telescope, (3) measurement of the diameters of the star images on the photographic plates. The difference between the photographic and photovisual magnitude of any star is called its *color index*.

Star Colors. — Some of the stars, like Rigel, are white with a blue tinge, others like Sirius or Vega are nearly pure white. Capella is yellowish, while Betelgeuse and Antares are distinctly reddish. As we shall see later, difference in color means a difference in

temperature and spectrum, or difference in evolution. On any ordinary photographic plate a white star will photograph more quickly and give a stronger photographic image on the plate than a red star of the same visual magnitude. Hence, the photographic measures will make the white star brighter in magnitude than the red star. The difference between the photographic and visual magnitudes is an index of the color, as the name implies. As we shall see later, the color of a star depends on its spectrum.

Henry Draper Catalogue. — Harvard College Observatory has finished this magnificent catalogue giving 225,300 stars, down to about the ninth magnitude. In addition to the coördinates of each star, the right ascension and declination referred to the position of the equator and ecliptic for the year 1900.0, the catalogue gives the photographic and photovisual magnitudes and also the spectral types. This is a great storehouse of information for use by the astronomer.

Numbers of Stars. — By counting all the stars of the first eight or nine magnitudes, and then by the estimation of the number of stars of fainter magnitudes from sample counts of many regions of the sky, Seares has given the following interesting table.

NUMBER OF STARS BRIGHTER THAN SUCCESSIVE MAGNITUDES
Harvard visual scale

Magnitude	No. of Stars	Ratio	Magnitude	No. of Stars	Ratio
0	3		8	46,200	
		3.7			3.0
1	11		9	139,300	
		3.5			2.7
2	39		10	380,000	
		3.4			2.7
3	133		11	1,026,000	
		3.4			2.5
4	446		12	2,590,000	
		3.3			2.3
5	1,466		13	5,890,000	
		3.2			2.2
6	4,730		14	13,120,000	
		3.2			2.1
7	15,000		15	27,500,000	
		3.1			2.1
8	46,200		16	57,100,000	

It will be seen that the total number of stars in the whole heavens brighter than magnitude 6.0, that is, visible to the naked eye, is 4730. (Some trained eyes can see stars slightly fainter than the sixth magnitude.) For the visual refractor of 26 inches aperture at the Leander McCormick Observatory, a star of magnitude 16.0 is at the limit of visibility.

From the table it is seen that for the first eight magnitudes, there is a slowly declining ratio of gain, but beyond this the decline of the ratio is faster. Taking into account the slower rate of gain, it is estimated that to the twentieth visual magnitude, which, indeed, is slightly beyond the limit the eye can see with the 100-inch reflector on Mount Wilson, the stars number 500,000,000. About three times this number of stars, or roughly one star for each person now living on the earth, could be photographed with moderate exposures with the giant reflectors at the Mount Wilson Observatory, if applied over the whole sky. If the slowing up of the rate of gain continues as indicated, there cannot be many stars fainter than the thirtieth magnitude. Their total number is therefore limited — something like thirty or forty billions. To state it comparatively, there are in our system about twenty stars for every human being now alive.

This conclusion does not allow for the bodies of starlike size, perhaps very many in number, which are dark, or which shine feebly by reflection, as the earth and moon do. Neither does it allow for the possibility that the decline of the ratio of gain in numbers, from magnitude to magnitude, may imply an obstruction of light in space.

It is easy to see that probably the faintness of the stars of high magnitude is largely due to their immense distance quite as much as to their intrinsic faintness. But it may be that a part of it depends on loss of light on the way to us. We have seen, in considering the solar system, that millions of meteors strike the earth's atmosphere daily. If space, generally, is tenanted by such objects in equal profusion, even though they are individually very small, they must, by their immense number, cut off and absorb some light in the course of such enormously long journeys as light makes in coming from the faintest stars to us.

Furthermore, the escape of atoms and molecules of gas from the atmospheres of stars and planets (and doubtless other stars besides

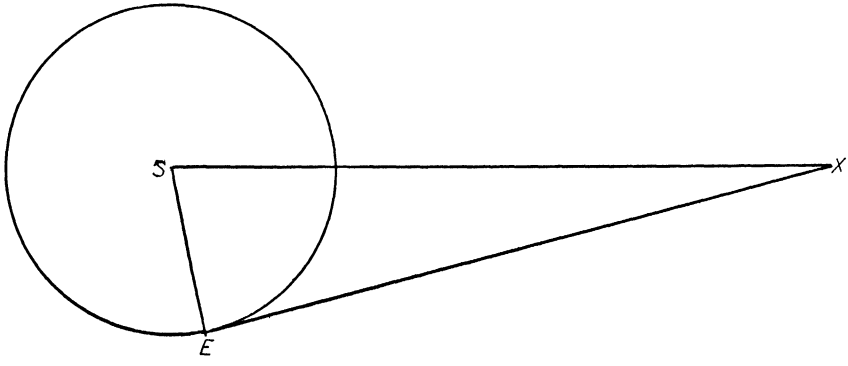
the sun have planets) must also provide some obstruction to light. These atoms and molecules, however, being small compared to the wave-length of light, would tend to scatter the violet rays more than the red. So we should expect the faintest stars to be redder than the brighter ones, on the average. Apart from a special exception, which we shall mention later, this does not appear to be confirmed, so that astronomers tend to think light-scattering by molecules and atoms in the depths of space is not important.

The argument does not apply as regards bodies similar to meteors, for they would weaken rays without altering their color. Accordingly, we are not in a position to say with confidence that there is no light absorption. Hence, we cannot say that the number of the stars does not exceed thirty or forty billions, but we certainly can say it is not much less.

Intrinsic Brightness of the Stars. — The brilliancy of illumination from an electric light depends on the distance of the light. If the distance is doubled, the intensity of the light is reduced four-fold, for the brightness depends inversely as the square of the distance. The same law holds also for the sun and the stars. If the sun were removed to the average distance of the stars, it would shine like an average star. If Sirius were placed where the sun is, we would receive so much light and heat that life on the earth as we now know it would be impossible. To compare the light of our star, the sun, with that of other stars, it is necessary to know the distance of the stars. If, now, when distances become known, we imagine the sun and the stars all at a standard distance, then we can ascertain the intrinsic brilliancy. Electric lights are compared by their " candle power." The " absolute brightness," or brilliancy of any star at a standard distance, may be likened to candle power.

Stellar Distances. — Distances in the solar system are expressed either in miles, or in terms of the astronomical unit whose length is the distance from the earth to sun. If the distance, even to the nearest fixed star, were expressed in miles, the number would be so great that it would convey little meaning. Astronomers therefore prefer the term *parallax*, when referring to the distance of the stars. This is a small angle, measured in seconds of arc, between two lines meeting at the star, one line from star to sun, the other from star to earth. In other words, the parallax of a star is the angle at the star subtended by the distance from earth to sun.

If S is the sun, E the earth, and X the star, then the angle SXE is the parallax, usually designated by the Greek letter π and expressed in seconds. An angle may be measured in degrees, minutes and seconds, or in radians. In the latter units, an angle is measured



by the ratio of its arc to the radius. The parallax being always very small, less than a single second of arc for the nearest fixed star, the angle SXE (measured in radians) is equal to $\frac{SE}{SX}$

But one radian is equal to 206,265″; and SE = 93,000,000 miles.

Hence, SXE (measured in seconds) $= \frac{93{,}000{,}000 \times 206{,}265}{SX} = \pi$

and therefore $SX = \frac{19{,}200{,}000{,}000{,}000}{\pi}$ miles,

where π is the parallax of the star measured in seconds. A star whose parallax is 1″ is at a distance from the sun (or earth) of 19.2 $\times 10^{12}$ miles, or 206,265 times the distance of earth from sun. Light traveling at the great speed of 186,300 miles per second takes 3.26 years to travel this colossal distance.

Hence, the distance of a star (in light-years) $= \frac{3.26}{\pi}$

The nearest of the fixed stars, Alpha Centauri, is so far distant that it takes its light $\frac{3.26}{0.75}$ or 4.3 years to reach us.

Trigonometric Parallaxes. — The only direct method of measuring the distances of the stars is by employing the principles of trigonometry, as used by the surveyor in finding the distance across a river that cannot be traversed. On account of the annual journey

of the earth about the sun, an observer at the end of six months, without any effort on his part, finds himself on the opposite side of the earth's orbit, 186,000,000 miles from his previous location. Hence, it is easy to see that when Copernicus assigned to the earth the humbler part of revolving about the sun instead of being center of all things, as Ptolemy had regarded it, he required of his followers a great faith. For 300 years, until the first stellar distance was measured, they had to believe that the stars are so far away that the earth's yearly cycle of 500,000,000 miles around the sun neither brings any of them apparently nearer, nor makes the nearer ones seem to cross over those more distant. In other words, the stars must be so very far away that the radius of the earth's orbit, 93,000,000 miles, is as nothing in comparison. It was not until Bessel, Henderson and Struve measured star distances, about the year 1840, that this faith began to be replaced by certainty. At the beginning of our present century, hardly over a hundred star distances had been measured, and a third of these depended on angular measurements too small to be trusted as real.

Parallaxes by Photography. — The most accurate method of measuring stellar distances directly is by means of photographic plates taken with the largest telescopes in existence. Ordinarily a series of plates are taken at six-month intervals, at five successive seasons, that is, continuing over two years. Although the work is done by photography, both visual and photographic telescopes are employed. For the latter, the ordinary photographic plate, sensitive to the blue and violet, is utilized. For the visual refractor a special method of observation becomes necessary which was first applied successfully about the year 1900. The reader will remember that for a visual refractor the optician brings the yellow and green rays to a sharp focus. The red, at one end of the spectrum, and the blue and violet at the other end, are not in the best of focus. Consequently, if photography were attempted by a visual telescope and ordinary plate, the star images would not be sharp, since the plate used is sensitive to blue and violet rays, which are out of focus, and is not sensitive to yellow and green rays, which are in sharp focus. By the use of a yellow color-filter which absorbs the blue and violet rays and does not permit them to reach the photographic plate, and by the use of a special plate, (called an isochromatic plate) sensitive to yellow and green light, it is possible to

photograph the stars by visual telescopes, and to obtain star images as sharp (and probably sharper) than is possible with photographic telescopes, whether refractors or reflectors.

Schlesinger was the first to utilize a giant telescope for parallax determinations, when he employed the 40-inch visual refractor of Yerkes Observatory with a focal length of 62 feet. At the present time (1927) parallaxes of first quality have been obtained by photography for 2000 separate stars. The observatories taking the main part in this work have been: Allegheny, McCormick, Yerkes, Greenwich, Mount Wilson and Swarthmore. Allegheny and McCormick have each completed 800 parallaxes, while each of the other observatories have finished between 200 and 300 stars. All of the observatories engaged in this work are in the United States except Greenwich. These trigonometric parallaxes are of very high value in astronomy, and form the basis of much of the surprising progress of recent years.

Indirect Methods of Deriving Parallaxes. — Proper motions have been extensively used for this purpose. It is perfectly clear, of course, that if a star moves at a certain rate in a certain direction, the angle apparently moved over in a century will depend first on how far away the star is, and second on how the direction of the star's motion lies compared to our line of sight. The greatest effect will be produced if the motion is exactly at right angles to the line of sight, and if the star is near. If it is assumed that there is no reason why the stars should go in one direction rather than another, or in other words that their real motions are at random, we may say that the average apparent proper motion of a large number of stars is very nearly eight-tenths of the real average value. For we see some of the motions fully extended and some foreshortened to nothing, and on the average they are foreshortened to about eight-tenths of their value.

Actually there are many other factors to consider. The stellar motions are not altogether at random directions in space, but have certain preferential motions. Stars of different spectral types differ in speed, and differ in real brightness. Hence the proper motions offer no royal road to relative distances, even when averages from very large groups of stars are considered. But the late Professor Kapteyn, after long and profound investigation, determined certain formulæ for average parallaxes corresponding

to average proper motions for the various magnitudes and types of spectrum. These have lately been revised by his successor van Rhijn, using newer data.

The immense distances of stars may be seen if we translate van Rhijn's parallax value 0″.0014, given for magnitude 10, into light-years and into miles. The numbers are over 2300 light-years and 14,000,000,000,000,000 miles.

So we can estimate star distances from proper motions taken wholesale. There are some other interesting by-products of proper motions which give us the relative distances within certain families of stars. Looking back from the observation-car platform along a railroad track, while riding smoothly on a long continental journey, we sometimes see miles at a stretch where the track is straight, and the two rails seem to approach till they meet in the dim distance. Though they seem thus to approach and meet, we know that they are parallel. Similarly, if a lot of stars were moving along together in parallel paths, these paths would seem to us to meet in one point. Or to turn the proposition round-about, if the directions of motion of a lot of neighboring stars seem to meet in a point, these stars probably form a physically connected system or cluster, whose individual members are moving in parallel paths at equal rates. If the rates were very unequal, though the paths were parallel, the stars would not be neighboring ones, for they would have become widely separated during the immense time which star processes consume.

If the cluster is quite a deep one, so that some of the stars composing it are much farther from us than others, their proper motions will seem correspondingly smaller, though we know that actually the motions are closely equal. In such a case, the parallaxes are directly proportional to the apparent proper motions. If by any means one parallax of the cluster can be measured, then the parallaxes of all become known immediately.

Lewis Boss discovered such a moving cluster in Taurus. It includes, besides many fainter stars, several whose distances are known by trustworthy measurements. Accordingly, all the other distances in this group are as well determined as their proper motions, and these will be more and more accurately known as time goes on. There are several other well-known moving clusters, for instance, one including the bright stars of the Great Dipper, called

the Ursa Major group. Although widely separated in the sky, the brilliant Sirius belongs to the Ursa Major cluster. The brighter stars of the Pleiades form a group with a parallax 0″.010, corresponding to a distance of 326 light-years.

The spectroscope furnishes another means of deriving parallaxes by indirect methods. This will be taken up in Chapter XV. The orbital motion of double stars furnishes still another method.

CHAPTER XIV

STELLAR SPECTRA

The spectroscope is the most important adjunct that has been applied to the telescope in modern times, and its revelations have been astounding. We have seen in Chapter II how it is possible to ascertain the physical constitution of the sun, in spite of the enormous intervening distance. The vast distances, even of the

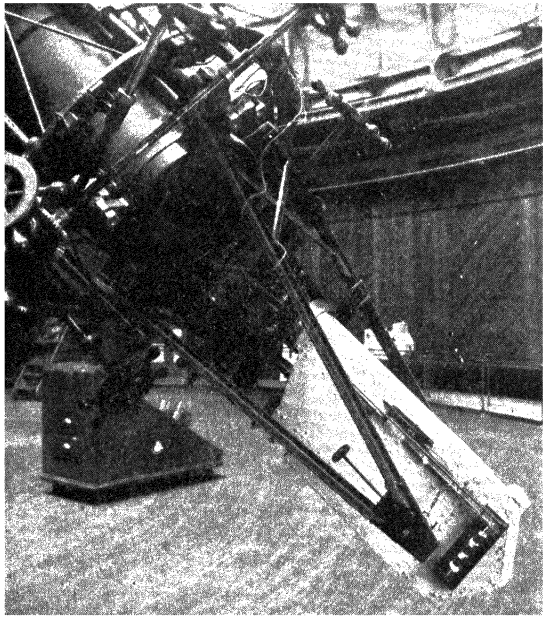


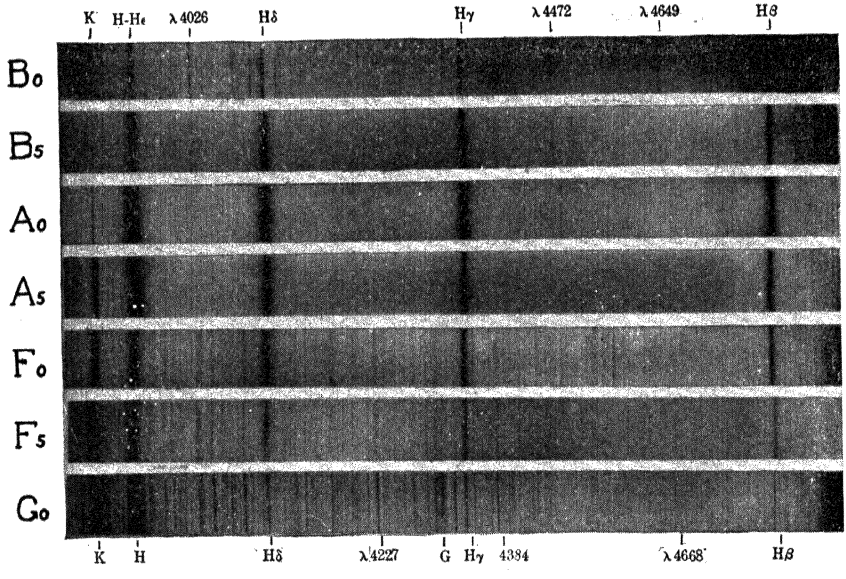
PLATE 44. SPECTROSCOPE ATTACHED TO THE LICK REFRACTOR.

stars, present no serious obstacles. All that is necessary is that the star gives sufficient light so that it may be spread out into a spectrum and yet impress the photographic plate. Fainter and fainter stars may be investigated by increasing the size of the telescope, the greatest aperture being that of the 100-inch mirror at Mount Wilson.

In the usual practice, if we omit consideration of the so-called objective prism or slitless instrument, the telescope (either reflector or refractor) concentrates the light of a star on the slit of the spectroscope. After passing through the narrow slit, the light falls on the lens of the *collimator* and emerges as a *parallel* beam of light. It now falls on the prism where the light is spread out into a spectrum. The lens of the *camera* brings the light to a focus on a photographic plate. (If used for photography, the instrument is called a *spectrograph*). The apertures of the collimator and camera are determined by the size of the prism, or prisms. The focal length of the collimator is determined by the ratio of aperture to focal length of the telescope objective. Cameras of different focal lengths may be utilized for changing the scale, or extension, of the spectrum. A second or a third prism may be utilized for increasing the dispersion.

The first investigations of stellar spectra by Fraunhofer, over a hundred years ago, showed enormous differences in the appearance of the lines of their spectra. Some displayed a multitude of lines, very similar to the solar spectrum, while others showed few lines and still others had heavy bands of much greater strength than any found in the sun. Nearly all of the stars in the sky exhibit spectra of dark lines on a bright background, or, as we say, an absorption spectrum. Referring to Chapter II, this will be understood to mean that a star consists of a very hot central core emitting light which would yield a continuous spectrum were it not for the cooler gaseous layers surrounding the star. This cooler envelope, although itself at a very high temperature, causes the dark lines of the spectra. By measuring the positions of the dark lines and determining their *wave-lengths*, it is possible to ascertain the chemical composition of the gases in the outer envelope of the star. The unit of wave-length is called the angstrom, which is one ten-millionth of a meter. Most of the dark lines in stellar spectra have been identified with terrestrial sources.

Harvard Classification. — It is found that all of the spectra of the stars can be arranged in a continuous sequence of imperceptible gradations. Yet as the continuous band of the spectrum itself is often divided into seven principal colors, so also there have been many different systems of arrangement of stellar spectra into *classes* or *types*. That most frequently used was devised at Harvard College Observatory. The change in spectral type coincides with a



TYPICAL STELLAR SPECTRA, B_0 TO G_0

Spectra of stars ϵ Orionis, q Tauri, α Canis Majoris, β Trianguli, δ Geminorum, α Canis Minoris, α Aurigæ.

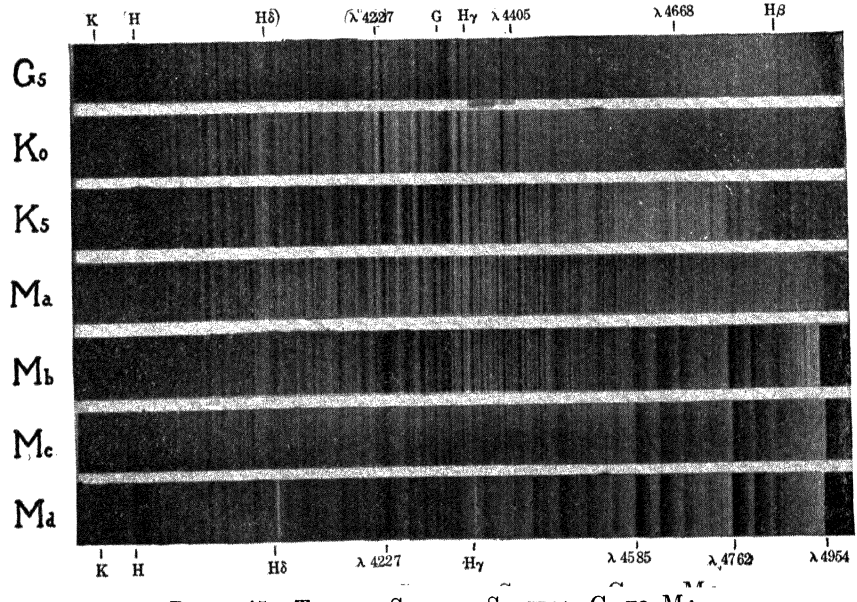


PLATE 45. TYPICAL STELLAR SPECTRA, G_5 TO Md

Spectra of Stars κ Geminorum, α Bootis, α Tauri, α Orionisi, ρ Persei, *W* Cygni, o Ceti. (Both figures from observations of Detroit Observatory, University of Michigan.)

change in color of the star. The great majority of the stars fall into six classes, denoted by the letters B, A, F, G, K, and M. The special features of each spectral class are given below in tabular form, and photographs of typical spectra are given in Plate 45. Each main class is divided into ten numbered sub-classes, so that, for instance, A5 is half way between A0 and F0.

CHARACTERISTICS OF TYPICAL STELLAR SPECTRA.

B	A	F
The few absorption lines are mainly of hydrogen and helium. Oxygen, nitrogen show less conspicuously.	Hydrogen lines predominate. Helium lines disappear. Lines of metals come in faintly, especially spark lines.	Metallic lines conspicuous. Arc lines of metals appear.
G	**K**	**M**
Solar type. Metallic arc lines predominate. Flaming arc lines also conspicuous.	Sun-spot type. Arc lines strong. Flame lines also conspicuous. Bands of compounds appear.	Flame lines prominent. Heavy absorption bands appear and are the conspicuous feature, indicating spectra of molecules, notably titanium oxide.

The descriptive terms "spark," "arc," "flame," refer to the several common ways of exciting spectra in the laboratory by the electric spark, electric arc, and the flaming arc. The spark is much hotter than the arc, and this is much hotter than the flame of the outer part of the flaming arc.

Changes in spectral class are accompanied by other changes as given below. The temperatures are in degrees Centigrade, reckoned from absolute zero, −273° C.

Spectral Class	B	A	F	G	K	M
Typical Star	Rigel	Sirius	Procyon	Sun	Arcturus	Betelgeuse
Color	Blue	White	Pale yellow	Yellow	Reddish	Red
Color index	−0.4	0.0	+0.4	+0.8	+1.2	+1.6
Color class	b	a	f	g	k	m
Surface temperature	16,000°	11,000°	8,000°	6,000°	3,500°	2,700°

Accompanying the fall of surface temperature from B type to M type, the region of greatest intensity in the spectrum shifts

steadily from violet to red, and when indicated on a wave-length scale is found beyond the visible end of the violet for B type, and beyond the visible end of the red for M type stars. When a very small dispersion is employed, the position of maximum intensity is determined by investigations of the *effective wave-length.*

PLATE 46. STAR CLOUD IN SAGITTARIUS. (Barnard.)

Distribution of Stars of Different Types. — It will be of great interest to see whether the stars of different spectral types are distributed uniformly over the sky, or whether some of the stars have a preference for certain locations. The natural reference for the starry universe is the Milky Way, or Galaxy. With a little care, we find that the crowded Galaxy is like a flat ring, symmetrically placed among the stars whose poles are in the northern constellation Coma Berenices [1] and the southern constellation Cetus.

[1] Right Ascension $12^h\ 50^m$, Declination N. 27° 12′.

It stretches with varying brightness through the constellations Aquila, Vulpecula, Cygnus, Cepheus, Cassiopeia, Perseus, Auriga, Taurus, Orion, Monoceros, Argo, Crux, Circinus Norma, Scorpius, Sagittarius, Serpens, Ophiucus, Scutum Sobieski, Taurus Poniatowski.

Astronomers frequently reckon positions from the Milky Way, or Galaxy, and speak of galactic latitudes and longitudes, as we locate places on the earth by terrestrial latitudes and longitudes. In the previous chapter we have taken a census of the sky, and have learned the total numbers of stars of various magnitudes.

The Milky Way a Crowded Retreat. — Turning from number to arrangement, we can learn something very interesting about the probable shape of our starry system. Let us arrange our star counts in zones parallel to the Milky Way, or Galaxy, and use the term "galactic latitude" to designate the angular distance on either side of the central line of the Galaxy. Rather than give entire numbers for the whole zones, let us give average numbers per square degree. The result is somewhat as follows:

AVERAGE NUMBERS PER SQUARE DEGREE OF ALL STARS BRIGHTER THAN CERTAIN DESIGNATED MAGNITUDES

Magnitude	At Galactic Latitudes:							
	5°	15°	25°	35°	45°	55°	65°	80°
9 5	10	7.3	5.5	4.4	3.9	3.7	3 5	3.4
10 5	29	20	14	11	10	9	8	8
11 5	81	53	36	28	23	21	19	17
12 5	210	130	86	63	51	44	39	35
13 5	510	300	192	135	105	88	75	64
14 5	1,140	680	400	267	200	160	132	112
15 5	2,480	1,480	800	514	370	282	230	195
16.5	5,500	3,160	1,590	933	660	500	400	330

It is plain that stars of all degrees of brightness are much more numerous in the Milky Way than near its poles. But this effect is

greatly augmented for fainter stars. Thus, comparing the star density at 5° with that at 80° of galactic latitude, we find:

Magnitude	Density Ratio
9.5	3.1
12.5	6.1
16.5	16.6

What does this mean? Evidently that, since the faint stars do not exist proportionately plentifully towards the poles of the Galaxy, either we look right through the star system to vacant space within a comparatively moderate distance in that direction, or else some very regularly distributed and gradually augmented absorbing medium cuts off more of the light rays that come to us from thence. It is so much simpler to conceive the former alternative, that all astronomers are agreed that we should regard the stars as situated in a space shaped like a lens, a watch, or an oyster-shell, extending immensely farther in the plane of the Milky Way than it does at right angles thereto. But the thinning out of stars of fainter magnitudes seems most probably to indicate that even in the Galaxy itself we see through the entire star system.

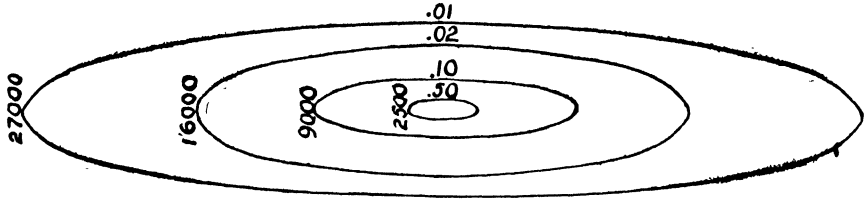


FIG. 35. OUR STAR SYSTEM. (After Kapteyn).

The ellipses represent boundaries of regions, at right angles to the plane of the Milky Way, where the star density [number of stars per unit of volume] is 0.01, 0.02, 0.10, and 0.50 compared to the star density near the sun. These boundaries lie at distances 27,000, 16,000, 9,000, and 2,500 light-years distant in the plane of the Milky Way, but only $\frac{1}{5}$ as far distant towards its poles. Thus our Galaxy is watch-shaped.

In other words, the stars do not appear to extend out to infinite distance in any direction, and much less far towards the constellations Coma Berenices and Cetus than towards constellations like Sagittarius, Perseus, and Aquila which lie in the Milky Way. This conclusion is supported by another fact long ago pointed out. If

the stars existed without bounds in all directions, their number would be infinite, and they would totally close in the view in every direction, even though each individual was almost a mere point. So that, unless their light was absorbed in coming to us, the whole heavens would blaze like the sun. This is not so, and the limited extent of the starry system readily explains it.

More Homes in the Milky Way. — Now that we have divided our stars into types, or into tribes, as it were, we shall find that some of them, like human tribes, have homes. This comes out as follows. The table gives numbers of stars within equal areas situated at certain average Galactic latitudes.

NUMBERS OF STARS ABOVE $6\frac{1}{4}$ MAGNITUDE OF SPECTRUM TYPES AT DIFFERENT GALACTIC LATITUDES

Galactic Latitude	B	A	F	G	K	M	All
60°	37	296	156	128	378	101	1,096
40	85	345	152	128	377	108	1,195
20	227	539	200	170	459	126	1,721
8	367	705	212	183	505	122	2,094
All	716	1,885	720	609	1,719	457	6,106

Looking down each column of this grouping of bright stars, we see that the red M stars are quite cosmopolitan, showing little preference for one part of the sky over another. The F, G, and K stars concentrate very slightly towards the Milky Way region. But of the blue B stars, there are ten times as many in the Milky Way neighborhood as at 60° from it, and the A types show a similar but less decided preference. The total numbers of bright stars of the several clans are also interesting. The M types are very few, B, F, and G somewhat more numerous, but A and K types include six-tenths of the whole number of these bright stars. It is quite changed for faint stars.

This immediately leads us to inquire whether the blue stars are concentrated towards the center of the star system, or are scattered all the way out to the bounds of the Milky Way. The answer is very decisive. We must first of all remark that though our solar system is not in the exact center of things, as was suggested by some astronomers many years ago, it lies comparatively near the center,

and not near the confines of the immense extension of the Milky Way. In the second place, we may assume, as indeed we shall show later, that the B stars are nearly equal to each other in real absolute brightness. The reason that they apparently differ is mainly because some are farther away than others.

With these two ideas in mind, consider this little table which, like an earlier table, shows the change of ratio of numbers of stars brighter than a given magnitude.

Visual Magnitude	Ratios:			
	B	A, F	G, K, M	All
2.5				
	3 1	2.9	4.0	3.4
3.5				
	2.7	3 2	3.5	3.2
4.5				
	2.6	4 4	3.2	3.4
5.5				
	1.7	4.1	3.2	3.3
6.5				

We see from the second column that the blue B stars are increasing more and more slowly as they grow fainter, and with a few more magnitudes the gain will probably cease altogether. This seems to mean that beyond a certain distance, corresponding to which average stars become apparently of eighth or ninth magnitude, there are no more of them. Quite the contrary with A and F, and as for the G, K, and M types, they practically hold their own in rate of increasing numbers.

Hence, it appears that the blue B type stars are few in numbers and are concentrated in the middle of our starry system. Thus, if we could take our stand outside of it, at an immense distance, so that the whole of our stars would run together into a hazy cloud, as the Milky Way does to the naked eye, it would probably be a yellowish cloud. The blue part of its make-up would be insignificant. This conclusion is supported by color indices of stars too faint for the spectroscope to observe. At the sixteenth magnitude,

PLATE 47. THE GREAT NEBULA IN ORION. (Mt. Wilson Observatory.)
A mass of gas probably illuminated by the influence of a neighboring star.
To the eye the whole nebula appears starlike and lies in Orion's sword.

there are no stars in some regions of the sky bluer than color-class f. Much more observing is needed to fully prove the matter, but apparently the blue stars are really few, and are central in our starry system.

Distribution of Nebulæ. — While we talk of the tribal homes of the stars, we may naturally turn a little aside to see the same sort of thing among the nebulæ — those celestial cousins of the stars of whose exact kinship we know so little. We are sure that these cloudlike objects are neither terrestrial clouds nor any part of our solar system, because they keep their places among the stars. They fall into four classes: (1) Those which are diffuse, resembling our earthly clouds. Of such are the nebulæ in the Pleiades, in Orion, in Sagittarius, and in Cygnus. (2) The planetary nebulæ, small clear-cut forms with a central star. (3) The spiral nebulæ, somewhat like the forms of spiral sea-shells. (4) The elongated and globular nebulæ, neither exactly planetary nor exactly spiral but, like them, definitely formed, not vaguely diffuse.

Now it is a very interesting thing that no spiral nebulæ fall in the Milky Way, although there are perhaps hundreds of thousands of them in the sky, and that nearly all of the diffuse nebulæ and planetary nebulæ do fall in the Milky Way, and hardly any of them much outside of it.

New Stars. — We sometimes think of our universe as a grand system which began in some unknown way almost an eternity ago; which, in our time, pursues its majestic course without a ripple to mark the even current of its flow; and which imperceptibly moves towards some far-off end lying almost an eternity in the dim future. As we shall see later, there are, nevertheless, evidences of tremendous catastrophes occurring when new stars, or novæ, suddenly blaze forth in the sky.

Spectroscopic Studies of Stellar Motions. — Beginning just before the opening of the twentieth century, spectroscopic work by photography became standardized. Campbell, of the Lick Observatory, developed the photographic stellar spectrograph to high perfection, and also installed this line of observing at a branch station in Chile. These two Lick Observatory spectroscopic investigations went on for many years, till they had covered all the bright stars of both hemispheres to the 5.5 magnitude. The work was published in the year 1910, and is a classic. More recently,

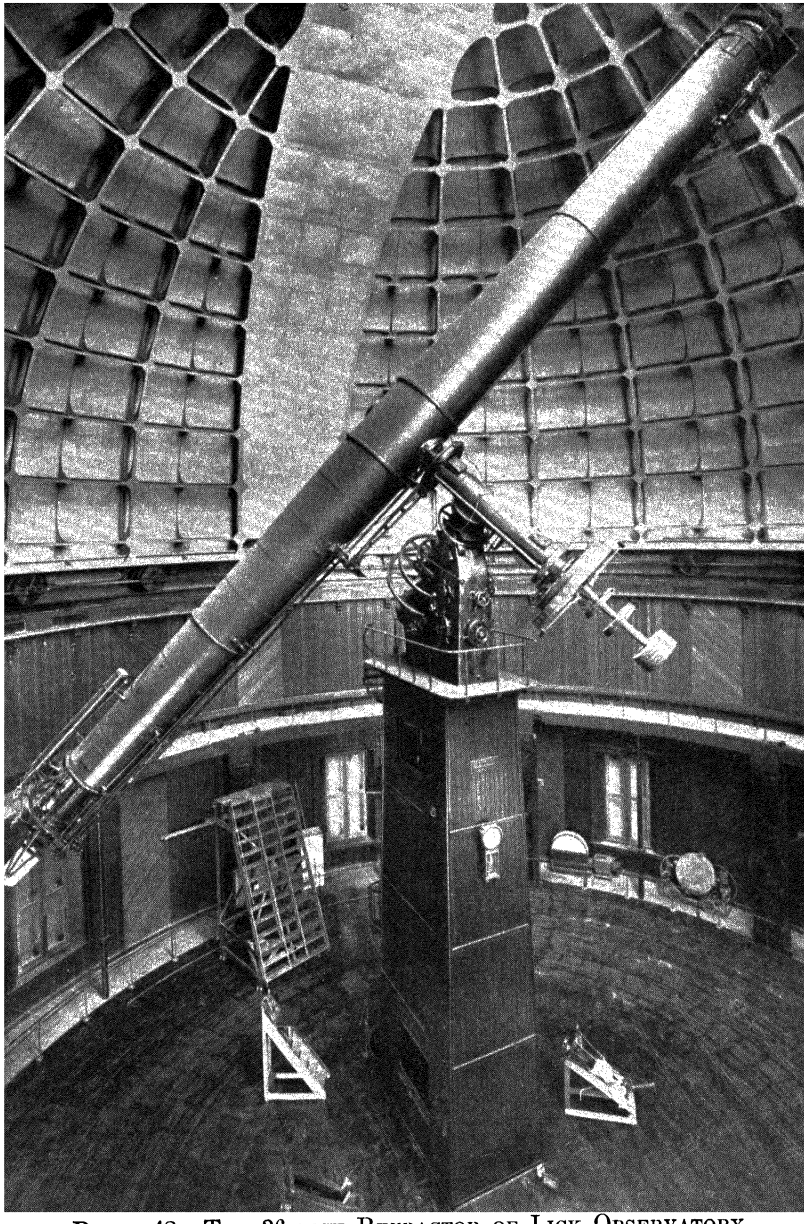


PLATE 48. THE 36-INCH REFRACTOR OF LICK OBSERVATORY.
With spectrograph attached.

the giant reflectors at Mount Wilson, of 60-inches and 100-inches in aperture, have been engaged in similar work under the direction of Adams, and also the 72-inch reflector at Victoria under the guidance of Plaskett. These mammoth reflectors are splendidly suited for spectroscopic studies. They have no chromatic aberration, the light of all colors being brought to the same focus, and as the reflectors are of much greater aperture than the largest refractors, they possess much greater light-gathering power. Spectra are therefore photographed much more quickly by these reflecting telescopes, and consequently much fainter stars may be investigated.

Comparison Spectrum. — After the telescope is set on a star, and before the exposure is begun on its spectrum, there is a small window turned at the slit in order to allow the light of the electric arc, or spark, of iron or titanium to give its spectrum of bright lines. After a suitable exposure is made on this comparison spectrum, a window is again turned to allow the light of the star to pass into the spectrograph. At the end of the exposure on the star, the window is again placed so as to photograph for a second time the comparison spectrum. The developed photograph shows the star's spectrum in the middle with the comparison spectrum on either side. Many important adjustments of the spectrograph are necessary. While the photograph of the stellar spectrum is being made, the telescope must follow the star accurately, for if the star's light does not pass through the slit it will not impress itself on the photographic plate. " Guiding " on the star is necessary. If the temperature of the interior of the spectrograph changes appreciably during the exposure, the adjustments of the spectrograph will change, with the result that the spectral lines will not be sharp, and the comparison spectrum at the beginning will not be exactly superimposed on that taken at the end of the exposure. In Plates 44 and 48 is shown the Mills spectrograph of the Lick Observatory attached to the 36-inch refractor. By an electric thermostat, the temperature is not allowed to vary more than 0°.1 C during the exposure. For the brighter stars the exposures may be of a few minutes. For the fainter stars it is necessary to increase the exposures. These may run to 2, 3, or more hours, and even sometimes to 10 or even 20 hours (on several nights). The exposure required depends on the telescope, the magnitude of the star, and the dispersion of the prism or prisms.

Radial Velocities, or Motion in the Line of Sight. — The comparison spectrum shown in Plate 49, is for the purpose of deriving the wave-lengths. If the wave-length of a line in the star due to the chemical element titanium has a smaller value than that furnished by the comparison spectrum, then this shift in wave-length from the standard position gives, by the Doppler principle, a means of determining the velocity at which the star is moving

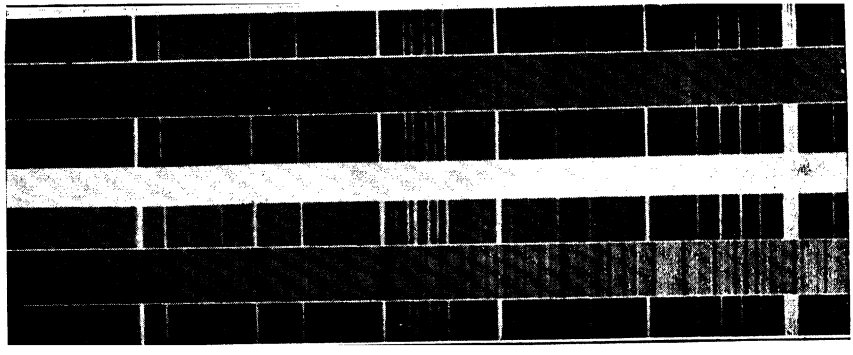


PLATE 49. SPECTROSCOPE BINARY MU ORIONIS, SHOWING LARGE DISPLACEMENT OF LINES. (Yerkes Observatory.)

The figure shows the spectrum of this star taken on two different dates. Some of the dark lines in the star's spectrum closely coincide with the comparison lines of titanium. In the upper spectrum the star's lines are only slightly displaced toward the right (toward the red); in the lower spectrum the displacement is in the same direction, but is much larger. This shift of the star's lines is due to the speed of the star in the line of sight, away from the earth (recession), which the measurements on the original show to be 19 kilometers (12 miles) per second on the upper spectrum, and 63 kilometers (39 miles) per second on the lower.

towards us. The speed is measured in kilometers, or miles, per second. With stars of many sharp lines, like the solar type, and with three-prism dispersion, it is possible to attain an accuracy in the radial velocities of 0.1 km. per second. From the motions in the line of sight thus measured, it is necessary to eliminate the effect of two motions of the earth, its diurnal rotation on its axis, and its annual revolution (at the rate of 18.5 miles per second) about the sun. When this has been accomplished, the motions of the stars are referred to the sun.

Spectroscopic Binaries. — An individual star, separated from other stars by great distances, will move with a constant velocity, since there is no friction to be overcome and no forces that will

accelerate or retard the motion. If the motion is not constant, but varies in amount, then we are confident that outside forces centered in a nearby star are at play. Thus have been discovered *spectroscopic binaries*. In the year 1889, Pickering found that the brighter component of the well-known double, Mizar, exhibited the dark lines in its spectrum *doubled*. The Third Spectroscopic Catalogue of the Lick Observatory, published in the year 1924, gives a list of 1054 spectroscopic binaries, while spectroscopic orbits are furnished for 248 stars. About one star in every five investigated is found to have a variable radial velocity.

Solar Motion. — The sun itself, like other individual stars, is in motion, and as it moves it carries the earth and the system of planets along with it. The motion of the sun impresses itself as an apparent motion on the stars and modifies the results derived from them. This has been known for many years. Sir William Herschel had suspected it by the run of the few proper motions known in his day. He had even made a very close guess as to the actual direction of motion, but of course, could not know the speed. It was only after trustworthy parallaxes become fairly numerous that the best proper-motion data could give, not only the direction, but the speed of the sun, with some accuracy. For though it could be determined that the stars towards which the sun approaches are apparently separating, and those in the opposite direction from which the sun is receding are closing in (as trees behave when one approaches or recedes from the edge of a forest), the angular distances involved must be reduced to actual or linear ones before the sun's speed becomes known. Enough parallaxes were available to Boss, so that in discussing his "Preliminary General Catalogue," published just before Campbell's spectroscopic work, he gives both direction and speed of the solar motion.

Campbell, however, was able to determine the solar motion in both direction and speed from the Lick Observatory spectroscopic results alone. In spectroscopic line-of-sight work, averages of large numbers of apparent motions give only half of the true average motion, if the directions of motion are at random in space. But the solar motion shows itself in full to increase the apparent rate of approach of stars in the direction we are going, and to produce an apparent rate of recession of stars in the direction we are leaving behind.

Campbell and his colleagues worked out the solar motion in both direction and speed compared to all the stars they observed, and also compared to each spectrum class separately. Suppose a lot of the stars, the blue ones of class B, for instance, formed a cluster with a common motion of their own. When referred to these, the solar motion must be different from its values referred to other stars not of that cluster. It is hardly possible to avoid systematic effects like this, either in spectroscopic or proper-motion work. The limited amount of observations available relate mainly to bright stars, presumably near us on the whole. Very possibly they may all belong to one family affected with some common motion.

Here are some of the results on the motion of the solar system and the place it is approaching in the sky.

THE MOTION OF THE SOLAR SYSTEM

Author	Date	Method	Number of stars used	Apex of Solar Motion		Speed Kilometers per second
				Right ascension	Declination	
W. Herschel	1783	Proper motion	13	262°	+ 26°	—
Boss	1910	Proper motion	5,413	270 5	+ 31 3	24
Campbell	1911	Radial motion	1,193	268 5	+ 25 1	19 5
Adams and Strömberg	1918	Radial motion	1,405	270	+ 29 2	21 4
Campbell and Moore	1926	Radial motion	2,119	271 5	+ 28 6	19 6

Solar Apex. — Compared to the brighter stars of our system, the sun is traveling in the direction of the constellation Hercules, not far from the bright star Vega, at a speed of about 20 kilometers, or 12 miles, per second. Knowing the motion of the sun, its effect can be removed from the apparent motions of the stars.

In the year 1910, when Boss and Campbell published their classic papers, it was still too early to combine proper motions and radial motions so as to know the total motion of the stars in space, except in a few cases where the parallaxes were known. Campbell had to content himself with working out average velocities for the

different spectral classes. He found the following curious results among others:

Spectral Class	Number of stars	Average radial velocity Kilometers per second
O and B	141	8.99
A	133	9.94
F	159	13.90
G and K	529	15.15
M	72	16.55
Nebulæ	13	23.4

When once the motion in the line of sight is measured for a star whose distance and proper motion are both accurately known, then, when the solar motion is eliminated, the actual speed and direction of the star in space is easily found by combining the three results.

The enormous increase in knowledge of the distances of the stars coupled with radial velocity observations extended to fainter stars has permitted many discussions of solar motion in addition to those given in the table. It is found that the position of the solar apex depends on the choice of material, that is, on the stars used for reference.

CHAPTER XV

THE INTERPRETATION OF SPECTRA

In order to understand aright the riddle of light that comes from the sun and stars, it is necessary to study the structure of the atom and thus gain some information concerning the process whereby light is emitted. Within the past decade, the physicist, chemist, and astronomer have combined in their attack on the atom, and have carried out in our laboratories amazing experiments with the highest degree of mechanical skill and penetrating insight. The work has not been limited to that performed in terrestrial laboratories, for the sun and stars are themselves laboratories where there are combined very high temperatures and very wide ranges of pressures that cannot be simulated by human skill.

Although the distances to the stars are enormous, still these distances are no obstacle to demonstrating that the sun and the stars are all made up of the same chemical elements that constitute our earth.

Electrons and Protons. — Within the last few years, it has been found that we can go farther even than this in resolving their composition. All the chemical elements, nearly a hundred in number, such as hydrogen, iron, oxygen and the rest, which used to be thought quite independent in very essence, one from another, are in fact made up of only two kinds of stuff. These two fundamentals are called electrons and protons. They exist as single particles of equal but opposite electric charges. All electrons are more like one another than carpet tacks, and all protons more like one another than wire nails, but a proton weighs about 1800 times as much as an electron. Hydrogen atoms have one of each, but oxygen atoms have 16 electrons and 16 protons. Heavy atoms, like those of mercury or lead, contain very many of each but may be made up in several ways to give the same chemical properties. In other words, there are several kinds of lead and also several kinds of mercury, indistinguishable to the chemist except in atomic weight. In all other respects the varieties behave alike.

We need not go farther, at the moment, into this curious by-path, however, because what we are emphasizing now is the great fact that all things on earth and elsewhere, whether gases, liquids, or solids — things as different as our own bodies and the ground we tread on, for instance — are made up of these same two kinds of building materials, electrons and protons. If we pass to the sun, 93,000,000 miles away, it is the same. Hydrogen, oxygen, iron, and many other chemicals are there to be sure, but all are made of electrons and protons.

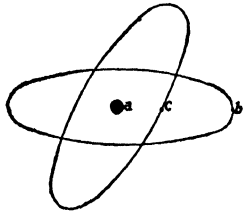


FIG. 36. BOHR'S CONCEPTION OF THE HELIUM ATOM.

The nucleus, *a*, consists of four protons and two bound electrons. In the two circular orbits, which are conceived to be inclined at 120°, revolve the two outer electrons *b* and *c*.

The case of helium illustrates strikingly the identity of the materials all over the universe. Discovered in the sun, next recognized in the stars, finally found on the earth, it became at last well known, and is much used for scientific and technical purposes. But helium, like all the rest of the elements, is built of electrons and protons, four of each. So the bricks of our edifice are everywhere of the same two kinds.

Size of an Electron. — Let us form some notion of the size of our bricks. If we take the period at the end of the last sentence as our unit, then we must place 50,000,000,000 electrons in line to stretch across its diameter. Protons, though heavier, are still more minute. It is of no use to fill this page with a number large enough to indicate how many electrons and protons it takes to make up our sun, 864,000 miles in diameter! Even more hopeless it would be to convey an idea of the numbers of them in some of the stars, which, despite that they look so little, are many of them much larger than the sun.

Where mere numbers fail to convey an idea of the infinitesimalness of the atomic structure, a curious illustration which we owe to Aston may help us.

Aston held up a glass of water, saying, in substance: Suppose we could label every molecule of this water so that we could distinguish these molecules from all others. Then we might pour this water into the ocean and wait until evaporation, winds, rains, rivers and waves had thoroughly mixed these molecules with all

the other water molecules on the earth. When this process shall have been completed, let us fill another glass with water. How many of our original marked molecules would it probably contain? None at all you will perhaps say. But the answer is 2000! For in one glass of water there are 2000 times as many molecules as there are glasses of water in the ocean! How extraordinary! Yet we must note that Aston is speaking not of protons and electrons, but of the molecules, ten thousandfold bigger.

We shall wish to show how intimate a connection the electrons have with light. Before doing so, let us stop for a few moments to think of some very little and very great dimensions directly associated with light itself. This is by no means aside from our subject, for everything that we know about the heavenly bodies comes to us by studying their light.

Light is Wave-motion. — The energy of light appears to be propagated in waves or vibrations. A few years ago we should have said "light is a form of vibration," without any qualification. But light is now thought to come forth from its sources, such as hot bodies like the sun and stars, not continuously, like a wave, but by successive bits called "quanta." However, the subject is somewhat speculative as yet, and the quantum theory must still harmonize to a great extent with the vibration theory. Probably the two views are like the two ends of the same rope, and supplement each other; so we shall retain here the older view which was developed during the whole nineteenth century to great refinement, so as to explain all of the facts then known.

The vibrations of light-waves are far shorter than those produced by flinging a stone into a still pond. Instead of wave-lengths of inches, like water waves, we must take 500 waves of yellow light placed end to end to extend across the diameter of the period which ends this sentence. Of violet light it would require 750, and of red light 450 for the same stretch. So the waves of light, though short, are tremendously long compared to the diameters of electrons.

But when we come to the numbers of light-vibrations in a second, we begin to get back our appreciation of small things. For since light travels 186,000 miles in a second, it takes 500,000,000,000,000 vibrations of yellow light, end to end, each second to make up this enormous distance.

It might easily seem to one unfamiliar with the subject that

such numbers must be only rough approximations. But this is not so. Experiments on the subject are among the most precise in all the range of physics. The velocity of light is known to an accuracy of one part in 300,000, and the wave-lengths of definite rays of light are known to an accuracy of one part in 6,000,000.

Structure of the Atom. — We must specify more particularly than we have done how the electrons and protons are arranged in an atom. The protons and approximately half of the electrons reside in a central nucleus. Remembering that protons are about 1800 times as heavy as electrons, it is obvious that nearly all of the atomic weight is in the nucleus. We mentioned above that some of the chemical elements have several kinds of atoms, all similar in chemical behavior but of different atomic weights. We may remark here, in explanation, that this merely means to add or subtract one or more protons and an equal number of electrons in the nucleus. Being in equal numbers, these additions or subtractions satisfy each other electrically, and exert no influence to modify the chemical behavior of such an atom. An example is chlorine, which has two varieties of atoms, called *isotopes*, one kind of atomic weight 35, the other 37. As there are about three times as many of the lighter as of the heavier kind in every mass of chlorine, the observed atomic weight is 35.45.

So much for the composition of the atomic nucleus. As it has about twice as many positive charges (protons) as negative charges (electrons) the nucleus is positively charged with electricity. In hydrogen atoms, the positive nuclear charge is one unit, that of helium two units, that of oxygen eight units, and generally the positive charge of a nucleus is approximately half of the atomic weight of the element. This unbalanced positive charge is able to attract an equal negative charge of electrons. These bodies arrange themselves in rings, orbits, or some such-like configuration outside of the nucleus. The hydrogen atom has one, helium two, oxygen eight, and so on, of these orbital or outside electrons. It is the number of these which gives the atom its chemical character. Indeed, the number of outside electrons per atom is now called the "atomic number." These numbers run upwards, one by one, from hydrogen, 1, helium, 2, lithium, 3, and so on, up to uranium, 92, which has the highest atomic number. Two gaps in the series exist, showing that there are

probably in addition but two chemical elements in existence as yet undiscovered.

Quantum Theory. — Now we come to the relation of this atomic structure to light. The outside electrons make excursions, when urged by heat or electrical stimulus. Thus electrons may be driven away from their atoms and go free for a time. When this happens the substance is " ionized," as we say. Such is the condition of the rare gas in the bulbs used in wireless. When an electron passes from one ring or orbit to another ring or orbit, a definite " quantum " of light either is given out or extinguished. We say that light is emitted or absorbed in these cases respectively. Whether emitted or absorbed depends on whether the electron in the new condition has less energy of position and motion or more. This is the quantum theory of the origin of light. But still we believe the passage of light across the apparently empty spaces between the heavenly bodies is accomplished by wave motion and wave motion requires a medium. That medium is called the luminiferous ether. It cannot be seen or weighed or otherwise perceived. Nothing indicates it except by the imperious requirement the mind recognizes that where waves pass there must be a medium to convey them. This may seem a slender peg to hang the ether upon, but as yet physicists have not been able to avoid the conception.

We must take leave in our minds of our old idea of a solid body as being a space quite filled up with matter. Every atom, even in a solid, is separated from its neighbors. Besides that, every atom within itself encloses a quantity of free space as overwhelmingly larger than the total volume occupied by its electrons and protons as the great solar system, extending out to Neptune, is larger than the combined volumes of the sun and planets. A solid, then, is quite as little crowded with matter as a room is filled with the little motes of dust that dance in the sunbeam.

We have fixed our thoughts on the smallest things in nature, the electrons and protons which make up all matter, and the wavelengths of light which convey to us all the knowledge that we possess relating to the heavenly bodies. We have seen that the atoms are somewhat like our solar system, with a nucleus which we may liken to the sun, since it contains practically all the mass of the system; that the atoms also contain a group of outside

electrons which we may liken to the planets, since they reside at different distances from the central nucleus, since they are held together by the attraction of that nucleus, and since they occupy and disport themselves in a region of space which, though inexpressibly tiny as compared with our ordinary measures, is yet immense compared with the dimensions of these outside electrons themselves. We have seen that in some way not fully understood, the wave-trains of light originate discontinuously in bits of light energy, called "quanta," when electrons are shaken out of one orbit or configuration in the atoms into another with a loss of electronic energy. Such disturbances of atomic configuration may be caused by heat, and also by electric stimulation. By means of the wave-trains of light which are thus originated, the heavenly bodies touch each other, as we may say, across distances whose immensity defies words to express. It would take ten journeys round our world to reach the moon; four hundred journeys to the moon to reach the sun, twenty-eight journeys to the sun to reach the planet Neptune; ten thousand journeys to Neptune to reach the nearest star; and ten thousand journeys to the nearest star would certainly not carry us to the bounds of the universe of stars. All of this prodigious expanse of space is thronged with interesting objects from which we continually receive light messages which tell a wealth of knowledge about the celestial denizens. Modern astronomy is the interpretation of these messages.

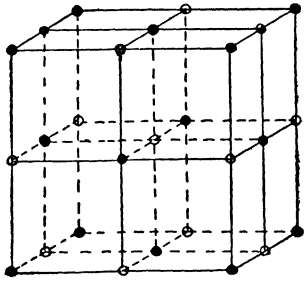


FIG. 37. The arrangement of the atoms, as it is in a crystal of common salt and many other similar substances. If the blackened circles represent sodium atoms, the open circles will represent the chlorine atoms in common salt. Equal distances separate all the atoms from their neighbors. In other types of crystals a different and more complex symmetry prevails.

Theory of Ionization. — In the preceding chapter, we spoke of three ways of exciting spectra in the laboratory, by the electric spark, the electric arc and the flaming arc. We have, consequently, got into the habit of designating lines in spectra by the terms, "spark lines," "arc lines," and "flame lines." These lines are produced by temperatures which are in a decreasing scale from

spark through *arc* to *flame*. In the spectrum of a sun-spot, the flame lines have greater intensities than the corresponding lines in the ordinary solar spectrum, due to the fact that the temperature of sun-spots (4000° C) is lower than that of the photosphere. In addition to the *decrease in temperature* from spark through arc to flame, there is also an *increase in pressure* in the gases emitting the light. All are familiar with the spark discharge produced in the laboratory by means of a vacuum tube.

Flash Spectrum. — The sun is the only one of the fixed stars which, on account of its proximity, permits us to examine its atmosphere in detail. This is possible at the time of a total eclipse, when the photosphere is covered by the moon, permitting the sun's atmosphere, called the chromosphere, to be investigated. Its spectrum is called the flash spectrum. If taken without a slit, the flash spectrum gives a direct measure of the height in kilometers that the gases of the chromosphere extend up above the photosphere. At increased elevations above the sun's surface, there is a very slow diminution in temperature but a very rapid decrease in pressure, or density, of the gases forming the chromosphere.

With the minute pressures of the sun's upper atmosphere, we have the conditions of a spark discharge. We speak of this by saying that the gas is ionized, by which we mean that one of the external electrons of the chemical atom has become dislodged. The atom is now a different individual than when it had its full quota of external electrons. Since each electron carries a unit charge of negative electricity, there is no longer an even balance between positive and negative electricity, but the now ionized atom has one unit of excess positive electricity. For this reason the ionized atom of calcium is designated Ca+.

The ionized atom, being constituted differently from the neutral atom, emits, or absorbs, light differently. In the spectrum the lines produced by the ionized atom are called *ionized* or *enhanced*. Sir Norman Lockyer was the first to call attention to the great importance of enhanced lines in the eclipse flash spectrum. His conclusions, in general, have been abundantly verified by more recent work at eclipses.

Although the flash spectrum is more or less a reversal of the ordinary solar spectrum, there are, nevertheless, great differences between the two spectra, particularly in the intensities of the lines.

In the flash spectrum, the enhanced lines have a much greater strength than the corresponding lines of the Fraunhofer spectrum. A discussion of the heights to which the gases rise above the photosphere gives unmistakable evidence that atoms forming the enhanced lines rise to much greater heights, for every element considered, than do the normal or neutral atoms. For instance, Ca+ atoms extend to heights of 14,000 kilometers above the photosphere, while the maximum height of the neutral atom of calcium is only 5000 kilometers. At increased heights, pressures are greatly diminished with the result that ionization takes place with greater facility.

In the year 1920, Saha embodied these ideas in his theory of ionization, one of the most important contributions to science of a decade which has been so filled with startling revelations. This theory has been of incalculable value in the interpretation of spectra.

Spectroscopic Stellar Parallaxes. — We have seen that the *apparent brightness* of a source of light depends not only on its *intrinsic brightness*, which we have popularly called "candle-power," but also on its distance. Hence, to determine the intrinsic brightness of different stars, from their apparent brightness, we must place them all at the same distance. It is usual to reduce the apparent brightness to the condition of a parallax of 0″.1, and under this condition the intrinsic brightness of a star is called its *absolute magnitude*. If m is the apparent magnitude of any star, M its absolute magnitude, and π the parallax of the star, then we have the simple formula:

$$M - m = 5 + 5 \log \pi$$

For, let B_1 and B_0 represent the *apparent* brightness at parallax π and the *absolute* brightness at parallax 0″.1 respectively. Then, $\frac{B_1}{B_0} = \left(\frac{\pi}{0.1}\right)^2$. Hence, $\log \frac{B_1}{B_0} = 2 \log \pi - 2 \log (0.1)$. But by the rule of Chaper XIII, $M - m = \frac{2 \log \pi - 2 \log (0.1)}{0.4} = 5 + 5 \log \pi$.

If, therefore, we know the apparent magnitude of a star and its parallax we can find its absolute magnitude, and, conversely, if we know the absolute and apparent magnitudes we may immediately compute the parallax.

In 1914, when comparing the intensities of lines in the spectra of two stars of the same spectral type, but of different absolute magnitudes, Adams and Kohlschütter found that although the vast majority of lines in the two spectra showed no differences in intensities, yet withal there were very appreciable differences in certain individual lines. In the stars which are called " dwarfs " (for reasons that will soon be apparent), certain lines become strengthened in intensity, while in the " giants " these lines are weakened and others strengthened. When this discovery, which has had momentous consequences for astronomy, was made at Mount Wilson there was no physical explanation for the correlation found to exist between line intensities and absolute magnitudes of the star. With the publication of the theory of ionization, it was found that on account of the physical conditions existing in the atmosphere of the star, particularly the temperatures and pressures, the ionized lines become strengthened in the giant stars while the flame lines are weakened in the giants but become stronger in the dwarf stars. Adams and Kohlschütter's discovery opened at once a new road to parallax determinations. If the parallax of a star has been measured, the absolute magnitude of the star is readily computed from the above formula since the apparent magnitude is known. By taking the results from all of the trigonometric parallaxes and others available, the spectroscopic observers derive curves connecting intensities of certain lines in the stellar spectra with absolute magnitudes. Up to the present, 2500 spectroscopic parallaxes have been published by Mount Wilson, 1105 by Victoria, and many others by Lockyer Observatory, Arcetri, Harvard and Yerkes. The methods followed differ mainly in the spectrum lines chosen for investigation and the manner of measuring or estimating intensities.

It is evident that spectroscopic methods must be standardized by first investigating stars of known absolute magnitudes. For this purpose are employed the data furnished by the trigonometric, the dynamic, and the indirect parallax methods. The proof of any discovery is successful predicting. This test the spectroscopic parallax methods meet brilliantly. The trigonometric method remains the only direct method of deriving stellar parallaxes. The disadvantages, compared with the spectroscopic method are the greater length of time necessary for the trigono-

metric method, in that it is necessary to accumulate a series of photographs in an interval spread throughout two years, and the practical limitation of its results, for individuals, to stars of less than 500 light-years distance. The spectroscopic method applies to stars, however distant, if they give light sufficient to yield good photographic spectra.

In the immediate future, both methods will be followed with great zeal, for it is still necessary for the trigonometric observers to

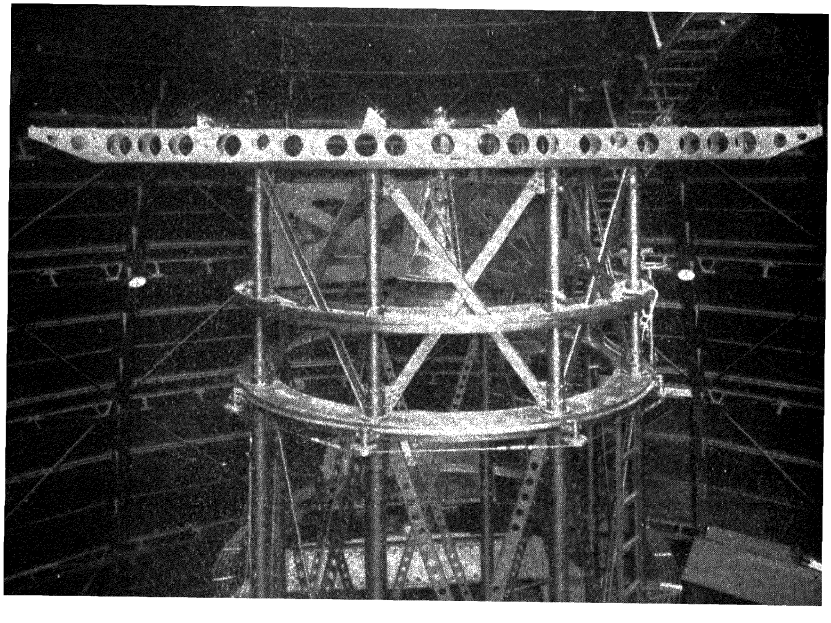


PLATE 50. STELLAR INTERFEROMETER. (Mt. Wilson Observatory.)
The steel beam, 20 feet long, is fixed to the top of the tube of the 100-inch refractor. The four triangular projections act as mirrors to bring two separated beams of light from a star and cast them downwards to be observed for interference. When the distance of the two outer mirrors is just sufficient, the interference disappears, and the diameter of the observed star is calculated.

furnish more stars to be used as standards by the spectroscopic observers. So rapidly has this part of astronomy developed within the first quarter of the twentieth century, that what looked perfectly hopeless in 1900 is now an accomplished fact. That is, the actual motions and distances of the stars can be laid down to scale so extensively that the boundaries of our system, the main features

of its migrations, and the actual diameters of some of its members are known. Before giving this picture as we may draw it now, we must explain how we know anything about the star diameters, for as everybody knows, the stars are all too distant to give real images in any telescope.

Diameters of the Stars. — In 1920, Michelson announced that he had succeeded in measuring the angular diameter (0″.046) of Betelgeuse, the brightest star in Orion. The work was carried out at Mount Wilson under his direction by Pease by a method using the interference of light. It is that property of light vibrations so beautifully seen in the colors of oil films in the streets on a rainy day, and in the colors of soap-bubbles. A long beam of structural steel was fixed to the upper end of the tube of the 100-inch telescope on Mount Wilson, seen in Plate 50. On this steel beam were two light-collectors (small mirrors) which could be set at any distance apart up to the length of the beam, or about 20 feet. The starlight from these two mirrors was reflected together and examined in an eye-piece. Alternations of bright and dark, called "fringes," resulted. But it was found that with a certain separation of the two light-collectors, the fringes almost disappear. For then the bright fringe produced by light of one side of the star falls on the dark fringe due to the other side. At this position, the separation of the two light-collectors is measured, and the theory of the instrument shows how to calculate from it the diameter of the star. Knowing the angular diameter of Betelgeuse, its diameter in miles follows immediately if we know the parallax. All we need is to remember the definition of parallax, the angle at the star subtended by the distance (93,000,000 miles) from earth to sun, while the star's diameter is the angle at the earth (or sun) subtended by the diameter of the star. By trigonometric methods, the absolute parallax of Betelgeuse from the measures made at Allegheny, McCormick, Mount Wilson and Yerkes Observatories is $+0''.016 \pm 0''.003$. Hence, D, the diameter of Betelgeuse in miles, is found from the simple formula:

$$\frac{D}{93{,}000{,}000} = \frac{0''.046}{0''.016}$$

D is equal to 2.9 astronomical units, or 270,000,000 miles. The distance of sun to Mars is 141,500,000 miles. If, therefore, the center of Betelgeuse were placed at the center of the sun, its surface

would extend out almost to the orbit of Mars. It needs no stretch of the imagination to look upon this star as a " giant," for it has a diameter 300 times greater than that of the sun.

Stellar Diameters from Their Spectra. — As we have said several times, all that we have learned about the heavenly bodies comes to us in the story told by their light. The quantity of light which a star sends us depends, first, on its temperature; second, on its size; third, on its distance. Two objects totally different in make-up, like the incandescent mercury vapor in a Cooper-Hewitt lamp on the one hand, and a solid bar of carbon on the other, if heated equally hot, would give quite unequal amounts of light. But huge balls of gas, like the stars, are nearly enough alike in character so that we may fairly suppose that if at equal temperatures their surface brightness will be roughly equal. In that case, the total light they emit will be proportional to their surface areas, or to the squares of their diameters.

How shall we take account, though, of differences associated with different temperatures? Fortunately, in the laboratory the relations of temperature and total radiating power have been determined, and also the distribution of energy in the different colors. Even in those parts of the spectrum which, invisible to the eye, lie beyond the red and beyond the violet, these radiations are known. It is true that such studies have yielded exact laws only when applied to what is called a " perfect radiator," or " absolutely black body." But the distribution of energy in the spectrum of the sun and the brighter stars shows that these heavenly bodies are not widely departing from the conditions of the " perfect radiator." Hence, these laboratory laws are approximately applicable.

Such being the case, we are able to assign approximately the surface temperatures of the stars. Then we can observe their total output of radiation compared to that of the sun, which is known. For instance, the star Capella seems to be of a temperature of 5800° Absolute Centigrade, compared to the sun's 6000°, and sends us as much light on two square miles of the earth's surface as the sun does on one square centimeter (which is near the area of one's third finger nail). Knowing these facts, and the distance of Capella, we can compute from them that a " perfect radiator " at Capella's temperature, of 5800° Absolute Centigrade, must be no less than 11,000,000 miles in diameter to equal this bright star

Yet Capella is by no means unusually large, and quite middling in temperature. Applying the same methods, the following results have been found by Abbot for nine of the brightest stars. In the last column is given, for comparison, some results reached earlier by the interferometer.

STELLAR TEMPERATURES, RADIATION AND DIAMETERS

Star	Absolute Temperature Centigrade degrees	Radiant energy Square miles of earth's surface per horse power [1]	Diameter in miles	
			Abbot with Nichols Radiometer	Pease with Michelson Interferometer
Rigel	16,000	6,600	18,000,000	—
Vega	14,000	4,500	1,800,000	—
Sirius	11,000	3,200	1,100,000	1,900,000
Procyon	8,000	17,200	1,000,000	—
Capella	5,800	9,700	11,400,000	—
Aldebaran	3,000	8,400	61,000,000	35,000,000
Beta Pegasi	2,850	19,000	83,000,000	72,000,000
Betelgeuse	2,600	2,700	445,000,000	270,000,000
Alpha Herculis	2,500	5,900	790,000,000	—
Sun	6,000	0.000000213	864,000†	—

[1] Neglecting atmospheric absorption. Compare the areas with that of Massachusetts, 8266 square miles.

† Diameter measured trigonometrically.

Densities of Giant M-Stars. — Since the diameter of Betelgeuse is 300 times that of the sun, its volume is $(300)^3$ or 27,000,000 times that of the sun. All that we know of star masses, both by theory and by observation, indicates only a small range thereof. If we assume that the mass of Betelgeuse is as much as five times the solar mass, then the density of Betelgeuse is about one-millionth that of water, or one-thousandth that of the air we breathe.

Giants and Dwarfs. — The extraordinarily great diameter of Betelgeuse compared with that of the Sun or Sirius is a very striking fact. Here we come by the front door of actual diameter measurements to a remarkable subject first entered upon by the back door, as one might say, of stellar magnitudes. It is the classification of the stars into the " giants " and the " dwarfs." These happily descriptive terms were chosen by Hertzsprung, who,

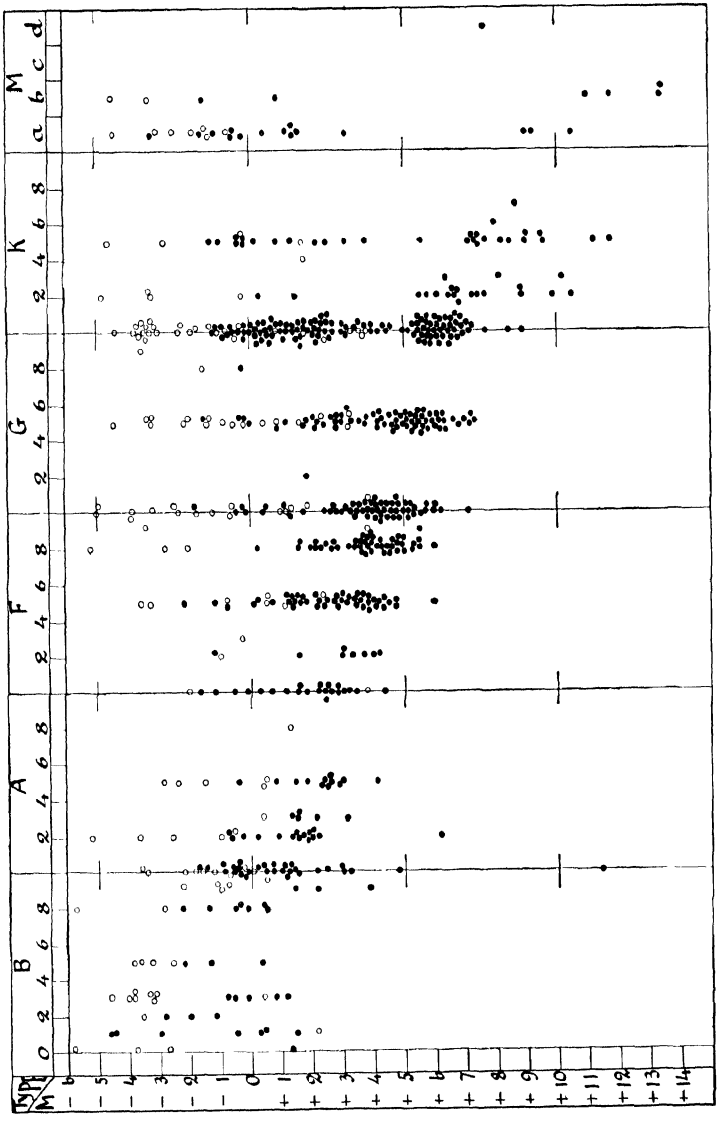


FIG. 38. CONNECTION BETWEEN SPECTRAL TYPES (plotted horizontally) AND ABSOLUTE MAGNITUDES (plotted vertically).

The black circles are for stars where the McCormick parallax is greater than 0".01; the stars represented by open circles have parallaxes less than 0".01, or approximatley the same size as the probable error.

with Russell, shares the discovery. By the latter, however, the more telling part of the work was done. Russell collected in the year 1913 all the stars, numbering between 200 and 300, whose distances were then approximately known, and calculated their absolute magnitudes. He divided the stars among the spectrum classes B, A, F, G, K, M, and made a diagram, now generally known by his name, by plotting the absolute magnitude of each star against the spectral type. In Fig. 38 is a similar diagram plotted from 675 stars whose parallaxes were measured at the McCormick Observatory by trigonometric methods. Every dot is a star. The dots arrange themselves along two lines, one placed horizontally at the top of the diagram, known as the "giant branch," the other inclined downwards, known as the "dwarf branch" or "main-sequence branch." Our sun is a dwarf, of type G0 and absolute magnitude 5.0. Three striking results appear:

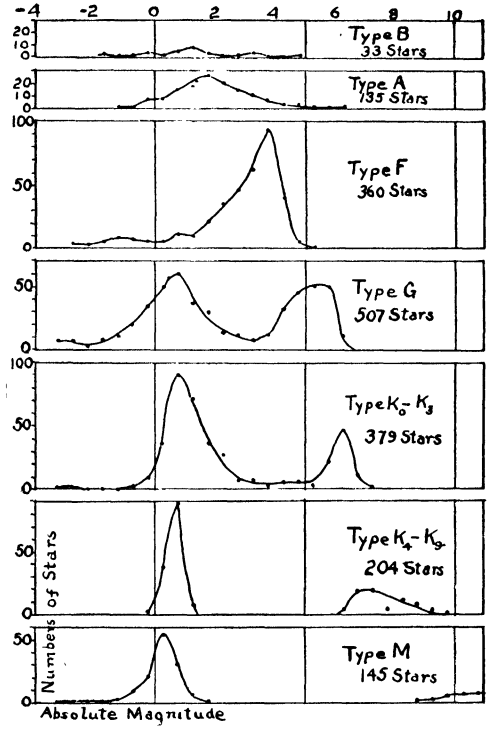


FIG. 39. GIANT AND DWARF STARS.

These results show very clearly for a larger number of stars the same distinctions which are shown in Fig. 38. The complete separation into very bright and very faint groups in the red stars of types K_4 to M, the nearly complete separation in types G to K_3, and the entire absence of such separation in types B and A are very evident.

1. All of the stars of the diagram, with few exceptions, lie close to either the giant or dwarf branch.

2. In classes B and A, there are no intrinsically *faint* stars. The exceptions are a few "white dwarfs" like o^2 Eridani and the companion of Sirius.

3. With the stars of M-type, there are no stars lying between

the giant and dwarf branches. The stars are either very bright or very faint.

Russell's generalization was strongly confirmed when the rich spectroscopic-parallax results of Adams became available. Adams' diagram for nearly two thousand stars is shown in Fig. 39. The classes B and A, to which spectroscopic results did not at first extend, are filled in by means of information of absolute magnitudes derived by Jackson and Furner from studies of double stars. That there are so few stars of the faint classes of dwarfs, K and M, is doubtless not so much due to the fact that these are absent in the sky, as that they are too faint to be readily photographed with the spectroscope.

Already when Russell found the classification into giants and dwarfs prevailing among K and M stars, it was well known by common observation, as well as by the exact work of Wilsing and Scheiner, that blue and white stars must be much hotter than red ones. Hence, it was no surprise that these stars were of smaller absolute magnitude (greater brightness) than many of the red ones. Yet one group of red stars as bright as the blue ones was found to be 10 magnitudes, or 10,000 times, brighter than another group of red stars. That no red stars lay between these extremes of brightness could only mean that two very distinct classes of stars having identical spectra must be recognized, of which one appeared to have 10,000 times as great areas, or 100 times as great diameters as the other. If the diameters were 100 times as great and the densities equal, the giants must have 1,000,000 times the mass of the dwarfs.

But studies of double stars, as we shall directly see, cut off this possibility. Quite to the contrary, in averages of considerable numbers, the stars do not seem to differ as much as 10-fold in mass. Individually, of course, there may be a few exceptionally large and small ones. This small range of masses and immense range of volumes drives us to the final conclusion, which we have already reached in the case of Betelgeuse, that the giant red stars must be nearly a millionfold less in average density than the red dwarfs. Thus, if the dwarf red stars are as dense as our earth, and surely that must be nearly the maximum possible for them, the giant red stars *must be about as rare as the gas in an old-fashioned lever vacuum pump worked to highest possible exhaustion.*

In other words, the density differs more than the heaviest solid metal, platinum, differs from the lightest gas, hydrogen, at atmospheric pressure. We shall see in another chapter how these facts have changed our ideas of how the stars grow old.

CHAPTER XVI

THE SYSTEM OF OUR STARS

Besides myriads of separate, steadily shining stars, crowded into cloudlike proximity in the Milky Way, our system contains great numbers of associated stars, star clusters, stars of variable brightness, and bright objects not at all starlike in photographic appearance.

Double Stars. — If two stars bright enough to be seen with the naked eye lie close together, the probability is very great that they are really revolving about a common center in mutual gravitational control. In so enormous an area as the whole sky, containing only about 5000 visible stars, only very seldom can two of them accidentally lie in close proximity. Of the thousands of double stars discovered by assiduous telescopic observation from Sir William Herschel's time till now, a large number have revolved through a part or the whole of an orbit since their discovery. The facts relating to these stars are carefully set forth in the great publication of Burnham, an enthusiastic double-star observer of great reputation in this field. Still more numerous are the close double-star observations of Aitken, who is now (1927) engaged in a revision and extension of Burnham's Catalogue.

Measures of Doubles. — For work of first quality, a visual refractor is employed, of large aperture and under fine conditions of seeing. A *filar micrometer* is used, consisting of one fixed thread and another thread moved by a very accurate screw. Measures for *position angle* and *angular distance* are made. The position angle of the component with respect to the principal star is measured from 0° to 360°, from the north point through the east. Distances are measured by first placing the fixed thread on the principal star and the moveable thread on the component, and then reading the head of the micrometer. If, now, the position of the threads is reversed and a second record is made, a measurement is secured for double the angular distance. Measures of doubles are also made from photographic plates. With large telescopes, it is found that visual measures are superior to those made from photographs, if the angu-

lar separation is less than 2″. With a greater separation, the accuracy of measures from photographs may be equal or even superior to the best visual measures.

Orbits of Double Stars. — It is beyond the scope of this book to enter fully into this question. We are, however, greatly interested in two of the quantities that come from the discussion of the orbit: (1) the *period* measured in years that it takes for the fainter star of the double to make a complete revolution about the brighter star; and (2) the *mean distance* (measured in seconds of arc) separating the two components of the double.

Optical Doubles and Physical Doubles. — The former name is given to stars that happen to lie near each other in the field of view of the telescope, while the latter name is given to those physically connected. Evidence of this connection is shown by orbital motion or by a common proper motion. A physical double is called a *binary* star, or more generally a *visual binary*, in order to distinguish it from an eclipsing binary and a spectroscopic binary.

Eclipsing Binaries. — Two other types of double stars are equally interesting. First are the eclipsing variables. These pairs lie too close together to be distinguished separately by the telescope, but in mutual revolution they partially or wholly eclipse each other. Hence, they produce a periodic variation of the brightness of what we see as one star, which is really two. The most celebrated of these systems is Algol, or Beta Persei.

Spectroscopic Binaries. — A second class of double stars is that of the spectroscopic binaries. Of these, Capella, one of the brightest stars, is an illustration. As we have said, the spectroscope measures velocities in our line of sight. Spectroscopic binaries are discerned because, owing to their mutual revolution, the line-of-sight velocity varies. Sometimes, as indeed with Capella, the two stars are so nearly equal in light that both give measurable spectra. In this case, the Fraunhofer lines cross over each other, as the two stars revolve, because first one and then the other star is revolving towards us. More often, only one spectrum is observed, but its lines shift their positions compared to laboratory spectra. Eclipsing variables are, of course, always spectroscopic binaries, unless one component is too small to produce motion detectable as line-shifting in the other by its gravitation.

Masses of the Stars. — Without these numerous double stars

we should be at loss to know the masses of the stars. Newton's law of gravitation yields a formula connecting masses and times of revolution with the distance of separation. We may regard the earth and sun as a binary star, and by applying the formula we may compare the masses of the double stars with that of the sun. Usually the only trouble in the process is in measuring the distance of the two stars apart. There is a different kind of dilemma for each of the three different kinds of double stars. Visual binaries observed by the telescope yield only angular separations. These angular values can be reduced to actual distances only if the parallax of the system is known. Such is the case with Sirius, Procyon, Alpha Centauri, Alpha Crucis, among the very bright stars, and less accurately with Rigel. There are, however, also a considerable number of fainter visual binary stars for which the parallax is well known.

The visual binaries obey Kepler's three laws of motion. As we have seen, these laws are simply a statement of the fact that gravitation is universal. Let us now compare two stellar systems. One system is the sun and the earth; the other a double star system, of masses m_1 and m_2, with period p, measured in years, and mean separation, a, measured in seconds of arc. Kepler's Harmonic Law can be applied, if all of the quantities entering into the formula are in the same *units*, for the sun-earth system and the double star system. If we know the parallax, π, of the double star system, then $\frac{a}{\pi}$ gives the *mean distance* separating the double stars measured in astronomical units. Hence, if the masses m_1 and m_2 are measured in units of the sun's mass (that of the earth may be neglected), then we have for the mass of the double star system:

$$(m_1 + m_2) = \frac{a^3}{\pi^3 p^2}$$

Eclipsing variables yield no means of measuring the separation of the two stars. They do indicate how large each star is, compared to their distance apart, what proportion of the combined light each star gives, and how much inclined the orbit plane is to a plane at right angles to our line of sight. If we suppose that the two stars are equal in mass, we can also find their densities compared to the sun. Most of them have densities much smaller than the sun.

Spectroscopic binaries fail to indicate precisely either their distance apart or the inclinations of their orbits. They give us a quantity which depends on both. If a spectroscopic binary is also either a visual or an eclipsing binary, the whole problem is solved, for in either case we then know the inclination of the orbit, and can find the distance apart of the two stars.

All three kinds of double stars yield the length of the period of revolution. Many of the visual binaries move so slowly that we shall have to wait many more years before they will have traveled far enough in their orbits to give the period accurately. On the other hand, eclipsing variables and spectroscopic binaries have such very short periods of revolution that within a few years of discovery their times are known to a very high precision. As we have said, the double stars are weighable against the sun just as soon as the period and distance apart are found. While the distance apart is not known in the cases of many of the spectroscopic binaries, we can always assign to it the minimum possible value. Furthermore, if we collect the values for a large number of orbits, it follows that, because their inclinations will be distributed at random, we can estimate the average inclination, and from it the average distance of the pairs apart, and from this their average masses.

In one way or another, therefore, we have learned a great deal about star masses from double-star measurements. In the following paragraphs there is a summary of the kind of information these stars teach us.

Visual binaries, like other stars, are crowded towards the Milky Way, and this effect is more exaggerated among them than among single stars. The closer the pairs, the more numerous, relatively, they are in the Milky Way. Whether in the Milky Way or not, close pairs are far more numerous than wide pairs. Visual binaries tend to frequent the yellow and light-red classes of stars, while eclipsing and spectroscopic binaries strongly prevail among blue stars. Of 14 visual binary systems, mainly of yellow stars, well known in the year 1918, and enumerated by Dr. Aitken, the average combined mass of the pair was 1.76 times that of our sun. Of 32 spectroscopic binaries, nearly all blue or white stars, which he enumerates, the average minimum mass of the brighter star was 5.1 and that of the fainter 4.3 times that of our sun. Though

these latter figures are but minimum values, because the inclinations of the individual orbits were not known, they could not reasonably be more than twice as great.

Hence, we may draw the conclusion that stars in general are of about the same mass as our sun, but the blue and white ones are rather more massive, yet not often tenfold more so. This is the sort of evidence which, with the recent results on star diameters, goes to prove that some giant stars are far rarer in their constitution than our atmosphere, while some dwarfs are several times denser than water, and not much different from our earth in that respect.

The System of Sirius. — Sirius and its companion make one of the most interesting systems in the sky. Discovered to be a double star in 1862 by Alvan G. Clark, it has been under continued observation ever since. Its orbit is well-determined, with a period of fifty years. Since the parallax is accurately known, the mass of the system is found to be 2.5 times that of the sun. Moreover, Sirius is a little more than three times more massive than the companion and hence the mass of the companion is about 0.6 that of the sun. Sirius, however, gives 10,000 times more light than the companion. The latter is a " white dwarf " of spectral type F0 and temperature 8000°. With these results, Eddington has found that the companion is smaller in diameter than Uranus, and that consequently the density must be 50,000 times that of water, or 2500 times heavier, volume for volume, than platinum. And yet this star, with its enormous density is a gas which obeys the laws of " perfect " gases! It was announced by Eddington from theoretical conclusions depending on the theory of relativity, that on account of the great density of the companion of Sirius the shift of its spectral lines would be about equal to that produced by a velocity of 20 kilometers per second. At the Mount Wilson Observatory, by means of spectra taken with the 100-inch reflector, Adams has confirmed these interesting conclusions. These results have far-reaching consequences: (1) The relativity shift as predicted by the Einstein theory is confirmed. (2) It is necessary to conceive of an atomic structure, such that stellar matter may obey perfect gas laws with the enormous density of 50,000 times that of water. This leads to the assumption that the external electrons of the atoms, under the conditions existing in the com-

panion of Sirius, are knocked off, with the result that the atomic fragments may approach much more closely together without interference than is possible under ordinary conditions.

We shall again refer to this interesting system in Chapter XVII since it affords a splendid illustration of how beautifully the advances in physical and astronomical science go hand in hand.

New Stars, or Novæ. — A brilliant star appeared, in November 1572, in the constellation Cassiopeia, where none had ever been seen before. The famous astronomer Tycho Brahe made a careful record of it. From the eleventh day to nearly the end of November, it was brighter than any of the fixed stars, exceeded the light of Jupiter, and almost rivalled Venus in luster. Some people even saw it in daytime. Soon it began to decline, and by March, 1574, became invisible.

Kepler, Tycho's great pupil, also records a wonderful new star which was first seen on October 17, 1604, in the constellation Serpentarius. This star also, for a time, exceeded the brilliance of any of the fixed stars and planets, except Venus, but soon faded, and ceased to be visible after about a year.

In the first quarter of the twentieth century, we have seen two brilliant new stars, Nova Persei of 1901, and Nova Aquilæ of 1918. Neither was quite the equal of these famous earlier ones, but both were bright enough to rival any of the fixed stars. They were eagerly watched by skilled telescopic and spectroscopic observers, so that the history of such outbursts is now pretty well known. Nova Persei was discovered on February 21, 1901, by Rev. T. D. Anderson, of Edinburgh, Scotland. It was then of 2.7 magnitude and shone with a bluish-white light. There was a rapid increase in brightness until, on February 23, it reached 0.0 magnitude, and was then brighter than any fixed star except Sirius and Canopus. An immediate search of the photographic plates of the Harvard College Observatory showed that on February 2, 6, 8, 18, and 19, 1901, up to within two days of Dr. Anderson's discovery there was no star there as bright as 10.5 magnitude. Later it was discovered to have been of about the fourteenth magnitude before the outburst.

After reaching its maximum on February 23, the brightness almost immediately declined, and by February 28 had reached the second magnitude. A temporary slight recovery was followed by a further decline, so that by March 18 it reached the fifth magnitude.

Then began an almost periodic fluctuation, with extremes about two days apart. For instance, on March 19 and 21, the magnitudes were 6.5 and 4.7 respectively, showing a range of nearly sixfold in brightness within two days.

So the fluctuations went on, but gradually with longer intervals and decreasing brightness, until by summer the condition became fairly steady between sixth and seventh magnitude. Slow decline continued, and by July, 1903, the brightness reached the twelfth magnitude. It has fluctuated between that and the fourteenth ever since. From February 23, 1901 to July, 1903, there was a range of over 60,000-fold in brightness! The Harvard photographs showed, however, that within a few days, in February, 1901, the star's brightness rose quite as much, from the fourteenth to the second magnitude.

To the spectroscope, the changes of the star were also interesting. On the first few nights, the spectrum was that of a white star of the ordinary A type, but quickly changed to one of numerous bright and dark lines, which is typical of the new stars. On March 19 began a series of fluctuations of the spectrum, corresponding with the beginning of the wide fluctuations in brightness. The spectrum was unusual, that is, different from ordinary new-star spectra, at the times when the brightness was at minimum. It would lie outside our scope to study the details of these changes.

Still another surprise was in store. In August, 1901, it was reported by French observers that a faint nebula surrounded the new star. This was soon photographed many times. The photographs showed a perfectly astonishing development. There appeared rings in the nebula which expanded in radius at a rate no less than 2 or 3 seconds of arc per day! There is no known proper motion among all the stars as much as a fiftieth part as great as this.

What could it mean? The answer depended on a measurement of the distance of Nova Persei. The parallax came out only 0.01 seconds. Hence, the star is about 300 light-years distant. A motion of two seconds of arc per day at that distance means a velocity of about 220,000 miles per second. This is about the velocity of light. The difference might easily be explained by the roughness of the observations. Astronomers believe that the apparent motion of the nebula was really the outrush of light from the star. The outburst of light, traveling 186,000 miles per second, illuminated

successively more and more distant parts of nebulous surroundings, that had been dark before.

Perhaps the most impressive thing about the whole matter is that the catastrophe happened three centuries ago. To us the star was new in February, 1901. In reality, Elizabeth was Queen of England when it happened, and the Pilgrims had not yet landed at Plymouth rock. It took light, Nature's swiftest messenger, 300 years to bring us the tidings.

A quarter of a century after its discovery, Nova Persei is still visible in a fair sized telescope. Its light is fluctuating, at times being brighter and at other times fainter than the thirteenth magnitude.

Distribution and Number of Novæ. — There are some interesting data about the new stars, as a class, which Lundmark has recently collected. In the first place, note their arrangement in the sky. Of 78 bright new stars recorded since Tycho Brahe's time, 35 were within the Milky Way, 22 within the bounds of the Great Nebula of Andromeda, 6 included by other spiral nebulæ, and 2 within nebulæ not spirals. Thus, of the whole 78, only 13 were disconnected with the Milky Way and nebulæ.

The average gain of brightness of 21 new stars over their former estate was 9.5 magnitudes, almost 10,000-fold. They all appear to return to their original brightness within a few years. They are usually very distant, probably of the order of hundreds or thousands of light years. Thus, the real moments of the flashing up of many that have been observed since Tycho Brahe's time were probably quite as long ago as the building of the pyramids.

Some novæ have apparently expanded so as to present telescopically real disks, not mere points or spurious disks like ordinary stars. It is possible that this indicates an explosion from within. The occurrence is not so rare as one might think, for we must remember that it is only when a new star becomes bright that it is noticed. Bailey estimates that at least 9 novæ each year reach the tenth magnitude, or brighter. At this rate, there must be hordes of them that are still fainter. Lundmark, therefore, suggests that since the life of the stars is very long, and their numbers limited, as we have seen, there must be a fairly large percentage of stars that have the experience of becoming novæ at some time in their careers. Eddington remarks as food for thought

that they are apt to be recruited from stars in some such state as our sun. If such a catastrophe should come to it, the Biblical description of the end of things on earth, " when the elements shall melt with fervent heat," would be very appropriate.

Variable Stars. — We have already spoken of two strongly contrasting types of stars whose light varies. They are the eclipsing double stars and the novæ. The one is perfectly regular in its periodic changes, the other has a paroxysm of brightness once for all, and then fades into an irregularly fluctuating faintness.

There are other types of variables. One of the classes most widely observed is the *long period variables*, including stars with periods of one hundred days or more. The typical star of this kind is Mira (Omicron Ceti). Its average period between maxima of brightness is 330 days, but individual periods differ from this over a range of 40 days either way. At minimum, the light of the star is not always the same, but ranges from eighth to ninth magnitude. Much greater differences occur at maximum. Sometimes the peak of brightness reaches the second magnitude, and sometimes does not exceed the fifth. Thus, the range of brightness in some periods is as great as 300-fold, while at others it is less than 50-fold. The rate of increase from minimum to maximum is more rapid than the rate of decrease from maximum to minimum. Another star of the same type is Chi Cygni. This star has a very large range of brightness, sometimes reaching 4000-fold. Its period is about 406 days.

The Sun a Variable Star. — Our sun exhibits some of these characteristics, but far less conspicuously and more deliberately. In the eleven-year period of sun-spots, there is a range of solar brightness which differs from period to period, but is not yet known to have exceeded 3 per cent, or about 0.03 magnitudes. The sun-spots rise to maximum numbers much more quickly than they decline from maximum to minimum. Their numbers at maximum are variable over two or threefold. Whether the range of the sun's actual brightness behaves as the sun-spots do, the observations are as yet not long enough continued to prove. However, the sun is certainly brighter at times of maximum sun-spots and varies irregularly.

About half way between the Mira type and the new stars is the extraordinary variable star Eta Argus. It varied irregularly, from 1750 to about the year 1832, between second and fourth

magnitudes. Increasing in brightness in 1843, it was nearly equal to Sirius. By 1869, it ceased to be visible to the naked eye, and is now only 7.5 magnitude. Like Nova Persei, Eta Argus is surrounded by nebulosity which is sometimes called the "Keyhole nebula."

Cepheids. — Another type of variable star is very important for several reasons. It is called the Cepheid type, after the star Delta Cephei. The variability in this class is of short period, ranging from eight hours to twenty days, as a rule. Many such stars have been found in the Megellanic clouds and in the globular clusters. Those of a single globular cluster must all be nearly equally distant from us, because the cluster is so distant that in comparison with its distance from us, all its objects are near together. Hence, the apparent relative changes of brightness of cluster variables indicate truly their real relative changes. This led Miss Leavitt to a discovery, afterwards greatly expanded by Shapley, namely that the cluster variables of equal brightness have equal periods. Shapley even arranged a scale connecting periods with brightness, so that to any Cepheid whose period is known the absolute magnitude can be assigned. In short, a Cepheid variable star is regarded as a standard object whose absolute brightness is ascertained from a knowledge of its period of variation. This is known as the "period-luminosity" law. Shapley used this fact, as we shall see, to measure the distances of the star clusters.

Although the spectroscope seems to indicate that Cepheid variables are double stars, they are not so. The distance between the supposed pairs turns out to be impossibly small. They would have to be in contact, or even lying within one another. The type of spectrum changes as well as the radial velocity. Cepheid stars become redder at their minimum brightness. At this time, too, the star appears to be receding with almost maximum rapidity from us. This could not be the case if the minimum were due to an eclipse. At such a time, the two stars of an eclipsing variable would be moving at right angles to our line of sight, and there would be no relative radial motion.

It is now generally believed, as suggested by Shapley, that the variation is due to a pulsation of the star. He imagined alternate expansion and contraction to be taking place. Such a change

would no doubt produce large changes of temperature, suitable to effect the changes of color and of spectral type just mentioned. Cepheid variables appear to be extremely massive. The pulsation hypothesis as to their variation is highly interesting, as we shall see, in its relation to the source of heat which sustains star radiation over such immense periods as are involved in star life.

Star Clusters. — Already we have noticed that stars sometimes go in groups together. The Pleiades, the Taurus stars, the Ursa Major cluster, are all examples of families of hundreds of stars

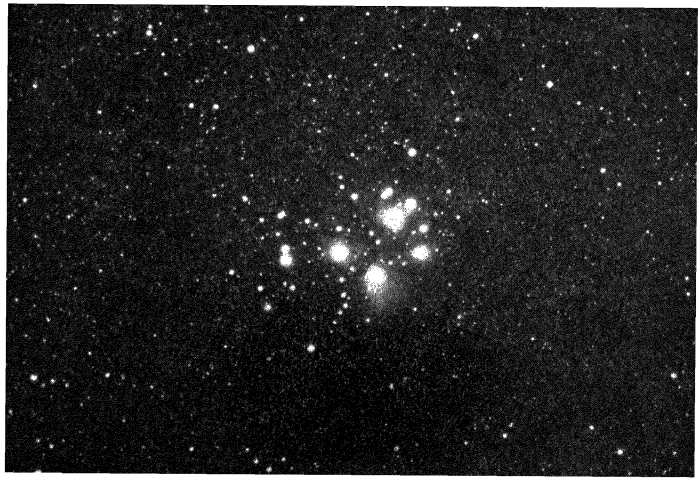


PLATE 51. THE PLEIADES AND ASSOCIATED NEBULOSITY.
(Lick Observatory.)

that are traveling together. If we could get far enough away we should find these groups closed up, so that we should not need the tedious comparison of proper motions to convince us that they were really physically connected.

There are many star clusters, especially in the Milky Way, that are so remote that they present this clear evidence of physical connection. For instance, there is the open cluster Præsepe in the constellation Cancer, and many others. All of these clusters are found to be within our own stellar system. The distances, the magnitudes, and the colors of the individual stars, all bear so great a similarity to those of stars surrounding them that there can be no doubt of it.

There is another story to tell of the globular star clusters. Take the Hercules cluster for example, which is shown in Plate 42. To the naked eye but a small, faint, insignificant patch of light, hardly even noticeable indeed, a great telescope brings it out as one of the most beautiful objects in the heavens. There is a perfect host of stars, so closely packed that they resemble bees in a swarm. On a photograph of five hours exposure with the 60-inch reflector on Mount Wilson, Pease and Shapley recorded 35,000 stars of this cluster, all within an area only two-thirds the diameter of the moon.

It is not believed that this number of stars, great as it is, at all represents the real population of the Hercules star cluster. The fact is that this system lies far, very far indeed, beyond the most of the great star host of our own Galaxy. According to Shapley, the distance is 33,000 light-years. At such an immense distance, even a 5-hour exposure with the 60-inch reflector cannot take the impress of intrinsically faint stars. It is as if we should stop with the seventeenth magnitude in our own system. We may well suppose that if all the stars to the same degree of faintness could be photographed in the Hercules cluster that exist in our Galaxy, the number would run into millions.

Shapley has determined the distances of the globular star clusters in many ways. One of the best is through the Cepheid variables that occur in some of the clusters. As we saw above, by taking into account known distances of some of these Cepheid stars which are found moderately near us, he drew a curve which shows the absolute magnitude in terms of the period of variation. The curve is very well supported by all the observations, so that it seems fair to assume that all Cepheids, wherever they are, can be assigned absolute magnitudes as soon as their periods are observed. Hence, knowing the absolute magnitudes and deriving the apparent magnitudes of the Cepheid variables from the direct photographs, it is only a step forward to derive the parallaxes, or the distances, from the formula on page 211.

With this scheme and several other independent ones, Shapley obtained closely accordant values of the distances of the globular clusters. These range for the various clusters from about 20,000 to over 200,000 light-years. We must suppose, therefore, that in these objects we see other galaxies of stars than ours. We cannot

tell if any of them have equally as numerous a star population as ours, but there is no good reason to doubt that some of them may. We are seeing some of these distant star systems by light which began its journey probably long before there were men on earth. None of them began to send the light we now see as recently as the time when the first glimmerings of human history began. All the wars and empires of ancient and modern times have been carried on while these flying beams which are just arriving were yet in mid-course in the heavens.

Shapley points out some queer things about the distribution of the globular clusters in space. Though in nearly equal numbers on both sides of the plane of the Milky Way, there are none within 4000 light-years of that plane itself. Their numbers increase as they came nearer the Milky Way up to a certain limit, and then come to a full stop. Moreover, the globular clusters are not scattered all around the ring of the Milky Way, but 48 out of the 69 known lie within one quadrant. It is the quadrant of the great line of preferential motion spoken of in the following chapter. Not a single globular cluster lies in the quadrant opposite to this preferred one.

Suppose we could take up our abode on some habitable spot in a distant cluster, for instance, in the one called " N. G. C. 7006," which Shapley puts at 220,000 light-years distance. We should require a large telescope to make out the brightest stars of our own Galaxy. Probably we should discern that it had a somewhat elliptical shape, corresponding to the extension along the Milky Way. Similarly, Pease and Shapley have observed ellipticity in nearly all of the globular clusters.

In one respect we should find our own Galaxy exceptional. It would show no such concentration of stars in its middle portion as some of the other clusters. Thus, in " N. G. C. 5272 " are found no less than 15,000 stars, which, seen from the earth, exceed the 20th magnitude, all lying within 30 light-years of its center. There are probably but four or five stars actually as bright as these lying within 30 light-years of our sun.

The Nebulæ. — Having considered the solar system, including the sun, planets, asteroids, moons, comets, and meteors; the stars of our system, among whom the sun is just an average one in luster and size; the double stars, variables and new stars; and the great

globular clusters which seem to be remote systems comparable in many respects to our own Galaxy; there still remains in the celestial compass other types of objects called nebulæ. "Cloud-like" they are named, and justly so. Yet they are not at all in the nature of clouds, for they have no relation to our atmosphere, but lie among the stars and star clusters, at tremendous distances.

There are several kinds of nebulæ, very different in appearance and in nature. If we photograph the group of the Pleiades, all of

PLATE 52. THE RING NEBULA IN LYRA.
(Mt. Wilson Observatory.)

the familiar bright stars will be found wrapped in nebulosity as if in bridal veils. The great nebula in Cygnus seen in Plate 43, and the angry-looking great nebula in the sword of Orion, shown in Plate 47, which seems so like a star to the naked eye, are other examples of these diffuse, irregularly-shaped kinds of nebulæ. Viewed in the spectroscope, many of the irregular nebulæ show a discontinuous spectrum of bright lines, in contrast to the continuous dark-lined spectra of the stars. Hydrogen is conspicuously present, but there is no counterpart in the laboratory to some of these bright nebular spectral lines. They appear to represent an unknown substance, or an unknown modification of a familiar one, called nebulium.

Related to these diffuse and irregular bright-line nebulæ by a similarity of spectrum, are the annular, or planetary nebulæ. They also give bright-line spectra of the type just described. In form, however, they are exceedingly different. For example, there is the Ring Nebula in Lyra, shown in Plate 52, with its central star, reminding us distantly of the rings surrounding the planet Saturn.

Curtis has listed 78 planetary nebulæ visible in the northern skies, of which 56 show conspicuous central stars. Hubble concludes that all bright nebulosity may reasonably be thought to derive its light from involved or neighboring stars. He finds a remarkable relation between the light of the nebulæ and the light of their involved stars. If the spectrum of the involved star is of a type " earlier " than B1, that is of type O or B0, for instance then the associated nebula will show bright lines. If the star has a spectrum of later type, as B5 or A, for example, then the nebula will show a continuous spectrum of dark lines. None of the nebulæ are associated with yellow or red stars.

Hubble believes that the light of stars involved and associated with nebulosity is weakened to our view by this circumstance. It is the starlight itself, he thinks, which gives the nebula the power to glow, either by scattering, as our atmosphere scatters sunlight, or by absorption and re-emission. He finds only one case of a galactic nebula without a dominating star, and this may possibly be a case where the nebula itself obscures the star.

In recent years, the idea of extensive dark nebulosity has come to the fore. The late Professor Barnard photographed and listed a very large number of dark nebulæ. There are many regions, very bright in stars, where well-marked lanes or larger vacancies with very definite borders may be photographed. Such a region is the famous " Coal-sack " in the bright Milky Way region of the Southern Cross. An example even more striking as a proof of the reality of dark nebulosity, obscuring for us whatever lies behind, is found south of the star Zeta Orionis, shown in Plate 53. In Hubble's opinion, these dark nebulosities would be bright if there were brilliant O, B, or A type stars near enough to them to excite them to glow. We may regard the presence of such nebulous matter, light or dark, as very widespread in the celestial spaces.

PLATE 53. A DARK NEBULOSITY NEAR ZETA ORIONIS.
(Mt. Wilson Observatory.)

Notice how completely the fainter stars are blotted out by this nonluminous gas which lies between us and them.

Spiral Nebulæ. — Let us turn now to another type of objects also called nebulæ, but differing widely both in form and spectrum from those we have been discussing. Only one of these is readily visible to the naked eye. It is the Great Spiral Nebula of Andromeda. Even to visual observation with great telescopes, the spiral and spindle nebulæ are disappointing. Photography, however, shows their fascinating structure and large number in an impressive way. Curtis, from counts made in 1918 on photographs by the Crossley reflector, estimates that there are fully 700,000

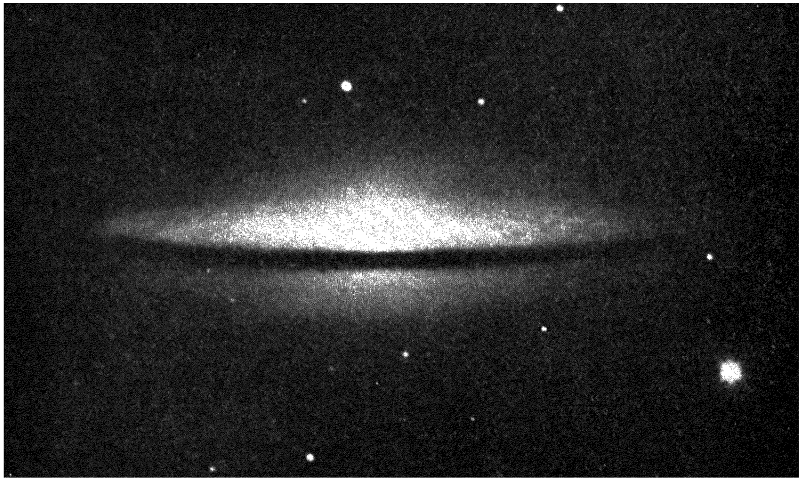


PLATE 54. A SPIRAL NEBULA SEEN NEARLY ON EDGE.
(Mt. Wilson Observatory.)

This object reminds us in its shape of our own galaxy, but it is probably not yet advanced to the stage of separate stars. The dark band lying at the outside of the spiral is probably matter of the same sort as that which lies within, but too cool to give light of its own, and hiding by its substance the light of the bright parts nearer the center.

of these objects in the sky within the range of our present great reflectors.

Many of them appear as two-branched spirals. A Fourth-of-July pinwheel, sending out its showers of sparks, particularly at the last, as it slows down just before expiring, gives some impression of the form of a spiral nebula, if seen broadside on. They are flattened objects like oyster-shells, and many of them are tilted at such angles

to our vision that they are much fore-shortened. They may even be seen edgewise so that their spiral character cannot be quite certain. They will never turn over to be seen differently. The ones seen on edge will always appear so, and the ones seen broadside on will never be presented edgewise.

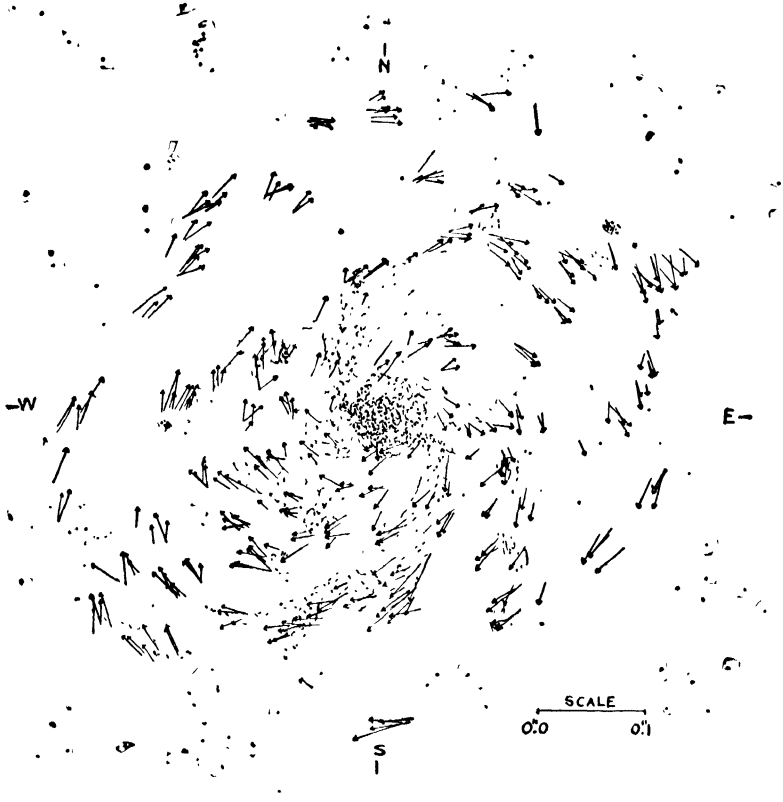


FIG. 40. EVIDENCE OF MOTION ALONG THE ARMS OF SPIRAL NEBULA (van Maanen).

The arrows show the direction, and their lengths, taken with the scale, show the magnitude of motions measured by van Maanen by comparing photographs of this nebula taken about 10 years apart. The general affect is to wind up the arms so as to produce a new convolution in about 100,000 years.

In some cases the arms of the spirals recede rapidly, with little curvature, leaving a very open appearance. In others, as in the Great Nebula of Andromeda, they are wound up like a clock-spring into many close convolutions. It is very typical of the spiral arms, of whatever openness, that there are two arms which start from

diametrically opposite sides of a central bright core. This circumstance has led many to suppose that there were forces akin to the tidal forces at work in their original formation. For, like the arms of spirals, tides occur simultaneously at opposite ends of a diameter.

By no means do all members of the class of nebulæ that we are now discussing appear spiral, nor can they be thought to be spiral, seen edgewise. A very large number of them are globular, ellipsoidal, or spindle-shaped, without any evidence of arms, excepting that some spindle-shaped nebulæ show pointed tips, as if incipient arms were in formation. We could easily imagine that a globular nebula might become flattened, then spindle-shaped, and finally spiral by the influence of rotation and gravitation. We shall recur to this idea, in the next chapter.

The spiral nebulæ almost all show their arms broken into knots and patches of various sizes. These are not sharp, pointlike objects, like stars, but some of them are sufficiently definite for accurate measurements of position. Van Maanen has seized upon this to study the motions within the spirals. He measured the positions of many of the knots in several spirals, as presented on photographs taken ten or twenty years apart. One might well be incredulous that any motions would be found within so short intervals. Longer intervals were not available because astronomical photography with great telescopes is so young an art. However, van Maanen was rewarded for his difficult measurements by the discovery that every spiral examined showed motion. It was in the sense outward along the arms, in such a fashion that the arms would tend to coil as time goes on. Thus in the course of many thousands of years he finds that the spirals will add a coil to those they now have, tending to become less open and more convoluted. The time required for forming a new coil would be of the order of an hundred thousand years.

Long as this period is, compared to human affairs, we are apt to be surprised at its brevity as an epoch among the heavenly bodies. Doubtless the earth and sun have lasted longer than a billion years, and it seems extraordinary that anything so conspicuous as the formation of a new coil on a nebula could be accomplished within a time ten-thousandfold shorter.

Our astonishment at the rapidity of the process is emphasized by the enormous scale on which it occurs. The stars, as we have seen, vary in diameter from a few hundred thousand to a few hundred

million miles. Yet none of them presents a true disk to the telescope, even of the nearest of them, not 10 light-years away. But the spiral nebulæ, on the contrary, cover spaces of real angular dimensions, some even as large as that occupied by the full moon. It is not because they are nearby either. There is difficulty in measuring their parallaxes, but astronomers are agreed at least in this, that they are very distant. The order of their distances seems to be hundreds of thousands or even millions of light-years. Hubble, indeed, has observed quite a number of Cepheid variables of different periods which seem to be definitely connected with the outer regions of the Great Nebula of Andromeda. Using Shapley's method he found that these Cepheids agree well together in indicating for the Great Nebula a distance of nearly a million light-years! A spiral as wide-angled as the full moon at 1,000,000 light-years, would be 10,000 light-years across.

The distribution of spiral and associated forms of nebulæ with reference to the Milky Way is remarkable. Curtis has expressed this in a very striking way by printing his thesis in an arrangement similar to that which the objects he describes occupy in space. Thus:

THE FACTOR OF SPACE DISTRIBUTION

100,000 ± Spiral Nebulæ
Distance unknown [2]

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.
.

The Milky Way and stellar universe
is believed to be roughly lens-shaped and
about 3,000 by 30,000 or more light-years in extent. In
this space occur nearly all the stars, nearly all the diffuse
nebulosities, nearly all the planetary nebulæ, nearly
all new stars,[1] nearly all clusters, nearly all
the variable stars, etc., but
NO SPIRAL NEBULÆ

.
.
.
.
.

100,000 ± Spiral Nebulæ
Distance unknown[2]

[1] Excepting in spiral nebulæ.

[2] Hubble has since proved that several spirals are about a million light-years away.

In some of the photographs of spirals there are very beautiful evidences of dark nebulæ. They lie in long streaks against the edges of the spirals, like the streaks of cloud which sometimes cut the sun's disk while it is setting. As we remarked in speaking of the new stars, they have seemed to be associated with spiral nebulæ in a good many instances. Of 78 new stars recorded since Tycho Brahe, 22 occurred in the limits of the Great Nebula of Andromeda. As would be expected in view of the great distances of the spirals, such new stars as seemed to lie within them were much fainter than the average seen elsewhere. Of course, there is a greater chance of observing faint novæ within spirals than elsewhere, because the spirals are more apt to be photographed and closely studied than equal areas of sky at random.

The spectroscope has had its say about the spiral nebulæ. They do not give bright-line spectra like the irregular and diffuse nebulosities or planetaries. On the contrary, their spectrum is such a spectrum as our system of stars as a whole would present if we viewed it from a habitable world in the star cluster " N. G. C. 7006." The velocity of the spiral nebulæ in the line of sight referred to the sun is very great, as we have already remarked. Measurements by Slipher, Wright, Pease and others give velocities from 300 to 1000 kilometers per second, while stars seldom give over 100. Not only is the average speed of spiral nebulæ in our line of sight very great, but the range of speeds among themselves is even greater. This is a significant fact to which we shall recur later on.

Van Maanen's determinations of motion along the arms of spirals have confirmatory spectroscopic evidence. Pease found a variation of velocity in our line of sight at the different parts of a spiral seen on edge. This, of course, would have been the result of a rotation in the manner discovered in spirals seen broadside-on by van Maanen.

We have dwelt quite long on these remarkable celestial objects because of the views which astronomers take as to their place in the scheme of stellar evolution. Evidently of enormous extent, and probably of enormous mass, they may well be looked upon as actually developed systems of stars. The outer parts of the nebula of Andromeda, usually photographed as nebulosity by moderate sized telescopes, have been resolved into myriads of stars on photographs taken with the 100-inch reflector on Mount Wilson by Hubble.

The disklike flattening and circular outlines of spiral nebulæ are suggestive of our own Galaxy. There are, indeed, some astronomers who believe it probable that we ourselves dwell in a spiral nebula, which if photographed from a station in the Andromeda Nebula, or some even more distant one, would have the same characteristics as the many spirals we observe. This " Island Universe Theory," so called after a happy expression of Herschel's, we shall have occasion to compare with the recent views of Jeans in the next chapter.

CHAPTER XVII

BUILDING THE UNIVERSE

Now that we have been introduced to many different phases of astronomical research, let us see how far we can go in solving the riddle of whence we have come and whither we are tending. We shall begin with the simplest and gradually evolve the more complex.

Matter is Electricity. — All atoms consist of two kinds of electrons. These are neither less nor more than unit charges of electricity. Here, at the very foundation of all things, begins that duality in electricity, in magnetism, in chemistry, in sex, which we remark throughout Nature. The positive charges are called protons, the negative ones simply electrons. Matter, then, is composed of electricity. Electricity is but a form of energy. The forms of motion, such as mechanical motion of bodies, heat motion of molecules, wave motion of light and radiation, and the motions of the free electrons around their nuclei, are also manifestations of energy. Fundamentally, all is energy. Matter is its passive state, the other forms, its active state.

In the atoms we see foreshadowed the systems of the stars. For as the planets revolve about the sun, and the double stars about each other in orderly orbits, so, it is supposed, do the free electrons revolve about the nuclei of the atoms. Revolving motion holds the attracting bodies apart in atoms, probably, as in star systems. It was a triumph of the nineteenth century to show that the same kinds of atoms which compose the earth are also the material of the celestial bodies. To the twentieth century was reserved the triumphs of proving that all atoms are composed of similar constituents, and of revealing the plans of their architecture.

Without the minute study of light, the stars would be unknown. How wonderful that light also searches out for us the structure of the atom! In the intricate relations between electrons and light we discover clues that indicate what the stars are, how they are evolved, and why they continue to shine.

The Universe is One. — We are now in a position to investigate the grandest scheme that the mind can contemplate in the realm of motions. The atoms with their complex maze of orbits; the solar system with its law-abiding, tireless march of the planets, satellite-attended as they are, around the sun; the double stars that ceaselessly encircle one another, some almost in contact in their nearness, others so far apart that even light itself takes full years to pass between them — all these fascinating examples of the wonders of motion are insignificant compared to the scope of the grand procession we are now about to survey. It is no less than the orderly march of our whole starry system, in numbers twentyfold exceeding human kind, in space extended over cubic quadrillions of miles.

It is only within the last years that this tremendous spectacle could be presented. We have remarked that when, in 1910, there appeared almost simultaneously the classical papers of Boss and Campbell, it was not yet possible to piece together the proper motions and the radial motions so as to disclose the real motions of the stars in space. The distances of the stars were then still lacking. This has been to a good degree supplied, partly by the tireless labors of the trigonometrical parallax observers, partly by the happy discovery of Adams that the measurement of star distances lies within the province of that amazing instrument, the spectroscope. The two great telescopes on Mount Wilson, that of the Dominion Observatory at Victoria, and several others now engaged in spectroscopic work, have greatly increased the number of stars whose radial motions and distances are known.

Using the distances determined by Adams and his collaborators, Strömberg has at length been able to work out the real motions in space of several thousands of stars. Imagine the suspense, the almost bated breath, with which he may well have approached the end of his computations, and collected the grand total of evidence as to whither and how fast the stars are moving! Would they be found, perhaps, to wheel majestically about some center which could well be called the capital of the universe? Would the motions add to our knowledge of the evolution of the separate stars, and show which are old and which are young in star years? Would the results even give a measure of the duration of star life, and tell us whether to count it in billions or, perchance, in trillions

or quadrillions of our years? Would there come from this discussion any evidence to show whether the Universe is finite or infinite in its extent, and whether its space is simply geometrical after the

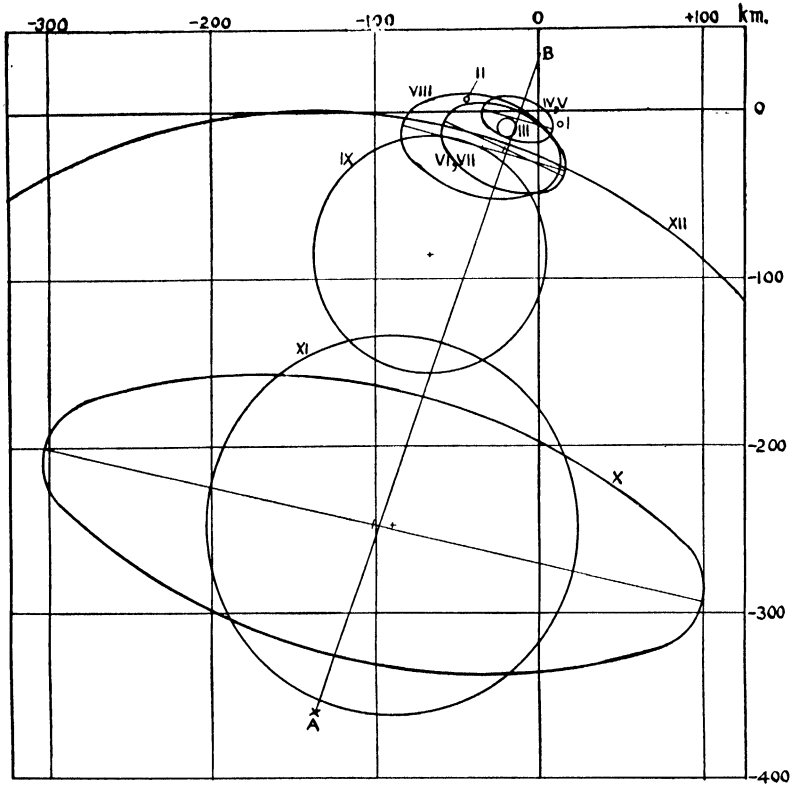

FIG. 41. THE CELESTIAL OBJECTS MOVING ALONG THE GREAT CELESTIAL WAY. (Strömberg, Mt. Wilson Observatory.)

The elliptical figures show where and how widely the different groups of stars and nebulæ would disperse if all should be collected at our sun and set free to move away from him for a given time at their actual rates and directions in space. The plane of the figure is approximately that of the Milky Way. There would be a dispersion above and below the plane of the paper about to the extent of the shorter axes of the ellipses. Figures I to XI relate to stars of various types. The great circle XII whose center is *A*, relates to the spiral nebulæ. These have greatest dispersion of any celestial objects and also the greatest average motion away from the sun.

old plan of length, breadth, and thickness, or embraces the fantastic curvatures of the fourth dimension?

Such questions may have occurred as the end of the assembling of the data approached, but no one could have recognized more

clearly than these observers that it must take the labors of future generations of astronomers to resolve all of them. What was really found was indeed startling enough.

Imagine a great celestial thoroughfare stretching almost straight away in the general line from the sun to a point east of the bright star, Antares. It lies practically in the plane of the Milky Way. Consider the stars by groups. There will be a group of the giant blue stars of type B, another of the dwarf yellow stars of the type G, in whose class our sun belongs, and so on, enumerating all the other well-known classes of our starry system. Then we must go farther afield and think of the globular star clusters, like that famous one in Hercules, objects which lie far beyond the ordinary reach of our system. Think also of the spiral nebulæ, some of them so far distant that the light that now reaches our eyes came into being a million years ago. Thus classify all the celestial objects.

All of these groups will be found on parade along the great thoroughfare we have suggested. They have been happily compared by Adams to a lot of swarms of bees, all flying in the same direction as swarms, but flying at different rates. Like swarms of bees, however, the individuals that compose these groups are darting hither or thither, while still remaining with the swarm in its general course along the great thoroughfare.

The following little table and Fig. 41 give an idea of the average speeds of the groups along their great racing course, measuring their rates from the sun, as if it were stationary. The reader will readily see that we can no longer speak without qualification of a solar velocity compared to the stars, for the solar velocity with respect to the different groups goes through an enormous range. Moreover, the direction of it shifts steadily towards the north, as we consider it with respect to swifter and swifter moving star groups.

Within the groups, the rates of motion hither or thither of the group individuals themselves increase, as the rate of motion grows of the group as a whole, measured from the sun.

Only less remarkable than the motion of all the divisions of the heavenly host along the great celestial highway, is the fact that nearly all of the groups of stars show greater dispersion at right angles to it than along its course. This is shown by the elliptical

figures in the diagram.[1] It was the great astronomer Kapteyn who first drew attention prominently to this wide generality of preferential motion, which he designated as the two-drift system. Though important, it must now take a secondary place compared to the universal march along the great celestial highway.

No doubt this remarkable procession of the stars and other celestial objects has a profound bearing on the great subject of the

VELOCITIES OF CELESTIAL OBJECTS AWAY FROM SUN

Objects	Number observed	Average velocity Km. per second
Giant A and F stars	153	21
" G "	224	20
" K "	325	18
" M "	98	16
Dwarf A and F stars	153	23
" G "	154	40
" K "	112	33
" M "	16	27
Globular clusters	16	266
Spiral Nebulæ	43	401

evolution of the universe. It is highly extraordinary, to say the least, that though we may go as far as the telescope will penetrate, to distances too great to be justly expressed or realized, even to the outlying globular clusters and spiral nebulæ themselves, yet all the host of heaven seems to bear one allegiance to and be governed by one principle of order. Though there is infinite variety of detail, there is entire unity of organization throughout the whole visible universe. The Universe is one. Its mighty thoroughfare seems to be an axis of absolute character, a datum line from which to reckon all positions.

Universal Evolution. — In order to set things in orderly array and to see how far a probable outline of the grand procedure of universal evolution can be given, we may jot down the principal and most significant facts which have been elaborated in preceding chapters.

[1] The line of preference for this greater dispersion lies between the opposite points in the sky marked by right ascension 90°, declination + 10°, and right ascension 270°, declination − 10°.

1. We live on a non-luminous solid spheroid, over five times denser than water, that revolves, unimpeded, with other spheroids about a star, our sun, over 300,000 times as massive as the earth, and nearly 93,000,000 miles away. The sun's density is 1.4 times that of water, and his surface temperature about 6000° Absolute Centigrade, or nearly twice the temperature required to gasify everything on earth. So the sun is probably gaseous and his high density depends partly on enormous gravitational compression, partly on including atoms of heavy metals. The sun's enormous output of energy of radiation appears to have been maintained without notable diminution for fully a billion years.

2. Our sun with the solar system finds itself at some distance from the center of a galaxy of some forty billion stars arranged in a lens-shaped space. Among them, he is of average brightness, mass, density, motion, position, spectrum, and temperature.

3. Ninety-nine per cent of the stars fall readily into six classes. They are distinguished by the character of their spectra as B, A, F, G, K, M, in the Harvard nomenclature. Of these, the M type is red and cool, and the B type is blue and hot. Outside of these six major classes are a few others containing relatively small numbers of stars, some as cool as M, some hotter than B. The spectral types merge by insensible gradation from B to M.

4. In the types F, G, K, and M, there is a cleavage, so that these stars are classed as giants and dwarfs in view of their wide ranges of diameter and volume. Between giants and dwarfs of the same spectral type there are some inconspicuous but highly significant differences of spectrum. Our sun appears to be a G-type dwarf.

5. From double-star observations, we learn that there is probably but a small range of mass among the stars, perhaps not over 100-fold. On the contrary, their range in volume, in density, and in total radiation exceeds 100,000,000-fold.

6. Among starry systems, fairly equal pairs of double stars are very common. Many of the companions are dark. It is not possible to observe whether other stars are attended by small cool planets, as our sun is, but there are reasons for believing such solar-like systems may be rare.

7. Catastrophes occur in the heavens. Their evidence is the sudden flaring up of a star to 10,000-fold brightness, followed by

PLATE 55. A GROUP OF NEBULOUS FORMS. (Mt. Wilson Observatory.)
Showing the gradations from circular through elliptical to cusp- or spindle-shaped and finally to the spirals seen broadside and on edge.

gradual return to its former state. There is reason to think such catastrophes may happen to a large proportion of stars sometime in their many billion-year-long lives.

8. All of the stars are in motion. Their behavior may be likened to that of a number of swarms of bees who chanced to migrate along a common course at different speeds. Within each swarm, there is always a criss-cross flight of individuals, some going in the direction of the swarm as a whole, and others in all other directions including the opposite. Yet as a whole each swarm moves forward, despite the varying internal motions of its members. So all the stars of our Galaxy, if arranged in groups of the common spectrum classes, are found to be traveling at unequal rates as groups along a common preferential way. The separate individuals of the several groups exhibit a wide diversity in direction and velocity of motion. The common preferential way is nearly in the plane of the Milky Way and in the direction towards the constellation Sagittarius.

9. Apparently outside our Galaxy, lie many clusters of stars at immense distances. Each of them contains a multitude of stars. Some clusters may even contain millions of them, so that they approach the star-population of our own Galaxy. We may perhaps regard these populous clusters as other systems something like ours.

10. The nebulæ fall into two types. One is of gaseous nature, small density, feeble or no luminosity, and irregular or annular shape. This type is associated with the very hot stars of our Galaxy. When luminous, these nebulæ seem to derive light-giving power from associated stars. Nebulæ of another type, including globular, spindle-shaped, and spiral forms, seem to be of enormous mass and distance and to lie perhaps outside our Galaxy. These may be considered as possible reservoirs of future galaxies, if not, indeed, already composing systems of innumerable stars, too far distant to discriminate.

11. Spiral nebulæ and star clusters have very great velocities of dispersion in their own classes, and very great velocities along the preferential way, compared to a mean of all the stars of our Galaxy taken as a datum or zero of velocity.

With these facts in mind, we now take up the fascinating problem of how the stars came to be.

To begin with, we must admit that as yet we have no conception of the processes by means of which all the enormous mass of matter included in these various celestial forms came into being from electrons and protons. No one has constructed atoms, although physicists have disintegrated them in the laboratory. Possibly the constructive processes require temperatures and pressures, or other conditions, as wholly outside of our means as, so far, they are outside of our knowledge.

Having admitted that the formation of the atoms so far escapes observation, we begin with the globular, spindle-shaped and spiral nebulæ, and inquire if development might reasonably go on from thence. This is the subject of a very notable investigation by the distinguished mathematician, Dr. J. H. Jeans.[1] He first lays a scale of proportions whereon our earth is ultra-microscopic, our sun a microscopic speck of dust, the solar system like a threepenny piece, and the furthest star-cloud 14,000 miles away.

Jeans then draws attention to the spindle-shaped nebulæ. These are found spectroscopically to be rotating rapidly about their shortest diameters. The mathematician calculates from the laws of dynamics what shapes they must assume if, as seems likely, they are gaseous masses. From the law of constant angular momentum, the rotation must grow more rapid as the gaseous mass gives off radiation and consequently condenses. Along with increasing velocity of rotation the figure flattens, and its circumferential edge sharpens. Further shrinkage and increased velocity involves the disruption of the mass, with matter going off from the sharpened edge.

If there were no other bodies in the universe, it would be impossible to say how the break would occur. But the attraction of other celestial bodies tends to raise small tides, so that there is a resultant direction where the nebula is in a trifling degree elongated in its diameter. This is the diameter from which now start to stream away armlike masses of the ejected material. Thus a spiral nebula begins to be born.

The process of shrinkage and ejection goes on from antipodal points. An even-flowing rope-shaped stream of gas is maintained in each of the opposite spiral arms. Continuing in rotation, but only with the linear velocity of the surface of the nucleus, the arms

[1] See "Nature," March 1, 1924.

lack velocity sufficient to hold them radial. Thus, as we have seen in the results of van Maanen, these circumstances produce the effect of winding up the arms.

Basing his computations on van Maanen's results, Jeans computes the mass and finds the density of the gas remaining in the nucleus of some of the very long-armed nebulæ, nearly all of whose material has been ejected. It comes out smaller than the pressure in the best vacuum pumps. He says: "The small amount of gas in an ordinary electric light bulb, if spread out through St. Paul's Cathedral, would still be something like 10,000 times as dense as the nucleus of a spiral nebula."

PLATE 56. THE FINE SPIRAL NEBULA IN CANES VENATICI.
(Mt. Wilson Observatory.)

Note the two spiral arms starting opposite each other, and showing breaks and condensations, which may indicate a galaxy of stars in the making.

But the arms cannot remain continuous. As a jet of water separates into drops, so, though for different reasons, nebular arms form detached knot-like aggregations under the influence of gravitation. The theory of their formation is clear, and enables the mathematician to compute what ought to be the size, mass and distance apart of the separate gas masses in the arms. When the calculations are performed, the very encouraging result comes out that the masses of single condensations must be approximately those of average stars.

Thus, the presumption is strong that here is a real step in star-evolution. Let us recapitulate. From a gaseous mass of extremest rareness, there forms a rotating figure, which assumes more and more a flattened form. At length it ejects arms, which wind up into the form of spiral nebulæ. These arms break up under gravitational force, and form separate knots of gas, each of sufficient mass to make ordinary stars. The number of stars so born from a single nebula may run to millions. It is the birth of a star cluster. Very satisfactory is the observation that star clusters and spiral nebulæ are similar in having very high migration-velocities along the great preferential way.

Such a process as this which Jeans describes reminds us of Laplace's famous nebular hypothesis of the origin of the solar system. Nevertheless that will not do for the solar system at all. One trouble is that in the solar system almost the whole mass is in the central sun. This could not be so if there had been a shrinkage from, let us say, Neptune's orbit. For the " moment of momentum " could not have been preserved constant. Jeans' scheme for stellar evolution does not violate this principle however. In the later stages the mass is very largely in the ejected portions, far out from the center.

Jeans points out another difficulty in the solar system. We must recognize the immensity of spiral nebulæ, and that the sun, if it came from one, must have come from no more than a little speck, so to speak, of nebular matter. If we should suppose that a single knot of an arm of a great nebula passed along the same course of evolution as the whole had done, the laws of dynamics show that the result would be different because of the difference of scale. There would not result a solar system, but a binary star having two nearly equal masses in mutual revolution. These again may divide nearly equally if their rotation suffices, thus making a system like Epsilon Lyræ. The observed fact that fully a third of the stars are binary or multiple is then quite in harmony with what dynamics foretells. If the rotation and mass are adequate, the knot becomes a double or multiple star system. Otherwise, there result single stars.

Do all nebulæ follow this course? According to Jeans, many may not. If originally there is too little rotation, the shrinkage due to radiating and cooling will not impart sufficient acceleration of it

for separation. Motionless nebulæ would remain spherical till they grew old and cold and solid, without ever becoming the parents of star systems. Further on in the progress, if one of the large condensations in the arm of a nebula lacks rotation, it, too, may grow cold without ever forming a binary or multiple system of stars.

Nowhere in all this march of events is there a path towards a solar system. The evolution of spirals leads to single and double stars, but not to suns attended by planets and satellites. Jeans, however, points to another possibility arising in stars already formed. Here he follows in some measure the hypothesis proposed and extensively considered many years ago by Chamberlin and Moulton. Though the spaces between the stars are perfectly enormous compared to the diameters of the stars themselves, nevertheless, since time is long, there may come rare cases when one star approaches another near enough to produce monstrous tides upon its gaseous material.

These tides, if they become high enough, may generate spiral arms which will break up into knots. The result is much the same as before, but with a difference. Two stars rushing by each other at celestial velocities will remain within each other's influence but a few years. The time while they are near will not suffice to cause a great proportion of the star material to be forced out into the arms. Only slightly will the central mass be diminished.

We notice, however, that there are no double planets of nearly equal masses. The earth and moon are nearest equal, and they differ by 80-fold in mass. The other planets which have moons resemble the solar system in miniature. Moreover, there are other features of similarity. Just as the sun and planets lie nearly in one plane, and all rotate and revolve almost without exception in the same sense, so the individual planets and their satellites lie nearly in the plane of rotation of the planet. In the case of the earth, its moon rotates and revolves in the same direction as the earth. From analogy we may well suppose the satellites of other planets do so too.

These similarities between solar and planetary systems lead us to think they were formed in similar ways. Jeans examines the various circumstances of the solar system, and calculates the masses of the planets and satellites on the theory that they might have been formed by tidal action of perturbing bodies and succeeding

gravitational condensing effects. He finds himself constrained to conclude that many of the satellites and some of the planets were gathered together when, in cooling, the tidal arms had reached liquid or solid conditions. Only Mars, Jupiter, Saturn, and Uranus, he thinks, were born from the gaseous state.

This interesting theory of Jeans, having provided a rational interpretation of the spindle-shaped and spiral nebulæ as sources of star clusters, and individual stars in close approach as sources of solar systems, we are ready to proceed with the later stages of star life. Here we find the fruitful studies of Eddington. The matter has been popularly presented by Eddington himself in " The Scientific Monthly " for September, 1923, and with a somewhat more technical exposition, in his book entitled "The Internal Constitution of the Stars," 1926.

A star in its early stage, just condensed in the arm of a nebula, is to be regarded as a spheroid of very rare gas, hundreds of millions of miles in diameter, and many thousand times less dense than the air of the room. Not hotter, at least on its surface, than many laboratory sources of radiation, the star, a giant at birth, shines feebly with a red color. Its surface atoms are not excited sufficiently to lose electrons, and the surface temperature is even low enough to permit the existence of such compounds of atoms into molecules as titanium oxide, calcium hydride, cyanogen, and some others. The star is of the M type spectrum, and of the giant class.

These are exterior appearances. What of the interior? The temperature rises enormously towards the center of the star, reaching hundreds of thousands or millions of degrees. The pressure, also, must rise towards the center by reason of the weight of the tremendously thick mass of superincumbent gas. Yet the state of the star is purely gaseous. It is, indeed, of gas so rare that the laws of the so-called perfect gas apply. That is to say, the separate particles, some being molecules, some atoms, some electrons, and others fragments of atoms remaining after electrons are lost, shoot about in free paths very long compared to the radii of their little spheres of influence.

Lane's Law. — These are the ideal circumstances for the mathematical investigator. Not requiring to make allowances for the spaces actually occupied by the separate particles of the gaseous material, or for the mutual attractions and repulsions of them, his

problem is greatly simplified. Subject to two qualifications which we shall soon name, Lane's law applies in all its simplicity. This paradoxical expression maintains that for a star in a state where the laws of the perfect gas apply, the temperatures increase proportionally as the radius decreases when the star contracts by cooling. How can it be that cooling makes the star hotter?

Obviously, if the star radiates and thus loses heat, and has no supplies of heat other than its own store, it must contract at the surface by growing cooler there. Lower-lying layers must supply this loss, and all of them tend to cool. Cooling produces shrinkage. Imagine that this goes on till the star loses half its diameter. Then if all corresponding depths have the same relative densities as before, each corresponding depth will come to a state of density eight times as great as originally; for the sphere is now of half the diameter and therefore eight times less in volume than at first.

How about the pressures? Since the pressure depends on the attraction of the material, which acts as if concentrated at the center, corresponding depths will by Newton's law be subjected to four times the intensity of pressure, on account of being twice as near the center. Besides this, the gas lying vertically outside of any unit of surface area of an interior sphere will be four times as much as originally over the same unit area on a corresponding sphere. This is so because all corresponding spheres have been reduced to half diameter and one-fourth surface area, so that the gas column has been compressed laterally fourfold. Thus, the pressure at corresponding points has increased fourfold from the application of Newton's law, and fourfold from lateral compression, or four times four, equals sixteenfold altogether.

In order to maintain a condition of equilibrium in a perfect gas, the product of pressure and volume must be proportional to the absolute temperature. In our supposed star the volumes have diminished eightfold, the pressures increased sixteenfold, their product has increased twofold, therefore for equilibrium the temperatures must also have increased twofold. Thus we come to an application of Lane's law. If you halve the diameter, you must double the temperature.

What, then, will happen to our star? If it merely radiates light and other rays, losing no gas, it will grow smaller and smaller, but hotter and hotter, until it ceases to be a perfect gas, and Lane's

law ceases to apply. As it grows hotter, the color changes from deep red to light red, to yellow, to white, to blue, if the star is big enough to go through all these changes. The spectrum correspondingly passes from M type successively to K, G, F, A, and B if the star is big enough to go all the way. Many stars are not.

Radiation Pressure. — The relations between star mass and the hottest possible type which can evolve therefrom have been worked out by Eddington. They depend on a property which is not commonly thought of. It is the pressure of radiation. Clerk Maxwell, the great English physicist, showed theoretically, about the year 1875, that light must exercise a pressure. Nichols and Hull experimentally verified Maxwell's theory a quarter of a century after its publication.

Consideration of light pressure modifies Lane's law. For the pressure of gravitation in a star is sustained not alone by the expansive force of gases, due to the collisions of their particles and their elastic rebounding. Light pressure helps gaseous expansion to sustain gravitational pressure. Eddington has gone through the computations. He bids us imagine a series of gaseous spheres, each ten times as massive as the one before. The first contains 10 grams, the second 100 grams, and so on. Number one weighs as much as a letter, number five as much as a man, number ten as much as an ocean liner. All the stars whose masses we know lie between numbers 33 and 35 of this scale. Nearly all are between numbers 33 and 34. This is highly interesting, for Eddington's calculations show that, until we come to sphere 33, light pressure is nearly negligible compared to gas expansion, and after we reach sphere 35, gas expansion is nearly negligible compared to light pressure.

In Eddington's quaint words we should expect " something to happen " at this critical condition of gaseous masses, and " what happens is the stars." Masses smaller than No. 33 do not grow hot enough, by virtue of Lane's law, to shine. Spheres larger than No. 35 are too unstable because radiation pressure bursts them asunder. Sphere 33 is of half the mass of the sun, while sphere 35 has five times the sun's mass. Hence, we may suppose that Jeans' nebular condensations larger than five times the sun's mass will break up to form smaller stars, while those having less than half the sun's mass will never be hot enough to be visible.

Are the Stars Losing Mass? — There is a second possible

qualification of Lane's law. We are not sure that stars lose no material. According to the present view of atomic structure, matter seems to be a passive form of energy. May it not be transmuted into the active form of radiation? This does not happen, so far as we know, on earth, but perhaps it hapens in the conditions of tremendous temperature and pressure prevailing within the stars. There are, indeed, several considerations which incline us to think it may possibly be so.

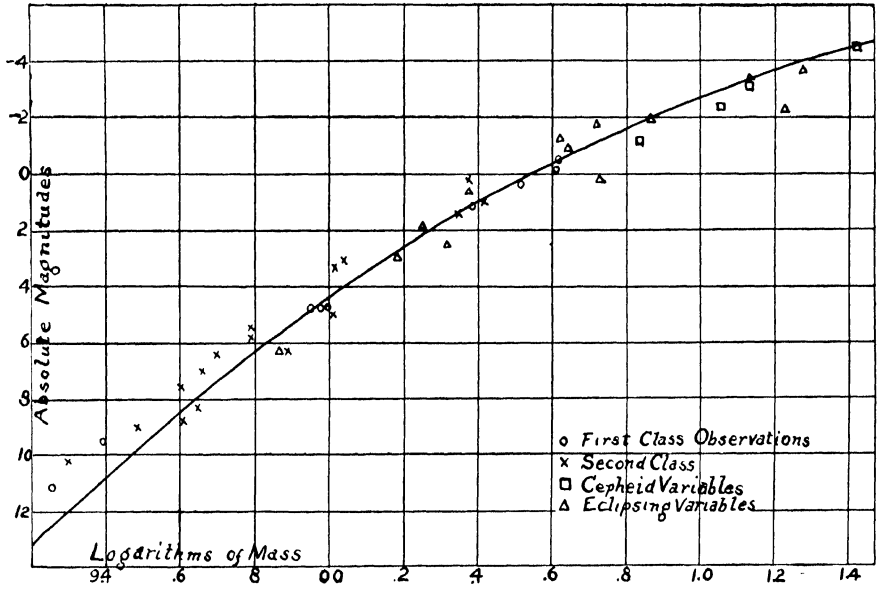

FIG. 42. THE RELATION BETWEEN MASS AND ABSOLUTE MAGNITUDE

The mass of a star may be known only when the star is double and its parallax accurately measured. Taking only those stars where the masses are known with the highest precision, Eddington plotted the logarithm of the masses against the absolute magnitudes and obtained the dot diagram given in Fig. 42. The smooth curve is entirely theoretical and is based on the supposed constitution of stars assuming them to be in the state of perfect gases. It is easy to see that the curve is in almost perfect accord with the observations over nearly its whole range of magnitudes.

This is highly satisfactory from one point of view, but very surprising from another. It is easy to comprehend that the giant

stars of rare gaseous constitution may readily obey the laws of perfect gases, but how about dwarf stars, like the sun and denser? The companion of Sirius has a density 50,000 times that of water. Are we to be asked to believe that a body at this enormous density is not a solid, but is still in a gaseous state? Manifestly, we must greatly modify our notions of what we mean by a gas. Eddington's explanation is this: Within a star the temperature is so high that nearly all of the atoms are highly ionized and are stripped of their external electrons. The individual fragments of atoms, thus stripped, are far smaller in volume and may be crowded together without interference much more closely than is possible with atoms under ordinary conditions. Hence, a compression a millionfold greater than under laboratory conditions is possible inside of a star, without carrying the condition outside the applicability of the laws of a perfect gas at ordinary temperatures.

Still there remains a difficulty. Hitherto astronomers have supposed that as the stars grow older they pass from red to blue through the several stages of existence as giants and then retrace their types as dwarfs. The turning point, it has been supposed, comes when their densities pass above the range of application of the laws of perfect gases. Now that dwarfs seem to be also perfect gases to all intents, what shall we think?

In his suggested explanation, Eddington, as we say, "kills two birds with one stone." He makes the hypothesis that the passive energy of the material of the stars is being changed into the active energy of radiation, so that the stars are continually losing mass. The loss of mass, if dependent on high temperature and pressure, would be slow for the red and yellow giants, but would grow more rapid with later stages. When the density becomes so great that interior heat cannot sustain highest surface luminosity, the decline through the dwarf stage from blue to red sets in. At the same time, this hypothesis provides a source of the enormous energy of radiation which a star emits in course of its long life.

The Age of the Earth. — There was for a good many years a controversy, between the physicists on the one side and the geologists and zoölogists on the other, over the age of the earth. It was inspired in part by the seeming impossibility of admitting that the sun had shone over 20,000,000 years at the present average rate. The geologists and zoölogists required hundreds of millions of years

for the deposition of the earth's stratified rocks, and for the evolution of species. These processes could not have been going on while the sun was cool. Yet there seemed to be but one large source of solar energy. It resided in the shrinkage of his volume, and it was insufficient to last a tenth long enough to suit the zoölogists and geologists. Later on, the physicists not only came over to their camp, but outbid them in demands on geological time. For they found that radium and uranium served as a clock to tell the age of rocks. These elements decompose, with loss of helium, and eventually are degraded into lead. Consideration of these transformations made the physicists demand at least a thousand million years since the earth was formed, and the rains began to wash to its surface. So the problem grew graver still. If Eddington's hypothesis of transmutation of star material into radiation is sustained, all will be simplified, for an enormous energy source will be provided. On this assumption the sun will last for another fifteen millions of millions of years.

It will occur to all that if this loss of mass is real, the year must be ever lengthening. For the sun must be growing less massive, its attraction must be diminishing, the earth's orbit must be gaining in diameter, and its period of revolution increasing. However, the change would doubtless be far too slow to have been detected by observation hitherto.

Such are some of the remarkable consequences of Eddington's investigations of the interiors of stars. It would lie outside our scope to follow into the mathematical paths which lead him to these results. One other curious thing about the star interiors ought not to be omitted, however. We are accustomed to think of the store of heat which a hot body holds as being the expression of the energy of motion of its molecules or atoms. But there is another part of it, namely the energy of the radiation not yet emitted, which momentarily exists within the body. This second part of the energy is too trifling to consider in a body no hotter than the blacksmith's iron, but in a star it is perfectly immense. One thinks at first blush, of course, that the rays must rush out from the interior, and can hardly be imprisoned an instant. Not so, for the temperatures are so tremendously high that the prevailing radiations are of the minute wave-lengths which we call X-rays. For them the star material is far from transparent. Complete

absorption or scattering occurs within a path of a few inches. A ray starting from the center of a star might generate almost an infinite succession of ray-children, in the course of its absorptions and re-radiations, and a thousand years might elapse before one of them was born near enough to the surface to escape.

We have now followed in hypothesis, not proved, but not improbable, the change of spherical into spiral nebulæ, the rise of star clusters and double stars from them, and the course of evolution of the stars themselves which depends so intimately on mass. We have seen that our sun is a G-type dwarf, well past the middle age of stars. We have seen that his possessing an attending family of planets and satellites is probably an unusual condition with stars, which was very likely brought about in his case by the near approach of some other star at some time, which perhaps was several billion years ago.

It now remains to see how this scheme of things is reconcilable with the extraordinary facts relating to the motions of the nebulæ clusters, and stars along the preferential way. Let us suppose that the objects of our stellar kingdom once formed a spiral nebula. Then, like other spiral nebulæ, it probably had a large motion in some direction as compared to the average position of all the spirals. Admit, if you please, that this motion was something like 400 miles per second along the preferential way. But the gravitational attractions, and possibly other disturbing influences, may well have modified the motions of individual members of the Galaxy depending on their masses and ages in stellar conditions. Thus, the several types of stars became separated somewhat in their average velocities with respect to the center of the Galaxy. More particularly, the older and smaller stars, of which our sun is one, would long have been subjected to these influences in exceptional force. They would consequently have achieved a more extensive dispersion of velocities than the groups of younger and more massive types of stars.

All this is in accord with Strömberg's chart. How is it, though, asks some reader, that our sun is moving nearly in the preferential way, and at a higher velocity with respect to his type companions, the G dwarfs, than with respect to other types like the M giants? This appears to be merely accidental. As we have said, the older dwarfs are naturally more highly dispersed in their velocities than

the younger and more massive giants. Our sun, being one of them, naturally acquired a considerable velocity measured from the center of G-type dwarf-star motions. This motion had to be in some direction. It happened nearly to coincide with the great preferential way, and was *forward* with our cluster, not backward or at some wide angle to the side, as it might have happened. Had the sun's motion happened opposite to its present direction, all the giant stars would have seemed to be moving faster than the G-type dwarfs with respect to the sun, and in the opposite sense to what now seems to be their course. In that case, too, the average motion of the spiral nebulæ would have seemed more than fifty miles per second slower than it now seems, though in the same sense along the preferential way as now.

In this way most of our big facts seem to fall into a consistent whole. He would be a rash fool who would dare to maintain that this scheme of things is surely the true one. Discovery has followed discovery at such a pace of late that another decade may well find evidences of very different tenor. The problem of the evolution of the universe is too large to be exhausted in a few generations. Even if at length the foundations of its solution shall seem to be established, it will doubtless occupy a thousand years of astronomical research to fill out the noble outlines of the structure, and reveal in its full beauty the grand system of the celestial hosts.

Langley tells us in his "New Astronomy" of a race of ephemera which live but for an hour. Generation after generation had established the great law that the sun always moves westward. Their greatest sages therefore agreed that the end would come when it should at length sink below the western horizon. Nevertheless the sun rose again in the east the next day!

APPENDIX

TABLE I — Astronomical Constants

Dimensions of the Earth (Hayford's Spheroid of 1909)

Equatorial radius a = 6378.388 km. = 3963.34 miles

Polar radius b = 6356.909 km. = 3949.99 miles

Oblateness $\frac{a-b}{b} = \frac{1}{297.0}$

Length of the day:

Sidereal = $23^h\ 56^m\ 4^s.091$ of mean solar time

Mean solar = $24^h\ 3^m\ 56^s.555$ of sidereal time

Length of the year

Tropical = $365^d.2422 = 365^d\ 5^h\ 48^m\ 45^s.98$

Sidereal = $365^d.2564 = 365^d\ 6^h\ 9^m\ 9^s.54$

Length of the month

Synodical = $29^d.5306 = 29^d\ 12^h\ 44^m\ 2^s.8$

Sidereal = $27^d.3217 = 27^d\ 7^h\ 43^m\ 11^s.5$

Nodical = $27^d.2122 = 27^d\ 5^h\ 5^m\ 35^s.8$

Solar parallax = 8″.80

Constant of nutation = 9″.21

Constant of aberration = 20″.47

Velocity of light = 299,796 km./sec. = 186,284 miles / sec. (Michelson, 1926)

1 astronomical unit (A. U.) = $149{,}504 \times 10^3$ km. = 92,870,000 miles

1 light-year = 6.3310×10^4 A. U. = 5.88×10^{12} miles

1 parsec = 3.258 light-years = 1.92×10^{13} miles

TABLE II — PRINCIPAL DATA OF THE SOLAR SYSTEM

Name and symbol	Number of satellites	Apparent angular diameter	Mean diameter in miles	Mass. ⊕ = 1	Density. Water = 1	Gravity at surface ⊕ = 1
Sun ⊙	—	1891″ to 1956″	864,000	332,000	1.41	27.6
Mercury ☿	0	4″.7 to 12″.9	3,100	0.04	3.8	0.2?
Venus ♀	0	9″.8 to 64″	7,700	0.81	4.9	0.8
Earth ⊕	1	.....	7,918	1.000	5.52	1.0
Mars ♂	2	3″.6 to 26″.0	4,230	0.108	3.96	0.4
Eros (433)	—	0″.02 to 0″.25	15?		3.?	
Ceres ①	—	0″.25 to 0″.69	488?	1/8000?	3.?	1/260?
Jupiter ♃	9	32″ to 50″	86,500	316.9	1.3	2.6
Saturn ♄	9	14″ to 20″	70,000	94.9	0.7	1.2
Uranus ♅	4	3″.4 to 4″.2	31,500	14.6	1.3	0.9
Neptune ♆	1	2″.2 to 2″.4	34,800	17.2	1.6	0.9
Moon ☽	—	1766″ to 2015″	2,160	1/81.56	3.3	1/6

Name	Mean radius of orbit. Millions of miles	Eccentricity of Orbit	Inclination of orbit to ecliptic	Sidereal period in mean solar time	
				Orbital revolution	Axial rotation
Mercury	36 0	0.20562	7° 00′ 12″	$87^d.9693$	88^d?
Venus	67.2	0.00681	3 23 38	224.7008	
Earth	92.9	0.01674	0 00 00	365.2564	$23^h\ 56^m\ 4^s.09$
Mars	141.5	0.09334	1 51 00	686.9505	$24^h\ 37^m\ 22^s.58$
Eros	135.4	0.22297	10 49 40	643.230	$5^h\ 16^m$
Ceres	257.1	0.07653	10 36 56	1681.414	?
Jupiter	483.3	0.04838	1 18 26	4332.580	$9^h\ 50^m$ to $9^h\ 56^m$
Saturn	886.0	0.05579	2 29 28	10759.22	$10^h\ 14^m$ to $10^h\ 38^m$
Uranus	1782.8	0.04712	0 46 22	30686.82	$10^h\ 50^m$
Neptune	2793.4	0.00855	1 46 22	60181.11	19^h?
Moon	238,857 miles	0.05555	5 08 40	27.3217	$27^d\ 7^h\ 43^m\ 11^s.5$

TABLE III — THE FIRST MAGNITUDE STARS

No.	Star	R.A. 1900	Dec. 1900	Mag.	Spectrum	Annual proper motion, μ	P.A. of μ	Parallax	Abs. mag.	Radial velocity km.	Diameter **
1	Achernar	$1^h\ 34^m0$	− 57° 45′	0.6	B5	0″094	108°	+ 0″049	− 0.9	—	—
2	Aldebaran ‡	4 30 2	+ 16 18	1.1	K5	0.205	160	+ 0 057	− 0.1	+ 55.1	35
3	Capella †‡	5 9.3	+ 45 54	0.2	G0	0 439	168	+ 0 075	− 0.4	+ 30.2	10
4	Rigel *†	5 9 7	− 8 19	0.3	B8	0.005	112	+ 0 007	− 5 5	+ 22 6	21
5	Betelgeuse †§	5 49.8	+ 7 23	0.6 − 1.2	M0	0.032	75	+ 0.016	− 3.1	+ 21.3	270
6	Canopus	6 21.7	− 52 38	− 0.9	F0	0.022	62	+ 0.005	− 7.4	+ 20 8	—
7	Sirius *	6 40.7	− 16 35	− 1.6	A0	1.316	204	+ 0.371	+ 1.2	− 7 4	1.4
8	Procyon *	7 34.1	+ 5 29	0 5	F5	1.242	214	+ 0 312	+ 3.0	− 3 5	1.0
9	Pollux §	7 39 2	+ 28 16	1.2	K0	0.623	264	+ 0.101	+ 1.2	+ 3.9	—
10	Regulus ‡	10 3 0	+ 12 27	1.3	B8	0.244	269	+ 0 058	+ 0.1	− 9.1	—
11	α Crucis *	12 21.0	− 62 33	1.0	B1	0.048	235	+ 0.030	− 1.6	+ 7.	—
12	β Crucis †	12 41.9	− 59 9	1 5	B1	0 054	241	+ 0.008	− 4.0	+ 13.	—
13	Spica †	13 19.9	− 10 38	1.2	B2	0.051	228	+ 0 009	− 4.0	+ 1.6	—
14	β Centauri †	13 56.8	− 59 53	0.9	B1	0.031	219	+ 0 018	− 2.8	+ 4.	—
15	Arcturus	14 11.1	+ 19 42	0.2	K0	2.287	209	+ 0 080	− 0.3	− 3.9	—
16	α Centauri *	14 32 8	− 60 25	0.3	G0	3.682	281	+ 0.758	+ 4.7	− 21.6	—
17	Antares ‡†	16 23.3	− 26 13	1.2	M0	0.032	189	+ 0 026	− 1.7	− 3.1	—
18	Vega §	18 33.6	+ 38 41	0.1	A0	0.348	36	+ 0.124	+ 0.6	− 13.8	2.0
19	Altair §	19 45.9	+ 8 36	0.9	A5	0.659	55	+ 0.204	+ 2.5	− 33.	—
20	Deneb §	20 38.0	+ 44 55	1.3	A2	0.004	117	+ 0.005	− 4.2	− 4.	—
21	Fomalhaut	22 52.1	− 30 9	1.3	A3	0.367	117	+ 0.137	+ 2.0	+ 6.7	—

* Visual binary. † Spectroscopic binary. ‡ Pair with common proper motion.
§ Wide pair probably optical. ** In millions of miles.

TABLE IV — THE NEAREST STARS

STAR	R.A. 1900	Dec. 1900	Mag.	Spectrum	Proper motion	Parallax	Abs. Mag.	Distance in light-years
α Centauri	$14^h\ 32^m.8$	$-60°\ 25'$	0.3	G0	3".682	".758	4.7	4.3
Barnard's Star	17 52.9	+ 4 25	9.7	M5	10.30	538	13.9	6 1
Lal. 21185	10 57.9	+36 38	7.6	M2	4.779	.392	10.6	8 3
Sirius	6 40.7	− 16 35	− 1.6	A0	1.315	.371	1.2	8 8
B.D. − 12° 4523	16 24.8	− 12 25	9.5	M5	1.24	.355	12.3	9.2
Innes's Star	11 12.0	− 57 2	12.		2.688	.340	14.7	9.5
Cordoba 5^h 243	5 7.7	− 44 59	9.2	K2	8.75	.317	11.7	10 3
τ Ceti	1 39.4	− 16 28	3 6	K0	1.920	.315	6.1	10.4
Procyon	7 34.1	+ 5 29	0.5	F5	1.242	.312	3.0	10.5
ϵ Eridani	3 28.2	− 9 48	3.8	K0	0.971	.310	6.3	10.5
61 Cygni	21 2.4	+38 15	5.0	K5	5.202	.300	7.4	10.9
Σ 2398	18 41.7	+59 29	8.8	K5	2.31	.287	6.5	11.4
Groom. 34	1 12.7	+43 27	8.1	M0	2.89	.286	10.4	11.5

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