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THE AURORA BOREALIS.

From a painting by Howard Russell Butler at Ogunquit, Maine. (*Courtesy of the American Museum of Natural History, New York*)

AN INTRODUCTION TO
Astronomy

By

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PREFACE TO THE SECOND EDITION

This revised edition brings the textbook again up to the times and makes numerous minor alterations in the interest of clearness in the presentation. The general plan of the new edition is the same as that of the original edition which appears to have been found useful in many places for a one-semester, non-technical course in beginning astronomy.

As examples of new features representing the progress of astronomy since the first publication of this book five years ago, the reader will find mention of the tenth and eleventh satellites of Jupiter, of the growing distrust of astronomers in the interstellar origin of the majority of meteors, and of the moving pictures of solar prominences. The conclusion that most of the "star clouds" of the Milky Way are openings in the dust clouds is largely a product of the past five years. More has been learned of the spectacular supernovae in the extragalactic nebulae.

Chapters XIII and XIV are entirely rewritten in order to include many advances in the knowledge of the galactic system and the exterior systems.

The author is indebted to a number of colleagues for suggestions which have been useful in the revision of the book.

ROBERT H. BAKER

University of Illinois Observatory,
May, 1940.

PREFACE TO THE FIRST EDITION

The methods which have proved useful in the larger text, "Astronomy," are employed again in this simpler "Introduction to Astronomy." This textbook is designed for shorter introductory courses. It undertakes to tell the story of the heavens in a way that will be understandable without special preparation.

Beginning right at home, with familiar aspects of the earth and sky, the descriptions progress by easy stages through the solar system to the stars, and finally to the galaxies beyond our own. Lists of questions at the ends of the chapters give opportunities for review, and brief lists of references suggest further reading on the various subjects.

The maps and the descriptions of the constellations, in Chapter V, are intended to promote the familiarity with the prominent star figures which adds much to the interest in the beginning course in astronomy. Many celestial photographs throughout the book, which have been generously contributed for the purpose, supplement the written accounts of features beyond the reach of the unaided eye.

The author is indebted to Professor Schlesinger for his critical reading of the entire manuscript, and to Dr. Harry E. Crull who read the manuscript and cooperated in the preparation of the lists of questions.

ROBERT H. BAKER

University of Illinois Observatory,
May, 1935.

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THE EARTH AND THE SKY

THE GLOBE OF THE EARTH — THE SEEMING GLOBE OF THE SKY — THE EARTH'S ATMOSPHERE

A small planet attending one of countless millions of stars, our earth could easily be overlooked except for one reason. The reason, of course, is that we live on the earth. Here we view the bewildering array of stars around us. In order to interpret the scene aright, we must know first of all something about the earth that looms so large in the foreground of the picture. The science of the heavens begins at home.

Our study of astronomy begins with the globe of the earth seemingly motionless at the center of the apparent globe of the heavens, and encompassed by the atmosphere through which we look out at the stars.

The Globe of the Earth

Primitive folk supposed that the earth was flat, except for its mountains and valleys and lesser irregularities. Dwellers along the shores of the Mediterranean Sea could readily regard the earth as oblong; they naturally measured longitude in the east and west direction which seemed to them to be lengthwise, and latitude toward the north and south along the width of their world.

Many early people who lived in fairly level country pictured the earth as a circular disk, just as it seemed to be; they were at its center, while over its rim the sky shut down like a blue bowl inverted over a flat dish. It is easy enough to imagine a world like this as we look around us today; and it is often convenient to represent the sky as an inverted bowl.

The idea that the earth is round like a ball was taught by learned men of Greece as early as the fifth century B.C. It was prompted at first simply by the fitness of things; the earth ought to be a globe to match the globe of the heavens which they now imagined completely surrounding the earth. But soon the Greek philosophers were calling attention to sights which showed that the earth itself is a globe, or at least that its surface is not flat.

1.1. The Earth's Surface Is Curved. The progressive disappearance of a ship as it puts out to sea shows that the earth curves downward from the place where we are watching. The upper parts of the ship remain visible for a time after the hull has gone down out of sight.

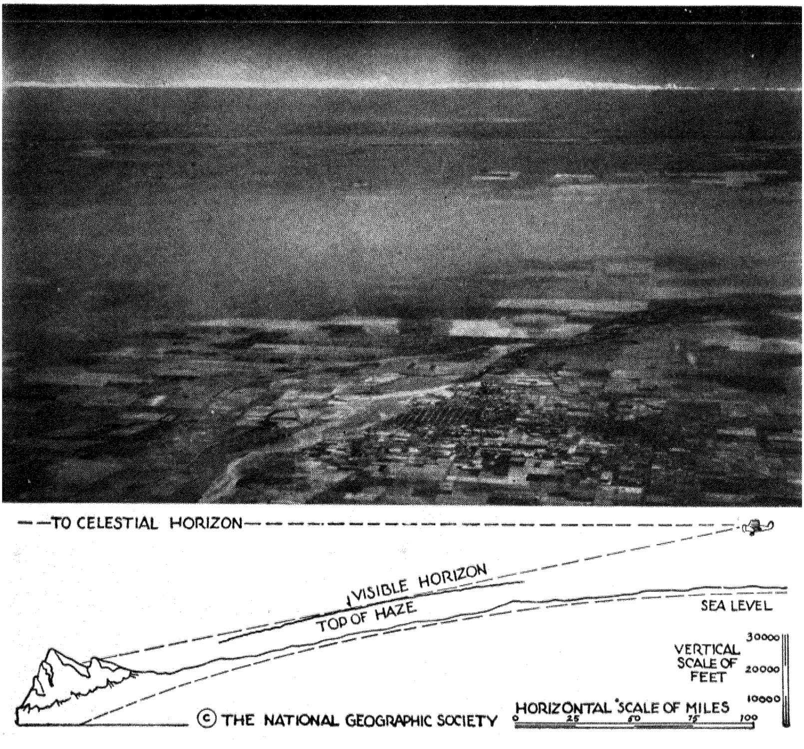


FIG. 1.1. The Earth's Surface is Curved. Photograph from an airplane four miles above sea level in Argentina. The white line at the top represents the celestial horizon. The visible horizon 153 miles away is formed by the top of a stratum of haze 6700 feet high. Above this horizon the tops of the Andes rise, nearly 300 miles from the airplane. (*Courtesy of The National Geographic Society*)

A similar effect on land is clearly shown in Major Stevens' remarkable photograph of the Andes Mountains (Fig. 1.1) which was taken from an airplane four miles aloft over the plains of Argentina nearly three hundred miles east of the mountains. Above the horizon line, where the sky and a floor of haze seem to meet, the still more distant peaks of the Andes rise like the superstructure of the departing ship. And this horizon line itself is plainly curved in the original photograph, showing for the first time in this way that the earth is round.

The earth's shadow as it falls on the moon during a partial eclipse is always part of a dark circle, a shadow such as a globe would cast. This familiar evidence of the earth's rotundity was mentioned by the Greek philosopher Aristotle in the fourth century B.C. Another proof that he gave is even more convincing.

1.2. The Stars Shift As We Travel.

If we travel north or south even a moderate distance, the heavenly bodies seem to move noticeably in the opposite direction. Stars now pass overhead which did not do so before. If we travel south, constellations which could not be seen before make their appearance above the southern horizon.

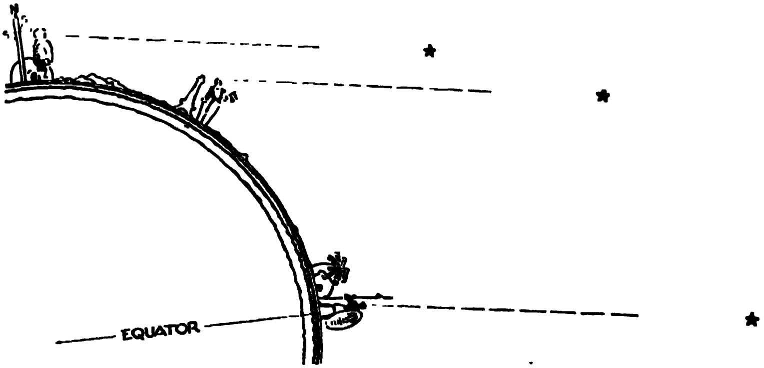


FIG. 1.2. The Stars Shift in Proportion to the Distance We Travel North or South.

A journey upon a flat earth might cause all the scenery to shift in the opposite direction, it is true, just as trees and houses pass by when we drive along the highway. But this effect would become very small indeed for objects as remote as the stars. As it is, a good day's drive toward the south is enough to make the daily courses of all the celestial bodies incline northward through an angle equal to the height of the Great Dipper's bowl. If the earth were flat, the stars overhead could be no more than four thousand miles away to be displaced as much as this.

The celestial bodies are certainly more remote than four thousand miles. Even the moon is a quarter of a million miles away, while the distances of the stars are measured in millions of millions of miles, as we know today. But if they were all only four thousand miles away, and if the earth were flat, the stars ahead of us or behind us would not be displaced as far as those overhead, as they are when we travel north or south around the curve of the earth (2.11).

The idea that the earth is a globe was not a new one, therefore, when Columbus began his voyages; it had been held by learned men for two thousand years. But the dimensions of the globe were not agreed upon in Columbus' time. His plan to reach India by a shorter route toward the west arose from his acceptance of an estimate of the size of the earth that was much too small.

The voyage of Magellan gave a striking demonstration to everyone that the earth is not flat, a proof which has become quite commonplace today when so many people sail or fly around the world. If the earth had the shape of a doughnut, one could also sail around it, of course. It remained for careful measurements to show that the earth is a globe, and that it is very nearly a perfect sphere.

1.3. The Size of the Earth. Suppose that the earth is a perfect sphere. Suppose that we start out directly toward the south and travel right on around until we are back home again. Our course would be a great circle. It would be possible to take a yardstick along and measure the distance around the circle as we go. But there is a better way.

If the earth is a perfect sphere, there is no need to measure clear around it. It is enough to measure the number of miles in one degree, that is to say, the distance we must go north or south to cause the courses of the celestial bodies to be displaced one degree. Then multiply by 360, the number of degrees in the circumference of a circle.

The length of one degree of a great circle around the earth is about 69 miles. Accordingly, the earth's circumference is nearly 25,000 miles, and its diameter is nearly 8000 miles.

Measurements of the size of the earth seem to have begun according to this plan as long ago as the fourth century B.C. The best-known and perhaps the most accurate of the early attempts was made in the third century B.C. by Eratosthenes, celebrated geographer and librarian of the great museum in Alexandria. He observed that the sun stood a fiftieth of the circumference of the heavens away from the point overhead at noon on the longest day of the year. At Syene (near Assuan) in upper Egypt, some five hundred miles south of Alexandria, the sun was said to be directly overhead at noon on that day. The earth's circumference came out, therefore, about 25,000 miles.

1.4. Positions of Places on the Earth. A common way of locating a place on the earth's surface is with reference to the natural or conventional region which contains the place. So Havana is in Cuba, and Cleveland is in Ohio. While this is near enough for some purposes, a more precise position is often required. A ship in distress does not radio simply that it is in the Atlantic Ocean, of course; it specifies its longitude and latitude.

For the accurate locations of places on the earth we imagine circles around it and draw these circles on globes that represent the earth. The *equator* is the great circle halfway between the north and south poles, dividing the earth into the northern and southern hemispheres. Circles which pass through both poles and which therefore cross the equator at right angles are *meridians*.

The *prime meridian*, or *meridian of Greenwich*, passes through the Royal Observatory at Greenwich, near London, England. It crosses the equator in the Gulf of Guinea, at the point whose longitude and latitude are both zero.

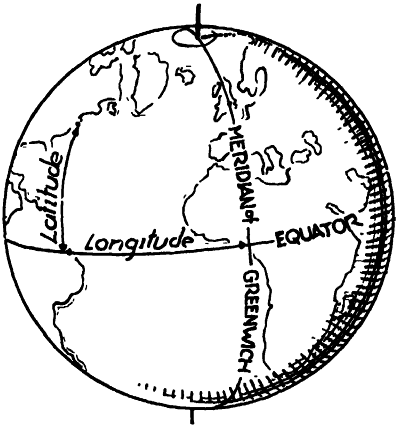


FIG. 1.4. Longitude and Latitude.

The *longitude* of a place is its distance east (−) or west (+) of the prime meridian. It is measured either in degrees or hours. Since the earth turns completely around, through 360°, in the course of a day, 24 hours equal 360°; so one hour of longitude is the same as 15° of longitude.

The *latitude* of a place is its distance in degrees north (+) or south (−) from the equator. As an example, the longitude of the U. S. Naval Observatory in Washington, D. C. is +5 hours 8 minutes, or + 77°, and its latitude is + 38° 55′.

1.5. The Earth Bulges at the Equator. If the earth were a perfect sphere, a meridian would be a perfect circle, so that anywhere at all one would travel exactly the same distance in miles north or south to go one degree along it. Careful measurements show, in fact, that one degree of latitude is not far from 69 miles in all parts of the world. So the earth is nearly a perfect sphere, but not quite; for the length of a degree becomes a little greater as we go north.

One degree of latitude equals:

68.7 miles near the equator,
68.8 miles near latitude 20°,
69.0 miles near latitude 40°,
69.2 miles near latitude 60°,
69.4 miles near the poles.

The meridians curve more rapidly, therefore, at the equator than at the poles (Fig. 1.5). From this and other evidence we know that the earth bulges at the equator.

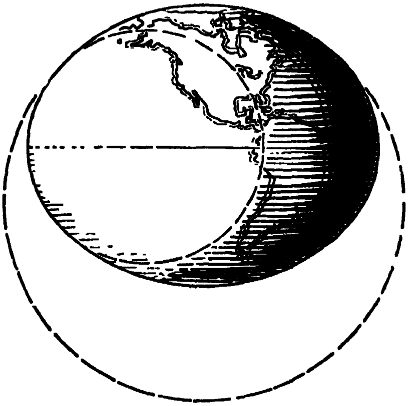


FIG. 1.5. A Meridian is Part of a Larger Circle at the Pole Than at the Equator.

The earth's diameter at the equator is 7926.68 miles, and the diameter from pole to pole is 7899.98 miles, or 26.70 miles less than at the equator. These dimensions were calculated from measurements by the United States Coast and Geodetic Survey.

If the earth is represented by an 18-inch globe, the diameter at the equator is only a sixteenth of an inch greater than at the poles, and the highest mountains rise scarcely more than a hundredth of an inch above sea level. A globe such as this could easily pass casual inspection as a perfect sphere.

1.6. Up and Down. If the earth is a globe, are there then people at the antipodes hanging head-downward? And if anyone should visit the moon, how could he manage to hold on up there? As children we asked questions like these. Later we learned that all bodies attract things toward them. The precise statement of Newton's law of gravitation appears in Chapter VII.

According to this law, the attraction between any two bodies becomes greater, the closer they are together, and the greater their masses.

that is to say, the quantity of material they contain. And it is easy to show that a sphere attracts things toward its center.

Objects near the earth's surface are attracted most strongly by the earth itself. If they are unsupported, they fall faster and faster as they come down nearly in the direction of its center, nearly so because the earth is nearly a perfect sphere. This acceleration of *gravity*, which gives things weight in proportion to their masses, is somewhat less at the equator than at the poles (2.5).

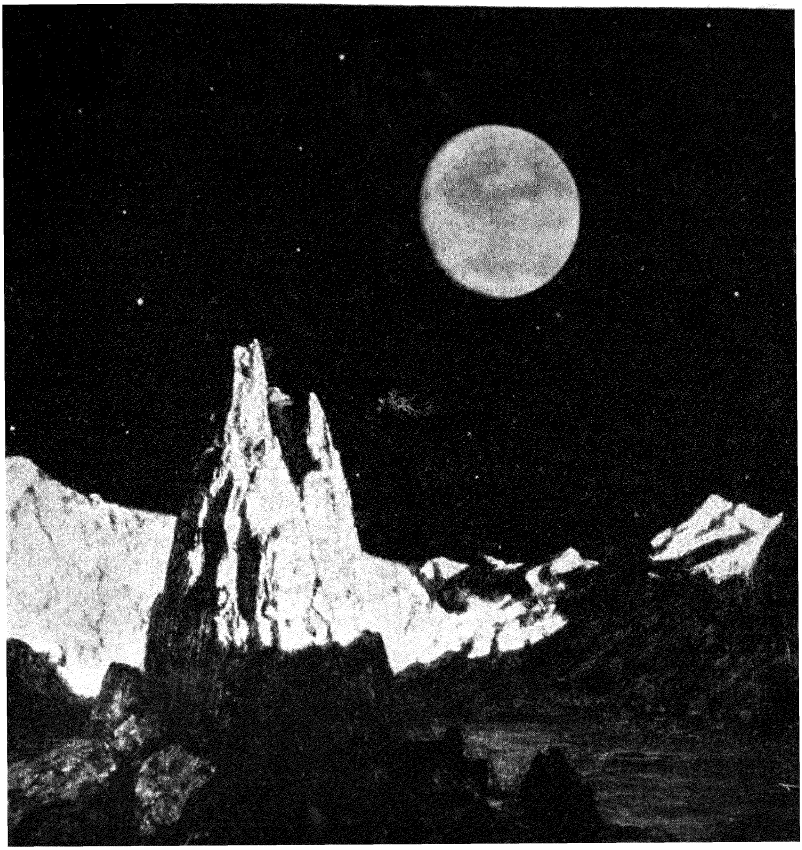


FIG. 1.6. The Earth as Seen from a Crater on the Moon. From a painting by Howard Russell Butler. (*Courtesy of the American Museum of Natural History, New York*)

If we suspend a weight at the end of a cord and allow it to come to rest, the direction of the cord is the *direction of gravity* at that place.

The cord is then the *plumb line,* or the *vertical line,* showing exactly the directions "up" and "down," directions that change with relation to the stars as we go around the curve of the earth.

Near the moon's surface, "down" is almost directly toward the center of the moon, while the earth appears among the stars in the sky in its true aspect as just one of the celestial bodies.

1.7. The Earth Itself. So the earth is a great globe nearly 8000 miles in diameter. Not a perfect sphere even when the irregularities of its surface are smoothed, it bulges a little around the equator; the equatorial diameter is about 27 miles greater than the diameter from pole to pole.

The earth's mass is 6.6×10^{21} tons, or 66 followed by twenty ciphers. In other words, the material that the earth contains would have this vast weight all together, if it could be weighed little by little at the earth's surface. The best measurements of the earth's mass have been made by special methods in physical laboratories.

The earth is 5½ times as massive as a globe of water of equal size; its *density* averages 5½ times that of water. While the rocks near the surface are less than three times as heavy as water, the density grows greater downward until at the center it is ten times that of water.

Borings show that the temperature of the rocks increases with increasing depth. This and the added evidence of volcanoes and hot springs might lead us to suppose that the earth is a molten mass surrounded by a relatively thin crust. But the compression increases toward the center, and the temperature that is required to melt the rocks increases accordingly. It may be that the earth is solid clear to its center.

But we leave these matters to the geophysicists, and look away from our earth, for a while, to the sky around us.

THE SEEMING GLOBE OF THE SKY

The globe on which we live is so large that its curvature can easily pass unnoticed at first. The small portion of the earth that we see around us in fairly level country looks flat, and the sky resembles a hollow dome resting on the rim of the world.

The blue dome of the daytime sky is certainly not very great; it is usually only a few miles to the border of the landscape where the sky descends. Shut in as we are in the daytime, we could readily get a wrong impression of the importance of the earth and of ourselves in the universe. Only the sun and the moon shine down conspicuously through the bright veil of the sunlit air to remind us that there are things beyond the earth.

But when the sun has set, the earth seems to shrink in the gathering darkness. The sky seems to expand enormously. When the stars come out, and especially as we watch them rise and set, it is then easy to imagine that the sky goes down out of sight far beyond the rim of the earth and continues on around below us.

1.8. The Sphere of the Stars. We know that the celestial bodies are not equally far away. The moon is much nearer than any of the planets. The most remote planet is only a step toward the distant stars, while the stars themselves lie at very different distances from us. Yet all these bodies are so far away that the depth of the scene is likely to escape our notice completely. All the stars, at least, seem equally remote, just as though they were attached to the inside of a hollow globe.

We call it the *celestial sphere.* This apparent sphere of the stars was recognized and regarded as a material globe by the scholars of ancient Greece before they began to picture the earth as a globe also. It stood for two thousand years thereafter almost unquestioned as the boundary of the visible universe.

The celestial sphere is only a seeming globe, as we know today. It remains as a convenient way of representing the heavens for many purposes. There is no need to imagine that the stars are attached to the sphere, however, as people did long ago. We may just as well suppose that all the stars are inside at various distances from us, and that the sphere itself is the background against which we view them.

The celestial sphere is as vast as we care to imagine it. Its center can be the center of the earth, the observer's place on the earth's surface, the sun, or anywhere else. Picturing the sky in this way, we can represent the stars on the surface of a globe or on a plane map, and describe their positions in very much the same way that towns are located on the globe of the earth.

1.9. Places of the Stars. The *apparent place* of a star is its place on the imagined celestial sphere. It signifies the star's direction and tells us nothing else about its position in space. If two stars have nearly the same direction from the earth, though one may be far behind the other, they have nearly the same apparent place in the sky.

We speak similarly of the apparent places of the sun, moon, and planets, where they appear in projection among the stars. We say that the sun is entering the constellation Leo, referring only to its direction. We remark on the nearness of the moon to a bright star, and notice how a planet is changing its place slowly among the stars around it.

So the *apparent distance* between two celestial bodies is their difference in direction; and this should not be given, of course, in linear measure such as inches or feet. There is little meaning in the statement that the full moon looks as large as a dinner plate, or that the Pointers of the Great Dipper seem to be ten feet apart.

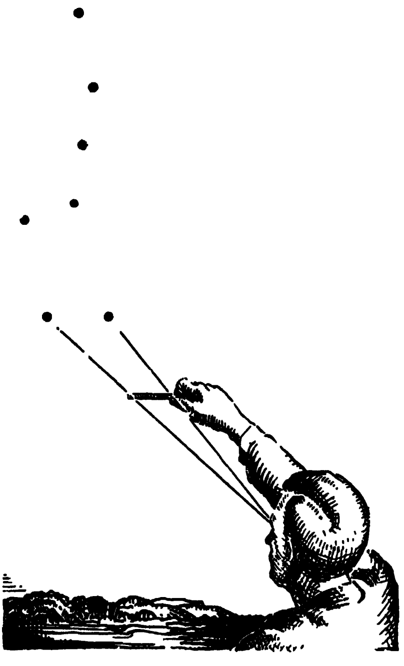


FIG. 1.9. The Distance Between the Dipper's Pointers is About Five Degrees.

Such distances are given in degrees or other angular measure. The apparent diameter of the full moon is about half a degree. The apparent distance between the pointer stars of the Dipper is a little more than five degrees. These are often used as measuring sticks for estimating other distances in the sky.

How shall we describe the place of a star so that others will know where to look for it? One way is to specify the constellation in which the star appears. The celebrated star Algol, for example, is in the constellation Perseus. Anyone who can recognize the different constellations then knows about where to find Algol. It is much like saying that New Haven is in Connecticut.

A more precise way is to locate the star with reference to circles, such as the horizon, which we can readily imagine on the celestial sphere.

1.10. The Horizon. The *visible horizon* is the line where the sky seems to descend to meet the earth. It is usually an irregular line on land, formed by the tops of trees and houses and hills; its form changes from place to place.

Clearly, the visible horizon is unsuited to the purposes of astronomy. An almanac giving the times of sunrise or moonrise above this irregular line would be of local interest only. At sea, of course, the visible horizon is a smooth enough circle in calm weather, but a circle that is depressed as the observer is elevated above the water. The horizon of astronomy is more generally useful.

The celestial horizon, or simply the ***horizon,*** is the great circle of the celestial sphere that is halfway between the zenith and nadir. Sight along a perfectly level surface, perhaps a table top, and you are looking toward the horizon. This circle cuts generally below the tops of houses and hills which form the visible horizon on land; and it lies above the sea horizon, unless one's eye is at the surface of the water. But what precisely are the zenith and nadir?

Sight along a vertical line (1.6). This line leads upward to the *zenith,* the point in the sky that is directly overhead, and downward through the earth to the *nadir,* the point directly underfoot. Since the vertical line changes direction as we travel around the curved surface of the earth, the places of the zenith, nadir, and horizon among the stars depend on where we are. So as we travel south, constellations come up above the horizon which were not visible before.

1.11. The Celestial Meridian. It is easy enough to point out the line of the horizon. One has simply to extend his arm horizontally; then as he turns around he will trace roughly this important circle which is halfway between the zenith and nadir.

It is equally easy to trace the courses of other imaginary great circles in the sky through the zenith and nadir. *Vertical circles* we call them because they cross the horizon vertically. While there can be as many vertical circles as we wish to imagine, one of them is more useful than the others; that is the celestial meridian.

The *celestial meridian* is the vertical circle that passes through the north and south poles of the heavens. We shall consider in the following Chapter the locations and significance of these two poles whose positions in the sky determine the direction of the celestial meridian. They determine also the positions of the four cardinal points of the horizon: north, east, south, and west.

North and *south* are the opposite points where the celestial meridian crosses the horizon. *East* and *west* lie halfway between them in the two directions around the horizon. When the cardinal points are located, it is proper to define the celestial meridian as the vertical circle which passes exactly north and south around the heavens.

The north star stands almost directly above the north point of the horizon. To those who can recognize this star (Fig. 2.8) there is no difficulty about finding directions on a clear night. The sun is above the south point just at midday by the sun itself; and it rises exactly in the east and sets in the west at the beginning of spring or of autumn.

In these and other ways almost everyone has learned the directions of north and south from his home, and so can trace the course of the celestial meridian across the sky through these points and the zenith.

1.12. Azimuth and Altitude. Just as a town is located precisely when its longitude and latitude are known, so the position of a star can be given by its azimuth and altitude.

Azimuth, as astronomers reckon it, is measured in degrees westward along the horizon from the south point. So the azimuth of the south point is 0°, of the west point 90°, of the north point 180°, of the east point 270°. The azimuth of a star is measured from the south point around the horizon to the foot of the vertical circle through the star. Navigators and surveyors often reckon azimuth from the north point instead.

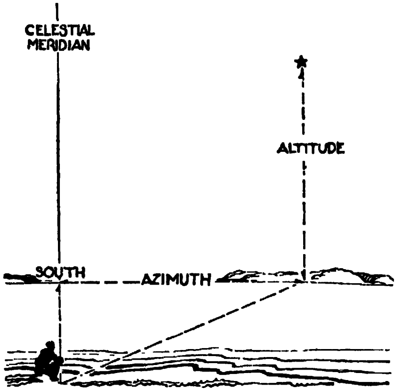


FIG. 1.12. Azimuth and Altitude of a Star.

The *altitude* of a star is its distance in degrees above, or below, the horizon. It is 0° if the star is rising or setting, 45° if the star is halfway up in the sky, and 90° if it is exactly overhead. Its complement, the *zenith distance,* or the distance in degrees from the zenith, is often used.

This is an easy way of locating a celestial body. It can be done with the engineer's transit, which is an azimuth-altitude instrument, or less precisely with no instrument at all. Where, for example, would you look for a star whose azimuth is 90° and whose altitude is 45°? Halfway up in the west, of course. And if its azimuth is 180° and its altitude is 30°, you would find the star a third of the way up in the north.

But this way of locating the celestial bodies is limited in its usefulness; for it gives their positions only at one instant and at one place on the earth. The azimuths and altitudes are continually changing as the stars move westward across the sky, and they differ at the same instant for observers in different places.

We find in the following Chapter a more nearly permanent way of locating the celestial bodies, relative to the equator instead of the horizon. Meanwhile, we turn our attention to the earth's atmosphere and notice particularly how it affects our view of the heavens.

The Earth's Atmosphere

1.13. If There Were No Air around the earth, there could be no one living here to view the heavens. Air is necessary for life as we know it. We must have air to breathe, of course, and the animals and plants which provide our food must have air also.

The air protects us, too. It fends off the deadly ultra-violet rays of the sun that would destroy us, if they could penetrate to the earth's surface. It checks the onrush of the millions of meteors that bombard us every day. These celestial missiles are so intensely heated by impact with the air that most of them are reduced to dust and gas before they can reach us.

While the air shields us from the harmful glare of the sun, it lets through much of the beneficial radiation to light and warm the earth's surface. Then, like the glass covering of the greenhouse, the air prevents the rapid escape of the heat, protecting us from serious extremes of temperature between day and night.

An airless world is a lifeless world, surely. Such is our moon. Some of the planets themselves have no atmospheres. But other planets have gases and clouds around them; it may be easier to interpret the features that are seen on the disks of those cloudy planets, if we have learned first of all something about the air around the earth.

Our immediate interest in the earth's atmosphere, however, is in its influence on the appearance of the heavens. Here at the bottom of the vast seething ocean of air we look up at the celestial bodies. How does the air affect the view?

1.14. The Region of Clouds. Our atmosphere is a mixture of gases surrounding the earth's surface to the height of several hundred miles. It weighs all together something less than a millionth of the weight of the solid earth.

The air becomes more rarefied very rapidly as we ascend. Half of the gas by weight lies within three miles and a half of sea level. It grows rapidly colder too, for the air is warmed by radiation from the ground more than by the sun's rays directly. At the uppermost level of the clouds the atmosphere is naturally divided into two layers, the troposphere below and the stratosphere above.

The *troposphere* is the lower layer of the atmosphere that extends to the height of about seven miles above sea level. It is the region of rising and falling currents and of clouds. It consists chiefly of nitrogen and oxygen in proportions of about four parts to one by volume. Water vapor and carbon dioxide in relatively small amounts play important rôles. There are other gases too, and dust in variable quantity.

Rising air is favorable to the formation of clouds; the moisture condenses as the air is cooled by expansion and by contact with its cooler surroundings. Fog-like *stratus clouds,* or layer clouds, form at an average elevation of half a mile. *Cumulus clouds,* or "woolpack clouds," rise from flat bases which are about a mile aloft. The cirro-cumulus clouds of the "mackerel sky" have average altitudes of four miles. The feathery *cirrus clouds* of ice crystals may be as high as seven miles or even a little more.

1.15. The Stratosphere extends on upward from the region of clouds. Manned balloons have soared a few miles above its base. Sounding balloons have carried self-registering instruments to an altitude of 22 miles to inform us of conditions as high as that above sea level.

There is little water vapor in the stratosphere; otherwise the gases occur here in about the same proportions as in the lower regions. The air continues to grow rarer with increasing elevation above the highest clouds, but the temperature does not continue to fall. There are strong horizontal currents. Conditions above the 22-mile limit are made known to us in part by the heights at which the air is still abundant enough to promote three familiar phenomena:

Twilight is sunlight reflected by the air above us after the sun has set. Evidently the duration of twilight depends, among other things, on the height at which the air is still dense enough to reflect the sunlight appreciably; for the higher such air extends, the longer it will remain in the sunshine after the sun has gone down on the earth below. The observed durations of twilight inform us that the air reflects sunlight in considerable amounts up to an elevation of 45 miles.

"Shooting stars" make their appearance sometimes as high as a hundred miles. The air is still dense enough at that elevation to retard the swift flights of meteors, and to heat them in this way until they glow.

Streamers of the *aurora,* or *"northern lights,"* have been observed as far as five hundred miles aloft, showing that very thin air persists to this elevation at least.

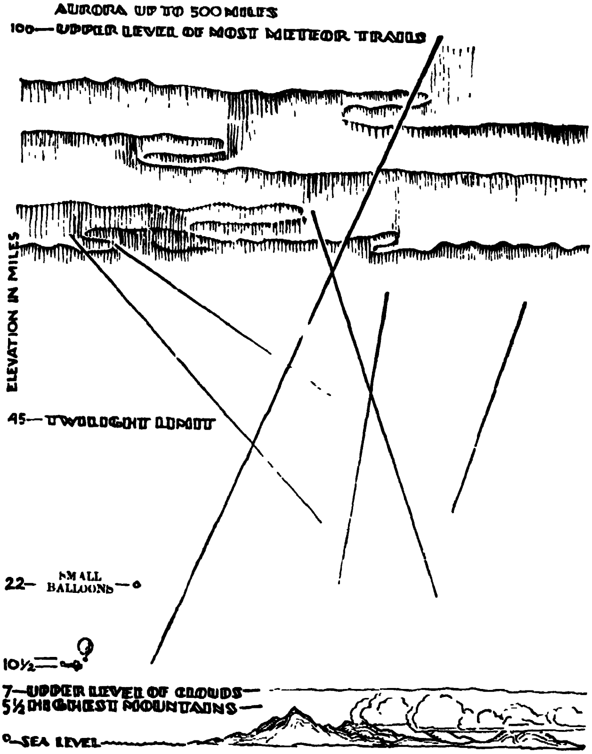


FIG. 1.15. Cross Section of the Atmosphere.

1.16. The Daytime Sky. It is not merely the greater brightness of the sun that hides the stars in the daytime. An observer on an airless world like the moon could see the stars plainly in full daylight. It is because the air reflects the sunshine down to us from all quarters of the sky that the fainter starlight does not show.

So the sunlit air conceals most of the universe beyond. The sun and moon shine through, of course, and the planet Venus can be glimpsed in the blue sky at times without the telescope. But the features of the daytime sky are chiefly things of earth—clouds, airplanes, birds, and the like. The color of the clear sky is blue, while the light of the sun itself appears yellow. Why is that?

Sunlight is composed of many colors, as we observe when it passes through a prism, or through raindrops or the spray of the waterfall. Sunlight contains all the colors of the rainbow. The green of the foliage, the varied colors of flowers and fruit, and the sunset hues are abstracted from sunlight; so also is the blue of the sky.

The blue of the sunlight is scattered by the air molecules more than the yellow, and the yellow more than the red. So on a clear day the sky takes on the blue color of the light that is scattered down to us most profusely, a blue that deepens as we ascend above the dusty and humid layer of air near the ground. The sky remains blue as far as manned balloons have risen into the stratosphere, but it must eventually deepen to black, of course, at a height so great that there is little or no air above.

Similarly, the deep yellow, orange, and red of the sunset are the colors of light which penetrate farthest through the air, and which can still come through the greater thickness of air that intervenes between us and the setting sun.

1.17. Twilight. If there were no air around the earth, the change from day to night would be abrupt. As the last sliver of the setting sun sank behind the hills, daylight would be turned into darkness as though by the snap of a switch. It is so on the moon, as the sharp dividing line between day and night clearly shows (Fig. 1.17).

But the transition from day to night is gradual with us. The sky remains bright after sunset while the air is still in the sunlight. It darkens slowly as the earth's shadow rises through the air, and takes on the full darkness of night when the shadow has reached the 45-mile level.

Civil twilight lasts about half an hour in the latitude of New York, until the sun's center has sunk 6° below the horizon. Then it is no longer possible without artificial illumination to continue outdoor operations that require good light.

Astronomical twilight ends when the sun's center is 18° below the horizon; by that time the fainter stars can be seen overhead. The whole duration of twilight in the latitude of New York varies from about an hour and a half in March and September to two hours in June. All these figures apply as well to the morning twilight that precedes the sunrise.

The duration of twilight varies not only with the time of year, but also, and in a more striking way, with the observer's latitude. Twilight is shortest near the equator, where the sun goes straight down and so reaches the 18° limit in the shortest time. There at the equator the twilight seems surprisingly short to the traveler, especially in the mountains above the densest of the reflecting air.

Twilight lasts longer as the latitude increases. North of latitude 48½° astronomical twilight lasts all night on June 22, while civil twilight persists on that date from latitude 60½° to about 66° where the midnight sun is seen.

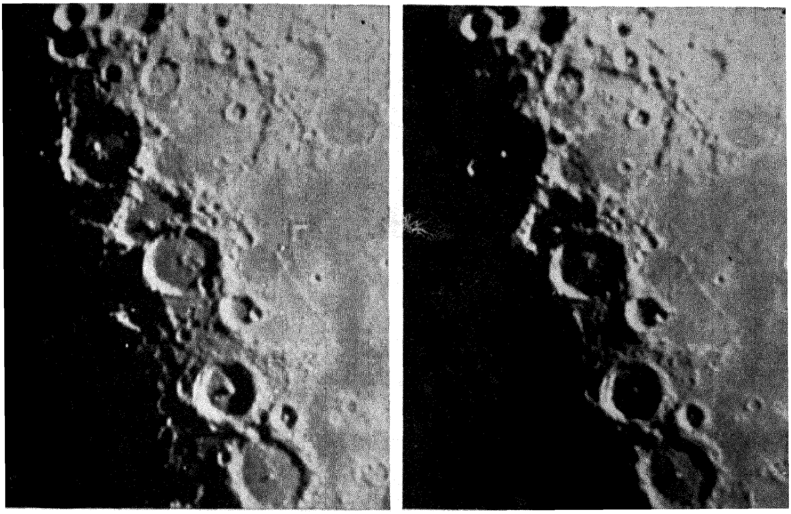


FIG. 1.17. Sunset on the Moon. The sunset line is moving toward the right. No twilight intervenes between day and night as it does on the earth. (*Photographed at the McMath-Hulbert Observatory*)

The times of the beginning and ending of twilight, also of sunrise and sunset, and moonrise and moonset, can be easily found for any date and any latitude from tables in the *American Ephemeris and Nautical Almanac*.

1.18. Refraction of Light. There is another aspect of the setting sun as familiar as its reddened color. The sun at its setting, and at its rising too, is sometimes flattened noticeably at the top and bottom so that it resembles a football. This aspect is produced by the refraction of sunlight in the atmosphere.

Whenever a ray of light passes slanting from one medium into another, as from air into glass or from lighter into denser air, its direction changes at the boundary between the two media. If the second medium is the denser, the ray goes on through it more nearly at right angles to the boundary. If the second medium is the less dense, the ray becomes still more slanting.

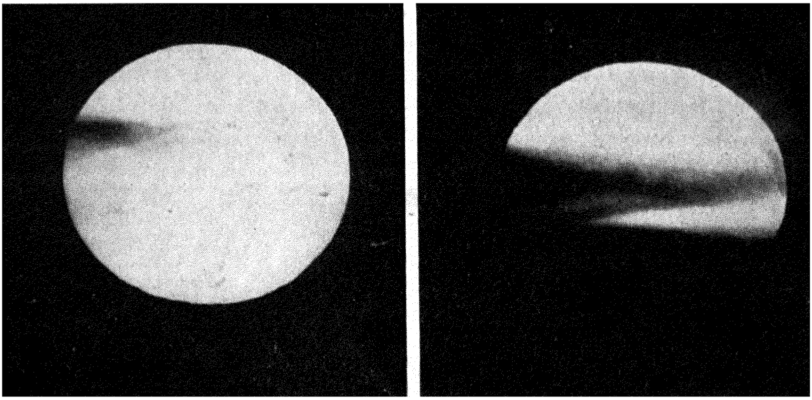


FIG. 1.18. Flattening of the Setting Sun by Refraction. (*Photographed at Yerkes Observatory*)

Refraction of light is this abrupt change in the direction of the ray of light when it passes from one medium into another, except when the ray is exactly perpendicular to the boundary. This term "ray of light" is intended to mean simply the direction in which the light is traveling. It is the custom to explain refraction as though the light were traveling in waves.

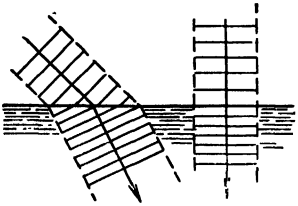


FIG. 1.18A. Refraction of Light. A ray of light passing from a rarer into a denser medium is refracted toward the perpendicular.

Suppose that the sun or any other source of light is a sort of disturbance from which waves proceed in something like the way that waves spread out over the surface of a pond when a stone is dropped into the water. Then a ray of light is a narrow strip of the wave pattern extending straight out from the source. Scientists of former days took these light-waves quite literally; they imagined an all-pervading "ether" in which the waves were produced.

The speed of light in a vacuum is always the same (11.3). It becomes less when the light passes through a medium such as air; and the denser the medium, the slower the progress of the light.

So it is easy to see (Fig. 1.18 A) what happens when a "ray" of light passes slanting from empty space into a layer of air. The speed is reduced, and more than that, if the direction is slanting, one side of each wave crest is retarded before the other. Accordingly, the wave is swung around, and the "ray" travels through the air in a less slanting direction.

1.19. Refraction Elevates the Stars. Starlight is refracted more and more as it comes down to us through air of increasing density.

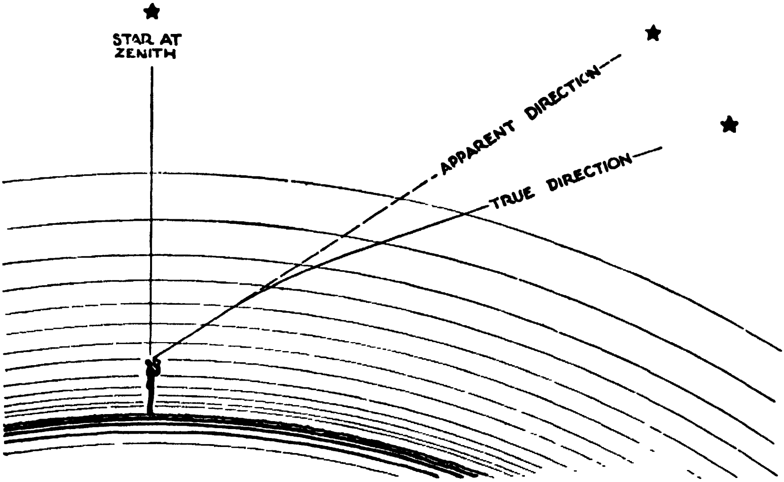


Fig. 1.19. The Stars Are Elevated by Atmospheric Refraction.

When it reaches the earth's surface, the light is proceeding in a more nearly vertical direction than before it entered the atmosphere. Unless the star is directly overhead, its apparent place — where we see it in the sky — is above its true place.

Atmospheric refraction increases the altitudes of the celestial bodies. This effect becomes greater with increasing distance from the zenith, but so gradually at first that for more than halfway down to the horizon the apparent displacement is not great enough to be detected without a telescope. As the horizon is approached, the amount of the refraction increases rapidly until it becomes really conspicuous. A star just on the horizon is raised above its true place more than the apparent diameter of the sun, or of the full moon.

Refraction brings the celestial bodies into view before they would otherwise rise, and keeps them in view for a little while after they would have set, if there were no atmosphere. Thus refraction increases the duration of sunlight each day.

It is owing to the rapid increase in the amount of the refraction effect as the horizon is approached that the setting or rising sun sometimes resembles a football. The lower edge of the sun near the horizon is elevated by refraction considerably more than the upper edge.

1.20. Twinkling of the Stars. One of the first things we notice about the stars is their twinkling; their light is unsteady. Especially near the horizon, where a greater thickness of air intervenes, the stars flicker in a striking way at times, while the very brightest ones seem to burst momentarily into rainbow hues.

The air near the earth's surface is often in commotion. Warm currents are rising, cold currents are falling, while horizontal movements of layers of different densities add to the confusion. Viewed through this turmoil the stars twinkle because of the variable refraction of their light, just as the landscape seems to quiver when we look out over a hot radiator or through the "heat waves" over the highway on a summer day.

Yet the bright planets do not twinkle, as a general thing. They are luminous disks and not points of light, as even a small telescope shows. Each point of the disk twinkles like a star; but the different points do not do so in unison, because their rays take slightly different paths through the disturbed air. Similarly, the moon shines with a steady light.

The stars do not twinkle as we view them through the telescope on nights when the atmosphere is disturbed. But everything looks blurred at such times. The "seeing is bad"; and like the "static" of radio reception, there is not much to do about it except to hope for better conditions next time.

1.21. Rings Around the Moon. Lunar halos have no special astronomical significance. Yet they are often noticed and commented on by watchers of the evening skies, and they are fine examples of refraction effects. Solar halos arise from the same cause.

The luminous rings that we see at times around the moon are produced by ice needles and snowflakes in the air, particularly in the high cirrus and cirro-stratus clouds. These six-sided crystals refract the moonlight, concentrating it in places. While many effects are possible, the most common one is a single ring around the moon having a radius of 22°. This ring often shows the colors of the rainbow, with the red on the sharper inner edge the most prominent of all.

"Moon dogs" are two enlargements in the ring on opposite sides of the moon. These appear when many snowflakes in the clouds float with their bases horizontal. A second ring having a radius of 46° and parts of other rings are seen less frequently. The impression that a ring around the moon or sun gives warning of an approaching storm has some basis in the fact that the filmy clouds which form the halos are likely to fly ahead of storm clouds.

1.22. The Aurora. A luminous arch appears sometimes low in the northern sky, its highest point in the direction of the magnetic pole.

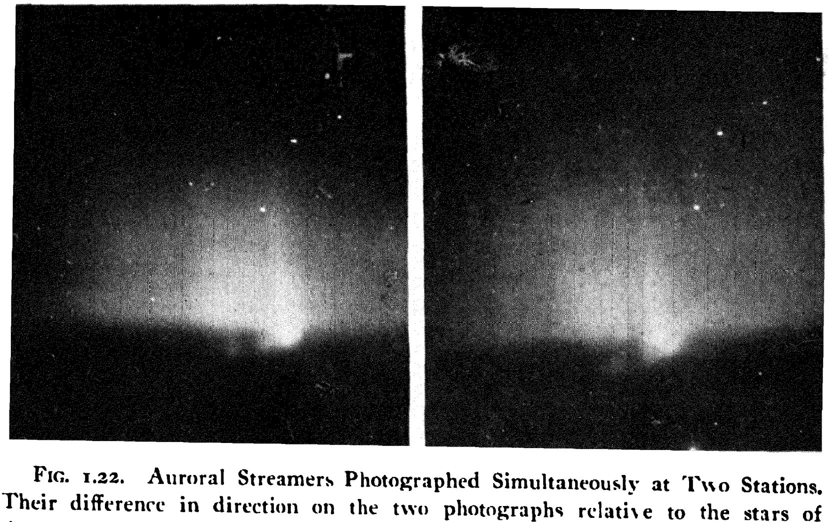


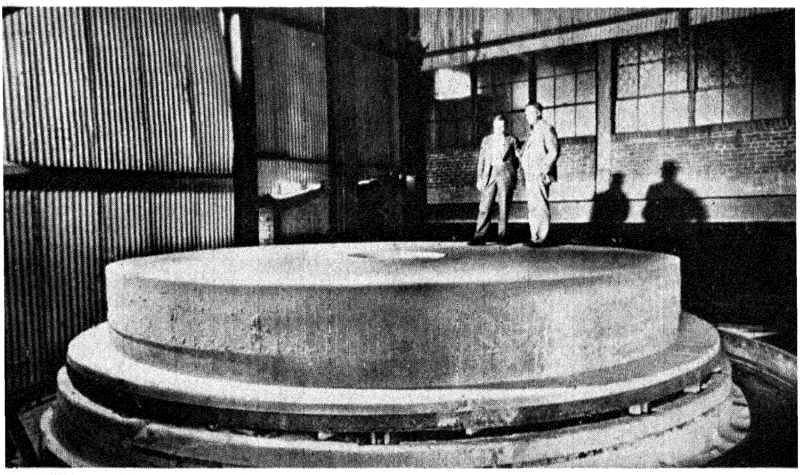
FIG. 1.22. Auroral Streamers Photographed Simultaneously at Two Stations. Their difference in direction on the two photographs relative to the stars of the Dipper's handle made it possible to determine the heights of the streamers. (*Photographs by Carl Stormer, Norway*)

Streamers like searchlight beams rise above the arch, dissolving, reforming, drifting. At times the glow spreads in patches, streamers, and draperies to all quarters of the sky. White or pale green is the more usual color of the light, though vivid green, yellow, and red are not uncommon.

Displays of the aurora, which we sometimes call the "northern lights," occur more often in the northern part of the United States than in the southern part, and still more often in Canada. They frequent the higher latitudes, as a general thing, not only in the northern hemisphere but in the southern hemisphere as well, where they are most conspicuous in the southern sky.

The displays are likely to be most frequent and brilliant on those occasions when spots are most numerous on the sun. Always they are accompanied by unusual activity of the compass needle, which informs us that a "magnetic storm" is occurring, and sometimes by serious interference with telegraphic and radio service.

The aurora is an illumination of the rarefied upper atmosphere, resembling the familiar glow in the vacuum tube. Though only rarely bright enough to be seen distinctly in our latitudes, this illumination is diffused faintly over the sky at all times. The energy that causes it comes from outside and presumably from the sun. Perhaps it comes in streams of electrified particles or in the sun's ultra-violet rays. Whatever the precise cause may prove to be, it seems probable that the same sort of stimulation of rarefied gases can account for the light of comets and nebulae also.



Disk of Glass for the 200-Inch Telescope. Cast at Corning, New York. (*Photograph from Wide World Photos, Inc.*)

QUESTIONS ON CHAPTER I

1. Are the gradual disappearance of a ship below the horizon and the circular shadow on the moon during its eclipse conclusive proofs that the earth is a globe?

2. What would be the distribution of land and water if the earth were motionless?

3. What are the longitude and latitude of the place where you are?

4. How many full moons could be placed side by side between the Pointers of the Great Dipper? What is the length of the Dipper?

5. Name the circle which includes all stars whose azimuths are 0°; whose azimuths are 180°; whose altitudes are 0°.

6. What are the azimuth and altitude of a star that appears halfway between the southwest point of the horizon and the zenith?

7. Compare the visible horizons as seen from an airplane and from the ground below it; the astronomical horizons.

8. It is sometimes said that stars can be seen in the daytime from the bottom of a deep well. What is your opinion of this statement?

9. State the real place of the sun when its lower edge appears to touch the horizon; of a star that appears directly overhead.

10. Does the sun appear larger when it is near the horizon because it is then nearer us, or because of refraction, or for some other reason?

11. If the earth's atmosphere were removed, and if we could still view the heavens, what differences would we notice?

12. Enumerate some of the dangers which would be likely to be encountered in a voyage to the moon.

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CHAPTER II

THE EARTH TURNS ON ITS AXIS

THE EARTH'S ROTATION — THE APPARENT ROTATION OF THE HEAVENS — THE TIME OF DAY

Our first conventional picture of the earth and sky is too simple, of course. This view of the globular earth standing motionless at the center of the celestial sphere must be altered as our study proceeds. First of all, it must be redrawn to account for the apparent daily rotation of the heavens.

2.1. The Stars Rise and Set, circling westward daily and keeping precisely in step as they go around. The patterns of stars such as the Great Dipper look the same day after day and year after year. It is as though the stars were set like jewels on the inner surface of a rotating hollow globe.

The idea of the turning globe of fixed stars was taught by the Greek philosophers as early as the sixth century B.C. and it remained the generally accepted view for two thousand years thereafter. These scholars imagined that the celestial sphere turned from east to west around the earth once a day on an axis which passed slanting through the earth's center.

People who gave any thought at all to the matter must certainly have reasoned that the rising and setting of the stars and the alternation of day and night could be caused equally well by the daily rotation of the earth from west to east. In fact, some scholars of early times seem definitely to have favored this alternative; Aristarchus of Samos, who lived in the third century B.C., was one of these.

But the common sense of the times held for the stationary earth. If the earth were rotating daily, it was pointed out, the equator would be whirling eastward faster than a thousand miles an hour. A thousand-mile gale would blow steadily from the east, which certainly does not occur; it was not understood that the air could turn around with the earth. Moreover, anyone could see that the earth was not moving at all.

So the heavens continued to turn westward daily around the motionless globe of the earth in the minds of most people, until Copernicus championed the earth's rotation, four centuries ago. A thousand miles an hour is fast going, to be sure. But consider what enormous speeds the far-away stars would need to have in order to circle around us once a day.

Copernicus could point only to the greater reasonableness of the earth's rotation. In later times the telescope showed that the sun, moon, and planets are rotating, thus suggesting that the earth might well be turning also. Nowadays, we recognize a number of things going on around us which would not be likely to occur if the earth did not rotate.

The distinction between *rotation* and *revolution* is more definite in astronomy than in some other sciences. Rotation is motion around an axis within the body; revolution around a center outside it. The earth rotates on its axis once a day and revolves yearly around the sun.

The Earth's Rotation

The earth rotates from west to east on the axis whose extremities are its north and south poles, once around in a sidereal (2.17) day. Among the consequences of the earth's rotation which may be regarded as proofs also are: the directions of prevailing winds and ocean currents, the whirling of cyclones, the changing direction of the Foucault pendulum, and the bulging of the earth's equator. These effects, unlike the rising and setting of the stars, arise from the earth's rotation more plausibly than from any other cause we can imagine.

2.2. Deflection of Air and Ocean Currents. The speed at which a point on the earth's surface is carried around in the rotation becomes progressively less with increasing distance from the equator. At the equator the speed exceeds a thousand miles an hour. In the latitude of New York it is around eight hundred miles an hour. In southern Alaska it is reduced to five hundred miles; and so on, until just at the pole there is no motion at all.

Consider an air current moving north from the equator, and carried eastward all the while by the earth's rotation. Since it is going from a place where the rotation is faster, the current forges ahead as it moves north and so angles to the right. If the current is moving south from the arctic region instead, it is going from a place of slower rotation, and therefore falls behind. Again it is deflected to the right.

Consider next an air current moving either north or south in the southern hemisphere, and you will see that it must be deflected to the left. Accordingly, we have this rule which applies to air currents or to anything else that is moving *along* the earth's surface:

The earth's rotation deflects moving things always *to the right in the northern hemisphere,* and *to the left in the southern hemisphere.*

The directions of prevailing winds and ocean currents follow this rule, as we can see from maps which show their directions. They prove, therefore, that the earth rotates from west to east. Notice, for example, how the trade winds blow, or how the Gulf Stream starts north and then swings to the right to warm the shores of western Europe. And notice how cyclones whirl; these, too, are examples of deflection by the earth's rotation.

2.3. Cyclones Caused by the Earth's Rotation. *Cyclones* are the large areas marked "low" on the weather maps, which are likely to bring stormy weather. They are areas of low barometric pressure into which the surface air is pouring from surrounding regions. These inflowing currents are deflected by the earth's rotation according to the rule already given; they reach the center of the area, therefore, by a somewhat roundabout way, and set the whole area whirling.

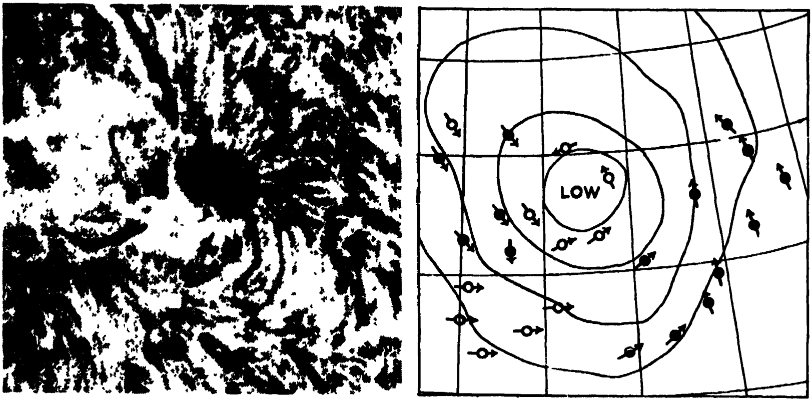


FIG. 2.3. Cyclones on the Earth and Sun. (*Photograph by Mount Wilson Observatory*)

Since by our rule the deflection of moving objects is opposite in the two hemispheres, it is easily seen that the directions of the whirls must be opposite also. Cyclones in the northern hemisphere turn always in the counterclockwise direction, or contrary to the direction taken by the hands of a clock. Cyclones in the southern hemisphere spin in the clockwise direction.

Anyone can see for himself that this is so by referring to the weather maps on which the arrows fly with the winds. It will be noticed that the anticyclones, or "highs," show the influence of the earth's rotation equally as well. The air flows outward from these areas, and should whirl in the opposite direction to that of the neighboring cyclones, which is invariably the case.

These whirling regions of the earth's atmosphere have their counterparts on the sun, as we shall see. Sun-spots are vortices whose opposite turning in the two hemispheres shows the influence of the sun's rotation.

2.4. The Foucault Pendulum. A convincing proof of the earth's rotation was first demonstrated to the public by the physicist Foucault on the 31st of May, 1851. Under the dome of the Panthéon in Paris Foucault freely suspended a heavy iron ball by a wire more than 200 feet long, and started it swinging in the north and south direction. Slowly the direction of the swing changed. Those who watched the experiment were watching, in fact, the turning of the earth under the invariable swing of the pendulum.

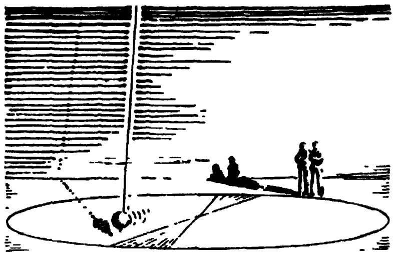


FIG. 2.4. The Foucault Pendulum.

This celebrated experiment has been often repeated. Any one can try it for himself, if space can be found in which to swing a very long pendulum. The pendulum should be freely suspended. The weight should be heavy, and should carry a pointer to show precisely the direction it is taking. Air currents and twists in the wire should be avoided; else the pendulum may soon be going around in an ellipse.

The behavior of the Foucault pendulum can be explained simply as a deflection effect of the earth's rotation. This deflection is always to the right in the northern hemisphere; here the south end of the swing shifts accordingly to the west, the north end to the east. So the direction of the swing turns around slowly with respect to the meridian beneath it. It can turn, because the Foucault pendulum is not constrained, like the pendulum of a clock, to swing in any particular direction.

The Foucault pendulum in the latitude of New York changes direction at the rate that would take it completely around in about 32 hours.

At the pole it would go around in 24 hours, while exactly on the equator it would not change at all from the original direction of the swing.

Other consequences of the earth's rotation may be mentioned. Falling bodies deviate to the east of the point directly under them when they begin to fall; but the amount of the deviation is too slight to be easily observed. The gyrocompass is a rotating device whose axis sets itself parallel to the axis of the earth's rotation. This invaluable modern aid to the navigator would not show the direction of north as it does, if the earth did not rotate. Then, too, there is the bulging of the earth's equator to be considered.

2.5. The Equator Bulges Because the Earth Rotates. The equator is more than 13 miles farther from the earth's center than are the poles. In this sense it is downhill toward the poles. Then why does not all the water of the oceans accumulate in these lowest regions around the poles? And why does the Mississippi River flow "uphill" toward the equator? The reason is found in the earth's rotation.

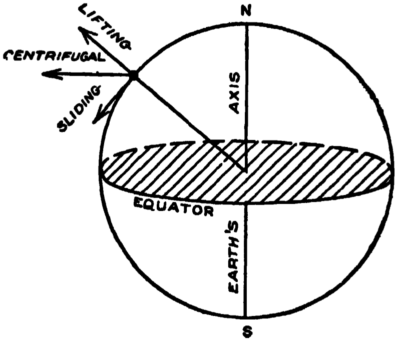


Fig. 2.5. The Earth's Rotation Diminishes the Weight of a Body at Its Surface and Propels It Toward the Equator.

All parts of the spinning earth experience a tendency to move away from the axis. It is the same centrifugal tendency that urges a stone to fly away when it is whirled around at the end of a cord. The effect on an object which shares the earth's rotation is partly to lift it so that its weight is diminished, and partly to slide it toward the equator. An object weighing 190 pounds at the pole is a pound lighter at the equator where the centrifugal effect is greatest, though part of the decrease in weight is owing to the greater distance of the equator from the earth's center.

The sliding effect of the earth's rotation operated long ago to produce the equatorial bulge. It could be imagined that material was moved toward the equator until the upslope in this direction was steep enough to offset the sliding effect. The bulging at the equator is a consequence of the earth's rotation. If the rotation should cease, the water of the oceans would rush to the polar regions; the Mississippi River would at once reverse the direction of its flow.

2.6. Changing Speed of Earth's Rotation. Since we have no scientific understanding of the beginnings of the celestial bodies, we accept their motions as readily as we do the existence of the bodies themselves. It is their changing motions that interest us specially. Does the earth turn round and round on its axis with perfect uniformity? The rotating earth is the master clock for the whole world, as we shall notice. Is this clock perfectly reliable?

Suppose that you begin with the idea that your watch is always right. As the days go by, however, you discover that everything is getting ahead of time by your watch. You miss trains which depart too early; the sun rises before it should; the town clock runs faster and faster. Presently you decide reluctantly that your watch must be running slow. It is so with the earth's rotation.

A number of periodic occurrences in the heavens, such as the circling of the moon around us, are forging ahead of their schedules as timed by the earth-clock. We conclude that the speed of the earth's rotation is diminishing. The length of the day is increasing by at least a thousandth of a second in the course of a century, and perhaps as much as twice this amount, as Brouwer points out.

The tides are the friction brakes that are slowing down the earth's turning. The tides are raised chiefly by the moon's attraction; and they follow the moon around once a month, while the earth spins under the tides once around in a day.

There are sudden and unpredictable changes too, in addition to this gradual one, as the studies of E. W. Brown and others inform us. The earth's rotation has run off schedule as much as half a minute, either fast or slow, after allowance for the tidal retardation has been made. Such irregularities would occur if the earth contracts sometimes and expands at other times only a few feet in its radius.

2.7. Wanderings of the Poles. The earth's north and south poles do not remain in precisely the same places on its surface. They are continually moving about. Accordingly, the equator is shifting, and the latitude of any point on the earth is changing. This effect, known as the *variation of latitude,* was discovered, in 1888, by the German astronomer Küstner, and has been carefully watched ever since.

Frequent observations of the stars are made at two chains of stations in different longitudes in the two hemispheres to determine how the latitudes are varying. Calculations based on these records keep us informed about the changing positions of the poles on the earth's surface.

The motions of the terrestrial poles are irregular, and so limited that accurate measurements of the latitudes are needed to show them at all. Neither pole can move much more than 40 feet from its average place; all the wanderings are confined to an area smaller than that of a baseball diamond. Moreover, there appears to be no possibility of wider migrations of the poles in the past which could have caused the marked changes in climate in geologic times.

This effect we are now considering is really a shifting of the earth on its axis. It must not be confused with precession (3.9), a top-like movement of the earth in which the axis itself is swung slowly around.

THE APPARENT ROTATION OF THE HEAVENS

2.8. The Celestial Poles. From our places on the rotating earth we watch the celestial scenery circling around us. The apparent globe of the heavens seems to rotate daily from east to west around an axis which is the axis of the earth's rotation prolonged to the sky.

The *celestial poles* are the two opposite points on the celestial sphere toward which the earth's axis is directed. They are the stationary points around which the stars circle daily. The north celestial pole is directly in the north, from a third of the way to a little more than halfway up in the sky as viewed from different parts of the United States, while the south celestial pole is similarly depressed below the south horizons of these places.

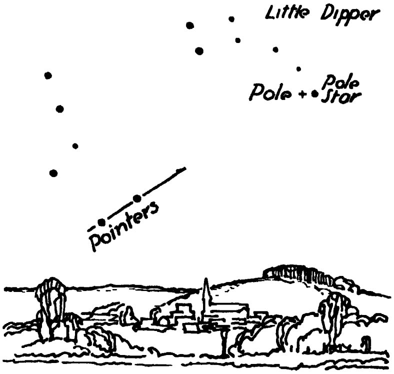


FIG. 2.8. The Great Dipper's Pointers Show the Way to the Celestial Pole.

To locate the north pole of the heavens, first find the Great Dipper. Almost everyone knows this fine figure of seven bright stars. The two stars which form the front of the Dipper's bowl are know as the Pointers, because they show the way to the pole star. Follow the line joining the pointer stars past the top of the bowl and five times as far again beyond, and you come to Polaris, the *pole star.*

Polaris is not precisely at the north pole of the heavens; there is space between for two full moons side by side. It is the bright star nearest the pole, marking roughly the place of this important point and the direction of north as well. Polaris is the *north star* also, the faithful guide to travelers on land and sea.

2.9. The Celestial Equator. Just as the earth's equator is imagined halfway between the poles, so the *celestial equator* is the imaginary great circle of the heavens halfway between the north and south celestial poles. It divides the globe of the stars into the north and south celestial hemispheres.

Everywhere, except exactly at the poles where it lies along the horizon, the celestial equator crosses the horizon at the east and west points, half of it always in view and half out of sight; that is why days and nights are of equal length when the sun is crossing the equator. The celestial equator has always the same position in the sky as viewed from the same latitude. Its position is different, however, from different latitudes.

The celestial equator arches higher and higher across the sky as we travel south, passing directly overhead when the equator is reached. As we travel north, it leans farther and farther to the south, until at the north pole it coincides with the horizon. In the latitude of New York the celestial equator is inclined about 50° to the horizon (its inclination is always the complement of the observer's latitude), and is 50° up in the south at its highest.

The direction of the celestial equator across your sky is traced out by the sun when it is crossing the equator, on March 21 or September 23, or very nearly by the daily circling of Orion's belt.

Hour circles in the sky are like meridians on the earth. They are half-circles which join the celestial poles, and which therefore cross the equator at right angles. While we may imagine as many as we like, it often happens that 24 of these half-circles are represented on the celestial globes equally spaced all around, one for each hour of the day.

And just as the location of a place on the earth is given by its longitude and latitude, so a celestial body is located by its right ascension and declination.

2.10. Right Ascension and Declination. The *right ascension* of a star is measured in hours, or sometimes in degrees, eastward along the celestial equator from the vernal equinox to the hour circle that passes through the star. (The vernal equinox is the point where the sun crosses the celestial equator on its way north, on March 21.)

The *declination* of a star is the star's distance in degrees north or south from the celestial equator; it is measured along the hour circle through the star. The declination is *plus* if the star is north of the equator; *minus* if it is south.

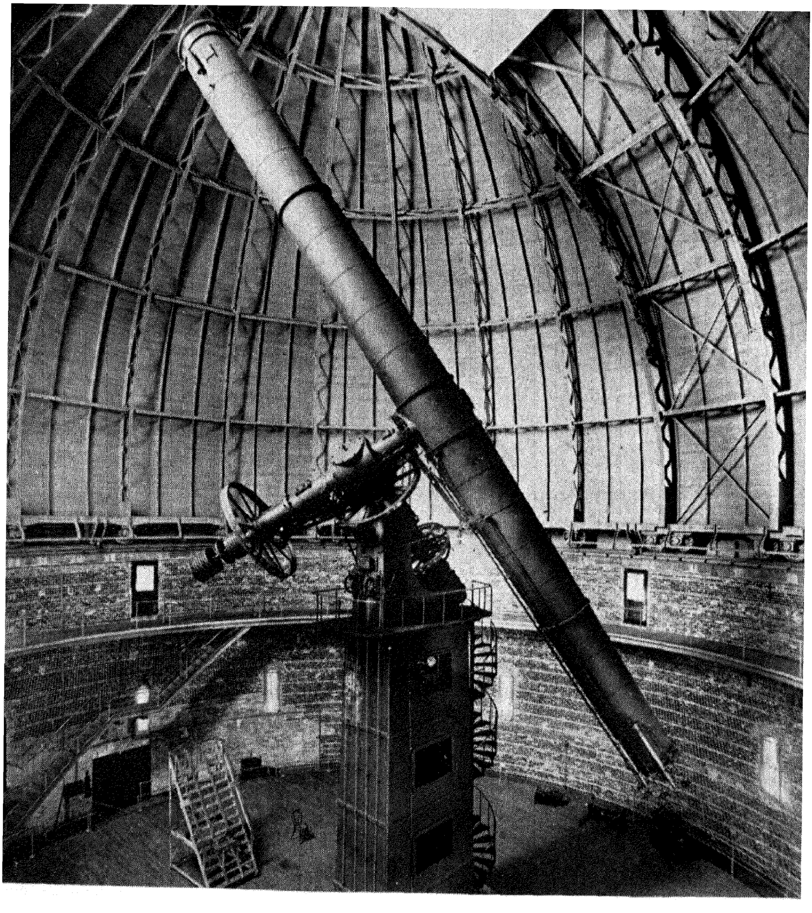


FIG. 2.10. Forty-Inch Refracting Telescope, Yerkes Observatory. The largest refracting telescope; its objective, a pair of lenses 40 inches in diameter at the top of the tube, focuses the light by refraction. This is an equatorial telescope. It can be turned parallel and perpendicular to the celestial equator. Graduated circles on the two axes facilitate the pointing of the telescope to any desired right ascension and declination.

Right ascension is like longitude, except that it is measured in one direction only. Declination resembles latitude. They might better have been called celestial longitude and latitude, except that those terms were already employed with a different meaning (3.6) when the celestial equatorial system came into use.

As an example, the right ascension of Arcturus is $14^h\ 13^m$, and its declination is $+ 20°$. So this star which closed the circuit to turn on the floodlights of the Chicago World's Fair is $14^h\ 13^m$, or 213°, east of the vernal equinox, and 20° north of the celestial equator. Can you now point to Arcturus from this description of its position? Not as readily without a telescope, to be sure, as when its azimuth and altitude are given.

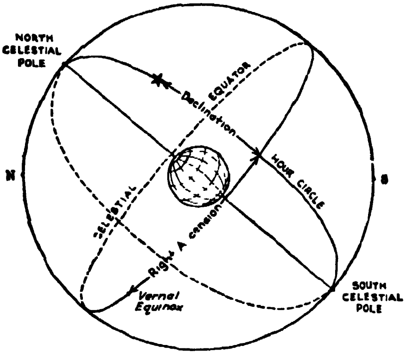


FIG. 2.10A. Right Ascension and Declination. Right ascension is measured eastward from the vernal equinox along the celestial equator. Declination is measured north or south from the equator.

Right ascensions and declinations are most generally employed in describing the positions of celestial bodies. They are more permanent than azimuths and altitudes. Yet they change as time goes on, not simply because the bodies themselves are moving, but also because the vernal equinox and celestial equator are in motion relative to the stars. Indeed, it seems impossible to find anything in the universe that is entirely stationary.

2.11. Altitude of Celestial Pole Shows the Latitude. We say ordinarily that the latitude of a place on the earth is its distance in degrees north or south from the equator. Since the earth is not a perfect sphere, it is better to say that *latitude* is the number of degrees a vertical line at that place is inclined to the equator.

It is easy to see, from Fig. 2.11, that *the latitude of a place is the same as the altitude of the north celestial pole.* So if this pole of the heavens stands directly over your head, altitude 90°, you are at the north pole. If it is halfway up in the north, altitude 45°, your latitude is 45° north; and if the celestial pole appears near your north horizon, you are not far from the equator.

In examining this Figure, it is well to remember that parallel lines are directed toward the same point in the heavens; like the rails of a track they seem to meet in the distance. We notice that the latitude of a place is also the same as the declination of the point directly overhead at that place.

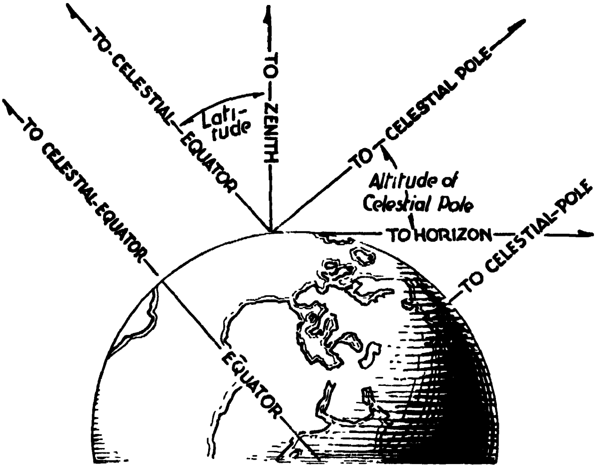


FIG. 2.11. The Latitude of a Place on the Earth Equals the Altitude of the Celestial Pole at That Place. The two angles are equal because they are both complements of the angle between the celestial pole and the zenith. Evidently the latitude is also equal to the declination of the zenith at the place.

Our rule determines the *astronomical latitude.* It depends on the vertical line, and is affected by anything that alters the direction of the vertical. A mountain near the place of observation would cause the plumb line to incline a little in its direction. Such "station errors" may make a difference of nearly a mile in the latitude, though they are usually very much smaller. *Geographical latitude* is the observed astronomical latitude corrected for station error; it is the latitude that would be observed if the earth were perfectly smooth and uniform.

The earth is mapped by observations of the celestial bodies. Here we have the rule for determining latitude. The different ways of finding the latitude, employed by the explorer, the surveyor, the navigator, or the astronomer, are really ways of finding how high the celestial pole stands, or the distance from the celestial equator to the zenith. One of the very earliest devices was the measurement of shadows at noon.

2.12. Shadows at Noon. The length of the shadow of a vertical shaft at noon by the sun informs us of the sun's distance from the zenith; the more nearly overhead the sun stands, the shorter is the shadow. When the height of the shaft is known and the length of the shadow has been measured, it is easy to calculate the sun's zenith distance in degrees.

If the shadow is measured on March 21 or September 23, when the sun is crossing the celestial equator, then the sun's zenith distance is the same as the declination of the zenith which, as we have seen, equals the latitude of the place. If the shadow is measured at noon on some other day, and if it is known how far the sun stands north or south of the equator on that day, then the latitude can be found as easily as before.

People of olden times determined latitude in this way. They obtained other information as well from the shadows. They could learn when the sun was farthest north or south; at such times the shadows at noon are shortest or longest. The obelisks of Egypt were certainly used for this purpose. The greater the height of the shaft, or gnomon, the longer is the shadow, of course, and the more accurately the sun's place can be determined. Yet the accuracy could not be great at best, for the ends of the shadows are not sharply defined.

The navigator today does much the same thing when he "takes the sun" at noon; he uses a sextant instead of a shadow to find the sun's zenith distance. Members of the United States Coast and Geodetic Survey and the astronomers in the observatories determine latitudes within a few feet easily by sighting stars with a special instrument known as the zenith telescope.

Let's turn our rule for latitude around. When we know our latitude, we know then how high the celestial pole stands, and how the stars seem to circle daily around it.

2.13. At the Pole, the Stars Never Set. At the north pole, the north celestial pole is directly overhead, while the stars go around it daily in circles that parallel the horizon. All stars to the north of the celestial equator, which here lies along the horizon, never set, while stars in the southern half of the heavens never come into view. If we include the effect of refraction (1.19), this statement and a few that follow must be modified a little.

When the arctic explorer reaches the north pole, there is nothing peculiar to be noticed about this point in the landscape; the pole itself looks very much like other parts of the region for miles around. The explorer knows when he has arrived at the pole because here the celestial bodies circle around the zenith.

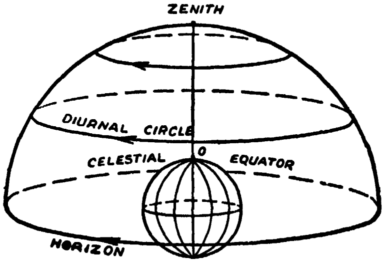


FIG. 2.13. At the Pole the Celestial Bodies Circle Parallel to the Horizon.

The sun, moon, and planets rise or set at the north pole whenever they cross the celestial equator. The sun rises about March 21, spirals slowly up the sky to an altitude of 23½° on June 22, and then spirals slowly down again to its setting about September 23. Twilight, lasting nearly two months, precedes the sunrise and follows the sunset. The moon rises and sets about once a month.

Everything is reversed at the south pole. There the south pole of the heavens stands in the zenith, while the stars of the southern celestial hemisphere circle parallel to the horizon. And the long day begins at sunrise about September 23.

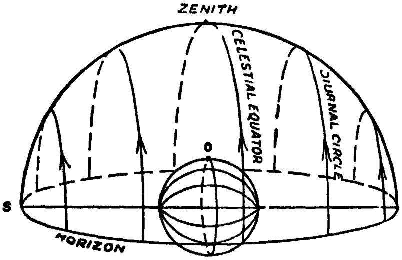


FIG. 2.14. At the Equator the Diurnal Circles are Perpendicular to the Horizon.

2.14. At the Equator, All Stars Rise and Set. Here the latitude is zero. So by our rule the altitude of the north celestial pole is zero; this pole stands at the north point of the horizon, while the pole star rises and sets as it circles close around the pole. The south celestial pole appears at the south point of the horizon. The celestial equator arches directly overhead from east to west.

All the stars rise and set at the equator. Their courses cross the horizon at right angles, and are all cut in two by the horizon. Accordingly, every star remains above the horizon just as long as it is down out of sight. The sun is no exception; days and nights at the equator are of equal length throughout the year.

At the equator the heavens can be seen from pole to pole, so that all parts are brought into view by their apparent daily turning.

2.15. The Heavens Turn Obliquely For Us who live between the pole and the equator. Suppose that we are observing from latitude 40° north, or about the latitude of Philadelphia.

Here the north celestial pole is 40° above the north horizon. The celestial equator arches across from the east point to the west point, leaning so that its highest point is 40° south of the zenith. The daily courses of the stars lean toward the south as well, since they are parallel to the equator.

FIG. 2.15. The Heavens Turn Obliquely for Us. Trails of stars approaching their setting. The sky is illuminated with zodiacal light (9.12).

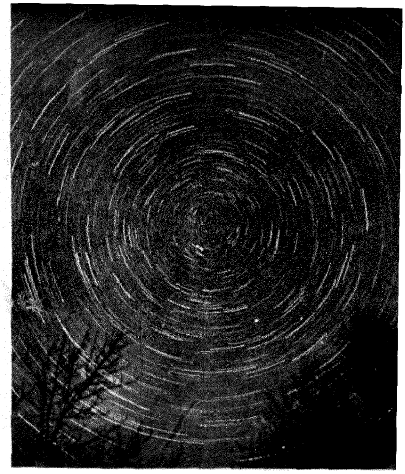


FIG. 2.15A. Circumpolar Star Trails. The plate was exposed for one hour. The bright trail a little way below the pole is that of Polaris.

(*Photographed at Yerkes Observatory*)

Half of the celestial equator is above the horizon. Northward from the equator the daily courses of the stars come up more and more above the horizon until they are entirely above it. Southward from the equator they are depressed more and more until they disappear completely. In this oblique arrangement as we view it, the celestial sphere is divided into three parts:

A circular region around the elevated north celestial pole contains the stars that never set. The radius of this cap is the distance of the pole from the horizon, which is the same as the latitude. So in latitude 40° the northern region of the heavens whose stars never set is 40° in radius. To this we must add half a degree because of refraction. The Dippers and Cassiopeia's Chair are well-known figures which are here always above the horizon in the north.

A circular region of the same size around the depressed south celestial pole contains the stars that never rise. From this radius we must subtract half a degree because of refraction. The famous Southern Cross belongs to this region that is never seen in latitude 40° north.

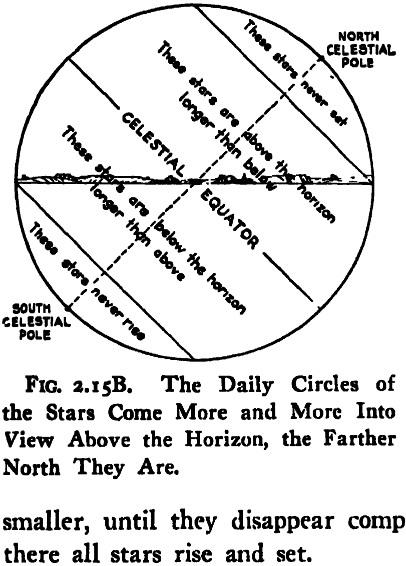


FIG. 2.15B. The Daily Circles of the Stars Come More and More Into View Above the Horizon, the Farther North They Are.

The remainder of the heavens, in a band extending 50° on either side of the celestial equator, contains the stars that rise and set in the latitude of Philadelphia. Leo, Pegasus, and Orion are among the constellations which rise and set.

If we travel north, the celestial poles move farther from the horizon. The polar caps grow larger and larger, until they run together when the pole is reached; there, as we have seen, no stars rise and set. If we travel south, the celestial poles approach the horizon. The polar caps grow smaller and smaller, until they disappear completely when the equator is reached; there all stars rise and set.

2.16. The Midnight Sun. *Circumpolar stars* go round and round the celestial poles without crossing the horizon. These stars do not rise or set because they are closer to one of the celestial poles than the distance of that pole from the horizon, which is the same as the observer's latitude. We can make this general rule about them, for those who observe in the northern hemisphere:

A star whose distance from the north celestial pole is less than the latitude of a place never sets at that place. A star whose distance from the south celestial pole is less than the latitude never rises. Here again we must not forget that a star as much as half a degree below the horizon is lifted into view by refraction of its light in the atmosphere.

Consider the sun on June 22. Its center is then 23½° north of the equator, or 66½° from the north celestial pole. On that day, when the sun is farthest north, it rises and sets in latitude 40°, and indeed everywhere in the United States and in all except the northernmost parts of Canada and Alaska.

How far north must we go on June 22 in order to see the sun circle around the pole without setting? Evidently we must go north as far as latitude 66½°, according to our rule. If we take into account the refraction effect and the size of the sun's disk, we must go at least as far as latitude 65¾° to see the sun at midnight.

FIG. 2.16. The Midnight Sun at Tromso, Norway. (*Photographed at 12.03 A.M., July 4, 1930, by Annie J. Cannon*)

The *midnight sun* is simply a special case of a circumpolar star. For those who are far enough north or south the sun at one season enters the region that is always above the horizon, and at the opposite season the region always below the horizon.

THE TIME OF DAY

We can set our watches by a clock that is regulated to agree with a clock in an observatory, or else directly by radio signals from the observatory clock itself. That clock in the observatory is regulated by the master timepiece of all, the clock in the sky.

It is really the earth's turning round and round on its axis that counts out the days and tells us the time of day. The earth's rotation is not perfectly uniform, as has been said (2.6). Yet it is remarkably reliable as compared with the best clocks that man has made. We keep track of this rotation by observing the apparent westward turning of the heavens that it causes.

2.17. Time by the Stars. Any one of the stars or any chosen point on the turning sphere of the stars can serve as the end of the hour hand of the great clock in the sky. The hour hand is that part of the hour circle which connects our time reckoner with the celestial pole. This hour hand swings around daily, telling the time to those who can read it. The rules are these:

A *day* is the interval between two successive transits of our time reckoner over the same branch of the celestial meridian. A star *transits* when it crosses the celestial meridian; and since the star does so twice a day, we distinguish between its *upper transit,* above the north pole of the heavens, and its *lower transit,* below the pole.

It is *noon* when our time reckoner is at upper transit, when this hour hand points straight up in the north. It is midnight when the time reckoner is at lower transit; then the hour hand points straight down below the pole. The hand of the sky clock goes around only once a day, of course.

Time of day is the *hour angle* of the time reckoner, that is to say, the angle between the chosen hour hand and the celestial meridian, measured in hours around to the west.

Instead of selecting one of the stars as the time reckoner for star time, or sidereal time, astronomers choose the vernal equinox, the point among the stars where the sun crosses the equator at the beginning of spring (3.7). So a *sidereal day* is the interval between two successive upper transits of the vernal equinox, or between two successive sidereal noons. *Sidereal time* is the hour angle of the vernal equinox; it is reckoned from sidereal noon through 24 hours.

2.18. The Solar Day is Longer Than the Sidereal Day. Suppose that the sun is just now at the vernal equinox, and that the two are crossing the celestial meridian together at upper transit. It is sidereal noon, and also solar noon—noon by the sun. The sidereal day ends when the vernal equinox comes around again to upper transit. Meanwhile the sun has been moving along eastward from the vernal equinox in its annual circuit of the heavens. As they come around to the meridian again the next day, the sun is lagging behind; it returns to upper transit nearly four minutes later than the return of the vernal equinox.

Thus *the solar day is nearly four minutes longer than the sidereal day.* The difference is more nearly $3^m\ 56^s$.

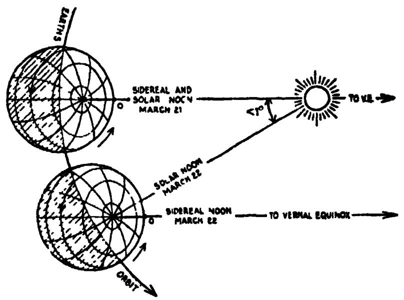


FIG. 2.18. The Earth Rotates Once in a Sidereal Day.

So the earth rotates once in a sidereal day (Fig. 2.18), not once a day by your watch which keeps sun time. Since the stars circle westward once in a sidereal day, they rise four minutes earlier by your watch from night to night, or half an hour earlier from week to week, or two hours earlier from month to month. And this is a fine arrangement indeed. There is no need to stay up late to study the constellations; we can wait until they rise at convenient hours.

Each night at the same time by your watch, therefore, the stars are a little farther toward the west than they were the night before. As the seasons go around, the constellations march slowly westward across the evening sky. Each season brings its own display of stars.

Sidereal time is kept by special clocks in the observatories, which are set directly by the star clock in the sky. Timed by these clocks, a star rises at the same time all year around, and there are 366¼ days in the year. Since our ordinary affairs are regulated by the sun and not by the vernal equinox, we prefer to keep solar time for most purposes. But there is this difficulty about setting our watches by the sun:

2.19. The Apparent Sun is Not a Reliable Timekeeper. There are times in the year when the apparent sun runs nearly a quarter of an hour slow, and there are other times when it runs more than a quarter of an hour fast of a uniform schedule. By *apparent sun* is meant the sun that we see. The lack of uniformity in its movements is caused by the varying speed of the earth's revolution around the sun and by the inclination of the earth's equator to its orbit, features that we have not yet considered.

Apparent solar days vary in length. On this account the *mean sun,* or average sun, is chosen for the keeping of civil time. This imaginary sun is a smooth-running timekeeper; its day has the same length throughout the year, the average of all the apparent solar days. The difference at any instant between the hour angles of apparent sun and mean sun, which is known as the *equation of time,* is tabulated for each day of the year in the nautical almanacs.

The accompanying Table shows how much the apparent solar time, or the time by the sundial, is fast or slow with respect to local mean time on the first of each month. These values of the equation of time are for noon by the sundial at Washington in 1935, but they hold within a few seconds for any place and any year at all.

EQUATION OF TIME

(Apparent sun fast or slow)

Jan. 1	3^m	27^s	slow	July 1	3^m	33^s	slow
Feb. 1	13	39	slow	Aug. 1	6	13	slow
Mar. 1	12	34	slow	Sept. 1	0	8	slow
Apr. 1	4	5	slow	Oct. 1	10	8	fast
May 1	2	54	fast	Nov. 1	16	20	fast
June 1	2	26	fast	Dec. 1	11	5	fast

Notice how rapidly the apparent solar time is falling behind at the beginning of winter, and how, accordingly, the times of sunrise and sunset by your watch are delayed at this season. After the sun starts north, on December 22, we look for an increase in the daily duration of sunshine. It does increase indeed, but not equally at the two ends. The sun begins to set later as soon as the middle of December; but it is not until along in January that it begins to rise earlier in the morning.

2.20. Civil Time is the time of day by the mean sun. The civil day begins at midnight, when the mean sun is at lower transit, and runs through two 12-hour divisions, before noon (A.M.) and after noon (P.M.), until the next midnight. The combined words "forenoon" and "afternoon" refer, of course, only to the two divisions of the daylight hours.

Astronomers prefer to have the hour hand of the civil clock go around the dial once a day, like the hour hand of the clock in the sky; in astronomical records 9 P.M. appears as 21^h. Some foreign nations keep the time in this way for other purposes as well.

Civil time, therefore, is the hour angle of the mean sun counted in 12-hour divisions from both lower and upper transits, or else from lower transit alone around through 24 hours.

2.21. How Time is Determined. The time of day can be determined by observing the sun's place and correcting to civil time by means of the equation of time. It can be found more accurately by observing the stars; for the stars are points instead of disks, and there are many of them. The rule is simple:

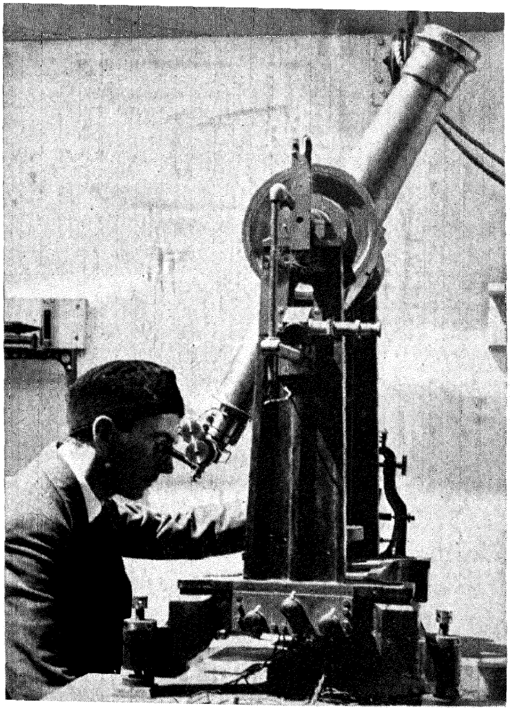


FIG. 2.21. Transit Instrument at the Naval Observatory, Washington.

The sidereal time is the same as the right ascension of a star that is crossing the celestial meridian at upper transit at that instant. Clearly what is needed is something to show the place of the celestial meridian precisely, so that the instant of the star's crossing can be observed. The transit instrument is used for this purpose.

The astronomical transit instrument is a small telescope which can be turned around on a single axis set precisely in the east and west direction. As the telescope is turned, it points always toward the celestial meridian whose place is represented by a vertical thread in front of the eyepiece. The observer points the telescope to a place where a star is about to pass. He watches the star as it moves across the field of view until it comes exactly to the mark representing the meridian.

Suppose that the sidereal clock reads $3^h\ 42^m\ 22^s.7$ at the instant the star is transiting. Suppose that the star's right ascension as given in a catalogue is $3^h\ 42^m\ 26^s.2$, which by our rule is the correct sidereal time at that instant. Then the sidereal clock is 3.5 seconds slow, and a simple calculation gives the correct civil time also.

2.22. Difference of Longitude Equals Difference of Time at the same instant between two places. This is true because there are 24 hours of longitude around the earth, while the earth rotates once in 24 hours. It matters not at all what kind of time is compared at the two places, whether sidereal, apparent solar, or local civil time, so long as the same kind is chosen.

What, for example, is the longitude of a place where it is 6 o'clock in the morning by local time when the clock at Greenwich is striking noon? Since the time at this place is six hours earlier than Greenwich time, its longitude is six hours west of Greenwich. Evidently the way to determine your longitude is to set your own clock right with the sun or stars, and then to compare this time with the time signals from Greenwich or a nearer station whose longitude is known.

Three ways have been mentioned already in which the celestial bodies are useful to us in our ordinary activities. In their daily circling around the celestial pole the sun and stars show the points of the compass. By their places in the sky they show the positions of places on the earth, the longitudes and latitudes of these places. Finally, they tell us the local time of day, from which our standard time is derived.

2.23. Standard Time. Local time is the same at any instant for all places on the same meridian from pole to pole. In the east and west direction the time changes in accordance with our longitude rule. In latitude 40° it changes 8 minutes in every hundred miles, becoming later toward the east and earlier toward the west.

In former times, each community kept its own local solar time, or any variation from this that it chose. But as means of travel and communication became more rapid, the keeping of many different kinds of time caused much inconvenience. Finally, in 1884, an international conference in Washington instituted a plan for keeping the same time over considerable areas of the world. In its ideal form, which has not been entirely realized, the plan of *standard time* is this:

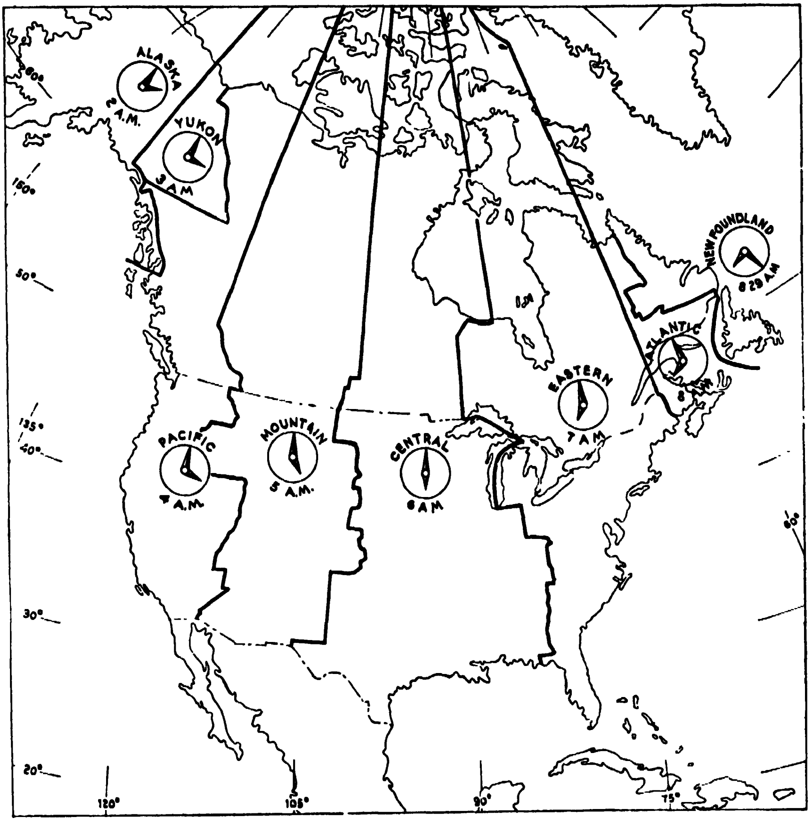


FIG. 2.23. Standard Time in the United States and Canada. The time is shown in each belt when it is noon at Greenwich.

Standard meridians are marked off around the world 15° or one hour apart, beginning with the meridian of Greenwich. The standard time for any place is the local civil time at the standard meridian nearest the place. Thus there are 24 standard time belts; the same time is kept uniformly through each belt, and from one belt to the next the time changes an even hour. The plan has been adopted only in part.

Five standard times are used, for the most part, in Canada and the United States, namely, Atlantic, Eastern, Central, Mountain, and Pacific standard times. They are respectively the local times at the standard meridians 60°, 75°, 90°, 105°, and 120° west of Greenwich, and are therefore 4, 5, 6, 7, and 8 hours earlier than Greenwich civil time, or *universal time,* as it is called for international purposes. The boundaries between the belts are made irregular by the requirements of railroads and the special preferences of communities and states.

"Daylight saving time," which is preferred in some localities during a part of the year, is one hour fast of the ordinary standard time.

2.24. Distribution of Correct Time. Observatories in various parts of the world distribute the correct time by telegraph and radio at specified hours. The Naval Observatory in Washington, for example, broadcasts standard time signals from the Arlington station, NAA, during the five minutes preceding the beginning of each hour; the frequencies most used are 113 and 9425 kilocycles. These dot signals are second beats of the crystal clock whose error during the broadcasts is never more than a few thousandths of a second. At certain seconds the dots are omitted (Fig. 2.24) so that the listener can readily identify the minute and second of each signal.

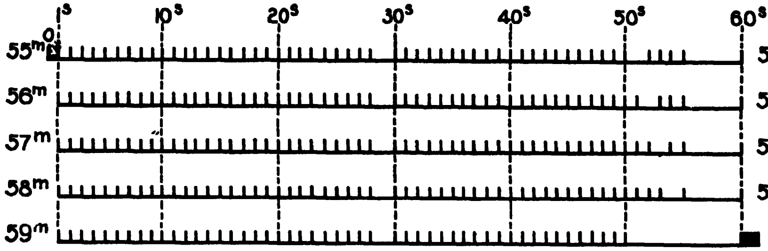


FIG. 2.24. Plan of Time Signals from the Naval Observatory. The short lines represent dot signals; these are omitted at the 29th second and before the beginning of each minute, where the number of signals immediately preceding the long breaks denotes the number of minutes before the beginning of the hour. The longest break of all comes before the long dash that announces the beginning of the hour.

2.25. Where the Day Changes. Eastward from Greenwich the time becomes later until it is 12 hours later halfway around the earth.

Westward from Greenwich the time becomes earlier until it is 12 hours earlier halfway around. There must be provision somewhere for a change of a whole day.

The "change of date line" is the standard meridian 180° or 12 hours from Greenwich, as nearly as possible. When this line is crossed on a westward voyage, as in going from America to Japan, the calendar moves forward a day; if the line is reached on Thursday noon, it becomes at once Friday noon. If the line is crossed on an eastward voyage, the calendar is set back a day.

Fortunately the 180° meridian passes mostly over the ocean. Where it runs across a group of islands, the change of date line is diverted to one side so that the group has the same day, and as a general thing the same day as that of the mainland from which the islands were colonized.

QUESTIONS ON CHAPTER II

1. Distinguish between rotation and revolution. Is the alternation of day and night a conclusive proof of the earth's rotation?

2. Since the earth rotates from west to east, a falling body should land a little way to the east of the point directly below it at the beginning of its fall. Explain.

3. Does the wandering of the poles (2.7) change the place of the celestial pole among the stars?

4. Suppose that the shadow of a vertical rod at noon is as long as the rod itself, and that the sun's declination is −5°. What is the latitude of the place?

5. Why is it more convenient to have the right ascensions of the stars increase toward the east rather than toward the west, as the azimuths do?

6. Which of the following stars never set, rise and set, or never rise in latitude 40° N: Arcturus, declination + 20°; Polaris, + 89°; Canopus, − 53°; Alkaid (at the end of the Great Dipper's handle), + 50°; Alpha Crucis, − 63°?

7. Suppose that Arcturus were selected as our time reckoner instead of the sun. What would then be the meaning of "noon"? What would be the inconvenience of the new plan?

8. Show that the solar day is about four minutes longer than the sidereal day.

9. How many sidereal days are there in a year? Explain.

10. If a star rises tonight at 9 o'clock, when will it rise tomorrow night? If a star is directly in the south at 9 o'clock tonight, at what time will it appear there a month from now?

11. What kind of time is kept by the sundial? By your watch?

12. When it is noon by the sundial on November 1, what is the local mean solar time? What is then the standard time, if the longitude of the place is 85° west of Greenwich?

CHAPTER III

THE EARTH GOES AROUND THE SUN

THE EARTH'S REVOLUTION — THE EARTH'S PRECESSIONAL MOTION — THE SEASONS AND THE CALENDAR

The earth's daily rotation from west to east accounts for the westward circling of the heavens around us. It explains the rising and setting of the celestial bodies. But while the stars seem to go around in perfect step, the sun lags behind more and more; its day is four minutes longer than the day of the stars.

The sun moves eastward against the turning background of the heavens. If we could view the stars in the daytime sky, we could watch the sun shift slowly toward the east among them as the day goes on. We could notice that the sun moves twice its breadth in one day, and that it circles completely around the heavens in the course of a year.

Although it is not easily possible to watch the sun's progress among the stars directly, this movement was recognized and charted by the earliest watchers of the skies; for it is clearly revealed by the steady procession of the constellations toward the west during the year.

3.1. The Westward March of the Constellations. A star rises or sets four minutes earlier by sun time from night to night, as we have noticed. In the four minutes that remain the star moves a little farther west than its position at the same time by the sun the evening

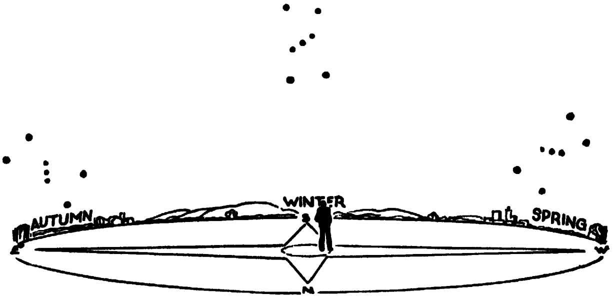


FIG. 3.1. Orion in the Early Evening at Different Seasons.

before. Thus as the seasons go around, the constellations march westward across the evening sky and down past the sun's place under the west horizon into the morning sky. Notice Orion's part in this unending parade; it is the brightest of the constellations and among the most familiar of all.

Orion comes up over the east horizon at nightfall in the late autumn, a tilted oblong figure sparkling brightly through the frosty air, with three stars in line near its center. It shifts slowly westward from night to night thereafter. As spring approaches we see its rectangular figure standing up-ended high in the south in the early evening. And as that season advances, Orion comes out farther and farther west, its oblong tilted the other way now, until it follows the sun so closely that it is lost in the twilight. Then some morning in midsummer we chance to look to the east just at dawn; and there is Orion again, on the other side of the sun.

The shifting of Orion and the other constellations past the sun's place shows that the sun moves eastward around the heavens. This pageant of the stars with the changing seasons and the round of the seasons themselves are consequences of the earth's revolution around the sun. But they do not prove that the earth revolves. These things could occur if the sun were circling yearly around the earth, as most people before the time of Copernicus supposed that it did.

The Earth's Revolution

Everyone knows today that the earth goes around the sun. We learn this fact at an early age and accept it as an item of common knowledge. We are told, too, that the sun is something like 93 million miles away, so that our earth must be speeding along at the exhilarating rate of 66,000 miles an hour in order to go all the way around in a year. Yet there is nothing whatever in our everyday experiences to convince us that the earth is moving in this way. Displacements of the stars that prove the earth's revolution beyond a doubt are too minute to be noticed without a telescope.

3.2. Aberration of Starlight. Raindrops fall vertically when there is no wind. Yet they came down slanting to one who walks rapidly through the rain, and still more slanting if he runs instead. As one's speed increases, the place from which the rain seems to fall shifts farther toward the direction he is going.

There is a similar effect on the direction of the rays of light from a star. This *aberration of starlight* is the apparent displacement of the star toward the direction the observer is approaching. It is a much smaller displacement, to be sure; no one can run or drive fast enough to change the places of the stars noticeably. Starlight comes down so much faster than the rain that its direction is hardly altered at all by ordinary speeds.

Even the earth's swift flight around the sun causes the stars to change their directions only 20½″ at the most. This displacement of the stars is too minute to be noticed by the eye alone. But it is readily observed with the aid of a telescope. Here we have a convincing proof of the earth's revolution.

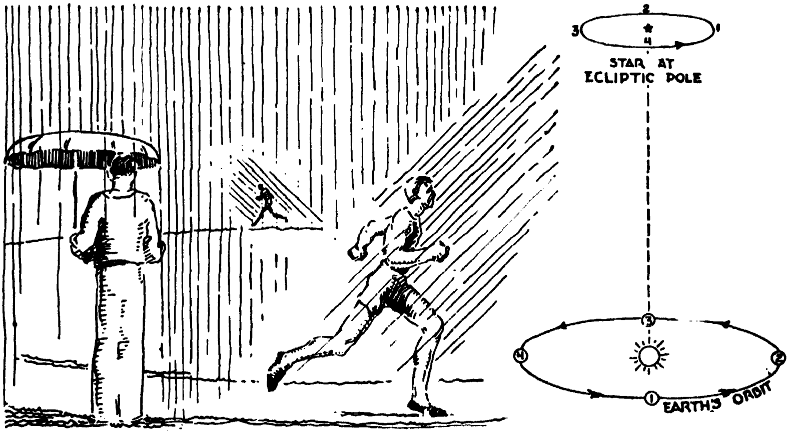


FIG. 3.2. Aberration of Raindrops and Starlight. Just as raindrops come down slanting to one who is running, so the stars are apparently displaced always ahead of us as we go around the sun. Each star seems, therefore, to describe a little orbit.

If the earth is taking us around the sun, the direction we are going must change continually. The direction of the star's aberration displacement must also change continually, for it is always in the direction of the observer's motion. If the earth revolves yearly, all the stars must seem to wheel in tiny orbits around their true places in the sky. This is what they seem to be doing, as the telescope clearly shows.

The aberration of starlight was first observed by the English astronomer Bradley who explained its important meaning in 1727. Henceforth there could be no doubt that the earth goes around the sun, and not the sun around the earth.

3.3. The Sun's Distance Varies. If the earth's course were a perfect circle with the sun at its center, the sun's distance from us would remain the same throughout the year. The sun's disk as we view it in the sky would have always the same size, therefore, except for the familiar illusion of enlargement when it is near the horizon. Indeed, there is no other change in its size that the unaided eye can see.

Yet the sun's apparent diameter does vary slightly, as more accurate measurements show. It is greatest about January 1, and smallest about July 1; the difference is one thirtieth of the diameter. So it appears that the sun is nearest us around the first of January and farthest away around the first of July, which might seem surprising to anyone who had forgotten that the seasons are not caused by our varying distance from the sun.

The sun's distance averages a little less than 92,900,000 miles; it varies from 91,300,000 miles in January to 94,500,000 miles in July.

The earth's orbit — its course around the sun — might still be a circle, to be sure, with the sun a million and a half miles out of center. It is really an ellipse. The early belief that all celestial orbits were perfect circles came to an end when Kepler, in 1609, showed that the orbits of the planets are ellipses.

3.4. The Earth's Orbit is an Ellipse of small eccentricity with the sun at one focus. This statement may need some explanation:

The *ellipse* is a plane curve such that the sum of the distances from any point on its circumference to two points within, called the *foci,* is always the same; the sum is equal to the longest diameter, or *major axis,* of the ellipse. This definition suggests an easy way to draw an

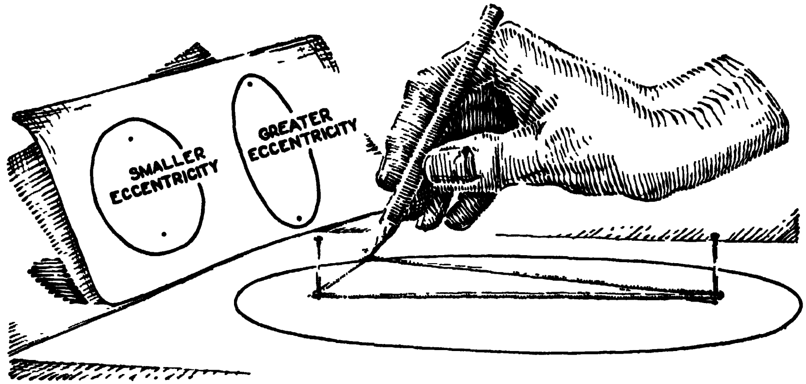


FIG. 3.4. How the Ellipse Can be Drawn.

ellipse (Fig. 3.4); and the drawing of several ellipses in this way makes clear the significance of the eccentricity.

The *eccentricity* of the ellipse denotes its degree of flattening. It is represented by the fraction of the major axis that lies between the two foci. If the eccentricity is zero, the foci are together at the center and the curve is a circle. The ellipse flattens more and more as the eccentricity increases. The earth's orbit is not far from circular, for its eccentricity is only one sixtieth.

Perihelion and *aphelion* are the points on the earth's orbit which are respectively nearest and farthest from the sun; they are at the opposite ends of the major axis. The earth arrives at perihelion about January 1 and at aphelion about July 1. These times move back and forth a little on the calendar, and they also advance progressively an average of 25 minutes a year; for the long axis of the earth's orbit is swinging slowly around in the direction, from west to east, of the earth's revolution.

The earth's *mean distance* from the sun is half the major axis of its orbit, or the average of its perihelion and aphelion distances. The earth stands at this distance from the sun in early April and again in early October.

3.6. The Earth Revolves Faster in Winter. We owe to Kepler not only the discovery that the orbits of the planets are ellipses with the sun at a common focus, but also the rule about their varying speeds in their orbits, which is known as the *law of equal areas*. For the earth in particular:

The line joining the earth to the sun sweeps over equal areas in equal intervals of time.

You can see from this rule how the speed of the revolving earth varies; the earth revolves faster in winter and slower in summer. Since we are nearer the sun in winter, the shorter line joining the earth to the sun must go around farther than the longer line of summer to sweep over the same area in a day (Fig. 3.5).

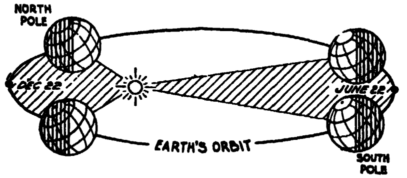


FIG. 3.5. The Earth Revolves Faster in Winter, because it is then nearer the sun.

The average speed of the earth in its flight around the sun is 18½ miles a second, or about 66,000 miles an hour. The speed is increased a little more than a quarter of a mile a second, at the most, in winter and is reduced the same amount in summer. The whole variation is rather small because the earth's orbit is so nearly circular.

It is owing partly to the variable speed at which we go around the sun that the apparent sun is not a uniform timekeeper (2.19). In winter, when the earth is going farther around than its daily average, the sun is displaced farther eastward among the stars than usual in the course of a day, so that it takes a longer time to complete its daily circuit of the heavens. On this account the apparent solar days are longest in winter. Ordinarily we say that the days are shortest in winter; but we are then referring only to the duration of daylight.

3.6. The Ecliptic. If you walk around a lamp in the middle of a room, the lamp may seem to be circling around you, appearing projected against the windows, doors, and pictures on the wall successively as it goes. It is the same with the sun. As the earth revolves yearly around it, the sun seems to be circling yearly around the heavens in the same direction the earth is revolving, from west to east.

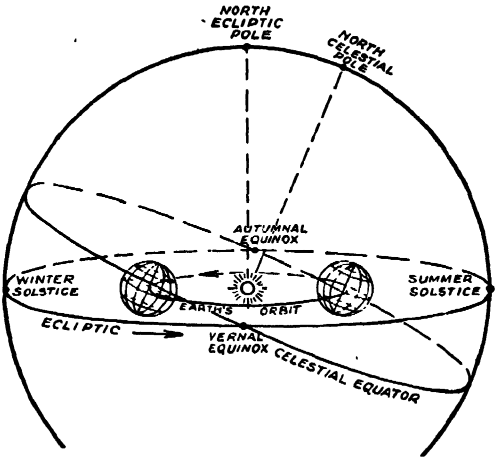


FIG. 3.6. The Celestial Equator is Inclined to the Ecliptic, because the earth's equator is inclined to the plane of its orbit around the sun.

But the sun's course is not directly toward the east, as we know. The sun moves north and south during the year as well; it withdraws as much as $23\frac{1}{2}^\circ$ from the equator in each direction before it returns. This shows that the sun's apparent path is tilted with respect to the celestial equator, and how much it is tilted.

The *ecliptic* is the sun's apparent annual path around the heavens. It is a great circle inclined 23½° to the celestial equator.

This circle of the celestial sphere must not be confused with the earth's orbit, the slightly elliptical course 186 million miles across, in which the earth revolves around the sun. The ecliptic and the earth's orbit lie in the same plane, one "over" the other, like the celestial equator and the earth's equator. The 23½° inclination of the celestial equator to the ecliptic shows that the earth's equator is inclined 23½° to its orbit around the sun.

The moon and the bright planets never wander very far away from the sun's path in their movements around the heavens. For this reason, the astronomers of early times, who were interested especially in the ways of the sun, moon, and planets, observed their positions relative to the ecliptic. They located all the heavenly bodies, in fact, by their celestial longitudes and latitudes.

Celestial longitude is measured from the vernal equinox eastward along the ecliptic. *Celestial latitude* is measured north or south from the ecliptic along a circle at right angles to it. Positions in the sky are still given in the ancient way with reference to the ecliptic, but they are more often referred to the celestial equator, by right ascension and declination.

3.7. Equinoxes and Solstices. The equinoxes are the two points where the ecliptic crosses the celestial equator. Days and nights are said to be equal when the sun arrives at either equinox, though refraction makes the duration of daylight a little longer at such times. The *solstices* are the two points on the ecliptic where the sun is farthest north or south from the celestial equator. Here the "sun stands still" as it turns back toward the equator.

These four important points on the ecliptic are equally spaced; they are 90° apart. They are definite points on the celestial sphere, whose positions among the constellations are shown on the star maps.

The *vernal equinox* is the point where the sun crosses the celestial equator on its way north; this occurs on March 21, when spring begins. The *summer solstice* is the northernmost point of the ecliptic, 23½° north of the celestial equator. The sun stands here on June 22, when summer begins.

The *autumnal equinox* is the point where the sun crosses the celestial equator on its way south; this occurs on September 23, when autumn begins. The *winter solstice* is the southernmost point of the ecliptic,

$23\frac{1}{2}°$ south from the celestial equator. Here the sun stands on December 22, when winter begins. These dates vary a little from year to year owing to the plan of leap years.

The two points on the celestial sphere that are 90° from the ecliptic are known as the *north and south ecliptic poles;* they are $23\frac{1}{2}°$ from the north and south celestial poles. The north ecliptic pole is situated in the constellation Draco (Fig. 3.10).

3.8. The Zodiac; its Signs and Constellations. The *zodiac* is the band of the heavens 16° wide through which the ecliptic runs centrally. It contains the sun and moon at all times, and the bright planets as well with the occasional exception of Venus. This is the reason for its special importance in the astronomy of olden times, and in the ancient and now discredited pseudo-science of astrology in which the places of the "wandering stars" had great significance.

Twelve *constellations of the zodiac* are placed along this band of the heavens. Recognized from very ancient times, they are included among the 48 original constellations (4.1). And since they are of unequal size, the *signs of the zodiac* were also introduced at an early time for the sake of uniformity; these are twelve equal divisions of the band, each 30° long, marked off eastward from the vernal equinox. Each sign, or block, of the zodiac took the name of the constellation it then contained.

The names of the twelve signs or constellations of the zodiac are: Aries, Taurus, Gemini, Cancer, Leo, Virgo, Libra, Scorpius, Sagittarius, Capricornus, Aquarius, and Pisces.

Meanwhile, the vernal equinox has moved westward among the stars, and the whole train of signs has followed along, because the signs are counted off from the equinox. Each sign has shifted past its constellation into the adjoining figure to the west. So when the sun arrives on March 21 at the vernal equinox, or "first of Aries," and the almanac says "sun enters Aries; spring begins," the sun is entering the zodiacal sign Aries. But it is then in the constellation Pisces, and will not enter the constellation Aries itself for another month.

This westward shifting of the vernal equinox is caused by a slow motion of the earth which now claims our attention.

THE EARTH'S PRECESSIONAL MOTION

3.9. The Earth Resembles a Spinning Top. If a top is spinning with its axis not quite vertical, as is likely to be the case, the axis moves around the vertical line in the direction the top is spinning. The pull of gravity acts to tip the top over. The spinning of the top resists this action, and the conical motion of its axis results, until the spin is so reduced that the top does fall over.

Similarly, the earth is spinning on an inclined axis, inclined to the ecliptic plane which is not far from the plane of the moon's motion around us. The pull of the moon on the earth's bulging equator acts to straighten up the axis of the earth's rotation by bringing the equatorial bulge into the plane with itself. But the moon's effort is resisted by the rotation. So the earth's axis moves slowly around the line joining the ecliptic poles in the direction opposite to that of the rotation. This is the precessional motion.

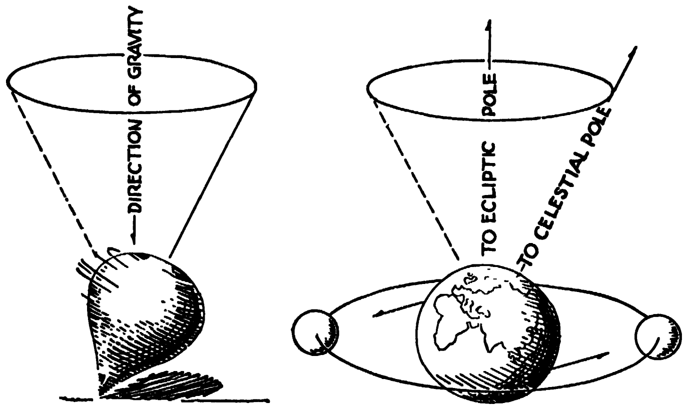


FIG. 3.9. The Earth Resembles a Spinning Top. The pull of the moon on the bulging equator of the rotating earth causes the precessional motion.

The earth's precessional motion is the slow conical movement of the earth's axis around from east to west. A single turn is made in 26,000 years at the present rate. It is a slow motion indeed, for the heavy earth is not easily persuaded to change its ways.

3.10. Circling of the Celestial Poles. The celestial poles are the two points in the heavens toward which the earth's axis is directed. These points change their places among the constellations, therefore, as the axis swings in the precessional motion. The celestial poles circle around the poles of the ecliptic.

The pole star, Polaris, is the nearest of the bright stars to the present place of the north celestial pole. Slightly more than a degree from the pole itself just now, this star at the end of the Little Dipper's handle has not always been the pole star (Fig. 3.10). Five thousand years ago, the star Alpha Draconis stood almost motionless in this place of distinction which Polaris now occupies.

The north celestial pole is drawing nearer Polaris; it will pass by about the year 2100 at the distance of half a degree. Thereafter, this pole star of ours will describe wider and wider daily circles, and its place in the north will be taken by other stars successively. In the year 7500, the star Alpha of the spire-like constellation Cepheus will mark the pole closely. In 14,000, the brilliant Vega will become the pole star.

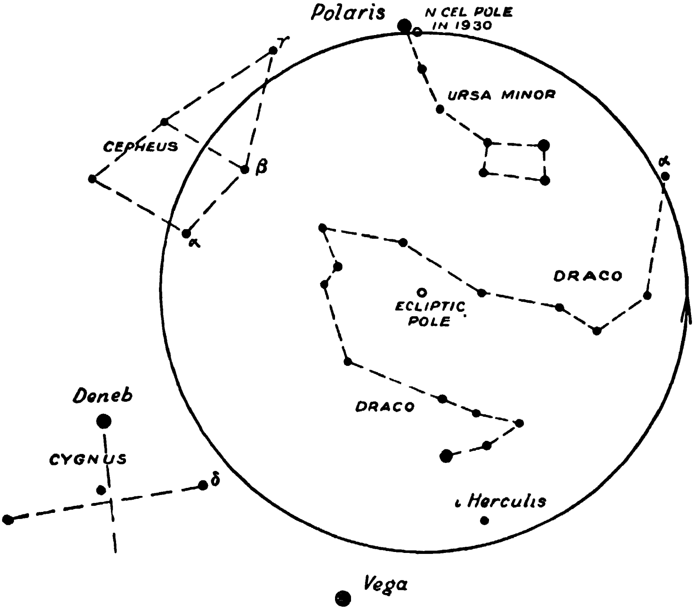


FIG. 3.10. Precessional Path of the North Celestial Pole. The celestial pole describes a circle among the constellations, having a radius of 23½° and the ecliptic pole at its center. Alpha Draconis was the pole star about 3000 B.C. In the year 7500 A.D. α Cephei will be the pole star, and in 14,000 A.D. Vega (α Lyrae) will have this distinction.

Thus our celestial pole circles in the counterclockwise direction among the stars in the north. The south celestial pole circles meanwhile around the south ecliptic pole; its place is not marked closely by any bright star at the present time. And since the celestial poles are the centers of the circumpolar regions, the stars that do not set and those that do not come into view are changing too. Six thousand years ago, the famous Southern Cross rose and set everywhere in the United States, while now it never appears except in the southernmost parts of this country.

The precessional paths of the celestial poles among the constellations are not perfect circles. They are somewhat wavy, for one thing. The little waves in these paths, which recur at intervals of about 19 years, are caused by the slight *nutation,* or nodding of the earth's axis as it goes around.

3.11. Precession of the Equinoxes. While the precessional motion has been regarded for convenience as a movement of the earth's axis, it can be viewed just as well as a movement of the equator. Consider again the gyration of the spinning top. Suppose that the top is half immersed in water (the surface of the water will represent the ecliptic plane), and that it continues to spin and gyrate nevertheless. The opposite points where the top's "equator" enters the water will move around along the surface of the water.

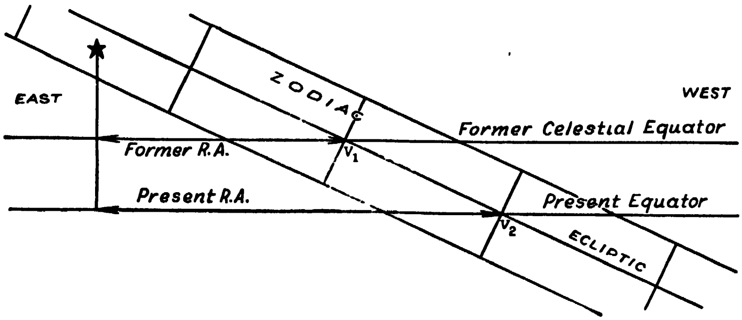


FIG. 3.11. Precession of the Equinoxes. The westward motion of the vernal equinox, from V_1 to V_2 causes the signs of the zodiac (the twelve equal divisions of the zodiac marked off from the vernal equinox) to slide westward away from the corresponding constellations of the zodiac. The right ascensions and declinations of the stars are also altered.

Similarly, the earth's precessional motion causes the equinoxes to slide around westward along the ecliptic, about 50″ in a year, and once around in 26,000 years, at the present rate. This *precession of the equinoxes* is accountable for the westward shifting of the signs of the zodiac out of the like-named constellations, an effect we have already noticed. There are other consequences of the precession of the equinoxes to be noted as well:

Right ascensions and declinations are changing. Right ascensions are measured eastward from the vernal equinox. Since the equinox is shifting toward the west, the right ascensions of the stars increase, as a general thing, as time goes on. The declinations of the stars change too; they are measured from the equator which is sliding along the ecliptic in the precessional motion.

The sidereal day is shortened by precession. This day by the vernal equinox is made a little shorter than the true period of the earth's rotation. The difference is slight, to be sure; it is only eight thousandths of a second, for the equinox does not shift very far among the stars in a single day. The length of the sidereal day is $23^h\ 56^m\ 4^s.091$ of mean solar time, while the earth rotates once in $23^h\ 56^m\ 4^s.099$.

The year of the seasons is shortened by precession. The year from vernal equinox to vernal equinox again is about 20 minutes shorter than the true period of the earth's revolution around the sun (3.17).

3.12. The Moving Earth. Three motions of the earth have so far been described:

(1) *The earth rotates* from west to east once in a sidereal day. Its equator is inclined 23½° to its orbit and, aside from very gradual changes such as precession, the equator keeps the same direction. The earth's rotation causes the apparent daily rotation of the heavens from east to west, and so the alternation of day and night. It has other consequences, such as the bulging of the earth's equator, and the deflections of the Foucault pendulum and of prevailing winds, which may be considered also as proofs that the earth rotates.

(2) *The earth revolves* from west to east around the sun once in a sidereal year (3.17). Its orbit is not far from circular, averaging about 92,900,000 miles from the sun. The earth's revolution is the cause of the sun's apparent yearly revolution around the heavens. It causes the little aberration orbits of the stars whose detection is regarded as proof that the earth revolves.

(3) *The earth's precessional motion* resembles the motion of a spinning top; it is completed once in 26,000 years at the present rate of progress. This motion causes the celestial poles to circle around the ecliptic poles, and the equinoxes to shift westward around the ecliptic. And since this shifting is readily observed, it may be considered as proof of the precessional motion.

Other motions of the earth will be noticed as our study proceeds. We shall find that our sun accompanied by the earth and the rest of the planets is speeding straight ahead through the star fields around us nearly in the direction of the star Vega, and that it shares in the general whirling of the whole Milky Way. But we are concerned first of all with two consequences of the simpler motions of the earth, namely, the seasons and the calendar.

THE SEASONS AND THE CALENDAR

Why is the weather warmer in summer than in winter? The answer is certainly not that the sun is nearer in the summer season; for we have seen that the sun is more than three million miles farther away in July than in January. The cause of the seasons is found in the inclination of the ecliptic to the celestial equator, so that the sun appears to go north and south yearly. Back of that, of course, is the inclination of the earth's equator to the plane of its orbit around the sun.

3.13. Cause of the Seasons. In summer in our middle northern latitudes the sun rises in the northeast, shines down from nearly overhead at noon, and sets in the northwest. The sun shines for a longer time during the summer days, and climbs higher than in the winter, so that its rays are more concentrated upon our part of the world.

The winter sun rises in the southeast, stands rather low in the south at noon, and sets in the southwest. It shines for a shorter time each day, and its rays come down more slanting, so that they are more spread out over the ground and more obstructed by the greater thickness of the intervening air.

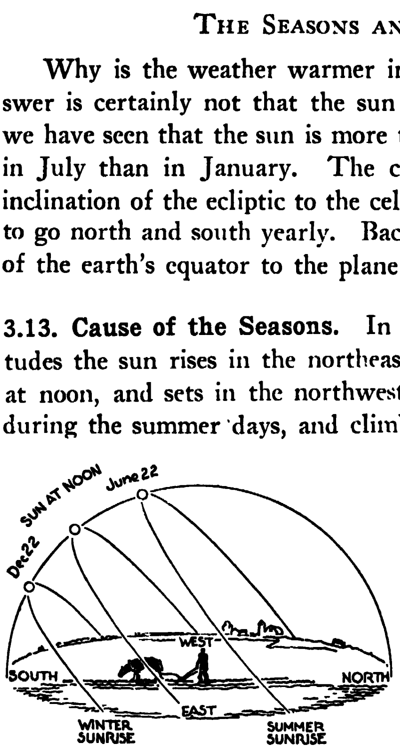


FIG. 3.13. Daily Circles of the Sun in Winter and Summer.

So the weather is warmer in summer. Or we can picture the cause of the changing seasons in terms of the inclined equator or axis of the revolving earth (Fig. 3.15). In summer the northern end of the earth's axis is inclined toward the sun; the sunlight falls for a longer time and more nearly vertically on the northern hemisphere. In winter it is the other way around.

If the moon's attraction could really succeed in straightening up the earth's axis, there would be no more changes of seasons, except for one who traveled north or south. If the earth's axis were to lean still farther, the seasons would become more extreme. If it leaned over into the plane of the earth's orbit, there would be no temperate zones at all.

3.14. The Climatic Zones. The positions and widths of the climatic zones are determined by the tilt of the earth's equator. Since this inclination is 23½°, the *torrid zone* extends 23½° north and south from the equator; everywhere in this region the sun stands directly overhead at noon in the course of the year.

The *tropic of Cancer,* 23½° north of the equator, forms the northern boundary of the torrid zone. Here the sun is overhead at noon on June 22 when it arrives at the summer solstice and enters the sign Cancer of the zodiac. The *tropic of Capricorn,* 23½° south of the equator, is the southern boundary of the torrid zone; here the sun stands overhead at noon on December 22 when it enters the sign Capricornus.

Similarly, the north and south *frigid zones* extend 23½° from the poles, and are bounded by the arctic and antarctic circles respectively. Though modified a little by the effect of refraction near their borders, the frigid zones are the regions where the sun remains visible at midnight at one season and does not appear even at noon at the opposite season. The extreme conditions obtain at the poles themselves, of course, where the sun shines continuously for six months and is completely out of sight for the following six months.

The north and south *temperate zones* lie between the torrid and frigid zones. Here the sun never reaches the point overhead, nor does it ever fail to come above the horizon at noon. But how does the climate compare in corresponding zones north and south of the equator?

3.15. The Seasons in the Two Hemispheres. Remember that the earth is more than three million miles nearer the sun in January than in July, and that the seasons in the southern hemisphere are opposite to those in the northern hemisphere. It is winter down there when we are having summer. And when we are in the midst of a severe "cold wave," we may read of a "heat wave" occurring in Argentina at the same time.

Summers in the northern hemisphere might well be a little cooler than summers in the southern hemisphere. Our summers occur when the earth is farthest from the sun, theirs when it is nearest the sun. Our summer seasons are a little longer, too, than theirs, for the earth wheels most slowly around the sun when it is farthest away.

By similar reasoning it appears that the northern winters should be milder and shorter than southern winters. So the northern hemisphere might seem to have the more agreeable climates. But the variation in our distance from the sun is only a small fraction of the whole distance. In addition, there is more water in the southern hemisphere to modify temperatures.

It would be unsafe to make a general comparison of the weather in corresponding latitudes north and south of the equator. Differences in elevation and in the effects of air and ocean currents would have to be considered. Compare, for example, the climates near the two poles. There is mostly water around the north pole. On the other hand, a great expanse of land surrounds the south pole, and high land too, so that the winter weather there is by far the more severe.

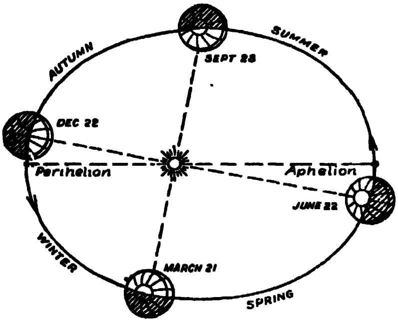


FIG. 3.15. The Seasons in the Northern Hemisphere. The earth arrives at perihelion soon after the time of the winter solstice.

3.16. The Lag of the Seasons. Summer in northern latitudes begins on June 22, when the sun arrives at the summer solstice and turns back again toward the south. The duration of sunshine is the longest on that day, and the sun climbs highest in the sky. Yet the hottest part of the summer is likely to be delayed until August when the sun is well on its way south. Why does the summer lag?

The sun begins its long coast toward the south on June 22. Thereafter, its rays bring less and less heat to our part of the world from day to day. But until about the first of August the diminishing receipts exceed the amounts of heat we are losing by the earth's radiation into space. The summer does not reach its peak until the incoming heat is reduced to the amount of the daily outflow.

Similarly, the winter weather is likely to be the coldest around the first of February. The sun starts its northward climb on December 22; but "as the days grow longer, the cold grows stronger," according to the old saying. The loss continues until the amount of heat we receive from the sun daily becomes as great as the daily loss.

There is a corresponding lag in the daily temperatures as well. The warmest part of a summer day is likely to come along in mid-afternoon when the sun is well on its way down the sky.

3.17. The Year of the Seasons is about 20 minutes shorter than the true period of the earth's revolution around the sun. This difference is caused by precession of the equinoxes, as has been said before.

The *tropical year* is the interval of time between two successive arrivals of the sun at the vernal equinox. Since the equinox moves westward in the meantime to meet the sun, this *year of the seasons,* from the beginning of spring to the beginning of spring again, is shortened. The length of the tropical year is $365^d\ 5^h\ 48^m\ 46^s.0$.

The *sidereal year* is the interval of time in which the sun appears to perform a complete revolution with respect to the stars. This is the true period of the earth's revolution around the sun. The length of the sidereal year is $365^d\ 6^h\ 9^m\ 9^s.5$ of mean solar time.

3.18. The Calendar. From very early times, people have felt the need of a continuous register on which they could record the dates of past and future events. They have looked to periodic celestial occurrences to provide such a register, just as they have for timekeeping during the day.

The flight of time is counted out noticeably by the apparent daily turning of the heavens, the monthly circling of the moon, and the apparent yearly round of the sun. The cycle of the moon's phases is completed once in 29½ days. The year of the seasons is a little less than 365¼ days. These three counters of time do not go evenly one into another, a fact that has caused trouble in all the calendars.

One calendar plan has made the lengths of the months alternately 29 and 30 days, so that they keep in step with the moon's phases. Since twelve of these short months contain only 354 days, an extra month must be added once in the course of about three years to keep the calendar in accord with the seasons. The Jewish calendar is an example of this luni-solar plan.

Ours is a solar calendar. The twelve months which round out the year are longer than the lunar months. This calendar has come down to us from the early Romans whose year originally began in March, as is shown by the four number months, from September to December (seventh to tenth) which have survived their meanings.

The months of the Roman calendar were lunar months at first, and the year was rounded out by the occasional addition of a month in the year at the discretion of those in authority. This early calendar at length fell so far out of accord with the seasons that a reform of the whole plan was instituted by order of Julius Caesar. The "last year of confusion," 46 B.C., was made 445 days long in order to correct the accumulated error, and the date of the vernal equinox was thereby brought to March 25. The new year began on January 1.

3.19. The Julian Calendar. The chief feature of the Julian reform was the adoption of 365¼ days as the length of the calendar year, which is only slightly greater than the length of the tropical year. This was accomplished conveniently by the plan of leap years. Three common years of 365 days were followed by a fourth year containing 366 days. The Julian calendar was a solar calendar; its months averaged longer than the lunar month.

The fifth month of the earlier calendar was renamed July in Caesar's honor. Later, in the reign of Augustus, the following month became August; and it is said that a day was then taken from February and added to this month to make it as long as Julius Caesar's month.

Since its average year of $365^d\ 6^h$ was $11^m\ 14^s$ longer than the year of the seasons, the Julian calendar fell behind with respect to the seasons, about 3 days in 400 years. When the Council of Nice convened in 325 A.D. the equinox occurred near March 21. It was at this meeting of churchmen that the rule was adopted for fixing the date of Easter:

Easter is the first Sunday after the 14th day of the moon (nearly the full moon) which occurs on or immediately after March 21.

DATES OF EASTER

1935	April 21	1941	April 13	1947	April 6
1936	April 12	1942	April 5	1948	March 28
1937	March 28	1943	April 25	1949	April 17
1938	April 17	1944	April 9	1950	April 9
1939	April 9	1945	April 1	1951	March 25
1940	March 24	1946	April 21	1952	April 13

As the date of the vernal equinox fell back on the calendar, March 21 and anniversaries such as Easter which are reckoned from it occurred later in the season. By the end of the sixteenth century the vernal equinox had fallen back to March 11. Another reform of the calendar was proposed in 1582, by Pope Gregory XIII. The corrected calendar, which is known as the *Gregorian calendar,* is the one we now use.

3.20. Our Present Calendar. Two changes in the calendar were made in the Gregorian reform. First, ten days were suppressed from the calendar of that year; the day following October 4, 1582 became the 15th of October. The date of the vernal equinox was restored in this way to March 21. The second change made the average length of the calendar year more nearly equal to the length of the tropical year, so that the calendar would not again get so rapidly out of step with the seasons.

Evidently the thing to do was to omit the three days in 400 years by which the Julian calendar was too long. It was done conveniently by making common years of the even century years whose numbers are not exactly divisible by 400. So the years 1700, 1800, and 1900 became common years of 365 days instead of leap years of 366 days as they would have been in the former calendar, while the year 2000 remains a leap year as before.

The Gregorian calendar is now in use in all Christian nations, though its acceptance was long delayed in some countries. It was not adopted in England until 1752. By that time there were 11 days to be suppressed in making the change; for the year 1700 was a leap year on the old calendar and a common year on the new one. By official decree in England the 2nd of September, 1752 was followed at once by the 14th. Whereupon, it is said, riotous crowds assembled to the cry of "Give us back our eleven days." Russia finally discarded the "old style" calendar in 1917, Yugoslavia and Rumania in 1919, and Greece in 1923, suppressing 13 days to make the change.

Our present calendar is not completely in step with the year of the seasons. Its average year is still too long by 26 seconds, which is hardly enough to bother about for many centuries to come. Agitation for further calendar reform arises from a different reason than before.

3.21. Suggested Calendar Reform. The desire for a regular division of time intermediate between the day and the month introduced another complication into our calendar, namely the week of seven days. The calendar difficulty just here is that the numbered days of the month fall on different days of the week from month to month, and for the same month from year to year. On what day of the week, for example, does the first of July fall in the year 1957?

Societies for the reform of the calendar have been active. Definite plans have been suggested. One of them is as follows: Let each month contain 28 days, so that all months will begin on the same day of the week always. Add another month to each year. And since this will provide only 364 days all together, add an extra day each year, a holiday perhaps, which shall be no day of the week or month at all. On leap years add another day of this sort between February and March.

A second plan, which proposes a somewhat less drastic revision, is known as the "world calendar." It rearranges the lengths of the 12 months so that the quarters are identical. Each quarter begins on Sunday and ends on Saturday, and its months contain 31, 30, and 30 days respectively, making 364 days in all. It is suggested that the 365th day of the common year follow December 30 and be considered an extra Saturday, and that the added day of the leap year follow June 30 as an extra Saturday as well.

QUESTIONS ON CHAPTER III

1. The form of the tiny aberration orbit of a star depends on its place in the heavens. Explain that this is so, taking as examples a star at the ecliptic pole and another on the ecliptic.

2. Draw three ellipses having the same major axis in the way suggested in Fig. 3.4. Make their eccentricities 0.2, 0.5, and 0.8. What is the relation between the eccentricity and the degree of flattening of the ellipse?

3. Does the ecliptic, like the celestial equator, keep the same place in your sky as the heavens turn? Explain.

4. In what constellation is the sun when summer begins? When winter begins?

5. What are the right ascension and declination and the celestial longitude and latitude of the sun at the beginning of summer? At the beginning of winter?

6. At what times in the year does the daily duration of sunlight change most rapidly?

7. Show that Polaris will rise and set for observers in latitude 40° when Vega becomes the pole star (Fig. 3.10).

8. How will the earth's precessional motion affect the seasons in the two hemispheres (3.15), if other conditions are unaltered?

9. Why is the day by the sundial, from noon to noon again, longer than the sidereal day? Why is it longest of all in the winter?

10. How would the widths of the different climatic zones be altered, if the inclination of the earth's equator to its orbit should become less than it is now? And if it should become greater?

11. Is it really a better plan to begin the calendar year on January 1 rather than at the time of the vernal equinox?

12. State some advantages and disadvantages of the plans of calendar reform mentioned in Section 3.21.

CHAPTER IV

THE SPHERE OF THE STARS

THE CONSTELLATIONS — THE STARS THEMSELVES

We have noticed how the earth is moving and how the heavens seem to be moving on this account. From our turning world we can now look out with a clearer understanding at the stars arrayed around us as they rise and set daily and circle slowly westward in a majestic procession with the changing seasons. This moving picture of the stars is the passing of the scenery as the earth spins on its axis and wheels around the sun.

There is no need as yet to consider the depth of the scene. It will be best to view it for a while longer just as though the stars were set on the seeming sphere of the heavens. Let's look first of all at the starry figures which form fine landmarks on the face of the sky.

THE CONSTELLATIONS

The charm of the evening sky consists in its variety. The stars are grouped in remarkable configurations which are so easy to distinguish one from another that they are well known to all who watch the sky. There are dippers, crosses, and triangles among the varied figures, and curving streams of stars that can suggest celestial rivers and serpents. These constellations transform a bewildering array of stars and more stars into a familiar, friendly scene for anyone who learns them.

The *constellations*, in the original sense, are configurations of stars. In modern practice they are also definite areas of the heavens, as we shall see.

Many of the constellations we recognize were known by the same names to the people of ancient Greece who learned them perhaps from their neighbors in Mesopotamia. Orion, the Pleiades, and the Great Bear are mentioned in the poems of Homer and Hesiod of nearly three thousand years ago. The Greeks named the starry figures after the heroes and animals of their mythology.

So began the strange picture book of the skies, the confusion of heroes, bears, dogs, serpents, and the rest that are depicted among the stars on the celestial maps and globes of former times. It is perhaps no more surprising that the constellations should have been named in this way than that a feature of the earth's surface is named Mount Washington. It was by a combination of events that the figures of the creatures remained so long on the star maps.

4.1. The Original Constellations. As many as 48 constellations were recognized by the Greeks two thousand years ago. Nearly all of these are described in the *Phenomena* which the poet Aratus wrote about 270 B.C. and which can be found in many libraries today; its opening lines are practically repeated in the beginning of St. Paul's celebrated sermon to the Athenians. The popularity of Aratus' poem did much to perpetuate the imaginary constellation figures which he vividly described.

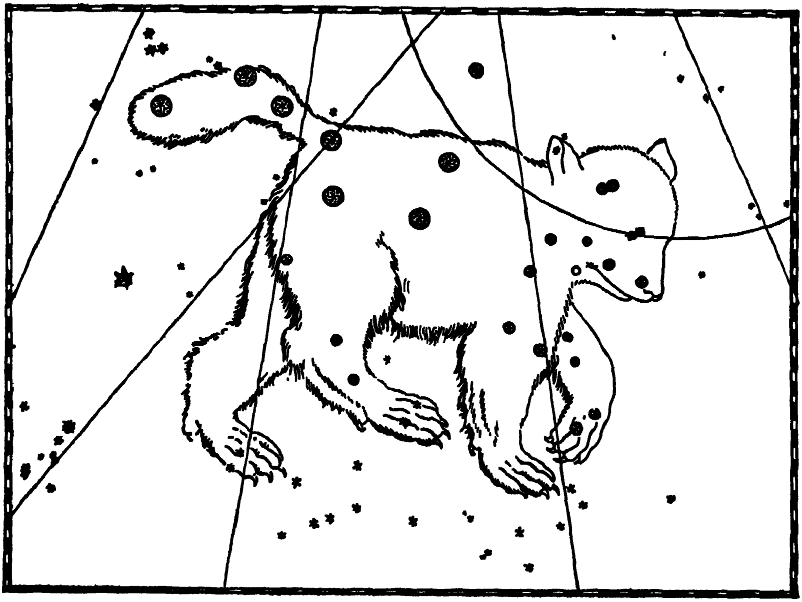


FIG. 4.1. The Great Bear. From Bayer's *Uranometria* (1603).

This celestial menagerie was made especially prominent by the publication of Ptolemy's *Almagest,* about 150 A.D. All the 48 original constellations are described in this book, and the places of the stars in the constellations are designated by their positions in the mythological figures. So the old picture book of the skies found an additional reason for its existence, especially since Ptolemy's book remained the leading authority in astronomy for more than a thousand years. Then too, famous artists of the middle ages and of more modern times as well vied with one another to produce the liveliest pictures of the imaginary creatures.

These creatures are not likely to appear on modern maps and globes of the heavens. They have nothing to do with the astronomy of today, except the connection with which they began; their names are still the names of the constellations in which they used to stand. Meanwhile, the constellations have increased in number, and they have taken on a new significance, though their oldest one as groups of stars survives as well.

4.2. Constellations as Divisions of the Sky. The original constellations did not cover the skies of the Greeks completely; they did not include the dull areas where there were no striking configurations of stars to claim attention. At that time, only those stars that were within the imagined figures belonged to the constellations. Fully ten per cent of the 1028 stars listed in the ancient catalogue of Ptolemy were included in no constellation at all. In addition, the part of the heavens around the south celestial pole that did not rise above the horizons of the Greeks remained uncharted.

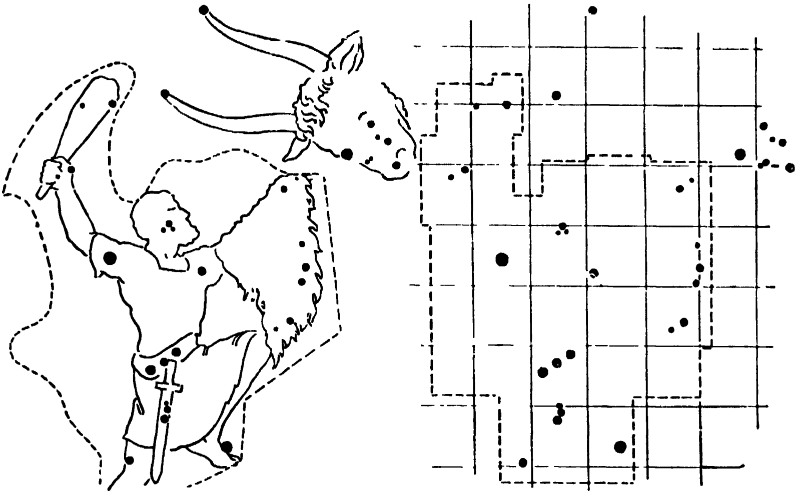


FIG. 4.2. Old and New Boundaries of Orion.

Celestial map makers of later times filled the vacant places with new constellations which they named after scientific instruments, various birds, and other things having no connection with the creatures of the legends. Not all of them survived. At present we recognize 88 constellations (Table 4.III) which completely cover the sphere of the stars from pole to pole. Seventy of these are visible, either wholly or in part, from the latitude of New York.

For the purposes of astronomy, the constellations are now definite divisions of the heavens marked off by boundary lines, just as the states are bounded. They serve chiefly to designate the approximate positions of the celestial bodies.

The constellation boundaries first appeared on the star maps at the beginning of the 19th century. They were frequently very irregular; they went around outside the legendary figures, making detours to avoid cutting across outstretched arms and legs and paws. These devious dividing lines were straightened for most of the south circumpolar constellations by the American astronomer Gould, in 1877, and finally for all the constellations by decision of the International Astronomical Union in 1928. The boundaries now run only from east to west and from north to south, though they zigzag considerably so as not to expatriate bright stars and variable stars from constellations with which they have long been associated.

4.3. Learning the Constellations. The best advice that can be offered to anyone who wants to know the constellations is to learn them. No one really need complain, as Carlyle did in his often quoted remark: "Why did not someone teach me the constellations and make me at home in the starry heavens, which are always overhead and which I don't half know to this day?" For it is easy enough to recognize the more conspicuous figures of stars.

The requirements are simple. A star map is needed, one that shows the principal constellations clearly, and not so many of the faintest stars as to be confusing. A flashlight to illuminate the map is helpful. A clear sky not dulled by reflections from near-by artificial lights, the absence of the moon or at least the nearly full moon, and an occasional half-hour under the evening stars complete the brief list.

Almost everyone knows the Great Dipper. Many people can recognize Cassiopeia's Chair, or Orion, or the Square of Pegasus. Find some constellation you know already, both in the sky and on the star map. Make a rule from the map for using stars of this constellation as pointers to show the way to a neighboring constellation. Perhaps a line through two bright stars extended five times as far beyond leads to the constellation you wish to find.

So you can go on, matching the configurations in the sky with those on the map. It is well, of course, if a mutual friend can introduce some of the constellations just at first.

Learning the constellations is not finding heroes and animals in the sky. No one can do that, to be sure. Nor is it fixing in mind just where the boundaries are placed. Learning the constellations, as a usual thing, is simply becoming acquainted with the different star figures. The maps and descriptions that follow are intended to aid in the identification of the constellations.

What Carlyle meant by his remark was clearly the regret that someone had not told him in his youth of the pleasure of knowing the constellations, which he experienced in later life. It is a pleasure indeed, and a fine introduction to an appreciation of the things that go on overhead. Learn the constellations as they march by through the year, and you will see.

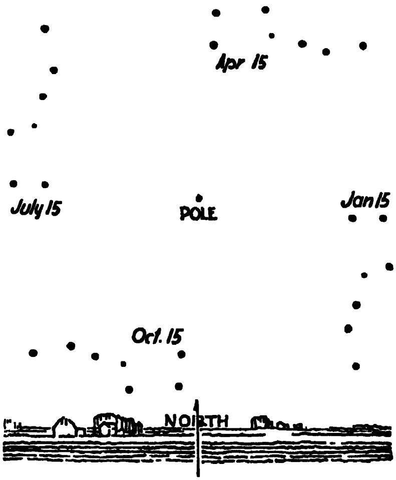


FIG. 4.4. The Great Dipper at 9 o'clock in the Evening at Different Seasons.

4.4. Directions in the Sky.

North in the sky is toward the north celestial pole whose place the pole star marks roughly. South is toward the south celestial pole. East to west is the direction in which the stars seem to circle daily. If these rules are remembered, there can be no confusion about directions in the sky.

The position of a star is clearly described when its directions from other stars are given in this way. Its position is also perfectly definite, if we say how it is related to two or more other stars; perhaps the star completes an equal-sided triangle with two others already known, or it may be in line with them. We have noticed how a line through the pointer stars of the Great Dipper leads to the pole star. Such directions remain unaltered through the day and year.

But it may be confusing to say that one star is above or to the left of another, unless the time is given also. Directions relative to the horizon change as the heavens go around. Face toward the region of the north celestial pole, for example, where the stars are circling in the counterclockwise direction. Above the pole, north is down and west is toward the left; below the pole, north is up and west is toward the right.

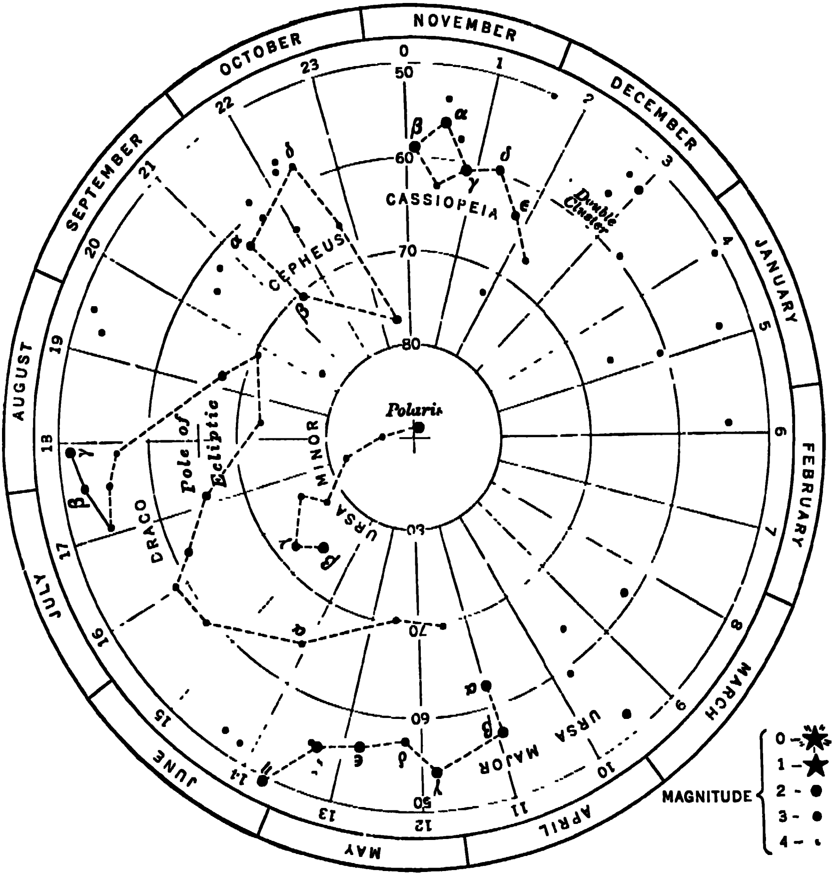
Notice how the Great Dipper changes its position relative to the horizon during the night, or from night to night in the early evening as the seasons progress (Fig. 4.4). Along in the winter, this fine figure of seven stars stands on its handle in the northeast. In spring it appears inverted high above the pole of the heavens. In summer the Dipper is seen descending bowl-down in the northwest, while in autumn it is right side up under the pole, where it may be lost to view for a time.

4.5. The Map of the Northern Sky. Map 1 shows the region of the heavens within 40° of the north celestial pole. This pole is at the center of the map. Hour circles in the sky flatten on the page into straight lines which radiate from the center like spokes from the hub of a wheel; they are marked around the edge of the map in hours of right ascension.

The evenly spaced circles around the center are circles of equal declination, from +50° at the edge to +90° at the center. The region whose stars never set is bounded by the circle whose declination is the complement of your latitude. Thus the map represents the north circumpolar region as seen from latitude 40° N.

Hold this map toward the north. Turn it around until the correct month is at the top. Now the map shows the appearance of the northern sky at 9 o'clock in the evening. The hour circle vertically under the date lies along the celestial meridian at this time of night on this date. For a different time of day, turn the map from the 9 o'clock position through the proper number of hours, clockwise for an earlier time and counterclockwise for a later one.

Broken lines join some stars on the map to emphasize the more striking figures such as the Great Dipper. In order to avoid confusion, the boundaries between the constellations do not appear on the maps. Faint stars barely visible without the telescope are not shown, as a



Map 1. The Northern Constellations.

general thing. Some constellations which offer little of interest to the naked eye are omitted.

4.6. The Northern Constellations. Everyone knows the Great Dipper; so this is a good place to start in learning the constellations. Notice, in Map 1, that when the line joining the two stars in the front of the Dipper's bowl is prolonged five times as far beyond them it leads almost directly to the pole star, close to the center of the map.

This famous star, Polaris, marks the end of the handle of the Little Dipper, a fainter figure of seven stars. Not far from the north pole of the heavens, Polaris remains almost motionless during the night. It is about a third of the way up in the north as viewed from the southernmost parts of the United States, and about halfway up from the northern parts of the country.

These two Dippers are the principal figures of the ancient celestial bears: *Ursa Major,* the Larger Bear, and *Ursa Minor,* the Smaller Bear. Three other constellations in the northern sky are to be specially noticed; they are Cassiopeia, Cepheus, and Draco.

Cassiopeia circles almost opposite the Great Dipper. Here seven stars outline a sort of high-backed chair that is familiarly known as Cassiopeia's Chair.

Cepheus immediately precedes Cassiopeia in the daily circling around the pole. Its stars are not so bright, and the figure they form is less conspicuous. Some people imagine here the figure of a church spire. The idea is to find in each constellation some figure that is easily remembered.

Draco circles ahead of Cepheus. A line from Cassiopeia's Chair through the spire-like Cepheus and continued about twice as far beyond leads to the V-shaped group which marks the head of the ancient Dragon. With the aid of Map 1 it is easy to follow the winding stream of stars as far as the tip of the imagined creature's tail near the pointer stars of the Great Dipper.

These five northern constellations appear again on the four maps for the different seasons.

4.7. Star Maps for the Different Seasons. Maps 2, 3, 4, and 5 show the constellations which cross the celestial meridian at 9 o'clock in the evening during each of the four seasons, all the way from the north pole of the heavens to the south horizon as seen from latitude 40° N. The pole is near the top of each map. Hour circles radiating from the pole are marked in hours of right ascension near the bottom of the map, while circles of equal declination go around the pole.

Select the map for the present season. Hold it toward the south. The hour circle above the date on which you are observing runs north and south across your sky at 9 o'clock in the evening; the stars along this circle are crossing the celestial meridian at this time. Accordingly, the central vertical line on each of the four maps successively represents the course of the celestial meridian at 9 o'clock in the evening on April 21, July 21, October 21, and January 21.

The declination number that equals your latitude is the position of your zenith on each map. If you are facing south, it will be necessary to lean over backwards in order to view the constellations north of the zenith as they appear on the map. It would be easier to face north and turn the map around. But the northern constellations are shown more conveniently on Map 1. They are repeated on the seasonal maps chiefly to show how they are related to the constellations farther south.

Descriptions of all of the really conspicuous constellations in the heavens are given in Chapter V.

4.8. Zenith Distance of a Star at Upper Transit. The Maps are arranged, as we have seen, to show what stars are crossing the celestial meridian at a particular time of the day and year. They are the stars along the hour circle that corresponds to that date. Any one of these stars can be pointed out, therefore, if we know its distance from the zenith.

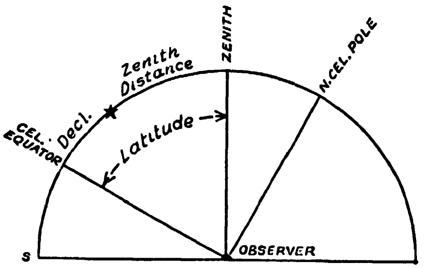


FIG. 4.8. A Star's Distance from the Zenith at Its Upper Transit Equals the Observer's Latitude Minus the Star's Declination.

A star reaches its highest point in the sky when it is crossing the meridian at upper transit. How far is the star then from the point directly overhead? The rule follows easily from the relation described in Section 2.11:

The zenith distance of a star at upper transit equals the observer's latitude minus the star's declination. If the zenith distance comes out positive, the star is south of the zenith; if it is negative, the star is north of the zenith. In the following examples the observer is in latitude 40° N.

(1) What is the sun's zenith distance at apparent noon on June 22? The sun's declination is then $+23\frac{1}{2}^\circ$. Its zenith distance is therefore $40^\circ - 23\frac{1}{2}^\circ = 16\frac{1}{2}^\circ$, south of the zenith.

(2) How close to the zenith does the bright star Capella pass? Its declination is $+46^\circ$. At upper transit its zenith distance is $40^\circ - 46^\circ = -6^\circ$, north of the zenith.

(3) What declination must a star have in order to pass through the zenith? By our rule the declination must be equal to the latitude. Thus stars whose declinations are less than the latitude pass south of the zenith, while those whose declinations exceed the latitude pass north of the zenith.

4.9. Celestial Globes and Planetariums. When the curved surface of the heavens is flattened out on the page, as in the star maps in this book, there is necessarily some distortion. The constellations cannot all be shown precisely in their relative shapes and sizes. Yet this is the most usual plan, and the most convenient one for many purposes.

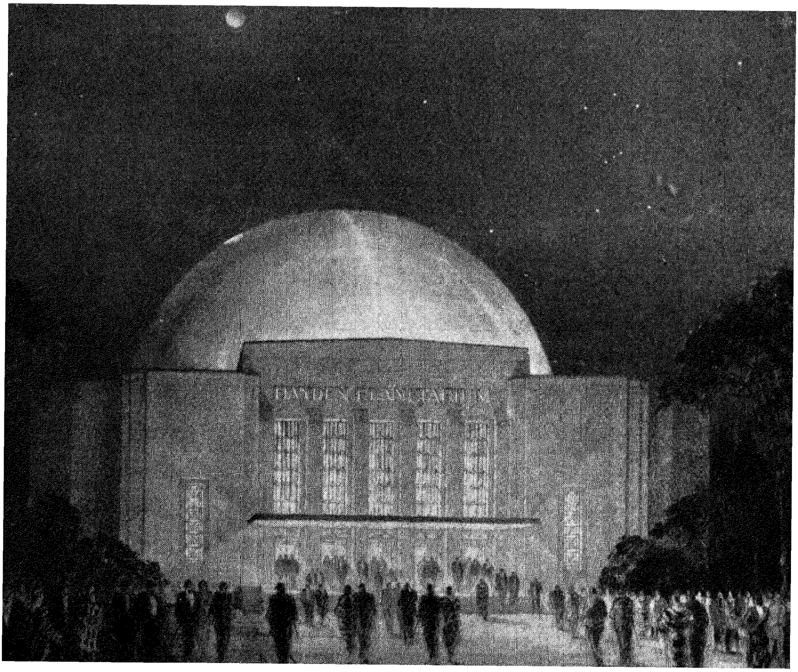


FIG. 4.9. Hayden Planetarium, New York. Architect's drawing. (*Courtesy of American Museum of Natural History, New York*)

Celestial globes can show the stars in their correct positions in all parts of the heavens. Often they are constructed so that they can be turned to show the part of the heavens that is above the horizon at any time and for any latitude. Many features of the sky that were described in the earlier chapters can be better understood if a globe is available.

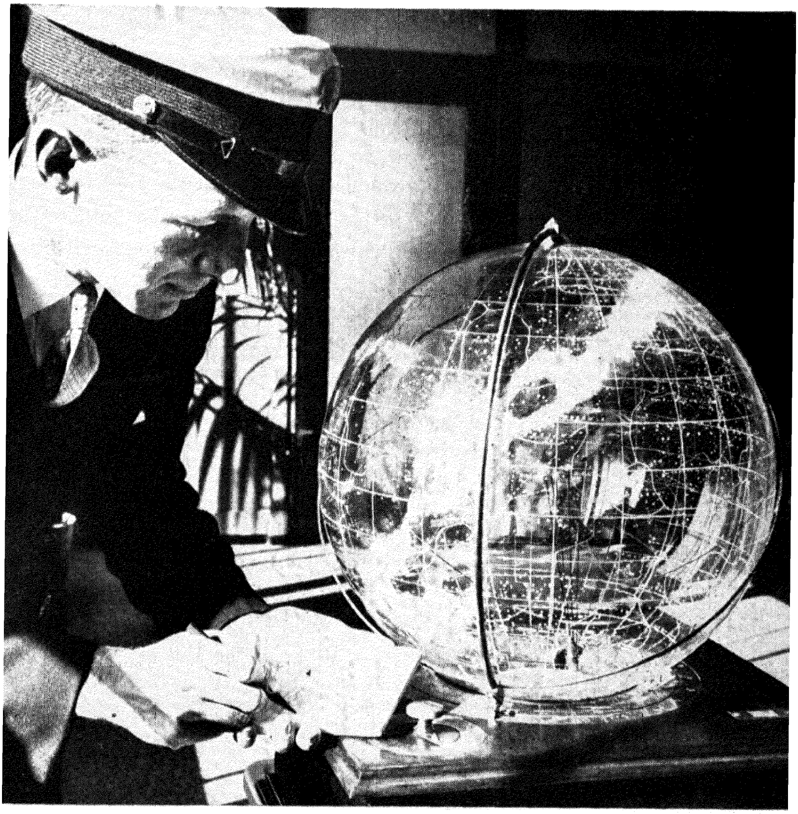


FIG. 4.9A. Transparent Celestial Globe on the Observation Roof of the RCA Building, Rockefeller Center, New York. Inside the globe there are representations of the earth and bright planets; these are supported by thin metal rods in such a way that they can be set at any time in their correct places relative to one another and to the constellations. (*By courtesy of Rockefeller Center, Inc.*)

A disadvantage of the ordinary celestial globe is that the stars are viewed from the outside; the constellations appear wrong side out. Some globes have been made large enough so that people can go inside and see the stars pictured on the inner surfaces, more nearly as we view the sky itself. The planetarium is a still more effective device for bringing the heavens indoors.

The Adler Planetarium in Chicago, opened to the public in 1930, is the pioneer in America. More recently completed ones are the Fels Planetarium in Philadelphia, the Hayden Planetarium in New York, the Griffith Observatory in Los Angeles, and the Buhl Planetarium in Pittsburgh. The Natural History Museum in Springfield, Mass., has a planetarium of somewhat simpler type. There are about twenty planetariums in different parts of Europe.

4.10. The Sky of the Planetarium is a large dome which forms the ceiling of the chamber in which the audience is seated. The planetarium instrument itself, shaped like a dumb-bell 12 feet long, rests on a carriage in the center of the room. It is a composite stereopticon, containing many projectors for picturing the heavens on the surface of the dome — the sun, moon, and bright planets, the stars and the Milky

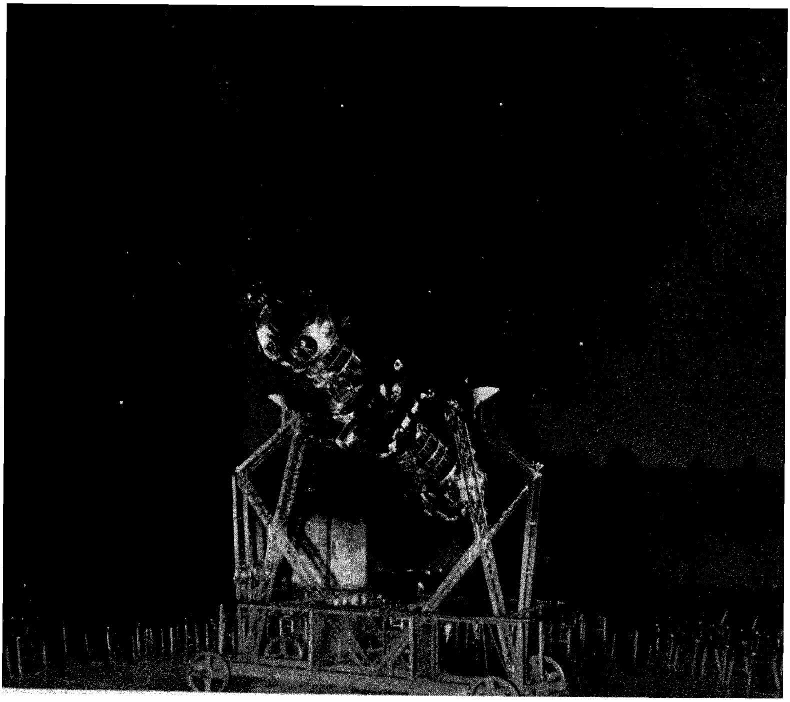


FIG. 4.10. Interior of the Fels Planetarium, The Franklin Institute, Philadelphia.

Way, all in their correct positions. The result is a remarkable representation of the real sky.

It is a moving picture of the heavens that is shown. The dumb-bell and its various parts are turned by motors controlled by switches at the lecturer's desk. The stars rise and set, and they do not fade completely when the sun rises. The sun steadily pursues its course among the stars. The moon in its changing phases, from new moon to new again, describes its monthly circuit of the heavens. The planets steer looped courses among the stars. All these movements are much faster in the planetarium than in the real sky; they are accordingly more readily observed and understood.

One motion of the planetarium instrument shifts the starry scenery rapidly northward or southward, just as it is slowly shifted when we travel south or north. In a few minutes, the audience can be taken to the north pole, then to the equator and on into the southern hemisphere where the Southern Cross is high in the sky.

It is also possible to go back in time thousands of years and view Alpha Draconis as the pole star, or forward until the brilliant Vega shines almost motionless in the north where Polaris now stands.

The Stars Themselves

There are other features of the star maps to be noticed before we are ready for the systematic study of the constellations. Individual stars in each constellation are designated by small letters of the Greek alphabet, and the brighter ones have special names as well. We shall notice also how the stars are classified in order of brightness.

4.11. Names of the Stars. The brightest stars and other specially famous ones are known to us by personal names which have been handed down through the ages. Some of these names are of Greek and Latin origin. Some are derived from the Arabic; names such as Algol, Altair (*al* is the Arabic definite article meaning *the*), and many others are survivals from the early times when astronomy was a favorite study of the Mohammedan scholars.

The stars were named not only by the scholars, but also by shepherds, sailors, and nomads of the desert. The stars told them the time of night and of the year, and guided them on their journeys. It was natural that the brighter ones should be called by names.

Procyon, meaning "before the dog," precedes the Great Dog Star in its rising. Aldebaran means "the follower"; it rises after the

Pleiades. Antares is the "rival of Mars," owing to its red color. These are examples of how some of the stars were designated. Other star names have come to us in a different way.

In the earliest catalogues, such as Ptolemy's, the stars were distinguished by their positions in the imaginary figures of heroes and animals. One star was the "heart of the Lion," another the "tail of the Bird." Transcribed later into the Arabic, some of these expressions finally degenerated into single words. Betelgeuse, the name of the bright red star in Orion, was originally three Arabic words meaning the "armpit of the Central One."

4.12. Designations of Stars by Letters and Numbers. The present plan of designating the brighter stars by letters was formally introduced by John Bayer, a Bavarian lawyer, in 1603. The star charts of his book, the *Uranometria,* were decorated with spirited drawings of the old constellation figures, a custom that continued to very recent times. The stars of the 48 original constellations were labeled with small letters of the Greek alphabet.

In a general way, the stars in each constellation were lettered in order of brightness, and the Roman alphabet was drawn upon if further letters were required. If there are several stars of nearly the same brightness in the constellation, they are likely to be lettered in order from the head to the foot of the figure.

The full name of a star according to Bayer's system is the letter followed by the genitive (possessive) of the Latin name of the constellation. Thus Capella, the brightest star in Auriga, is α Aurigae. The letters for some of the brighter stars are shown on the Maps. The small letters of the Greek alphabet and their pronunciations appear in Table 4.II, while the possessive endings of the constellation names can be found in Table 4.III.

On modern maps of the constellations, in which the separate stars are designated, it is customary to employ the Bayer letters as far as they go, and to add perhaps the personal names of the very brightest and best-known stars. Other stars are known by numbers; the star 61 Cygni is an example. The plan of numbering the stars from west to east across each constellation was used by the English astronomer Flamsteed in his catalogue which was completed in 1729.

Faint stars are usually distinguished by their running numbers in one of the many catalogues to which the astronomer can turn for information as to their positions, brightness, and other features. One of the nearest stars, for example, is known as Lalande 21185, from its number in the star catalogue by that author.

4.13. Magnitudes of the Stars. There are many stars in all parts of the sky. It is hardly enough to know simply the position of one that we wish to find. We should know also about how bright the star is. This requirement was clearly understood by the astronomers who made the earliest star catalogues. Nearly two thousand years ago, Ptolemy divided the stars into six classes, or *magnitudes,* in order of their brightness.

The brightest stars, about twenty in number, were assigned to the first magnitude. Bright stars such as Polaris were second magnitude stars. Each succeeding magnitude contained stars fainter than the one before, until the sixth magnitude remained for those barely visible to the unaided eye on a clear moonless night.

The number of magnitudes was gradually extended when the telescope came into use and as telescopes increased in power. Stars as faint as the 21st magnitude can be observed with the 100-inch reflector on Mount Wilson. Moreover, a definite rule was adopted nearly a century ago: If two stars differ by one magnitude (suppose that one star is of the third magnitude and the other of the fourth), the first one is slightly more than 2½ times as bright as the second. More exactly, the relation is:

Difference of Magnitude	Ratio of Brightness
1.0 magnitude	2.512
2.0 magnitudes	6.31
3.0 magnitudes	15.85
4.0 magnitudes	39.8
5.0 magnitudes	100

Aldebaran is not far from a standard first magnitude star. Vega is about 2½ times as bright; it is a star of the zero magnitude according to the rule. Sirius, the Great Dog Star, is more than 2½ times as bright as Vega; it is between magnitudes −1 and −2. So a few of the very brightest of the original first class were promoted to still smaller-numbered classes.

4.14. The Brightest Stars. The twenty stars in Table 4.I are brighter than magnitude 1.5, and are often called "stars of the first magnitude," though they range through nearly three magnitudes. Fifteen of these can be seen in their seasons throughout the United States and southern Canada. The remaining five become visible south of the following north latitudes: Canopus, 38°; Achernar, 33°; α and β Centauri, 30°; α Crucis, 28°, in southern Florida and Texas.

Sirius is the brightest star. Capella, whose declination is +46°, is the northernmost of these stars; it is circumpolar from the northern part of the United States. Alpha Crucis, in declination −63°, is the farthest south. It will be noticed that three of the southern stars have no personal names; they are known always by their designations in the Bayer system: Alpha and Beta Centauri, and Alpha Crucis.

TABLE 4.I. THE BRIGHTEST STARS

Name		Magnitude	Color	Map
Sir′i-us	α Canis Majoris	−1.6	blue	5
*Ca-no′pus	α Carinae	−0.9	yellowish	6
*	α Centauri	+0.1	yellow	6
Ve′ga	α Lyrae	0.1	blue	3
Ca-pel′la	α Aurigae	0.2	yellow	5
Arc-tu′rus	α Boötis	0.2	orange	3
Ri′gel	β Orionis	0.3	blue	5
Pro′cy-on	α Canis Minoris	0.5	yellowish	5
*A′cher-nar	α Eridani	0.6	blue	6
*	β Centauri	0.9	blue	6
Al-ta′ir	α Aquilae	0.9	blue	3
Bet′el-geuse′	α Orionis	0.9	red	5
*	α Crucis	1.0	blue	6
Al-deb′a-ran	α Tauri	1.1	reddish	5
Pol′lux	β Geminorum	1.2	orange	5
Spi′ca	α Virginis	1.2	blue	2
An-ta′res	α Scorpii	1.2	red	3
Fo′mal-haut′	α Piscis Austrini	1.3	blue	4
Den′eb	α Cygni	1.3	blue	4
Reg′u-lus	α Leonis	1.3	blue	2

* Not visible as far north as latitude 40° N.

The magnitudes in the Table are given to the tenth, which is about the smallest difference the eye alone can distinguish. They are apparent visual magnitudes, that is to say, as we *see* the stars from the earth. If we photograph them, we have a somewhat different order of brightness, for the blue stars photograph brighter than the red ones. If we could view them all from the same distance, the order would be still different; Sirius would not then head the list.

4.15. Colors of the Stars. The stars are of different hues. Their colors are not so pronounced, to be sure, as those of artificial lights. They seem pale indeed as compared with the vivid red and green lights of the airplane flying across against the background of the constellations.

Yet the colors of the bright stars are plain enough. Almost everyone has noticed the striking contrast between the red Betelgeuse and the blue Rigel diagonally across the oblong figure of Orion in the winter sky.

Betelgeuse and Antares are the reddest of the "stars of the first magnitude." Arcturus and Pollux are orange. Capella and Alpha Centauri are yellow like the sun. Beta Centauri and Alpha Crucis are the bluest of the bright stars. And there are various gradations in between. The fainter stars show colors too, when their light is concentrated by the telescope. Some of the double stars exhibit remarkable differences of color between their two components as they are viewed through the telescope.

The different colors of the stars result from their different temperatures, aside from any reddening of their light on its way to the earth. Just as a piece of metal changes from red-hot to blue-hot when it is heated more and more, so the stars vary from red to blue with increasing temperature. Red stars are relatively cool. Blue stars are much hotter.

4.16. The Number of Stars in the whole celestial sphere which are visible to the average eye under the best conditions does not greatly exceed six thousand. Scarcely more than half of the heavens is above the horizon at one time, of course, and the stars are not so bright near the horizon. Probably not more than two thousand stars are visible ordinarily to the naked eye at any one time on a clear moonless night.

So the number of stars that can be viewed with the eye alone is not so great after all as many people may imagine. Notice how few stars there are within the bowl of the Great Dipper, or inside the larger area of the Square of Pegasus. These are rather dull regions, to be sure. One can count three times as many stars in similar areas along the Milky Way. But even here the light comes chiefly from multitudes of stars too faint to be seen separately without optical aid.

The telescope reveals many more stars than the eye alone can see. Much depends on the clearness of the sky, and the quality of the telescope and of the observer's eye. In a general way, the numbers of stars that telescopes of different diameters bring into view over the whole heavens under fine conditions are as follows:

NUMBERS OF STARS VISIBLE WITH TELESCOPES OF DIFFERENT DIAMETERS

Visible with	Faintest Magnitude	Total Number
Eye alone	6	6,000
1-inch telescope	9	100,000
4-inch telescope	12	2,000,000
10-inch telescope	14	13,000,000
40-inch telescope	17	150,000,000
100-inch telescope	19	500,000,000
200-inch telescope	20.5	> 1,000,000,000

The numbers of stars that can be photographed with long exposures with these telescopes are still greater. But the numbers that the largest telescopes reveal are small as compared with the whole. The membership of our Milky Way system alone is estimated to contain 100,000,000,000 stars.

Our Maps do not show stars fainter than the fourth magnitude, as a general thing. We avoid confusion by this plan, for the stars increase rapidly in numbers with the addition of each fainter magnitude.

4.17. The Planets Among the Stars. The celestial bodies that move about among the constellations do not appear on the star maps, of course. The positions of the sun, moon, and planets (their right ascensions and declinations) can be found for any date from tables in the *American Ephemeris and Nautical Almanac.* They can then be marked on the Maps to show the positions of these wanderers with reference to the stars.

The planet Mercury makes its appearance occasionally in the twilight near the horizon, in the western sky after sunset or in the east before sunrise. Venus, the brightest of the planets, is by far the most conspicuous starlike object in the heavens. It appears sometimes in the west as the evening star, and at other times in the east as the morning star.

Mars is distinguished by its red color. When this ruddy planet comes unusually near us, at intervals of about 15 years, it is second in brilliance only to Venus. Mars is usually fainter than Jupiter, and at times has only moderate brightness.

Jupiter ranks next to Venus, as a general thing, outshining all the stars themselves. Saturn rivals the brightest stars. These two are more leisurely in their movements among the constellations; their places for a number of years to come are shown in Fig. 7.18.

The bright planets shine with a steady light, under ordinary conditions. In this way they can be distinguished from the twinkling stars around them. They can be recognized, too, by their movements among the stars, if they are watched from time to time. Examined with the telescope, these planets appear as disks, while the stars are not magnified by the largest telescopes.

4.18. Examples of the Use of the Star Maps. (1) Read from Map 2 the right ascension and declination of Regulus, in the Sickle of Leo.

Ans. Right ascension $10^{\mathrm{h}}\ 5^{\mathrm{m}}$, declination $+ 12°$.

(2) On October 11, 1940, Jupiter and Saturn are not far apart in about right ascension $2^{\mathrm{h}}\ 46^{\mathrm{m}}$, declination $+ 14°$. What is their position among the stars (Map 5)?

Ans. Between α Ceti and α Arietis; southwest of the Pleiades. They cross the meridian about 1 A.M. on this date.

(3) On what date does Sirius (Map 5) cross the celestial meridian at 9 o'clock in the evening? What is then its distance from the zenith as observed in latitude 40° N.?

Ans. February 15. Zenith distance 57°.

(4) Name some stars that pass almost directly overhead in latitude 40° N.

Ans. Algol, β Boötis, γ Cygni.

(5) On what date does Orion (Map 5) rise at 9 P.M.?

Ans. November 1. Since Orion is on the celestial equator, it rises six hours earlier than the time of its meridian transit. It must be remembered also that a star rises two hours earlier from month to month.

(6) Name one or more constellations whose stars outline the figure of a dipper; a cross; a square; a semicircle; a V-shaped figure.

TABLE 4.II. GREEK ALPHABET (SMALL LETTERS)

α	alpha	ι	iota	ρ	rho
β	beta	κ	kappa	σ	sigma
γ	gamma	λ	lambda	τ	tau
δ	delta	μ	mu	υ	upsilon
ε	epsilon	ν	nu	φ	phi
ζ	zeta	ξ	xi	χ	chi
η	eta	ο	omicron	ψ	psi
θ	theta	π	pi	ω	omega

TABLE 4.III. NAMES OF THE CONSTELLATIONS

Latin Name	Possessive	English Equivalent	Section	Map
*Androm′eda	Androm′edae	Andromeda	5.23	4, 5
Ant′lia	Ant′liae	Air Pump		
A′pus	A′podis	Bird of Paradise		
*Aqua′rius	Aqua′rii	Water Carrier	5.25	4
*Aq′uila	Aq′uilae	Eagle	5.16	3, 4
*A′ra	A′rae	Altar		6
*A′ries	Ari′etis	Ram	5.26	4, 5
*Auri′ga	Auri′gae	Charioteer	5.30	5
*Boö′tes	Boö′tis	Herdsman	5.10	2, 3
Cae′lum	Cae′li	Graving Tool		
Camelopar′dalis	Camelopar′dalis	Giraffe		
*Can′cer	Can′cri	Crab	5.4	2, 5
Ca′nes Vena′tici	Ca′num Venatico′rum	Hunting Dogs	5.8	2
*Ca′nis Ma′jor	Ca′nis Majo′ris	Larger Dog	5.34	5
*Ca′nis Mi′nor	Ca′nis Mino′ris	Smaller Dog	5.34	5
*Capricor′nus	Capricor′ni	Sea-Goat	5.24	4
†Cari′na	Cari′nae	Keel	5.36	6
*Cassiope′ia	Cassiope′iae	Cassiopeia	5.21	1, 4
*Centau′rus	Centau′ri	Centaur	5.36	2, 6
*Ce′pheus	Ce′phei	Cepheus	5.20	1, 4
*Ce′tus	Ce′ti	Whale	5.27	4, 5
Chamae′leon	Chamaeleon′tis	Chameleon		
Cir′cinus	Cir′cini	Compasses		
Colum′ba	Colum′bae	Dove		5
Co′ma Bereni′ces	Co′mae Bereni′ces	Berenice's Hair	5.8	2
*Coro′na Austra′lis	Coro′nae Austra′lis	Southern Crown		
*Coro′na Borea′lis	Coro′nae Borea′lis	Northern Crown	5.10	3
*Cor′vus	Cor′vi	Crow	5.6	2
*Cra′ter	Cra′teris	Cup	5.6	2
Crux	Cru′cis	Cross	5.36	6
*Cyg′nus	Cyg′ni	Swan	5.18	3, 4
*Delphi′nus	Delphi′ni	Dolphin	5.19	4
Dora′do	Dora′dus	Goldfish	5.36	6
*Dra′co	Draco′nis	Dragon	5.9	1, 3
*Equu′leus	Equu′lei	Little Horse		
*Erid′anus	Erid′ani	River	5.33	5, 6
For′nax	Forna′cis	Furnace		
*Gem′ini	Gemino′rum	Twins	5.31	5
Grus	Gru′is	Crane		4
*Her′cules	Her′culis	Hercules	5.11	3
Horolo′gium	Horolo′gii	Clock		
*Hy′dra	Hy′drae	Sea Serpent	5.5	2
Hy′drus	Hy′dri	Water Snake		6
In′dus	In′di	Indian		
Lacer′ta	Lacer′tae	Lizard		
*Le′o	Leo′nis	Lion	5.3	2

Table 4.III. Names of the Constellations—*Continued*

Latin Name	Possessive	English Equivalent	Section	Map
Le'o Mi'nor	Leo'nis Mino'ris	Smaller Lion		
*Le'pus	Le'poris	Hare	5.33	5
*Li'bra	Li'brae	Scales	5.14	3
*Lu'pus	Lu'pi	Wolf		3
Lynx	Lyn'cis	Lynx		
*Ly'ra	Ly'rae	Lyre	5.12	3
Men'sa	Men'sae	Table Mountain		
Microsco'pium	Microsco'pii	Microscope		
Monoc'eros	Monocero'tis	Unicorn	5.17	
Mus'ca	Mus'cae	Fly		6
Nor'ma	Nor'mae	Level		
Oc'tans	Octan'tis	Octant	5.36	
*Ophiu'chus	Ophiu'chi	Serpent Holder	5.13	3
*Ori'on	Orio'nis	Orion	5.32	5
Pa'vo	Pavo'nis	Peacock		6
*Peg'asus	Peg'asi	Pegasus	5.22	4
*Per'seus	Per'sei	Perseus	5.28	4, 5
Phoe'nix	Phoeni'cis	Phoenix		4
Pic'tor	Picto'ris	Easel		
*Pis'ces	Pis'cium	Fishes	5.26	4
*Pis'cis Austri'nus	Pis'cis Austri'ni	Southern Fish	5.25	4
†Pup'pis	Pup'pis	Stern	5.36	6
†Pyx'is	Pyx'idis	Mariner's Compass	5.36	5, 6
Retic'ulum	Retic'uli	Net		
Sagit'ta	Sagit'tae	Arrow	5.19	3, 4
*Sagitta'rius	Sagitta'rii	Archer	5.15	3
*Scor'pius	Scor'pii	Scorpion	5.14	3
Sculp'tor	Sculpto'ris	Sculptor's Apparatus	5.25	4
Scu'tum	Scu'ti	Shield	5.16	3
*Ser'pens	Serpen'tis	Serpent	5.13	3
Sex'tans	Sextan'tis	Sextant		
*Tau'rus	Tau'ri	Bull	5.29	5
Telesco'pium	Telesco'pii	Telescope		
*Trian'gulum	Trian'guli	Triangle	5.26	4, 5
Trian'gulum Austra'le	Trian'guli Austra'lis	Southern Triangle		6
Tuca'na	Tuca'nae	Toucan	5.36	6
*Ur'sa Ma'jor	Ur'sae Majo'ris	Larger Bear	5.1	1, 2
*Ur'sa Mi'nor	Ur'sae Mino'ris	Smaller Bear	5.2	1, 3
†Ve'la	Velo'rum	Sails	5.36	2, 6
*Vir'go	Vir'ginis	Virgin	5.7	2
Vo'lans	Volan'tis	Flying Fish		
Vulpec'ula	Vulpec'ulae	Fox	5.19	

* One of the 48 constellations recognized by Ptolemy.

† Carina, Puppis, Pyxis, and Vela once formed the single Ptolemaic constellation Argo Navis.

QUESTIONS ON CHAPTER IV

1. What constellations are mentioned in the Book of Job?

2. Might it be possible to fix the date when the original constellations were invented by the position of the center of the area of the southern heavens which they do not cover?

3. Make a rule from Map 5 for finding the star Sirius when the constellation Orion is known, and then a rule for finding the star Procyon.

4. Can you explain why the names of the months are placed as they are in Map 1?

5. Show that it is very nearly sidereal noon when Beta Cassiopeiae, the leader of the seven in Cassiopeia's Chair, is directly above the pole star. On what date does this occur at 9 o'clock in the evening?

6. Make a list of the brightest stars (Table 4.I). With the aid of the Maps, record for each star: (1) its right ascension and declination; (2) the date when it appears on the celestial meridian at 9 o'clock in the evening; (3) its distance from your zenith at that time.

7. Is the Alpha star always the brightest star in the constellation?

8. Compare the brightness of the stars Sirius and Procyon which differ by about two magnitudes. Compare the brightness of a 1st magnitude star with one of the 21st magnitude.

9. Why does a telescope show more stars than the eye alone can see?

10. How is it possible to distinguish the planets from the stars in the sky? Having found a bright planet, could you then decide which one it is?

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CHAPTER V

STARS IN THEIR SEASONS

STARS OF THE SPRING — STARS OF THE SUMMER — STARS OF THE AUTUMN — STARS OF THE WINTER

Any season of the year at all is a good time to begin the study of the constellations. These descriptions happen to begin with the "stars of the spring," the stars which cross the celestial meridian at 9 o'clock in the evening in the course of March, April, and May. It is simply a convenient way of dividing the visible heavens into quarters, one for each season and for each of the Maps 2, 3, 4, and 5.

The constellations for each season are situated, then, in a wide band which extends from the north celestial pole past the zenith and down to the south horizon in the early evening. Most of the constellations here associated with a particular season can be found in the east in the preceding season, and in the west in the following one.

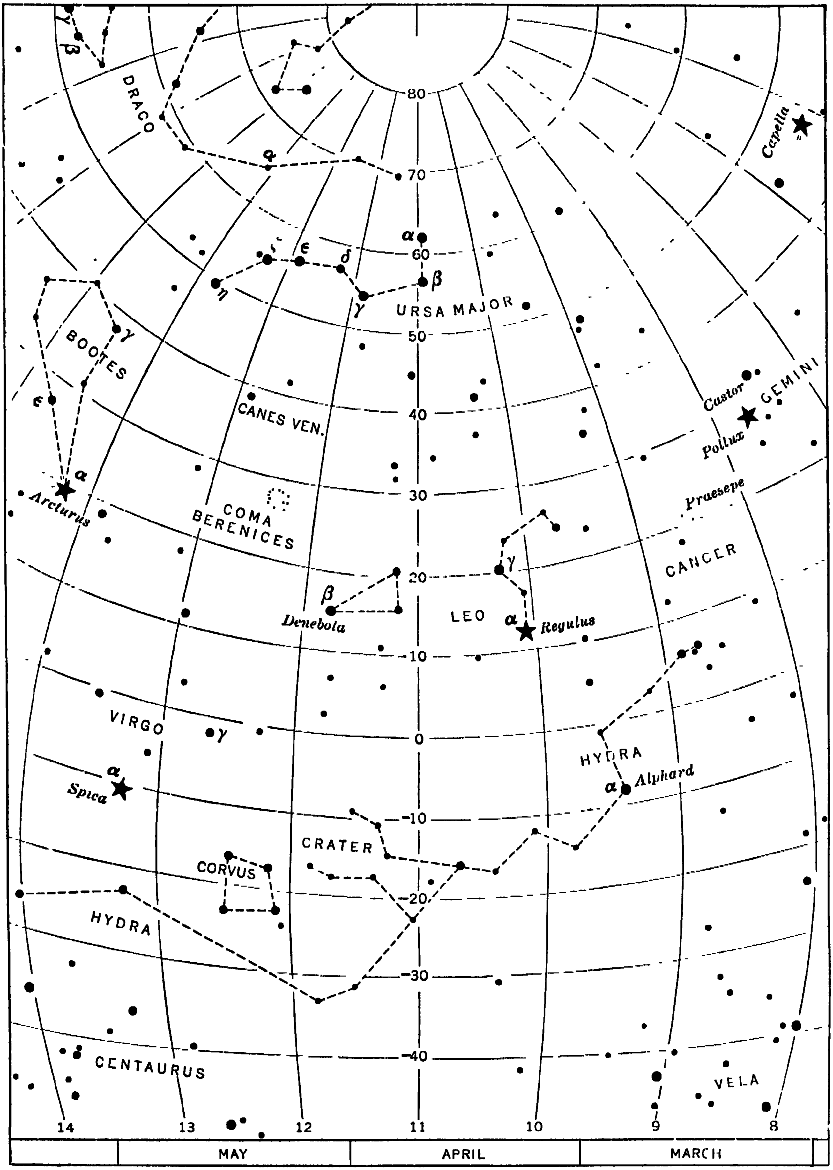
Our descriptions are limited to those constellations that display striking figures of stars, or other features of special interest to watchers of the skies. They refer to sights which are visible to the unaided eye, as a general thing. A field glass is suggested occasionally to improve the view, while a small telescope is needed in order to see a few of the objects that are mentioned.

The Maps for the four seasons extend as far south as the horizon of latitude 40° N. Map 6 shows the region around the south pole of the heavens, which is invisible from places as far north as this. The concluding Section of this Chapter describes the more prominent features of the south circumpolar region.

STARS OF THE SPRING (MAP 2)

5.1. Ursa Major. In the early evenings of spring the Great Dipper appears inverted high above the celestial pole in the north. This figure of seven bright stars has been known to many nations as the Wagon; in England it is called the Plough.

The Great Dipper is part of the large constellation *Ursa Major,*



MAP 2. Stars of the Spring.

the Larger Bear, whose stars extend for some distance to the west and south of its bowl. Three pairs of stars nearly equally spaced mark three paws of the ancient creature (Fig. 4.1).

Mizar, at the bend in the handle, is the most famous of the Dipper's stars, as the first double star to be specially noticed by the early observers with the telescope. It has a fainter companion, *Alcor,* that is clearly visible to the naked eye. Through even a small telescope Mizar itself is revealed as a pair of stars close together.

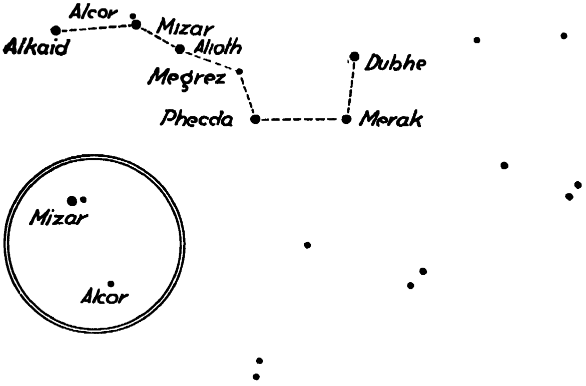


FIG. 5.1. Ursa Major. *Insert.* Mizar and Alcor viewed through an inverting telescope.

5.2. Ursa Minor. Following the line of the Pointers of the Great Dipper northward we come to Polaris, the pole star or north star. This celebrated star marks the end of the handle of the Little Dipper, the characteristic figure of *Ursa Minor,* the Smaller Bear.

The Little Dipper is a figure of seven stars also. Though less conspicuous than its larger neighbor, it is plainly visible in a clear sky, especially when the moon is not near its full. *Polaris* (α Ursae Minoris) is its brightest star. Next in brightness come the two stars in the front of its bowl, sometimes called the "guardians of the pole," because they march round and round it, nearer than any other bright stars except Polaris itself.

5.3. Leo, the Lion, is peculiarly associated with the spring season. The fine Sickle of this constellation appears in the east in the early evening when spring approaches, and becomes the most striking figure in the southern sky as the season advances.

Follow the line of the Pointers of the Great Dipper toward the south and a little farther than the distance of the pole in the opposite direction. There you will find Leo.

Six stars form the well known Sickle. The sickle figure and the right triangle to the east of it are the distinguishing features of this constellation of the zodiac. Perhaps the people of olden times placed a lion here to symbolize the fierce heat of the sun in midsummer, when it was passing through this constellation.

Regulus (α Leonis), the blue star of the first magnitude at the end of the Sickle's handle, is its brightest star. Denebola (β Leonis), at the eastern point of the triangle, and γ Leonis, in the blade of the Sickle, are stars of the second magnitude like the pole star. The second of these, a fine double through a telescope of moderate size, stands near the radiant of the Leonid meteors of November (9.10).

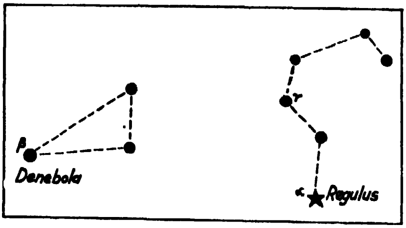


FIG. 5.3. The Sickle and Triangle of Leo.

5.4. Cancer, the Crab, is the dim zodiacal constellation to the west of Leo. A line from Denebola through the top of the handle of the Sickle of Leo and extended as far again beyond leads to a little foggy patch. This is Prae-se′pe, the "Manger," often known as the "Beehive." A field glass resolves it into a fine cluster of stars.

When the sun enters the zodiacal sign of Cancer, which precession has now shifted to the west into the constellation Gemini, it has reached the summer solstice, the northernmost point of its path around the heavens. The sun is then directly overhead at noon at the tropic of Cancer.

5.5. Hydra, the Sea Serpent, sprawls far across the southern skies of spring. It is the longest and largest of the constellations. A fairly bright group of stars south of Cancer marks the head of this creature of the ancient imagination. From here it is easy with the aid of the map to follow the winding stream of stars toward the southeast.

Its brightest star is *Alphard,* "the solitary one," a star of the second magnitude not far to the southeast of the head. Farther along, the stream of Hydra passes by the interesting figures of the Cup and the Crow.

5.6. Crater and Corvus. *Crater,* the Cup, looks like the object it was supposed to represent. While its stars are faint, its goblet form can be readily recognized on clear moonless evenings in spring, directly south of the triangle of Leo.

Corvus, the Crow, is a striking four-sided figure immediately east of the Cup. It is crossing the meridian at 9 o'clock in the evening on May 10. The celebrated Southern Cross is directly south of Corvus, 40 degrees away and out of sight from all except the extreme southern parts of the United States.

The two stars which form the slanting northern side of the figure of Corvus serve as pointers to direct us eastward to the bright star Spica in Virgo.

5.7. Virgo, the Virgin, is supposed to represent Astraea, goddess of justice, the last of the Grecian deities to leave the earth because of the growing wickedness of mankind. But there is nothing about this large constellation of the zodiac to suggest a goddess looking sorrowfully down at us. Indeed, the stars here form no striking figure at all. Virgo consists of Spica and the stars around it.

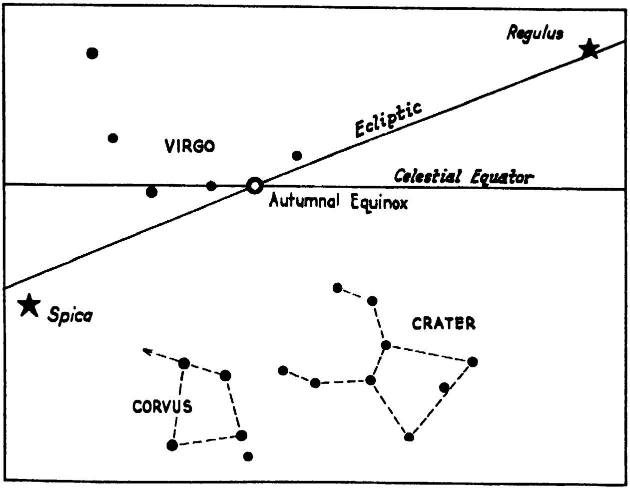


FIG. 5.7. How to Locate the Autumnal Equinox.

Spica (α Virginis) is a blue star of the first magnitude. It forms a fine equal-sided triangle with Denebola in Leo and the brilliant Arcturus which we shall look at again soon.

The course of the ecliptic is easy to trace in this region of the sky. A line from the Praesepe cluster through Regulus and Spica is very nearly the sun's path. Three fifths of the way from Regulus to Spica the ecliptic crosses the celestial equator. Just here in Virgo is the autumnal equinox where the sun crosses on September 23 on its way south.

5.8. Coma Berenices. A line from the end of the Great Dipper's handle to Denebola in Leo passes through two rather faint constellations. A third of the way along this line brings us to the moderately bright star *Cor Caroli,* or "Charles' Heart," named in honor of Charles II of England. It is the brightest star of the small modern constellation *Canes Venatici,* the Hunting Dogs.

Two thirds of the way along this line toward Denebola brings us to *Coma Berenices,* or Berenice's Hair, whose chief feature is a large loose cluster of stars (Fig. 12.14), "like a cobweb glistening with dewdrops." The stars of the cluster are revealed more clearly by a field glass. Indeed, a field glass is often useful to one who watches the stars.

Coma Berenices contains the north pole of the Milky Way (13.3). This whole region is a fine hunting ground for galaxies beyond our own, though large telescopes are needed to see them, as a general thing. Especially in the direction from the Great Dipper past Coma and southward through Virgo, the remote galaxies are very numerous, and are gathered here and there into vast clusters.

These are the prominent constellations that appear in the evening skies of spring between the north pole of the heavens and the south horizon. When summer begins, they have moved along westward, and other constellations have taken their places along the meridian to claim our attention.

Stars of the Summer (Map 3)

5.9. Draco. The V-shaped head of *Draco,* the Dragon, is on the meridian nearly overhead at 9 o'clock on the 1st of August; the point of the V is toward the west. The two stars at the eastern ends serve as pointers to direct us to the north pole of the ecliptic. When the line joining them is extended a little more than as far again beyond to the north, it leads to this important point which is unmarked by any bright star.

The winding stream of stars which represents the body of the Dragon curves almost completely around the ecliptic pole (Fig. 3.10), The apex of the sun's way is located near the eastern border of the constellation, the point in the heavens toward which our sun and its whole family of planets are speeding relative to the stars around us (11.8). The brilliant Vega in the constellation Lyra lies some ten degrees away to the northeast.

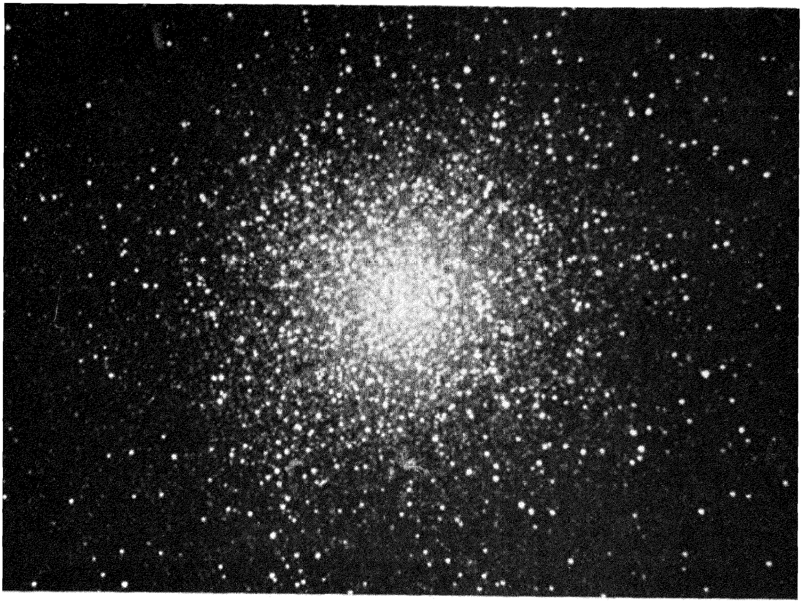


FIG. 5.11. Globular Cluster Messier 13, in Hercules. (*Photographed at the Dominion Astrophysical Observatory, Victoria*)

5.12. Lyra. Farther east along the line through the Northern Crown and the butterfly figure of Hercules we come to *Lyra*, the Lyre. The figure is a small parallelogram with a little triangle attached to its northernmost point. Vega marks one point of this triangle.

Vega (α Lyrae) is a blue star of the zero magnitude. It ranks fourth in brightness among all the stars, and first of all in the northern celestial hemisphere, though it is only by a very little the superior of Arcturus and Capella.

The star at the northern point of the little triangle, Epsilon Lyrae, is the famous "double double." It is really two stars, as you can perhaps see with the naked eye, and very easily with a field glass. A small telescope shows that each one is again a double star.

A somewhat larger telescope is needed to see clearly the fine Ring Nebula between the two stars on the southern side of the parallelogram of Lyra. The western one of these two stars is the well known eclipsing double star β Lyrae.

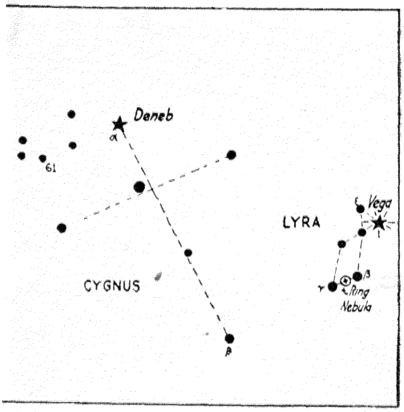


FIG. 5.12. Cygnus and Lyra. Showing the positions of 61 Cygni, the double-double ε Lyrae, and the Ring Nebula.

FIG. 5.12A. Ring Nebula in Lyra. (*Photographed at the Dominion Astrophysical Observatory, Victoria*)

5.13. Serpens and Ophiuchus occupy a large area of the heavens between Hercules and Scorpius far to the south. The head of *Serpens,* the Serpent, is an X-shaped figure immediately south of the Northern Crown. From here you can follow a stream of stars southward into a confusion of things that the map will perhaps assist in straightening out.

Alpha Ophiuchi, a star of the second magnitude near the northern border of *Ophiuchus,* the Serpent Holder, is the brightest star of this constellation. About 10 degrees to the southeast, a little V-shaped group of stars is likely to attract attention. It marks the head of Poniatowski's Bull, a modern constellation which never gained general recognition.

5.14. Scorpius. At nightfall in midsummer, the formidable figure of *Scorpius* (or *Scorpio*), the Scorpion of the zodiac, stands low in the south. Perhaps it resembles, as much as anything, the creature it was supposed to represent. Some people imagine here the figure of a kite with a long tail stretching southward and around to the east.

Its brightest star is *Antares* (α Scorpii), the "rival of Mars," because its color is red like that of the planet Mars. This star of the first magnitude is a giant red star; its actual diameter is something like three hundred times as great as our sun's diameter.

Libra, the Scales, can be found between Spica in Virgo and the northern part of Scorpius. Its stars are rather faint. Four of them form a nearly square figure which serves to distinguish this constellation of the zodiac.

5.15. Sagittarius. Directly east of Antares, six stars of the zodiacal constellation *Sagittarius,* the Archer, form the inverted Milk Dipper. This dipper figure is so named because of its location in the Milky Way. Five of its stars and some brighter ones farther south outline a rather convincing teapot — handle, spout, and all.

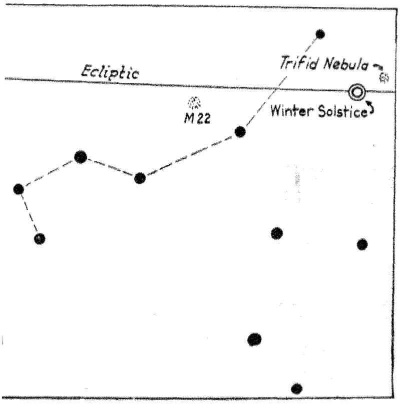


FIG. 5.15. Milk Dipper of Sagittarius. Showing the positions of the winter solstice, the globular cluster Messier 22, and the Trifid Nebula.

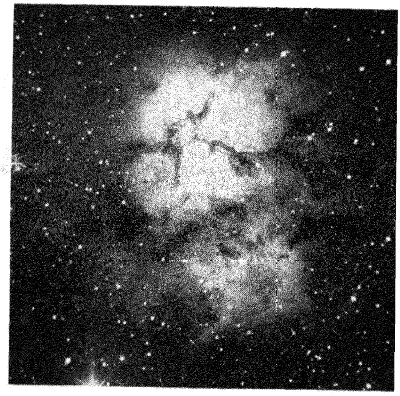


FIG. 5.15A. The Trifid Nebula in Sagittarius. (*Photographed at the Mount Wilson Observatory*)

The winter solstice is situated a little way southwest of the end of the Milk Dipper's handle. Here the sun stands on December 22 at the southernmost point of its course. The bright nebula Messier 8 is clearly visible to the naked eye only a little way south of this point. The fine Trifid Nebula is near by toward the north.

There are many interesting sights to be seen in Sagittarius, whether we look with the eye alone, or through a field glass or a telescope. There are foggy patches that we call nebulae; there are clusters and clouds of stars; the globular cluster Messier 22, north of the middle of the Milk Dipper's handle is worth looking at with a small telescope. Most impressive of all is the great Sagittarius star cloud west of the Milk Dipper, which stands in the center of our galaxy, some 30,000 light years away.

5.16. Aquila. Following the Milky Way northeastward from the Sagittarius cloud, we come presently to the bright area in the little modern constellation *Scutum,* the Shield, and beyond it to *Aquila,* the Eagle. Its brightest star is *Altair* (α Aquilae), a star of the first magnitude, the middle of three stars in line. Altair is directly south at 9 o'clock in the evening on the 1st of September. The brightest "new star" of modern times appeared in Aquila in 1918.

The star η Aquilae is a well known variable star of around the fourth magnitude. Its light fluctuates in a period of seven days, sometimes nearly twice as bright as at other times.

5.17. The Milky Way of Summer and Autumn. This luminous girdle around the heavens, that we call the Milky Way, glows with the light of countless millions of stars too remote to be visible separately to the naked eye. Its central line is inclined 62° to the celestial equator, crossing it in Aquila and again in *Monoceros* to the east of Orion.

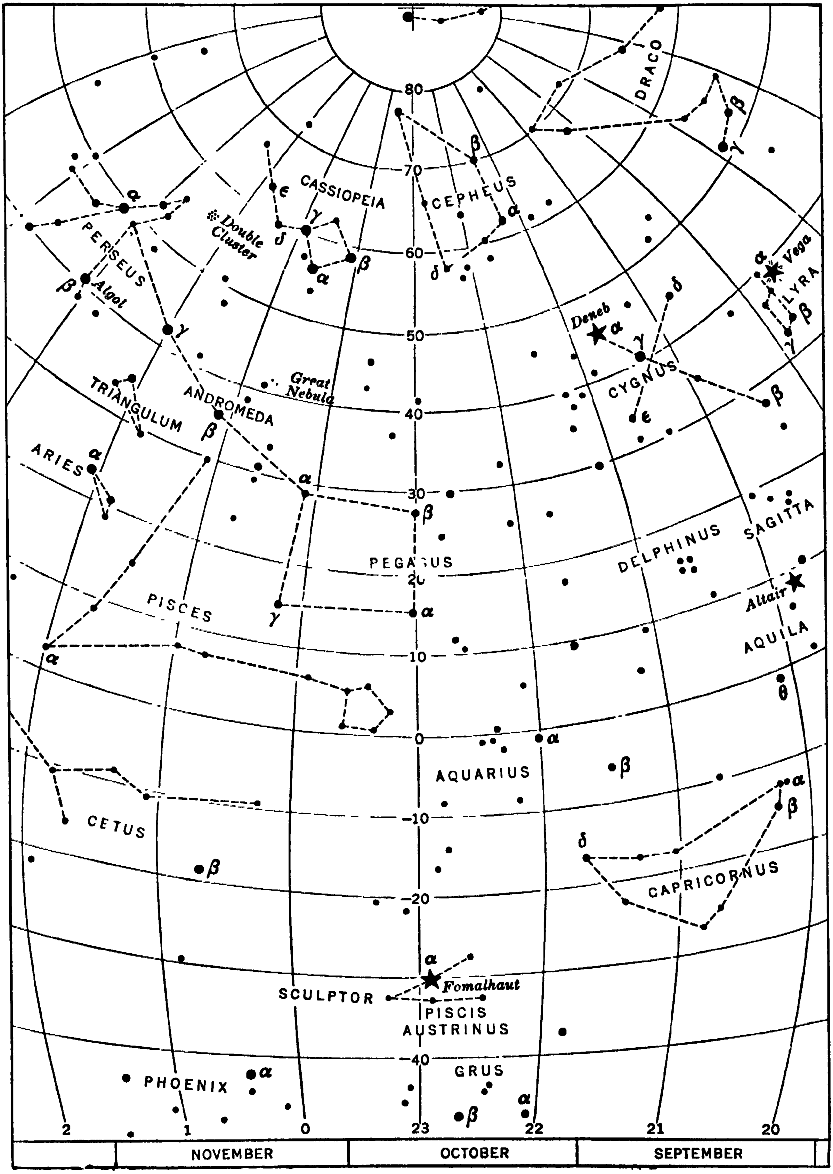
A part of the Milky Way arches across the evening skies of the late summer and early autumn. Another part is visible in the skies of winter. Still another part is always out of sight below the south horizon for those who live in middle northern latitudes. It is with the first and most spectacular part that we are now concerned.

Up from the south horizon the Milky Way takes its course through Scorpius, Sagittarius, and a part of Ophiuchus, then on past Scutum into Aquila. Through these constellations it runs in two parallel streams. The division is only apparent; it is caused by the intervention of a long cosmic dust cloud between us and the Milky Way. The western branch is dimmed and in places almost obliterated by the dust clouds for part of its course through these regions.

The Milky Way has bright areas where the dust clouds are thin. At many points it is interrupted by "dark rifts" of varied size and shape produced by heavier dark clouds. We follow on now past Aquila into the fine region of the Northern Cross.

STARS OF THE AUTUMN (MAP 4)

5.18. Cygnus. The Northern Cross is overhead at 9 o'clock in the evening early in September. One of the finest and best-known of the



Map 4. Stars of the Autumn.

star figures, it was the "Bird" of the ancient astronomers, and later became *Cygnus*, the Swan.

FIG. 5.18. The Northern Cross in the Milky Way. The North America Nebula appears to the left of Deneb at the top of the Cross. Beta Cygni at the foot of the Cross is out of picture at the lower right. (*Photographed by F. E. Ross, Yerkes Observatory*)

The Cross is set in a remarkable region of the Milky Way. *Deneb* (α Cygni), the "Tail" of the Swan, marks the northern end of its long axis which lies along the stream. *Albireo* (β Cygni) decorates the southern end; only a small telescope is needed to show that it is really an orange star and a fainter blue star close together.

Find the little triangle of stars which completes an oblong figure with α, γ, and ε Cygni (Fig. 5.12). The star at the western point of the triangle is 61 Cygni, a double star, as the small telescope clearly shows. Eleven light years away, this star was the first one whose distance was determined. More than a dozen stars are known today to be nearer than 61 Cygni.

Here in Cygnus begins the long rift in the Milky Way which extends southward almost as far as the Southern Cross. Smaller rifts can be seen here also; a transverse dark rift not far north of Deneb is especially noticeable.

5.19. Delphinus and Sagitta. A line from Vega through the foot of the Northern Cross and prolonged nearly as far again beyond leads to the constellation *Delphinus,* the Dolphin. A small diamond of rather faint stars and one or two other stars near by form the figure that has long been known as "Job's Coffin."

Sagitta, the Arrow, is another little figure of five or six faint stars; it is in the midst of the Milky Way, halfway between Altair and the foot of the Cross. It resembles an arrow as much as anything else. Both Delphinus and Sagitta are ancient constellations. The fine Dumb-bell Nebula (Fig. 12.18) is not far to the north of the eastern end of the Arrow, within the boundaries of the dim modern constellation *Vulpecula.*

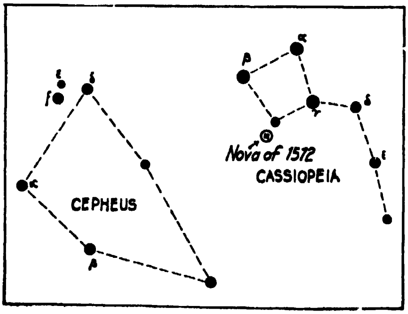


FIG. 5.20. Cepheus and Cassiopeia. Showing the positions of Delta Cephei and Tycho's Nova.

5.20. Cepheus intervenes between the Northern Cross and the pole of the heavens. This king of the old celestial royal family is not a conspicuous constellation. Some of its stars outline a large figure that might be likened to that of a church spire. At the eastern end of the base of the spire there is a little triangle formed by the stars, δ, ε, and ζ Cephei.

Delta Cephei is the famous variable star from which the whole class of Cepheid variables (12.4) is named. Its light fluctuates in a period of a little more than five days. At its maximum the star is as bright as its neighbor Zeta; at minimum it is only half as bright, now about equal to Epsilon. The changing light of δ Cephei can be watched from night to night with the eye alone. A small telescope reveals a fainter blue companion close to the yellow variable star.

In Cassiopeia, east of Cepheus, the Milky Way passes nearest the north celestial pole, and turns south to join the part of the glowing stream that we see in winter.

5.21. Cassiopeia is almost as well known as the Great Dipper which circles around the pole on the opposite side. Follow a line from the bend in the Dipper's handle through the pole star and an equal distance beyond, and you come to the zigzag row of five bright stars which form an irregular letter M, or W. These with two fainter stars outline Cassiopeia's Chair in the midst of the Milky Way.

Here, near the front of the seat of the Chair, the brightest new star on record burst into view in the fall of 1572 (Fig. 5.20). At its greatest splendor this nova rivaled the planet Venus. Slowly it declined, while the great Tycho Brahe watched it carefully, until it faded quite out of sight to the naked eye in the spring of 1574.

5.22. The Square of Pegasus is peculiarly associated with the autumn skies. As this season approaches we find it in the east balanced on one corner. It is crossing the meridian high in the south at 9 o'clock in the evening on the 1st of November. This square is the characteristic figure of *Pegasus,* the winged horse of the legends.

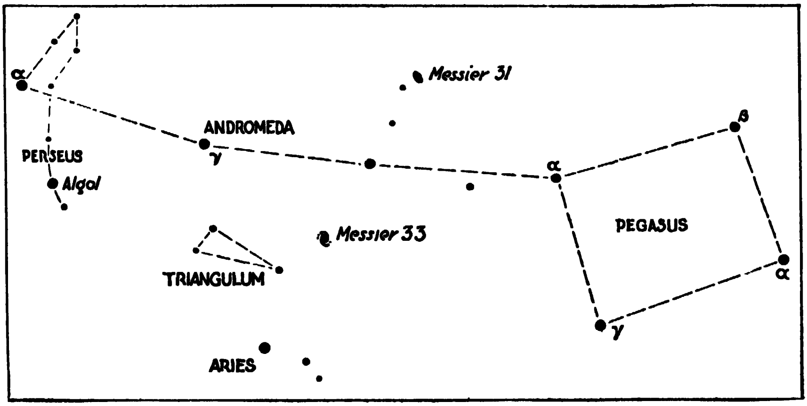


FIG. 5.22. Region of the Square of Pegasus. Showing the positions of the spiral galaxies Messier 31 and 33, and of Algol.

Four second-magnitude stars mark the corners of the great square; they are α, β, and γ Pegasi, and in the northeast corner α Andromedae. Set in a dull region of the heavens, the Square is easy to distinguish.

Imagine that the Square of Pegasus is the bowl of a very large dipper, and look for its handle extending toward the northeast. The first three stars in the handle are the brightest of the constellation Andromeda.

5.23. Andromeda is the princess of the often-told legend. The queen, Cassiopeia, had boasted of her daughter's beauty. And to punish the queen, Neptune had decreed that Andromeda must be chained to a rock where the terrible sea monster, Cetus, would come and devour her. Andromeda was rescued by the hero Perseus just in the nick of time. Perseus held up the head of Medusa with the snaky locks before the approaching monster, which was frozen to stone by the awful sight.

The old pictures of heroes and animals have disappeared from the star maps of today. But their names remain. And constellations in this region of the heavens still bear the names of the principal characters in the ancient Andromeda legend: Cepheus, Cassiopeia, Andromeda, Cetus, and Perseus.

The three brightest stars of *Andromeda* lie along the handle of the dipper figure, as has been said before. The most famous feature of this constellation is the great nebula in Andromeda. A line from β Andromedae, the second in the handle, through a fainter star a little way to the northwest and prolonged as far again beyond leads to the nebula.

An elongated foggy patch to the unaided eye and to the eye at the telescope as well, the Andromeda nebula is really a great spiral galaxy, as the photographs show (Fig. 14.3). It is the brightest, and among the nearest and largest, of the millions of galaxies that lie beyond our Milky Way.

5.24. Capricornus, the Sea-Goat, is located far south of the Northern Cross. A line from Deneb through Delphinus and continued as far again beyond leads to this rather dim constellation of the zodiac, which crosses the meridian around 9 o'clock in the evenings of September.

Our tropic of Capricorn takes its name from the sign of the zodiac which used to stand in this constellation, but which has now moved west into the constellation Sagittarius. When the sun enters this sign at the beginning of winter, it is directly overhead at noon at the tropic of Capricorn.

Capricornus presents a large irregular triangle of mostly faint stars to our view. Perhaps you will decide that it is the figure of an inverted cocked hat, or of a large bird flying toward you. The star α Capricorni at the western point of the triangular figure is really a pair of stars fully 6′ apart, and therefore easily resolved by the eye alone. β Capricorni is a double whose separation is about half as great; a field glass will be needed to show this pair.

5.25. Aquarius and the Southern Fish. Halfway between the large triangle of Capricornus and the Square of Pegasus there is a little triangle of stars with a fourth star at its center. This represents the tipped urn of *Aquarius,* the Water Bearer of the zodiac. From this urn a starry stream flows south into the mouth of the Southern Fish.

The prominent figure of *Piscis Austrinus*, the Southern Fish, is a V of stars, though the point of the figure lies a little way over the boundary in the modern constellation *Sculptor.* The bright star in the middle of the northern arm of the V is *Fomalhaut* (α Piscis Austrini).

The line of the western side of the Square of Pegasus prolonged far to the south leads to Fomalhaut, which is a star of the first magnitude; it is crossing the meridian at 9 o'clock in the evening in the middle of October.

This is a dim region of the heavens, as a general thing, through which the sun takes its way in the late winter and early spring. These constellations have watery names which suggest the rainy season. We come next to the Fishes.

5.26. The Vernal Equinox in Pisces. A little way south of the Square of Pegasus there is a pentagon of faint stars, from which a thin stream runs eastward, ending in a star a little brighter than the others. From here a second stream proceeds toward the northwest almost as far as Andromeda. The two streams are the ribbons to which the two Fishes are tied. *Pisces* is a faint constellation, easily lost to view in a murky or moonlit sky.

One of the constellations of the zodiac, Pisces contains the zodiacal sign Aries which precession has shifted out of its constellation. Here we find the "first of Aries," or vernal equinox, where the sun crosses the celestial equator at the beginning of spring. The line of the eastern side of the Square of Pegasus prolonged one length beyond toward the south leads nearly to this important point in the heavens (Fig. 5.26).

The constellation *Aries*, the Ram, is immediately east of Pisces. Its characteristic figure is a little flat triangle. Northward, half way toward γ Andromedae, another triangle marks the constellation *Triangulum* itself. These two triangles cross the meridian at 9 o'clock in the evening in early December. Next come the winter constellations.

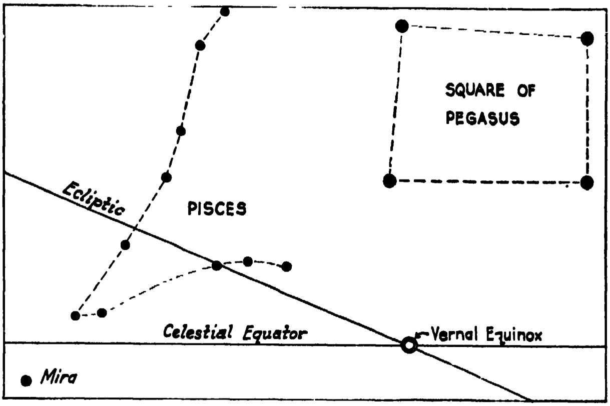


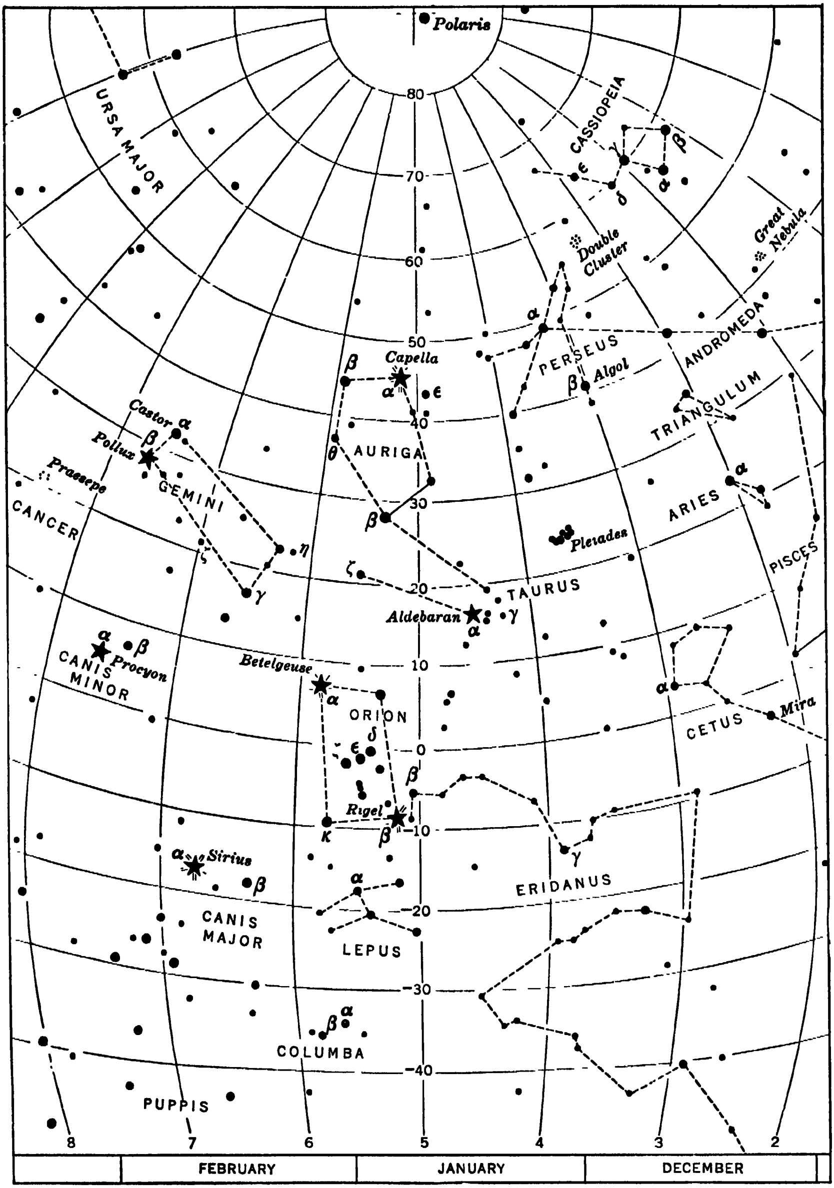
FIG. 5.26. How to Locate the Vernal Equinox.

STARS OF THE WINTER (MAP 5)

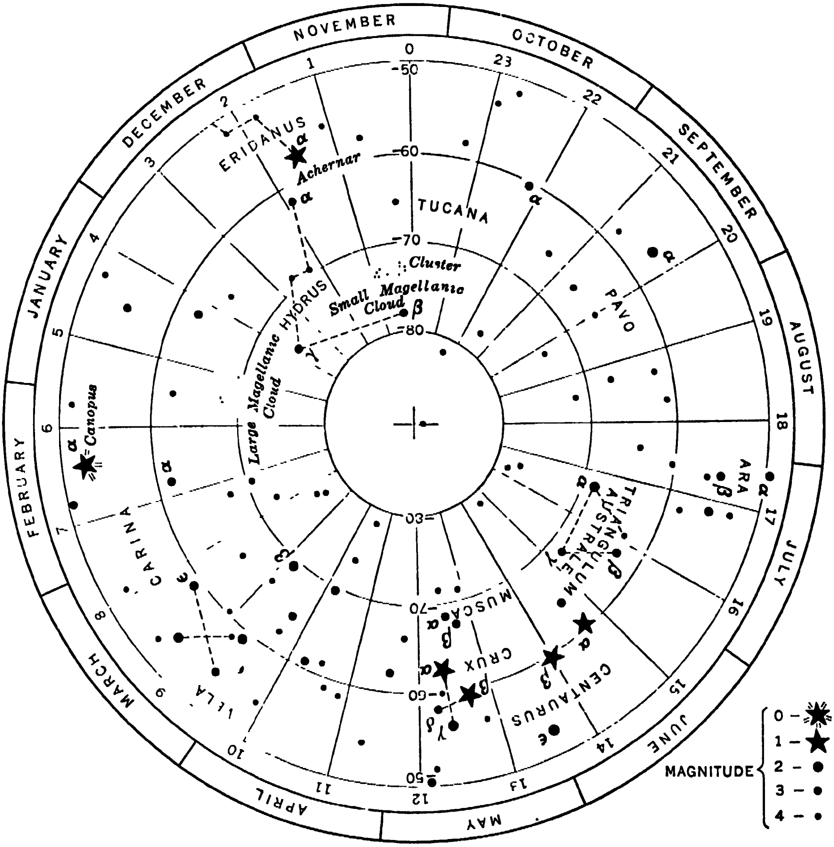
5.27. Cetus. The line of the eastern side of the Square of Pegasus prolonged twice as far beyond to the south ends near the second magnitude star *Deneb Kaitos* (β Ceti), the brightest star of *Cetus*, the Sea Monster. A large inverted dipper of five stars stands directly north of this star; and three times as far beyond in the direction of its bowl we find a pentagon which marks the head of Cetus.

These two figures, the dipper and the pentagon, are easy to recognize in a clear sky, if the moon is not near its full. *Mira*, the "Wonderful" (12.6), is located about halfway between them. This red star is sometimes plainly visible to the naked eye, while at other times it can be seen only through the telescope. The first variable star to be discovered, in 1596, Mira fluctuates somewhat irregularly in cycles of about eleven months.

5.28. Perseus. We have noticed the large dipper figure whose bowl is the Square of Pegasus. The first three stars in its handle belong to Andromeda. The end star in the handle is α Persei, or *Algenib;* it is the brightest of the constellation *Perseus*, whose figure is a large arrow pointing along the Milky Way toward Cassiopeia's Chair.



MAP 5. Stars of the Winter.



Map 6. Region of the South Celestial Pole.

A little way beyond the point of the arrow figure of Perseus there is a bright patch in the midst of the Milky Way, which invites the use of a field glass or, better, a small telescope. This is the famous double cluster in Perseus (Fig. 5.28), a fine pair of star clusters.

Algol, the winking "Demon Star" (Fig. 5.22), glows in the western barb of the arrow, where the old celestial picture book shows the snaky head of Medusa. This famous star is nearly overhead at 9 o'clock in the evening when winter begins. Normally about the equal of α Persei, Algol fades at intervals of 2 days 21 hours to only a third its usual brightness, while a fainter companion revolving around it is passing before the bright star. The first to be discovered, it is the best known of the eclipsing stars (12.2).

FIG. 5.28. The Double Cluster in Perseus. (*Photographed by F. E. Ross with the 60-inch reflector, Mount Wilson Observatory*)

The August meteors seem to come from a point in the constellation Perseus; they are known, therefore, as the Perseids. Their long bright trails add to the interest of the evening skies of midsummer, especially around the 10th of August when they are likely to be most numerous.

The shaft of the arrow of Perseus curving toward the south directs us to the Pleiades in Taurus.

5.29. Taurus, the celestial Bull, contains two fine clusters of stars, the Pleiades and the Hyades. The *Ple'ia-des*, or "Seven Sisters," have the appearance of a little short-handled dipper. Seven stars are plainly visible to the naked eye; the brightest of these is *Alcyone*. Two or three other stars in the cluster twinkle into view in a clear moonless sky. Still more are revealed with a field glass, while as many as a hundred stars may be seen here through a small telescope.

Southeast of the Pleiades, the somewhat larger *Hy'a-des* cluster in the form of the letter V marks the head of Taurus. *Aldebaran*, a reddish star of the first magnitude, glows at the end of the southern arm of the V; it is named "the follower," because it pursues the Pleiades in the daily circling of the heavens. Aldebaran was one of the four "royal stars" of olden times, which were supposed to rule over the four quarters of the heavens. The other three were Regulus in the Sickle of Leo, Antares in the Scorpion, and Fomalhaut in the Southern Fish.

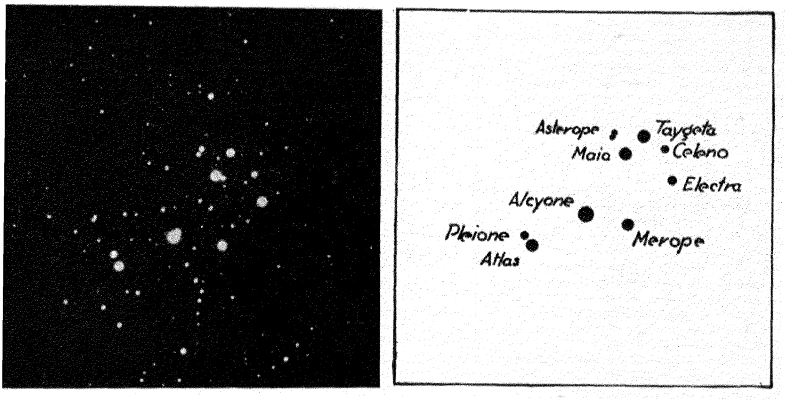


FIG. 5.29. The Pleiades. (*Photographed at Yerkes Observatory*)

The Hyades are the nearest to us of the open clusters of stars. They are moving together eastward and away from us, with the notable exception of Aldebaran. This star is not really a member of the cluster; it is in the direction of the cluster, but only half as far away.

The tips of the long horns of Taurus are marked by two bright stars: β Tauri, known also as *El Nath*, and ζ Tauri at the tip of the southern horn. Near this second star, the hazy Crab Nebula has sometimes been mistaken for a comet by observers with small telescopes. The central line of the zodiac passes between the two clusters and between the horns of Taurus.

5.30. Auriga. El Nath in Taurus is needed to complete the muffin-like figure of five bright stars that characterizes *Auriga,* the Charioteer. Brilliant *Capella,* yellow like the sun, is the northernmost of the five. A little triangle of stars near-by could serve as a signboard to point out this star of the zero magnitude, if indeed anything else is needed to distinguish it. The nearest of these three to Capella is dimmed by eclipse to one half its usual brightness once in 27 years, and the one directly south of it is eclipsed three times in eight years by a companion which spends a month each time in the crossing.

Capella (α Aurigae) is nearly overhead at 9 o'clock in the evening late in January. It is one of the three brightest stars in the northern celestial hemisphere. Arcturus in Boötes and Vega in Lyra are the other two.

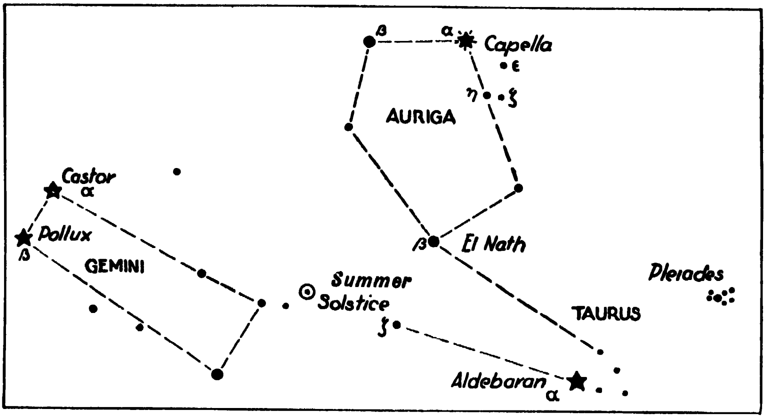


Fig. 5.30. Gemini, Auriga, and Taurus. Showing the position of the summer solstice.

5.31. Gemini, the Twins of the zodiac, are recognized by the rather long oblong figure their bright stars form. A line from Capella through θ Aurigae leads into the middle of this figure.

Castor (α Geminorum) and *Pollux* (β Geminorum) at the eastern end of the oblong figure are the brightest stars of this constellation. Castor is blue; it is really two blue stars close together, as a telescope of moderate size clearly shows. Pollux is yellow and slightly the brighter of the twin stars.

It was in this constellation that the planet Uranus was discovered by Herschel, in 1781. Here too, near δ Geminorum, the most remote planet Pluto was found at the Lowell Observatory, in 1930. The summer solstice is situated near the western border of Gemini, this northernmost point of the ecliptic where the sun stands at the beginning of summer.

5.32. Orion is the brightest and, next to the Great Dipper, the best known of the star figures. It is an oblong figure with three bright stars in line near its center. This constellation is peculiarly associated with the winter season. It rises at nightfall directly in the east as winter approaches; it appears in the south at 9 o'clock in the evening around the 1st of February, and is setting at twilight in the west as spring advances.

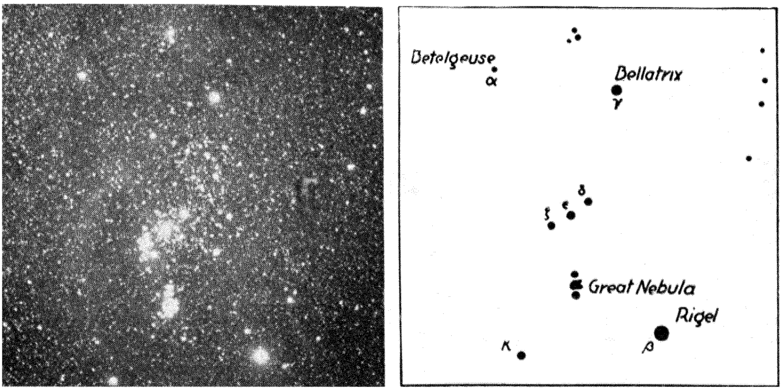


FIG. 5.32. Orion Tangled in Nebulae. Showing the position of the Great Nebula. Notice how faint the red Betelgeuse appears in the photograph as compared with the ordinary view. *(Photographed by Edwin Hubble, Mount Wilson Observatory)*

This fine region of the heavens inspired a lively scene in the old celestial picture book. Orion, a mighty hunter accompanied by his two dogs, stands with uplifted club awaiting the onrush of Taurus.

Red *Betelgeuse* (α Orionis), a variable star of the first magnitude, glows in his shoulder, at the northeast corner of the rectangle. Blue *Rigel* (β Orionis), diagonally across the figure, is still brighter. Three bright stars in line near the center of the rectangle mark Orion's belt. Three fainter stars in line a little way south of the belt represent his sword. His club extends into the Milky Way north of Betelgeuse, while the lion's skin over his arm is traced by a curving stream of stars between the rectangle and the V-shaped head of Taurus.

The middle star of the three in the sword is really a trapezium of stars, as the telescope shows. The great nebula in Orion surrounds this group; its foggy glow can be seen through a small telescope, though its full beauty is reserved for larger ones. On the photographs with long exposures we see great clouds of nebulosity throughout the region of Orion.

5.33. Lepus and Eridanus. *Lepus,* the Hare, is directly south of Orion. Though it is one of the original 48 constellations, it contains little of special interest to the eye alone.

Eridanus, the River, is a long stream of stars which are mostly rather faint. Beginning with β Eridani, northwest of Rigel in Orion, it is not difficult with the aid of a map to follow the winding stream southward until it disappears below the horizon. The first magnitude star Achernar (α Eridani), the "end of the River," is the bright twinkler of this constellation. It is a blue star, so far south as to be invisible in the United States, except in its extreme southern parts.

5.34. The Dog Stars. The three stars of Orion's belt are useful pointers. The line of these stars directs the eye northward to the Hyades in Taurus, and to the Pleiades beyond. It leads southward nearly to Sirius, the Great Dog Star, in the constellation *Canis Major,* the Larger Dog.

Sirius (α Canis Majoris) is a blue star of magnitude −1.6. It is the brightest star in the heavens, and one of the nearest. A large telescope is needed to see its celebrated dwarf companion. Sirius, Betelgeuse, and a third bright star across the Milky Way form a nearly equal-sided triangle. The third star is Procyon, the Little Dog Star.

Procyon (α Canis Minoris), a yellowish star of the zero magnitude, is directly south of the twin stars Castor and Pollux. Its name means "before dog" indicating that it precedes the Great Dog Star in its rising. It is the brightest star of the small and otherwise inconspicuous constellation *Canis Minor,* the Smaller Dog. Like its brighter neighbor, Procyon has a famous dwarf companion which is visible through large telescopes.

5.35. The Milky Way in Winter. The Milky Way of the winter evenings arches from northwest to southeast across the sky, passing overhead at 9 o'clock around the 1st of February. A single wide stream that gathers in bright patches and is interrupted by dark rifts, it has many features of great interest, though it is somewhat less spectacular than the part we see in the south in summer and autumn.

Upward from the northwest horizon it flows through the constellations Cepheus, Cassiopeia, and Perseus into Auriga. Just here the stream is rather dim, for in this direction we are looking the shortest way out of our galaxy, past fewer stars.

Few bright stars lie within the Milky Way from the zenith to the southeast horizon. The brilliant constellations form two lines along its banks. Taurus, Orion, and Canis Major appear on the west side, Gemini and Canis Minor on the east. The stream becomes very broad as it passes out of sight below the horizon.

5.36. The Region of the South Celestial Pole. After passing the Great Dog, the Milky Way goes on southward through the large area which formerly contained the single constellation Argo Navis, the Ship of the Argonauts. Argo was divided in modern times into four constellations: *Puppis*, the Stern, *Pyxis*, the Compass, *Vela*, the Sails, and *Carina*, the Keel.

FIG. 5.36. Region of the Southern Cross. The Cross and the "Coal Sack" are near the center. The bright stars at the extreme left are Alpha and Beta Centauri. (*Photographed by Margaret Harwood at the Arequipa station of Harvard Observatory*)

Canopus (α Carinae) lies far outside the Milky Way toward the west. This star of the *minus* first magnitude is south of Sirius, its only superior in all the heavens; it is invisible north of latitude 38° N. Carina and Vela contain the "false cross" which bears some resemblance to the Southern Cross farther east, though it is somewhat larger.

Crux, the famous Southern Cross, is set in a fine region where the Milky Way flows nearest the south celestial pole. This small figure of four bright stars, which resembles a kite fully as much as a cross, is never entirely visible north of latitude 28° N. and never comes into view at all north of latitude 34°. Its brightest star is the one farthest south; this is *Alpha Crucis*, a blue star of the first magnitude, about as bright as Aldebaran in Taurus. The "Coal Sack" is the remarkable pear-shaped dark rift in the Milky Way directly east of Alpha Crucis.

Here the Milky Way turns toward the north, passes through Centaurus, and finally emerges in Scorpius of the summer skies.

The brightest stars of *Centaurus*, the Centaur, have no special names. *Alpha Centauri*, a yellow star of zero magnitude, stands third in order of brightness among all the stars. It is a famous double star, and is famous also because its dim companion, Proxima, is the nearest star to our sun. *Beta Centauri* is a blue star of the first magnitude. These bright stars of Centaurus are invisible north of about latitude 30° N.

Omega Centauri, though labeled as a star of the fourth magnitude, is revealed through the telescope as a globular star-cluster (Fig. 12.15), the brightest and finest of them all. Scarcely less bright and remarkable is the globular cluster 47 Tucanae near the Small Magellanic Cloud.

The two Clouds of Magellan are never visible anywhere in the United States. From more southern latitudes they are conspicuous to the naked eye, appearing not unlike star clouds of the Milky Way, though they are far removed from that stream itself. The center of the Large Magellanic Cloud is located in the constellation *Dorado*, 21° from the south celestial pole. The Small Cloud is in *Tucana*, 17° from the pole.

Achernar has been mentioned before as the bright star at the "end of the River." It never appears from north of latitude 33° N.

The south pole of the heavens lies in the dim constellation *Octans*. There is no star as bright as Polaris within 20° of this point. Sigma Octantis, a star of magnitude 5.5 and therefore only barely visible to the naked eye, is only 50′ from the south pole, or a little less than the distance of our pole star from the north pole of the heavens.

CHAPTER VI

THE MOON IN ITS PHASES

THE MOON GOES AROUND THE EARTH — THE MOON'S SURFACE — ECLIPSES OF THE MOON

The moon is the earth's *satellite*, that is to say, its attendant. The moon revolves around the earth once a month while we are making our yearly voyage around the sun. Other planets have satellites going around them, and some of them are more abundantly provided with these small attendants than we are. Jupiter has eleven and Saturn nine. There are 28 known satellites in all the solar system.

6.1. The Earth and Moon are Like a Twin Planet. Of all the satellites our moon has the distinction of being the most nearly comparable with its primary in size and mass. The moon is 2160 miles in diameter, or more than a quarter of the earth's diameter, while its mass is one eighty-second part of the earth's mass.

No satellite of the other planets is visible to us except through the telescope. But the earth and moon would appear from the nearer planets as a fine double star plainly visible to the unaided eye. Especially from Venus they would present a remarkable sight indeed. The earth would be brighter than Venus ever appears to us, while the moon, half a degree from the earth at the most, would be as brilliant as Jupiter. The contrasting blue color of the earth and the yellow of the moon would add much to the beauty of the spectacle in the skies of Venus, if the skies there are ever clear.

Imagine the earth and moon joined by a stout rod. The point of support at which they would balance is the *center of mass* of the earth-moon system; it is the point around which the earth and moon mutually revolve. And it is the elliptical path of this point around the sun that we have hitherto called "the earth's orbit."

Careful measurements show that the center of mass of the earth-moon system is only about 2900 miles from the earth's center in the direction of the moon, and therefore within the earth itself. So the moon revolves around the earth, though not around its center. In the descriptions that follow it is easiest to think of the moon as going around the earth just as though the earth were stationary.

The distances which separate the celestial bodies are so great in comparison with the sizes of the bodies themselves that it is often impossible to have the two on the same scale in the diagrams. It is a good plan to keep this limitation of the diagrams in mind so as not to be deceived.

Suppose, for example, that the earth is represented by a circle half an inch in diameter. The moon on this scale would be a circle an eighth of an inch in diameter at the distance of 15 inches, while the sun would be represented by a circle 4½ feet across at the distance of nearly 500 feet. Evidently the distances must be reduced much more than the sizes in order to keep the diagram within the page and to show the bodies themselves clearly.

THE MOON GOES AROUND THE EARTH

6.2. The Moon's Path Among the Stars. Two apparent motions of the moon are known to everyone. First, the moon rises and sets daily. It circles *westward* around us along with the rest of the celestial scenery, because the earth is rotating from west to east. Second, the moon moves steadily *eastward* against the turning background of the stars, because it is revolving in this direction around the earth.

The moon moves eastward among the stars as much as its own diameter in an hour. An hour's watching is enough to show clearly that the moon is in motion. This fact is exhibited in a striking way when the moon passes over, or *occults,* a bright star. An hour after the star has vanished behind the eastern edge of the moon, or after a shorter time if the occultation is not central, it pops suddenly into view at the western edge.

In the course of a day, the moon moves eastward a little more than 13° with respect to the stars, or fully half the length of the Great Dipper. It is interesting to notice the moon's place among the constellations on as many nights as it can be seen in the course of a month, and to mark the place each time on a star map or globe.

The moon's apparent path is nearly a great circle of the heavens, which is inclined a little more than 5° to the ecliptic. It crosses the ecliptic, therefore, at two opposite *nodes.* The *ascending node* is the point where the moon crosses the ecliptic going north; at the *descending node* the moon moves south across the ecliptic.

These nodes *regress,* or slide westward along the ecliptic. Regression of the nodes goes on at a much faster rate than precession of the equinoxes. In only 18.6 years the nodes shift completely around the ecliptic.

So from month to month the moon's path among the constellations is noticeably different.

6.3. The Moon's Phases are the different shapes it shows. Our satellite is a dark globe like the earth itself. One half is in the sunlight, while the other half, turned away from the sun, is in the darkness of night. The phases represent varying amounts of the moon's sunlit hemisphere that are turned toward us successively in the course of the month.

It is the *new moon* that passes the sun. The dark hemisphere is then completely toward us. We can see nothing of the moon at this phase, unless it happens to pass right across the sun's disk, causing an eclipse of the sun.

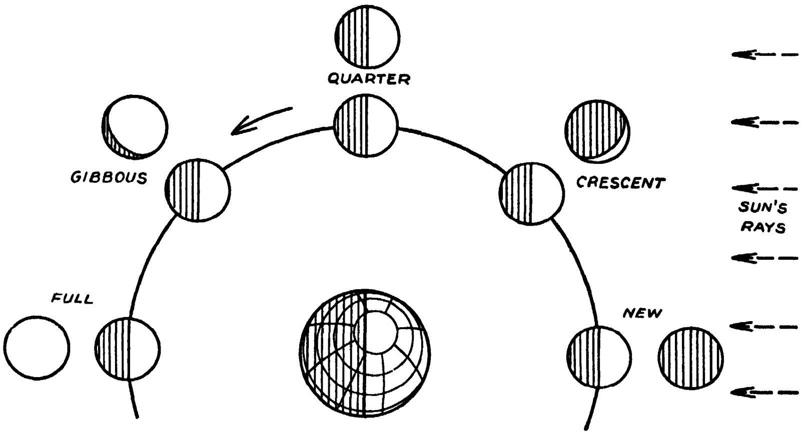


FIG. 6.3. The Phases of the Moon. The outer figures show the phases as seen from the earth.

It is not until the second or third evening after the new phase that the thin *crescent moon* is likely to be noticed in the west after sundown. The crescent grows thicker from night to night until the sunrise line, or *terminator,* runs straight across the moon cutting it in two. That is the *quarter moon* — the *first quarter.*

Then comes the *gibbous* phase as the sunrise line bulges out, giving the moon a lopsided appearance. Gradually the moon fills out, until a round *full moon* rises at about sundown. A little more than two weeks have elapsed since the new moon. The phases are now repeated in the reverse order as the sunset line advances; they are gibbous, quarter (the *last quarter* this time), crescent, and new again.

The horns, or *cusps*, of the crescent moon always point away from the sun's place; after the new phase they show the direction the moon is going. They point more nearly vertically in the early evenings of spring, and are more nearly horizontal in the autumn. The direction of their pointing follows the changing direction of the ecliptic with respect to the horizon.

6.4. Earthlight on the Moon. Often when the moon is in the crescent phase we can see the rest of the disk dimly illuminated. This appearance has been called "the old moon in the new moon's arms," for the bright crescent seems to be wrapped around the faintly lighted part (Fig. 6.4).

FIG. 6.4. Earthlight on the Moon at the Crescent Phase in the Morning Sky. The planet Saturn had emerged from behind the moon half an hour before. (*Photographed, August 24, 1916, by E. E. Barnard at Yerkes Observatory*)

The thin crescent is in the sunlight. The rest of the moon's disk is made visible by sunlight reflected from the earth. Just as the moon tempers the darkness of night for us, so the earth shines on the moon. If anyone lived on the earthward side of the moon, he would see the earth up among the stars in his sky (Fig. 1.6), and going through all the phases that the moon shows to us.

The full earth would look four times as great in the lunar sky as the full moon appears in ours, and something like forty times as bright; for the earth is not only a larger mirror to reflect the sunshine, but owing to the atmosphere it is a better reflector as well.

Earthlight on the moon is a bluer light than that of the sunlit moon, because a considerable part of it is sunlight reflected by our atmosphere. The air around us scatters the bluer colors most effectively, as the blue sky clearly shows. Earthlight is plainest when the moon is a thin crescent, for the earth is then near its full in the lunar sky.

6.5. The Month of the Phases, from new moon to new again, slightly exceeds 29½ days, on the average; it varies in length more than half a day. This is also called the *synodic month*. Since it is shorter, with a single exception, than the months of our solar calendar, the dates of the different phases occur earlier in successive months, as a general thing.

The length of the *sidereal month* averages 27⅓ days; this is the true period of the moon's revolution around the earth. At the end of this interval of time the moon has returned to nearly the same place among the stars. In the meantime, the sun has been moving eastward. More than two days must go by after the close of the sidereal month before the moon has gained a whole lap on the sun.

So the month of the moon's phases is longer than the period of its revolution around us. And so, you see, the moon at its full is always farther east among the constellations than it was the month before. This must be true, of course; for the full moon is opposite the sun's place which is shifting eastward all the time along the ecliptic.

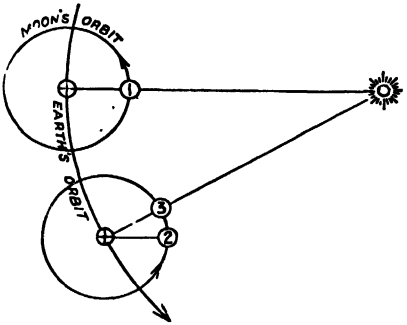


FIG. 6.5. The Month of the Phases is Longer than the Sidereal Month. Between positions 1 and 2 the moon has made one revolution, completing the sidereal month. The synodic month does not end until the moon has reached the position 3.

6.6. The Moon Rises Later from Day to Day. We have noticed that the solar day is about four minutes longer than the sidereal day, because the sun moves eastward against the turning background of the stars. The moon moves in this direction among the stars also, and much faster than the sun. If we kept time by the moon, the "moon day," from upper transit to upper transit again, would average 50 minutes longer than the day by the sun. This interval of $24^h\ 50^m$, which can vary as much as 15 minutes either way, is of special importance to those who live beside the ocean; for it is twice the interval between high tides.

Not only in its crossing of the celestial meridian but in its rising and setting also is the moon delayed an average of 50 minutes from day to day. Here the variation from regularity is even more marked. We notice it particularly in the rising of the moon near its full.

The *harvest moon* is the full moon that occurs nearest the *time* of the autumnal equinox, September 23. This moon near its full rises from night to night with the least delay of all. In the latitude of New York the moonrise can be as little as 13 minutes later than on the night before. So the harvest moon lingers longer than usual in the evening skies of the northern hemisphere. Otherwise it is not different from other full moons.

6.7. The Moon Moves North and South during the month, just as the sun does in the course of the year, and for the same reason. The moon's path around the heavens is nearly the same as the sun's path.

Consider the full moon. Since it is opposite the sun, the full moon is farthest north at the time of year when the sun is farthest south. The December full moon rises in the northeast, climbs high in the sky, and sets in the northwest. It shines for a longer time each night as though to compensate the dullness and shorter duration of the sunshine at that season. In summer it is the other way around. The full moon of June rises in the southeast, rides low in the south, and soon sets in the southwest.

In some years the moon ranges farther north and south than usual. The greatest range in its movement in declination occurs at intervals of 18.6 years. This was the case in 1932, when the moon was going fully 5° farther than the sun both north and south from the celestial equator. And many people remarked on it at the time.

This variation in the range of the moon's north and south motion is a consequence of the regression of the nodes (6.2), as anyone can see if he thinks about it carefully. But what of the actual course of the moon around the earth?

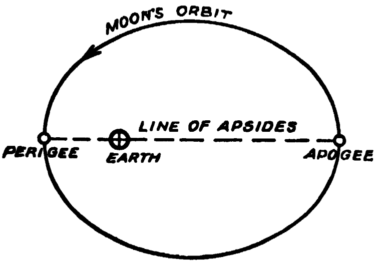


FIG. 6.8. Moon's Orbit Relative to the Earth. The orbit is an ellipse of small eccentricity (much exaggerated in the Figure) with the earth at one focus.

6.8. Orbit of the Moon. Everyone will agree that the moon's course around the earth cannot depart very much from a circle having the earth at its center. With allowance for its phases, the moon's disk does not vary conspicuously in apparent diameter during the month, as we view it with the unaided eye. This means, of course, that the moon's distance does not change greatly.

Measurements with the telescope show, however, that the disk of the moon is more than a tenth greater at one time in the month than at the opposite time. So the distance varies.

The moon's orbit is an ellipse having the earth at one focus. At *perigee,* where the moon is nearest the earth, its distance from the earth's center is 221,463 miles. At *apogee,* where it is the most remote, the distance has increased to 252,710 miles.

The moon's orbit around us is constantly changing, owing chiefly to the unequal effects of the sun's attraction for the moon and earth. For example, the long axis of the orbit swings completely around toward the east once in a little less than nine years. This is one of the many variations which astronomers have studied since the times of Hipparchus and Ptolemy. Thanks to the care that has been bestowed on this intricate problem, it is possible today to predict the moon's course among the stars, and the circumstances of eclipses and occultations with remarkable accuracy. The work of E. W. Brown of Yale University is a recent and valuable addition to our knowledge of the moon's motions.

6.9. Measuring the Moon's Distance. It is easy enough to see that the changing apparent diameter of the moon's disk during the month informs us of the changing distance of the moon. The smaller the moon appears, the farther away it must be. It is possible to learn the *form* of the moon's orbit by observing its direction and apparent size as it goes around us. But how can we determine the *size* of the orbit, in miles?

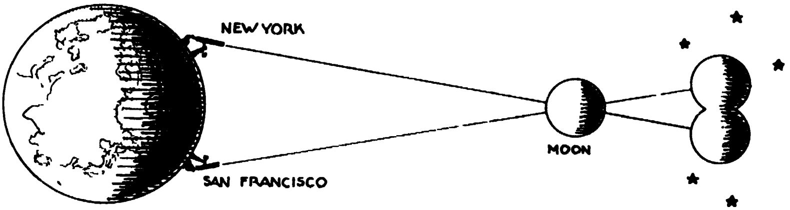


FIG. 6.9. The Moon's Directions Differ by Nearly Its Breadth as Viewed from New York and San Francisco.

Parallax is the difference between the directions of an object when it is viewed from two different places. Notice how a near-by object jumps back and forth against the distant background when it is viewed with the two eyes alternately. The nearer the object, the greater is the change in its direction. And the amount of the parallax becomes greater, of course, as the two places from which the object is observed are farther apart.

When the parallax has been measured, and the distance between the two points of observation is known, then the distance of the object can be calculated. This is the way that astronomers determine the distances of celestial bodies.

If two persons, one in New York and the other in San Francisco, observe the moon's position among the stars at the same instant, the two positions differ by nearly the full breadth of the moon, or nearly half a degree. When we speak of the moon's parallax ordinarily, it is as though one observer were at the earth's center and the other at the equator with the moon on his horizon. It is this equatorial horizontal parallax that is given for the sake of uniformity.

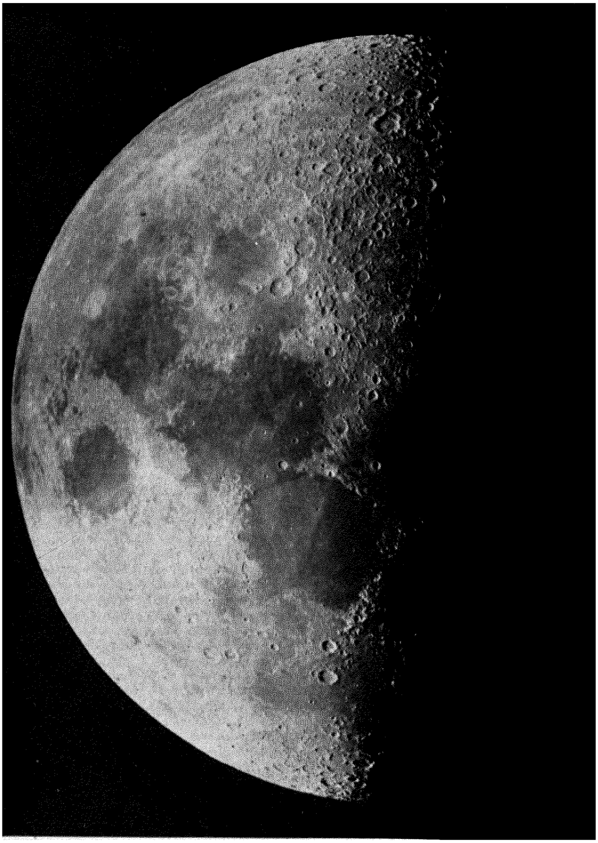


FIG. 6.10. The Moon at First Quarter. The moon is inverted and reversed as it appears ordinarily through the telescope. The mountains are plainest near the sunrise line, at the right, where the shadows are longest. (*Photographed at Yerkes Obervatory*)

The moon's parallax at its average distance is slightly less than one degree; its average distance from the earth's center is 238,860 miles. The distance varies considerably, as we have noticed, while the moon is going around us in its elliptical orbit.

FIG. 6.10A. Gibbous Moon, About Two Days After First Quarter. Notice that the group of seas which forms the "girl reading" is nearer the moon's western edge than in Fig. 6.10. The crater Copernicus is a little more than halfway down along the bulging sunrise line. (*Photographed at Yerkes Observatory*)

6.10. The Moon Turns the Same Hemisphere Toward Us. So far as it is revealed in the changing phases, the face of the "man in the moon" is always toward us. No one has seen the back of his head. This means that the moon rotates on its axis once while it is revolving once around the earth, that is to say, once in a sidereal month.

This statement is true in the long run. But anyone who watches the moon carefully during the month can see that the same hemisphere is not turned precisely toward us at all times. Spots near the moon's edge are sometimes in view and at other times turned out of sight, as Figs. 6.10 and 6.10A clearly show. The moon seems to rock as it goes around us. These apparent oscillations, or *librations,* arise chiefly from two causes:

(1) The moon's equator is tilted about 6½° to the plane of its orbit. Thus its north pole is brought toward us at one time, while its south pole is toward us two weeks later, just as the earth's poles are alternately presented to the sun during the year.

(2) The moon's revolution is not uniform. Since its orbit is an ellipse, the law of areas (3.5) holds here also. The nearer the moon, the faster it goes around us. Meanwhile the rotation proceeds uniformly. So the two motions do not keep perfectly in step, though they come out together at the end of the month. The moon rocks in the east and west direction, allowing us to see farther around in longitude at each edge than we otherwise could.

For these and other reasons fully 59 per cent of the moon's surface has faced the earth when the month is completed. The remaining 41 per cent is never seen; and if anyone lived in that region of the moon, he could never see the earth.

THE MOON'S SURFACE

6.11. The Lunar Seas. Two features of the moon are plainly visible to the unaided eye. Its changing phases are among the most conspicuous sights in the heavens, and were among the very first to be correctly explained. Second, the large dark spots that we see on the disk of the moon were as well known in olden times as they are today.

These blotches form the eyes, nose, and mouth of the familiar "man in the moon," the profile of the "girl in the moon," the "hare," the "frog," and other imagined figures. Formerly they were supposed to be large bodies of water, and they were given the watery Latin names that have now survived their original meanings. One is Mare Serenetatis (Sea of Serenity); another is Mare Imbrium (Sea of Storms).

The lunar seas cover about half of the moon's visible surface, and are specially prominent in its northern hemisphere. Roughly circular, they are all connected, with the exceptions of two small seas, Mare

Crisium and Mare Humorum, near the edges of the disk. Though we call them "seas," the dark spots are perfectly arid, relatively level plains.

There is still another feature of the moon's surface to be seen occasionally with the naked eye, and a very significant one. The sunrise and sunset lines are not perfectly smooth. Bright projections into the dark hemisphere show where the sun illuminates lofty peaks before it has risen in the valleys around them. The moon is mountainous. This fact was established beyond doubt when the telescope came into use.

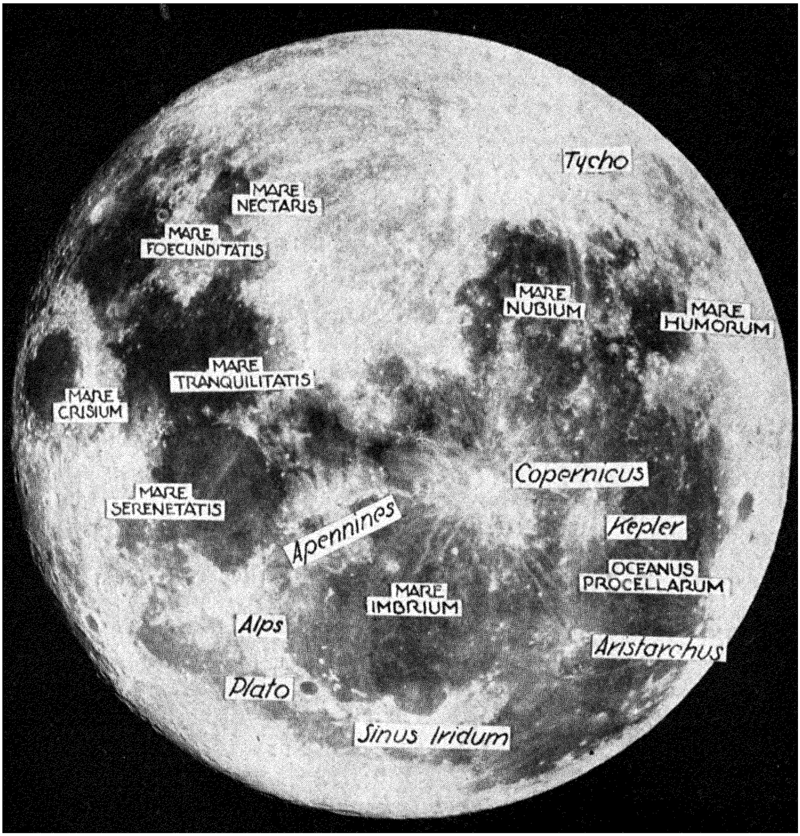


FIG. 6.11. The Moon Shortly After the Full Phase. As seen through the inverting telescope. The sunset line is appearing at the left. The longest ray system radiates from the crater Tycho near the moon's south pole. Shorter ray systems surround Copernicus and some other craters. (*Photographed at Yerkes Observatory*)

6.12. The Moon Through the Telescope. It was in 1609 that the great Italian scientist, Galileo, heard of the discovery by a Dutch spectacle maker which was destined to revolutionize astronomy. The spectacle maker had discovered that two lenses held at appropriate distances before his eye gave a clearer view of the landscape. Galileo fitted two small lenses into a tube and went out to view the heavens. He directed this little telescope toward the moon first of all.

Galileo observed the mountains on the moon, and estimated that they are comparable in height with our own mountains. This he could do by noticing how far from the sunrise line into the darkness the peaks first catch the rays of the sun. Like little stars they appear at first, growing larger until they join the bright regions as the sun rises on the valleys below.

The heights of the lunar mountains can be determined also from the lengths of the shadows they cast. They are heights above the surrounding plains which are not all at the same level. There are peaks in the Leibnitz and Doerfel ranges near the moon's south pole that rise as high as 26,000 feet above the plains.

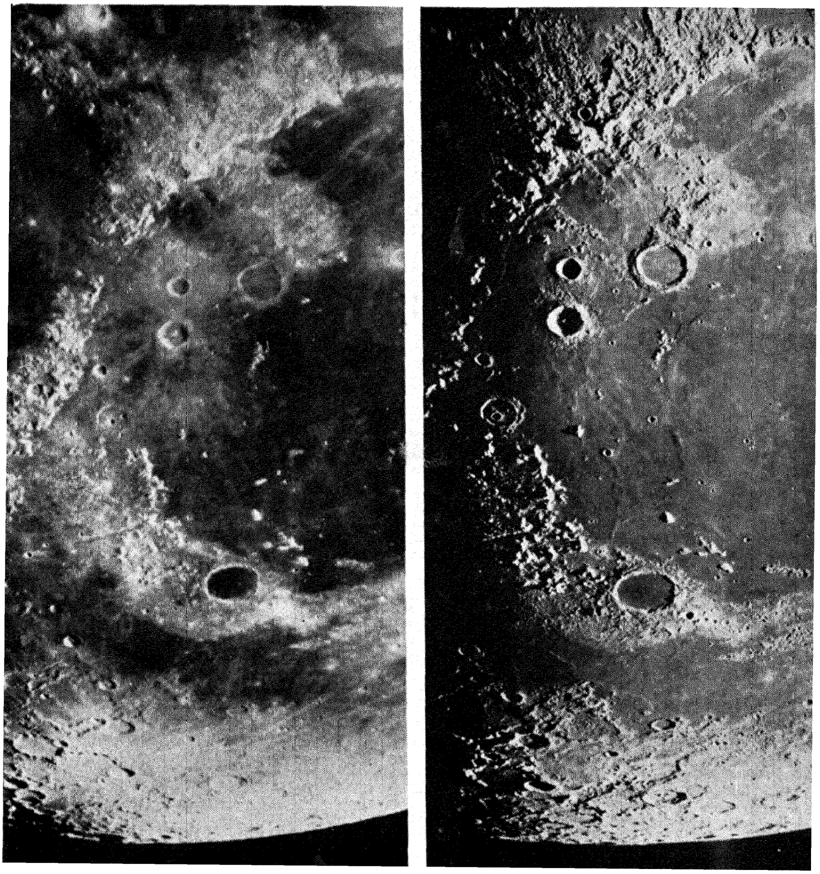
The lunar mountains are most distinct when they are near the sunrise or sunset line. There the shadows are long, as they are with us in the early morning or late afternoon. The sunlit peaks stand out in bold relief among the shadows. And the view along the terminator is especially good within about two days of the quarter phases.

Notice in the photographs (Fig. 6.13) how the moon's surface seems to flatten with increasing distance from the terminator. Near full moon the lunar mountains are not very plainly visible, but the seas and bright "rays" are then conspicuous.

6.13. Mountains on the Moon. There are only a few irregularities of the moon's surface that remind us at all of our own mountain ranges. Best known of these are the three ranges which form the curving western border of Mare Imbrium, the right eye of the "man in the moon," and separate it from Mare Serenetatis.

These are the Apennines, Caucasus, and Alps; their names are among the few that have survived from Hevelius' map of the moon (1647), in which the lunar formations have the names of terrestrial ones. With a few exceptions the mountains on the moon bear the names of distinguished scientists and philosophers of former times, according to the system introduced by Riccioli, in 1651.

The mountain ranges around Mare Imbrium slope abruptly toward it and more gradually outward. It is as though they were all that remained of a nearly circular rampart 700 miles across, which formerly surrounded the great sea. Perhaps the rest of the wall of this enormous ancient crater was razed by a flood of hot lava which hardened to form the nearly level sea.



Moon's Age, 18 Days. Moon's Age, 21 Days.

FIG. 6.13. Region of Mare Imbrium Under Different Illuminations. The lunar Apennines appear at the top, the Alps and the crater Plato below the center. (*Photographed at Mount Wilson Observatory*)

The mountains on the moon are generally arranged in the circular formations that we call the lunar craters.

6.14. The Lunar Craters have nearly circular walls, steep and often shelving on the inside and sloping more gradually to the plain outside. Lofty peaks surmount the walls; some of them rise as high as 20,000 feet above the plain. Lower peaks appear near the centers of many craters.

Some craters have floors depressed several thousand feet below the plain. In others the floors are elevated; the inside of the crater Wargentin is nearly as high as the top of the wall itself. Some craters have rough, bright floors; Aristarchus is the brightest of all. Others, such as Plato in the lunar Alpine region, are as dark inside as the seas.

The lunar craters exceed 30,000 in number. In size they range from pits a few hundred feet across, which are visible through only the largest telescopes, to "walled plains," such as Clavius near the moon's south pole, fully 150 miles in diameter.

Are the lunar craters volcanoes to be compared with our own Vesuvius, extinct reminders of a remarkable spectacle that the moon must have presented when they were in eruption? Or were they blasted out by the fall of meteors, as Meteor Crater in Arizona (9.18) is supposed to have been? The vast size of many lunar craters has been cited as evidence against both theories.

The cause of the *rays* awaits explanation also. These are bright streaks, often as much as five or ten miles wide, which radiate from points near a few of the craters, and pay little heed to irregularities as they spread out over the moonscape. Pease described the rays as the sunlit sides of low mounds whose shadows are visible also. The finest and longest ray system radiates from the crater Tycho, near the moon's south pole.

There are many *rills* as well; they are irregular clefts as much as half a mile wide and of unknown depths.

The variety of the lunar landscape, its pronounced contrast with the earth's surface, and the ease with which it can be clearly brought into view combine to make the moon a most remarkable spectacle through telescopes of even very moderate size.

6.15. The Moon Has No Atmosphere. It is easy enough to see without the telescope that the moon has no air around it, or at least no atmosphere comparable with our own.

There is no twilight on the moon; the sunrise and sunset lines form a perfectly sharp division between day and night. The moon's disk is undimmed near the edges where a greater thickness of air would intervene, if there were any air. The edge of the moon's disk is sharply defined against the sun at the time of a solar eclipse. The absence of clouds suggests the absence of both air and water.

Two neighboring worlds share the sunshine together. One, our earth, has air around it, so that it is the abode of life and activity. The other, our moon, is airless and therefore lifeless, a dead world where practically nothing happens. Why has the moon no atmosphere while the earth has an abundance of air? The answer is found in the feebler pull of gravity at the moon's surface.

The moon's mass is one eighty-second of the earth's mass. Its attraction is the same fraction of the earth's attraction for objects at equal distances from their centers. The moon is smaller than the earth, of course; its surface is nearer its center, but not enough nearer to make up for the smaller mass. Gravity at the moon's surface is only about one sixth as strong as the pull of gravity on the surface of the earth. It is not strong enough to hold an atmosphere around the moon.

6.16. Escape of Atmospheres. The molecules of a gas dart about incessantly. Their speeds increase as the temperature is raised, and are greater in lighter gases than in heavier ones. The molecules of hydrogen, the lightest of all gases, are moving as fast as a mile a second at the freezing temperature of water. The molecules of the air around us at ordinary room temperatures have speeds somewhat greater than half a mile a second.

These are averages. At the same temperature and for one kind of gas the speeds vary greatly. Collisions between the molecules bring some of them momentarily almost to rest, and propel others much faster than the average. Whether the molecules at their highest speeds can fly away into space depends on the strength of the pull of gravity.

The *velocity of escape* is the speed that a molecule, or anything else, must attain in order to escape from a celestial body. If a ball is thrown upward, it is soon brought down by the earth's attraction. Given a greater initial speed, the ball goes higher and returns to the ground after a longer time. With what speed must the ball be started so that it will never return? That critical speed is the velocity of escape.

Its value at the earth's surface is nearly 7 miles a second, without allowing for air resistance. The molecules in the air around us do not ordinarily have speeds as great as this; so the earth has retained its atmosphere, except some of the very lightest gases. But the velocity of escape at the moon's surface is only a mile and a half a second. An atmosphere could not remain there for any great length of time.

6.17. If We Could Visit the Moon, we should find conditions surprisingly different from those at home. The reduction of gravity to one sixth of its strength at the earth's surface and the consequent absence of atmosphere produce many unfamiliar effects on the moon.

Everything is lighter there, of course. No sound breaks the stillness, except as it is transmitted through the rocks. The deadly ultraviolet rays of the sun, which our atmosphere fends off, reach the moon's surface with their full intensity, while meteors come crashing down with undiminished sizes and speeds.

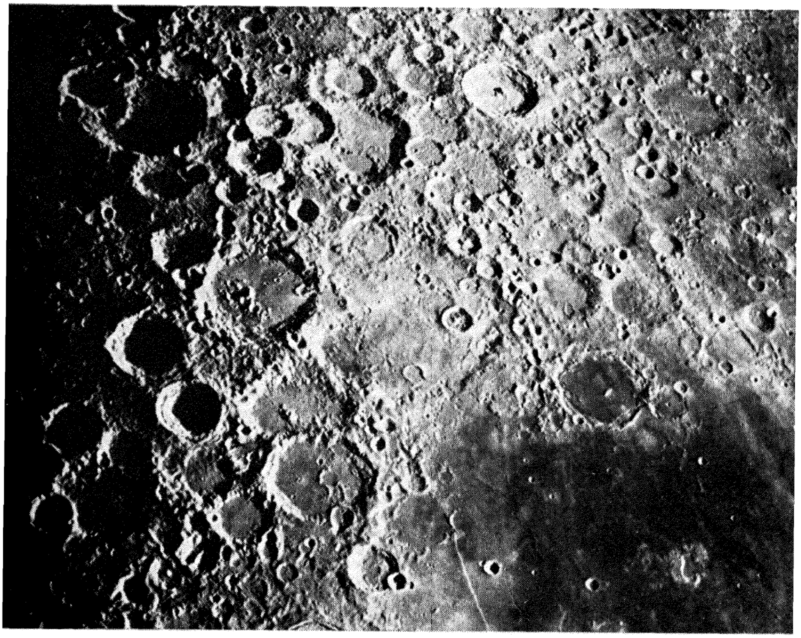


FIG. 6.17. Lunar Landscape at the Third Quarter. The crater Tycho with peaks at its center is near the top. The sea in the lower right corner is Mare Nubium. (*Photographed at Mount Wilson Observatory*)

The weather on the moon changes only from "fair and warmer" to "fair and colder," or the other way around, with the alternation of day and night. No fine coloring attends the sunset, and no twilight follows it. Night comes at once with the disappearance of the sun, while the temperature of the rocks drops fully 400° F. at sunset, as the measures of Pettit and Nicholson at Mount Wilson show.

A black sky, instead of a blue one, is filled with stars by day and night alike. The stars circle around toward the west once in 27⅓ days. The sun rises and sets once in 29½ days. Our earth is a bright disk among the stars, going through all the phases of the moon in our sky; it does not rise and set in the lunar sky, except perhaps as the result of the moon's librations.

The features of the moon's surface differ markedly from those of the earth, as we have seen. The moon is perfectly arid. There is no action of wind and water to wear down the mountain peaks, temper their slopes, and smooth out valleys between them. Great chasms yawn here and there over the landscape. The moon is an awful desert. We would not wish to prolong our visit.

ECLIPSES OF THE MOON

An eclipse of the sun occurs when the moon at the *new* phase passes directly across the sun's disk, obscuring it partly or completely. An eclipse of the moon takes place when the moon at the *full* phase plunges through the earth's shadow. New moon and full moon recur each month. But eclipses can happen at these phases only at two opposite seasons of the year.

6.18. Eclipse Seasons. In order to eclipse or be eclipsed, the moon must be almost directly in line with the earth and sun. This condition cannot be fulfilled every time the moon is new or full, because the moon's path around the heavens is inclined 5° to the ecliptic, in which the sun moves. So the new moon is more likely to pass north or south of the sun, while the full moon is only occasionally within the earth's shadow.

Eclipses can occur at the two opposite seasons when the sun is passing a node of the moon's path. The sun must be within 18½° of a node, at the most, in order to be eclipsed when the moon overtakes it; it must be within 12¼°, at the most, if the full moon is to pass into the earth's shadow.

Each eclipse season lasts a little over a month. In 1940, the middle times of the two seasons come in April and October. They come about 19 days earlier from year to year owing to the regression of the moon's nodes (6.2). The length of the *eclipse year* is 346.6 days; this is the interval between two successive returns of the sun to the same node of the moon's path.

Eclipses of the sun can best be considered in connection with the study of the sun itself, in Chapter X. Features of the sun are displayed on these occasions which are seen imperfectly or not at all at other times. We are concerned now with eclipses of the moon.

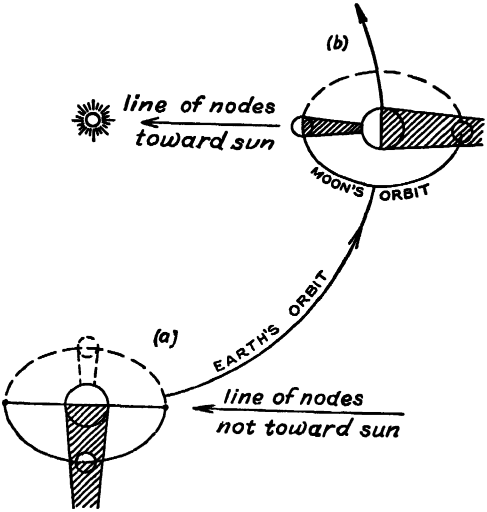


FIG. 6.18. Eclipse Seasons. Since the moon's orbit is inclined about 5° to the plane of the earth's orbit, eclipses can occur only at the two opposite seasons, as at (*b*), when the sun is near the line of nodes of the moon's orbit. At other times in the year, as at (*a*), the moon does not pass between the earth and the sun, nor into the earth's shadow.

6.19. The Earth's Shadow. Like every other opaque object in the sunshine the earth casts a shadow in the direction away from the sun. We are in this shadow during the night time, of course.

The *umbra* of the shadow is the part from which the sunlight would be entirely excluded, if it did not filter in through the earth's atmosphere. It is a long, thin cone stretching an average of 859,000 miles into space before it tapers to a point. This darkest part of the shadow is often meant when we speak of the *shadow*. It is surrounded by the larger conical region of the *penumbra* from which the sunlight is only partially excluded.

Suppose that a very large screen were held at right angles to the direction in which the shadow points, and that it were moved gradually out into space in that direction away from the earth. The earth's shadow would fall on this screen as a dark circle growing smaller with the in-

6.21. The Moon is Visible in Total Eclipse. The darkening of the moon in its passage through the penumbra of the earth's shadow is so gradual that it can easily be unnoticed. The first conspicuous effect is seen soon after the moon enters the umbra of the shadow. A dark notch appears at the eastern edge of the moon and slowly overspreads the disk.

The edge of the encroaching shadow is part of the circumference of a circle; it is a shadow such as only a globe could always cast. This was recognized by ancient astronomers as a convincing proof that the earth is a ball.

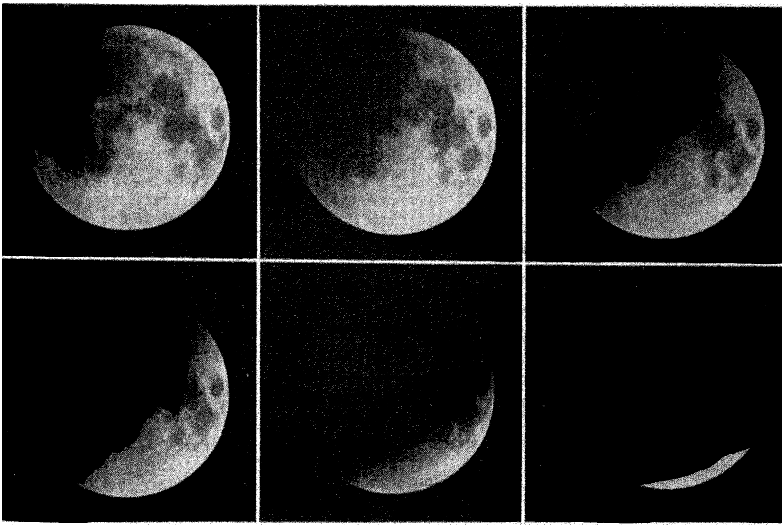


FIG. 6.21. Partial Eclipse of the Moon, March 22, 1932. Progress of the eclipse as the moon entered the earth's shadow until it became nearly total. (*Photographed by Albert W. Recht, Chamberlin Observatory, Denver*)

The shadow seems quite dark during the partial eclipse in comparison with the unshaded part of the moon. As totality comes on, however, the features of the moon's surface often become plainly visible. They are illuminated by sunlight which has filtered through the earth's atmosphere around the base of the shadow, and has been refracted and reflected into the shadow and onto the moon.

Occasionally the totally eclipsed moon has been practically invisible. This can occur when the region of our atmosphere around the base of the shadow is heavily clouded or very dusty. But as a general thing, enough light sifts through to show the eclipsed moon clearly. Red predominates in this light for the same reason that the sunset is red.

6.22. Occultations of Stars by the Moon. In its monthly course around the heavens the moon often passes over, or *occults,* bright stars and planets. The times and other circumstances of the occultations are predicted in the various almanacs.

These occurrences are interesting to watch, especially if a small telescope is available. The accurate observations of the times of disappearances and reappearances of the stars provide valuable checks on the precision with which the moon's movements can be calculated from present tables.

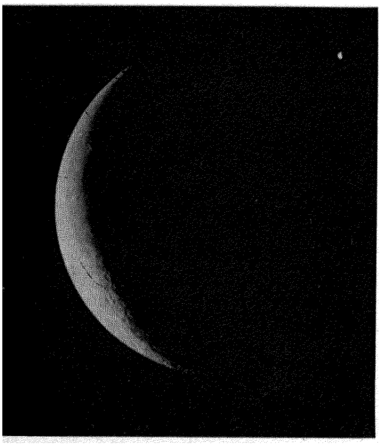


FIG. 6.22. Venus Emerging from Behind the Moon's Dark Limb. (*Photographed, January 13, 1923, by G. Van Biesbroeck, Yerkes Observatory*)

The stars vanish instantly behind the eastern edge of the oncoming moon, and pop into view with equal suddenness at the western edge an hour later, or after a shorter interval if the occultation is not central.

The fact that the stars are not dimmed or reddened at all up to the instant of disappearance is one of the many indications that the moon has no atmosphere. And the agreement of the observed intervals between disappearances and reappearances with the predicted intervals provides another indication of the same thing. Air around the moon would refract the starlight, delaying the disappearances and causing the stars to reappear sooner than they do, just as the refraction of sunlight in our atmosphere shortens the interval between sunset and sunrise.

QUESTIONS ON CHAPTER VI

1. What is remarkable about the moon as compared with the other satellites in the solar system? Is it the largest of the satellites (Table 7.II)?

2. Why are the horns of the crescent moon in the west most nearly vertical in the spring?

3. Is the moon at the full phase in the same constellation from month to month? Explain.

4. At what season is the full moon farthest north at its rising? When does it rise almost directly in the east?

5. Does the moon ever appear directly overhead from where you are? If not, how near your zenith can it pass?

6. The moon's parallax is about 1°; the sun's parallax is 8″.8. Compare the distances of the moon and sun.

7. If the moon did not rotate at all on its axis, how much of its surface could be seen in the course of a month?

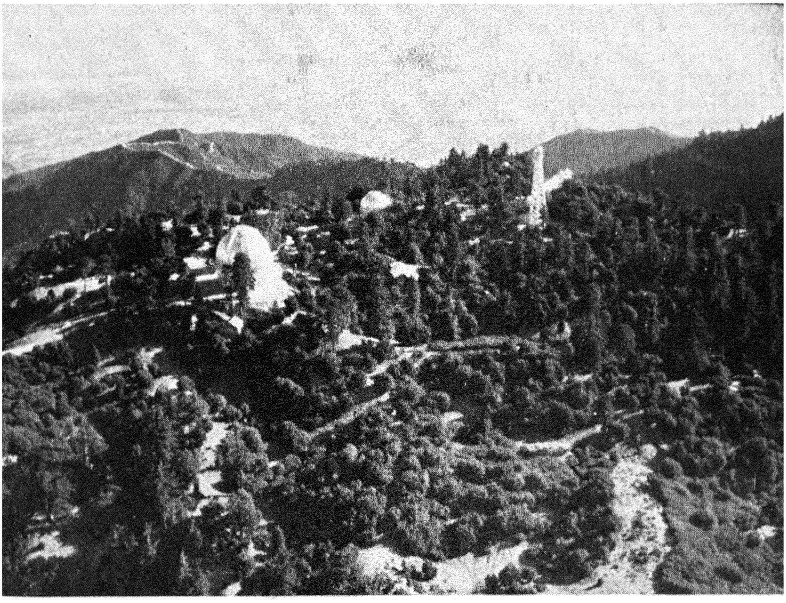
8. What can be learned about the moon and its ways without a telescope?

9. How often does the sun rise at any place on the moon? How often does a star rise? Does the earth rise and set as seen from the moon?

10. If you could visit the moon, what conditions would you find there different from those at home?

11. What causes an eclipse of the moon? Why cannot one occur every month?

12. When will the next eclipse of the moon be visible in the United States and Canada? Can the whole eclipse be seen from where you are?



Mount Wilson Observatory from the Northwest.

CHAPTER VII

THE PATHS OF THE PLANETS

STATIONARY EARTH OR MOVING EARTH? — THE LAW OF GRAVITATION — THE SYSTEM OF THE PLANETS

Seven bright celestial bodies move about among the seemingly "fixed stars" that form the constellations. They are the sun, the moon, and the five planets Mercury, Venus, Mars, Jupiter, and Saturn, which have the appearance of bright stars to the unaided eye. These were the *planeta,* or "wanderers," of the ancients.

These seven bodies are among our nearest neighbors in space. In the foreground of the starry scene, they are conspicuous objects in our skies. Their brightness and their complex movements against the background of the far-away stars have made them objects of special interest all through the ages.

STATIONARY EARTH OR MOVING EARTH?

7.1. The Planets Move in Loops. Anyone who has viewed the impressive spectacle of the moving heavens that is displayed in the planetarium (4.10) knows how the planets swing back and forth in their courses among the stars. Everything is speeded up enormously in the sky of the planetarium; celestial movements of a whole year can be run off in a few seconds. The looped paths of the planets are shown very clearly.

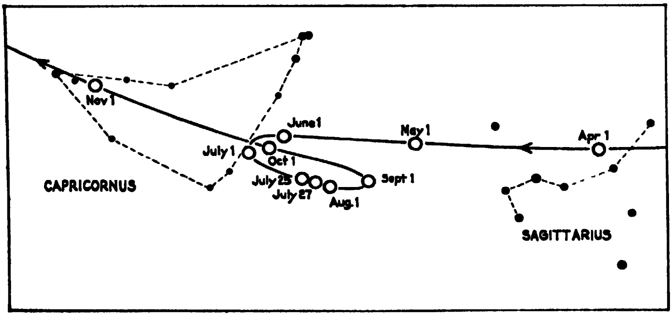


FIG. 7.1. Path of Mars Among the Stars in 1939.

For the most part, the planets move eastward through the constellations. We call this their *direct* motion; for it is in this direction that they revolve around the sun. At intervals, which are not the same for the different planets, they turn and move backward, toward the west; they *retrograde* for a while before resuming the eastward motion. They are said to be *stationary* at the turns. Thus the planets seem to march and countermarch among the stars, progressing toward the east around the heavens in series of loops.

It is easy to observe in the sky itself that this is so. Watch the red planet Mars from week to week, for example, beginning as soon as it comes into view in the east at a convenient hour of the evening. Notice the planet's position among the stars on each occasion, and make a dot in that place on the star map. The line of dots will show presently, as it does in Fig. 7.1, that Mars steers a devious course.

7.2. The Old Problem of the Planetary Motions. The looped motions of the planets were as easily recognized by ancient watchers of the sky as they are today. They are not haphazard; they proceed in an orderly way, as the scholars of Greece came to understand long ago. These learned men were eager to discover rules which govern the planetary motions, or at least which would permit these movements to be predicted precisely.

The early Greek philosophers had made important advances from the more primitive ideas of the world. As long ago as the fifth century B.C. they regarded our earth as a globe. Most of them believed, however, that the globe of the earth stood motionless in the center of the universe, while the sphere of the fixed stars turned westward around it daily, causing the stars to rise and set.

Within the sphere of the stars the seven wanderers shared its daily turning; but they moved also toward the east around the earth, and their distances from us were considered to be in order of the swiftness of the eastward movement. So the moon, revolving once a month, was nearest the earth. Then came Mercury, Venus, the sun, Mars, Jupiter, and finally Saturn. And only a little way beyond Saturn was the sphere of the heavens itself, the boundary of the universe. What lay beyond this star-strewn sphere no one could see or know.

Just how do the planets move around the earth so as to proceed in loops among the constellations? By what combinations of circular motions can their observed movements be represented? This was the problem the Greek philosophers wished to solve. Instinctively they felt that the celestial motions must be uniform and in circles. Then too, the circle is an easy figure for calculations.

Two answers to the problem received the greatest notice. The first one was worked out by Eudoxus, in the fourth century B.C. He imagined that each planet was attached to one of a series of concentric spheres which rotated around the earth in such a way as to produce the looped motion we observe.

It will be enough simply to mention this plan. Though it was adopted and improved by the great Aristotle, the plan was far from successful. It kept the planets always at the same distances from the earth, and could not, therefore, explain their changes in brightness.

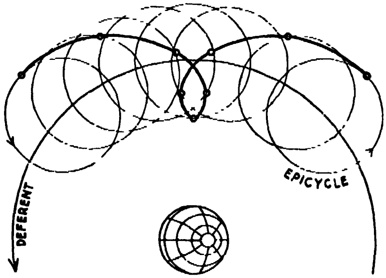


FIG. 7.3. Path of a Planet Around the Earth According to the Ptolemaic System. The planet revolved in a smaller circle whose center revolved meanwhile around the earth.

7.3. The Plan of Epicycles. The second and more useful plan for solving the ancient problem of the planetary motions is attributed to Apollonius of Perga, who lived in the third century B.C. It was accepted by Hipparchus, the most famous of the early Greek astronomers whose work was done at Rhodes, a century later.

Ptolemy, at Alexandria in the second century A.D., elaborated the plan and explained it in his book, the *Almagest,* which remained the authority in astronomy for more than a thousand years. This plan of representing the motions of the planets is known, therefore, as the *Ptolemaic theory.* It is a plan of epicycles.

Imagine a circle drawn around the earth at the average distance of one of the planets, Jupiter, let us say (Fig. 7.3). Imagine a wheel lying flat with its center on the circle, and that the planet is attached to the rim of the wheel. Suppose that the wheel turns steadily on its axle once around in a year, and that its center moves around the earth uniformly along the large circle once in twelve years. Now trace the motion of the planet itself.

In this arrangement the planet moves around the earth once in twelve years. It completes eleven loops meanwhile, as viewed from the earth, at intervals of about a year and a month. This is, in fact, the way Jupiter proceeds in its course among the constellations.

Similar combinations of uniform motions in small and large circles can be devised to represent the apparent movements of the other planets fairly well, and of the sun and moon also. These two bodies describe less conspicuous loops, to be sure, though their movements in the heavens are far from uniform.

Such was the plan of epicycles. The *epicycle* itself was the small circle on which the planet was supposed to move steadily. Its center was the *fictitious planet*, and the large circle on which it moved around the earth was the *deferent*. It must be remembered that these circles were not regarded as tangible things by the originators of the plan. It was mathematical and not physical machinery that Ptolemy described.

7.4. The Ptolemaic Theory, in short, attempted to explain the complicated movements of the sun, moon, and planets among the stars on the supposition that they went around the earth which was itself stationary, and that they moved always in circles with uniform speeds. According to the theory, these celestial bodies proceeded in epicycles whose centers were circling meanwhile around the earth. And all the motions were in the same direction, from west to east.

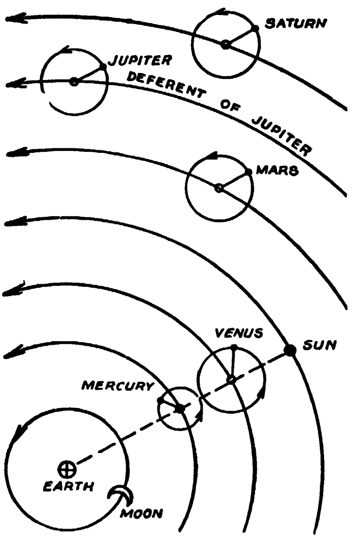


Fig. 7.4. Ptolemaic Theory of Planetary Motions.

Precise specifications were needed, of course, in order to predict the movements of each planet correctly. The sizes of its circles, the periods of the revolutions, and the positions of the fictitious planet and the planet itself on the circles at a particular time had to be given.

There were special requirements too, as Fig. 7.4 shows. The fictitious planets for Mercury and Venus must lie on the line joining the earth and sun, and the directions of the other planets from the centers of their epicycles must remain always parallel to this line.

The Figure shows only the main features of the system. As time went on, the plan grew more and more complicated. During many centuries that intervened between the decline of the early Greek culture and the revival of learning in Europe, Arabian astronomers carried on. They tried to perfect the Ptolemaic system so that it could represent precisely the motions of the planets which they observed. They tried to get a better fit by adding more epicycles.

Each planet was eventually provided with from forty to sixty epicycles turning one upon another. The system became a perfect nightmare of mathematical clockwork. Yet it did not predict satisfactorily the places of the planets in the sky very far ahead. It was then that King Alphonso X of Castile remarked that had he been present at the Creation he might have given excellent advice. The theory of epicycles had begun to seem unreasonable. The Ptolemaic theory of the central earth had failed.

Science cannot always choose at once the most fortunate basis for its inquiries. Sometimes it starts with assumptions that prove later to be incorrect. And in the effort to bring everything that is observed into agreement with them it may weave a tangled web. It was so with the theory of the central earth, which was destined for the broom of Copernicus.

7.5. The Earth in Motion. Great discoveries rarely, if ever, come suddenly "out of the blue sky." Almost always their beginnings can be traced in events that have gone before. Often we find that a new idea which amazes us was presented long ago to people who practically ignored it. Such was the case with the idea that the earth is moving.

From the times of the old Greek philosophers there was an undercurrent of opinion that the earth is not stationary. Pythagoras and his followers, who taught that the earth is a globe, believed that it was in motion, though their ideas about the motion were somewhat fantastic. Aristarchus of Samos, in the third century B.C., seems to have been convinced that the earth rotates on its axis daily and revolves yearly around the sun.

There were others too who caught glimpses of the truth. But little attention was paid to such bizarre ideas. Had not the great authorities, Aristotle, Hipparchus, and Ptolemy declared that the earth was stationary? Indeed, could not anyone see for himself that the earth did not move?

But by the time that Columbus sailed west on his famous voyage there was growing dissatisfaction with the theory of the central, stationary earth. The stage was being set for a new deal. Before the companions of Magellan had returned from the first trip around the world, a great European scholar had reached the conclusion anew that the earth is in motion, and was marshaling arguments to convince others that it is so.

His name, as we say it, was Nicholas Copernicus. Born in 1473 in the village of Thorn in Polish Prussia, he did not publish his theory of the moving earth until 1543, the year of his death.

7.6. The Copernican Theory. Copernicus' book, which was to proclaim his name through the ages to come, bore the modest title: *On the Revolutions of the Celestial Bodies.* It appeared before the days of eye-catching titles. People had to read the book to learn what it was about. Turning its pages we come to this:

"The order of the spheres is as follows: The first and lightest of all the spheres is that of the fixed stars, which . . . is motionless. . . .

"Then follows the outermost planet, Saturn, which completes its revolution around the sun in thirty years; next comes Jupiter with a twelve years' revolution; then Mars which completes its course in two years. The fourth one in order is the yearly revolution which includes the earth with the moon's orbit as an epicycle. The fifth place is Venus with a revolution of nine months. The sixth place is taken by Mercury, which completes its course in eighty days.

"In the middle of all stands the sun, and who could wish to place the lamp of this most beautiful temple in another or better place. Thus, in fact, the sun, seated upon the royal throne, controls the family of the stars which circle around him."

So Copernicus set the sun in the center instead of the earth which now took its rightful place as one of the planets revolving around the sun. He did not discard the assumption that the celestial bodies move in circles with uniform speeds. The new system remained, therefore, a system of epicycles. But some of the larger epicycles had now disappeared, those that were caused by the earth's revolution around the sun.

In the Copernican theory the sphere of the fixed stars remained as before the impassible boundary of the universe. Yet it had changed in an important way. This sphere of the stars had now become stationary. No longer required to turn daily around us, it could more easily be imagined larger than before. Copernicus pointed out that the daily rotation of the celestial sphere from east to west is only the passing of the starry scenery as the earth rotates on its axis from west to east.

7.7. Tycho's Observations. Born in 1546, three years after the death of Copernicus, Tycho Brahe greatly improved the instruments and methods of observing the positions of the celestial bodies. He saw clearly that an advance in the theory of the motions of the planets required more reliable data on their apparent motions among the stars. The most fruitful years of his life were spent at his fine observatory on the then Danish Island of Hven some 20 miles north of Copenhagen. He died in Prague, in 1601.

It was before the invention of the telescope. Tycho's chief instruments were large quadrants and sextants having plain sights. With these he and his assistants sighted the planets night after night, and determined their right ascensions and declinations with an accuracy never before attained. He gave special attention to the planet Mars, a fortunate choice because its orbit is not so nearly circular as the orbits of some other bright planets.

Tycho proposed a compromise between the Copernican and Ptolemaic theories. In the *Tychonic theory* the sun revolved around the stationary earth, while all the other planetary bodies except the moon, revolved around the sun. This plan represented his observations quite as well as did the Copernican theory. Moreover, the immobility of the earth seemed to be indicated by his failure to detect any oscillations in the directions of the stars during the year such as would be caused by the earth's revolution around the sun. Like all his contemporaries, Tycho was unaware that the vast distances of the stars made these annual oscillations too minute to be observed with his instruments.

7.8. The Planets Move in Ellipses Around the Sun. John Kepler, a German, was Tycho's assistant in his last years in Prague. He inherited the records of the planets, which his master had kept for many years, and which showed more precisely than ever before how the planets seemed to move among the stars. Kepler studied the records patiently in the hope of learning from them how the planets, particularly the planet Mars, are really moving.

Finally, in 1609, he announced two important rules about their motions; and in 1618, he found still another rule. They are known to us as *Kepler's laws:*

(1) *The planets move around the sun in ellipses having the sun in a common focus.* Thus the planets do not go around the earth, and their orbits are not circles.

(2) *Each planet revolves in such a way that the imaginary line join-*

ing it to the sun sweeps over equal areas in equal intervals of time. So its motion is not uniform, after all. The nearer the planet comes to the sun, the faster it moves, as we have already noticed in the case of the earth (3.5).

(3) *The squares of the periods of revolution of any two planets are in the same proportion as the cubes of their mean distances from the sun.* This useful relation is called the *harmonic law.*

Here ended the attempts to represent the movements of the planets by uniform circular motion centered in the earth. There was still no evidence, however, that the earth itself revolves around the sun.

THE LAW OF GRAVITATION

While Kepler (1571–1630) was formulating his laws which describe how the planets go around the sun, his contemporary Galileo (1564–1642), down in Italy, was laying the foundations of mechanics. He questioned the traditional ideas about the motions of things, and set out to determine for himself how they really move.

It remained for Isaac Newton (1642–1727), in England, to formulate clearly the new laws of motion, and to show that they apply not merely to the things immediately around us but to the celestial bodies as well. Thus astronomy became "a golden chain joining heaven and earth." The principal feature of the new mechanics was the concept of an attractive force which operates under the same simple rule everywhere in the universe.

7.9. The Concept of Force.

Before the time of Galileo, rest was supposed to be the natural state in nature. So it was easier to imagine the earth as stationary. Anyone who maintained that the earth was moving might well be asked to explain by what process the earth was kept in motion.

Galileo's experiments led him to suppose that uniform motion in a straight line is the natural state. Given a start in any direction, an object will go on forever in that direction and with the same speed unless it is interfered with. Rest is simply a special case where the speed happens to be zero.

The uniform motion of a body in a straight line, therefore, demands no explanation. It is only when the motion is changing, either in direction or speed, that an accounting is required. We say then that a force is acting on the body, and inquire as to where the force originates.

The strength of the *force* is measured by its effect on the body whose changing motion we are observing. It equals the mass of that body multiplied by its *acceleration*, or the rate at which its velocity (directed speed) is changing. The acceleration may appear as increasing or decreasing speed, or changing direction, or both. A stone falling vertically faster and faster as it nears the ground is accelerated. An object moving in a circle with unchanging speed is accelerated. In both cases a force is acting.

7.10. The Laws of Motion were formulated by Newton in his *Principia* (1687) substantially as follows:

(1) *Every body persists in its state of rest or of uniform motion in a straight line unless it is compelled to change that state by a force impressed upon it.* If a force is applied:

(2) *The acceleration is directly proportional to the force and inversely to the mass of the body, and it takes place in the direction of the straight line in which the force acts.*

(3) *To every action there is always an equal and contrary reaction.*

The second law defines force in the usual way (7.9). *The first law* states that if no force is acting there is no acceleration; the motion of the body remains unchanged. *The third law* asserts that the force between two bodies is the same in the two directions. A bat exerts no greater force on the ball than the ball exerts on the bat; but the lighter ball experiences a far greater acceleration than the heavier bat and batter combined.

Armed with these laws of motion Newton succeeded in reducing Kepler's three laws of the planetary movements to a single universal law. It is said that the fall of an apple one day as Newton sat in his garden started the great mathematician to thinking of this problem. Does this attractive force that brings down the apple control the moon's revolution around the earth? Does a similar force directed toward the sun cause the planets to revolve around it?

7.11. The Law of Gravitation. A force is continually acting on the planets, because their courses around the sun are always curving. It is an attractive force directed toward the sun; this fact can be deduced from Kepler's law of equal areas, though we shall not stop to do so.

From further studies of Kepler's laws Newton discovered the law of the sun's attraction. He found that the force between the sun and a planet is proportional directly to the product of their masses, and inversely as the square of the distance between them.

Newton next determined the law of the earth's attraction, comparing the acceleration of a falling body near the earth's surface with that of the moon sixty times as far away from its center. The moon falls toward the earth just as an apple does; it does not come down, of course, because it is moving so swiftly in the horizontal direction that its fall toward the earth serves only to keep it revolving around us. The attractive force between the earth and the things around it proved to vary again inversely as the square of the distance from the earth's center.

While his studies of this sort could not extend beyond the planetary system, Newton decided that he had discovered a universal law, and so announced it in his *law of gravitation:*

Every particle of matter in the universe attracts every other particle with a force that varies directly as the product of their masses, and inversely as the square of the distance between them.

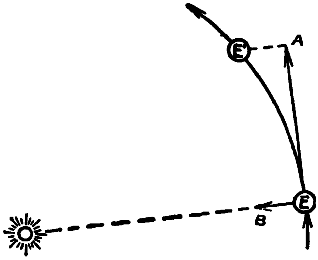


FIG. 7.12. Earth's Revolution Explained by the Laws of Motion. At the position *E* the earth, if undisturbed, would continue on to *A*, by the first law of motion. It arrives at *E'* instead, having fallen in the meantime toward the sun the distance *EB*.

7.12. How the Planets Revolve. Consider the earth as an example. By Newton's law there is an attractive force between the earth and the sun, whose strength is proportional directly to the product of the masses of the two and inversely to the square of the distance between their centers.

In response to this attractive force, which is the same in the two directions, the earth falls toward the sun, and the sun falls toward the earth as well, though much more slowly because the sun is by far the heavier of the two. Started from rest, the earth and the sun would presently come together.

But the earth is moving swiftly at right angles to the sun's direction. In one second it goes 18½ miles. Meanwhile it falls less than an eighth of an inch toward the sun. It is this slight deviation from the straight line course second after second throughout the year that causes the earth to revolve around the sun.

Properly speaking, the earth and sun mutually revolve around a point between their centers. The ancient problem of whether the earth or the sun revolves was not well stated, after all. Both revolve. If the earth and sun were equally massive, the point around which they wheel yearly would be halfway between their centers. This point is really only 280 miles from the sun's center; for the sun is a third of a million times as massive as the earth.

So as the planets revolve around the sun, nothing is required to keep them moving; the first law of motion explains their continued progress. It is the force directed toward the sun that causes the planets to revolve instead of going away into space.

7.13. Kepler's Laws Restated. When Newton had discovered the law of gravitation by means of Kepler's laws, he then showed that these laws are only approximately true.

The orbit of a planet relative to the sun would be an ellipse having the sun in one focus, if there were no other bodies to disturb its motion. As it is, the attractions of all the other planets cause many departures, or *perturbations,* from a simple elliptic orbit.

The course of a revolving body must be an ellipse, aside from the perturbations, according to the law of gravitation, as long as the orbit remains closed. If a planet moving at first in a circle could be speeded up more and more, its orbit would become a flatter and flatter ellipse until it opened at one end into a parabola or hyperbola (Fig. 7.13). The planet would then leave the sun never to return.

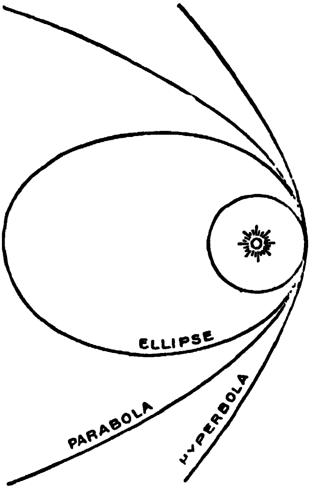


Fig. 7.13. Different Shapes of Orbits.

If the speed of the earth's revolution should increase from the present 18½ miles a second to 26 miles a second, we would depart from the sun forever.

Newton showed that Kepler's harmonic law should read as follows: The squares of the periods of revolution of any two planets, *each one multiplied by the sum of the masses of the sun and of that planet,* are in the same proportion as the cubes of their mean distances from the sun. But the masses of the planets are so small in comparison with the sun's mass that the original statement of the law is not far from the truth.

7.14. Weighing the Celestial Bodies. Since the law of gravitation views the physical universe as a scheme of masses and distances, it is of more than ordinary interest to know how the masses are measured. The masses of the celestial bodies, that is to say, the quantities of material they contain, or still more popularly, their weights, can be found by means of the more general statement of Kepler's harmonic law (7.13):

The squares of the periods of any two pairs of mutually revolving celestial bodies, each multiplied by the combined mass of the pair, are in the same proportion as the cubes of the mean distances that separate the pairs.

Suppose that we wish to determine the mass of the planet Saturn. Write this proportion, taking Saturn and one of its satellites as one pair and the earth and sun as the second pair. Let the unit of mass be the combined mass of the earth and sun, the unit of distance the mean distance between the earth and sun, and the unit of time the period of the earth's revolution around the sun. The relation becomes simply:

The mass of Saturn and its satellite equals the cube of the mean distance of the satellite from Saturn divided by the square of its period of revolution around Saturn.

So the combined mass of any independently revolving pair of bodies can be easily calculated, if their mean separation and period of revolution have been observed. It is possible in this way to weigh the planets which have satellites; the mass of the satellite is so small in comparison that the combined mass is very nearly the mass of the planet alone. It is sometimes possible to ascertain the combined masses of double stars as well (12.11).

It is far more difficult to weigh planets such as Mercury, Venus, and Pluto, which have no known satellites. Their masses can be determined by their disturbing effects on the motions of neighboring bodies. But the calculations are tedious, and the results are not so accurate.

7.15. Courses and Forces. Ancient astronomers tried to represent the planetary movements by combinations of circular motions centered in the earth. Copernicus set the sun in the center instead of the earth. Kepler discovered that the planets revolve around the sun in ellipses instead of circles and epicycles. So far, the interest was confined to the courses themselves.

Newton's law of gravitation turned the attention from the courses of the planets to mighty forces controlling them. This law has met with an amazing succession of triumphs. It has made possible the remarkably accurate predictions of the planetary movements. It has promoted discoveries of planets hitherto unknown, from their disturbing effects on the motions of planets already known. It applies equally well to mutually revolving stars. So far as we know, the law of gravitation is universal.

What is the nature of this attracting force? Is it a natural property of every particle of matter in the universe that it attracts other particles?

In his celebrated theory of relativity, Einstein leads us back from the forces to the courses again. He tells us that the sun exerts no attractive force on the earth. Instead, the properties of space are altered by the presence of the sun. It is perfectly natural for the earth to revolve around the sun, rather than to proceed uniformly in a straight line.

Yet for most purposes astronomers continue to make their calculations on the basis of the old law of gravitation. It is only rarely that the theory of relativity predicts events with noticeably greater accuracy. The advance of Mercury's perihelion around the sun is a well-known example. The apparent displacement of the stars away from the sun's place, such as has been observed at total eclipses of the sun, is an equally remarkable test of the occasionally greater merit of the modern theory in representing what goes on.

THE SYSTEM OF THE PLANETS

There were originally seven "wanderers" in the heavens, as we have seen; they were the sun, the moon, and the five bright planets. The current meaning of the word "planet," as a body revolving around the sun, began with the acceptance of the Copernican theory which added the earth to the list of planets, subtracted the sun, and reduced the moon to its proper station as the satellite, or attendant, of the earth.

The known membership of the planetary system has increased greatly since Copernicus' time. Knowledge of satellites attending other planets began with Galileo's discovery, in 1610, of the four bright satellites of Jupiter. The planet Uranus, barely visible to the naked eye, was discovered in 1781. Neptune, which is always too faint to be seen without the telescope, was found in 1846. The discovery of the still fainter and more remote Pluto, announced in 1930, completed the list of nine known *principal planets,* while in 1801, Ceres, the largest of the throng of *asteroids,* or *minor planets,* was the first of them to be discovered.

Our earth is one of nine principal planets which revolve around the sun. Our moon is one of twenty-eight satellites which accompany six of these planets. Hundreds of asteroids and great numbers of comets and meteor swarms, all wheeling around the sun, are also members of the large family to which the earth belongs. This celestial family, including the sun itself, is known as the *solar system.*

7.16. The Planets Named and Classified. The names of the planets in order of distance from the sun are:

Inferior planets	Mercury	Inner planets
	Venus	
	Earth	
Superior planets	Mars	
	The Asteroids or Minor planets	
	Jupiter	Outer planets
	Saturn	
	Uranus	
	Neptune	
	Pluto	

They are classified as inferior and superior planets, and also as inner and outer planets. The *inferior planets* are nearer the sun than we are, while the *superior planets* revolve outside the earth's orbit.

The four *inner planets,* which include the earth, are sometimes known as *terrestrial planets.* The five *outer planets* revolve outside the main zone of the asteroids. Before the tiny Pluto was added to this group, the four large outer planets, Jupiter, Saturn, Uranus, and Neptune, were often called the "major planets."

7.17. The Distances of the Planets from the sun are found in Table 7.1, where other information about the principal planets and their orbits appears as well. These are mean distances; the distances vary because the orbits are ellipses with the sun at one focus.

To find the greatest amount that a planet's distance departs from the mean, multiply the mean distance by the fraction representing the eccentricity of the planet's orbit. Thus the mean distance of Mercury is 35.95 million miles, and the eccentricity of its orbit is 0.206. The greatest variation from the mean is therefore 7.41 million miles. Mercury is about 28½ million miles from the sun at perihelion, and nearly 43½ million miles away at aphelion.

A relation known as *Bode's law* is an easy way to remember the relative distances of all except the most remote planets. Write in a line the numbers: 0, 3, 6, 12, and so on, doubling the number each time to obtain the next one. Add 4 to each number, and divide the sums by 10. The resulting series of numbers: 0.4, 0.7, 1.0, 1.6, 2.8, . . . represents the mean distances of the planets expressed in astronomical units, or the earth's mean distance from the sun.

Compare the distances determined by this rule with the actual distances in astronomical units given in the Table. The agreement is quite close, except for Neptune and Pluto, though it would be less impressive for Mercury if the rule of doubling the number had been followed from the start.

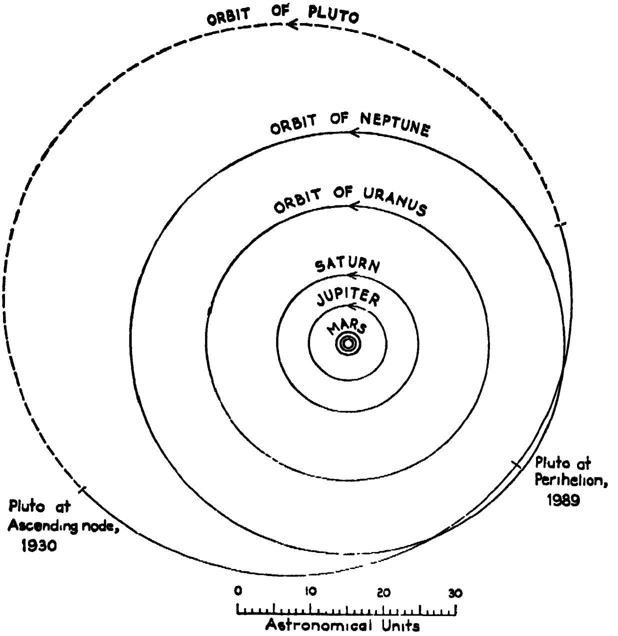


FIG. 7.17. Approximate Orbits of the Principal Planets. They are nearly circles with the sun at the common center, and nearly in the same plane. The orbits of Mercury, Venus, and the earth are too small on this scale to show clearly. The inclination of Pluto's orbit to the ecliptic plane is shown.

7.18. The Revolutions of the Planets around the sun, and of the satellites around their planets, exhibit some striking approaches to regularities:

(1) *All the planets revolve from west to east.* The majority of the satellites also revolve from west to east around their primaries. This is the usual direction of revolution and of rotation as well for all members of the solar system. Only a few exceptions are known.

(2) *The orbits of the planets and satellites are nearly circles,* as a general thing. They are ellipses of small eccentricity. This is true particularly of the larger bodies, as Table 7.1 shows. The smallest of the principal planets, Mercury and Pluto, have considerably flattened

TABLE 7.I. THE PLANETS

	Name	Symbol	Mean Distance from Sun		Period of Revolution		Eccentricity of Orbit	Inclination to Ecliptic
			Astron. Units	Millions of Miles	Sidereal	Synodic		
					days	days		
Inner	Mercury	☿	0.3871	35 95	87.969	115.88	0.206	7° 0′
	Venus	♀	0.7233	67.18	224.701	583.92	0.007	3 24
	Earth	⊕	1.0000	92.87	365.256	———	0.017	0 0
	Mars	♂	1.5237	141.50	686.980	779.94	0 093	1 51
					years			
	Ceres	①	2.7673	257 00	4.604	466 60	0 077	10 37
Outer	Jupiter	♃	5 2028	483 2	11.862	398.88	0.048	1 18
	Saturn	♄	9 5388	885 9	29.458	378.09	0.056	2 29
	Uranus	♅	19.1910	1782	84.015	369 66	0 047	0 46
	Neptune	♆	30 0707	2793	164.788	367.49	0.009	1 47
	Pluto	P	39.4574	3670	247.697	366 74	0.249	17 9

Name	Equatorial Diameter in Miles	Mass ⊕ = 1	Density Water = 1	Period of Rotation	Inclination of Equator to Orbit	Oblateness	Stellar Magnitude*
Sun ☉	864,100	331,950	1.41	$24^{d}.65$	7° 10′	0	−26.7
Moon ☾	2,160	0 012	3 33	27 32	6 41	0	−12.6
Mercury	3,100	0.04	3 8	88		0	− 1.2
Venus	7,700	0 81	4.86	30?		0	− 4.3
Earth	7,927	1.00	5.52	23^{h} 56^{m}	23 27	1/296	———
Mars	4,215	0 11	3 96	24 37	23 30	1/192	− 2 8
Jupiter	88,640	316.94	1.34	9 50	3 7	1/15	− 2.5
Saturn	74,100	94.9	0 71	10 14	26 45	1/9.5	− 0.4
Uranus	32,000	14.7	1.27	10 45	98	1/14	+ 5.7
Neptune	31,000	17.2	1 58	15 48	29	1/40	+ 7.6

* At greatest brilliancy.

orbits. Among the still smaller asteroids there are some orbits even more flattened.

(3) *The orbits of the majority of the planets and satellites lie nearly in the same plane.* With the exception of Pluto's orbit, the orbits of the principal planets are inclined less than 8° to the ecliptic plane, so

TABLE 7.II. THE SATELLITES

Name	Discovery	Mean Distance in Miles	Period of Revolution	Diameter in Miles	Stellar Magnitude at Mean Opposition
Moon		238,857	$27^d\ 7^h\ 43^m$	2160	−12
SATELLITES OF MARS					
Phobos	Hall, 1877	5,800	0 7 39	10 ?	+12
Deimos	Hall, 1877	14,600	1 6 18	5 ?	13
SATELLITES OF JUPITER					
Fifth	Barnard, 1892	112,600	0 11 57	100 ?	13
1. Io	Galileo, 1610	261,800	1 18 28	2300	5
2. Europa	Galileo, 1610	416,600	3 13 14	2000	6
3. Ganymede	Galileo, 1610	664,200	7 3 43	3200	5
4. Callisto	Galileo, 1610	1,169,000	16 16 32	3200	6
Sixth	Perrine, 1904	7,114,000	250 16	100 ?	14
Seventh	Perrine, 1905	7,292,000	260 1	40 ?	16
Tenth	Nicholson, 1938	7,340,000	264		
Eleventh	Nicholson, 1938	14,000,000	692		
Eighth	Melotte, 1908	14,600,000	739	40 ?	16
Ninth	Nicholson, 1914	14,900,000	758	20 ?	17
SATELLITES OF SATURN					
Mimas	Herschel, 1789	115,000	0 22 37	400 ?	12
Enceladus	Herschel, 1789	148,000	1 8 53	500 ?	12
Tethys	Cassini, 1684	183,000	1 21 18	800 ?	11
Dione	Cassini, 1684	234,000	2 17 41	700 ?	11
Rhea	Cassini, 1672	327,000	4 12 25	1100 ?	10
Titan	Huygens, 1655	759,000	15 22 41	2600	8
Hyperion	Bond, 1848	920,000	21 6 38	300 ?	13
Iapetus	Cassini, 1671	2,210,000	79 7 56	1000 ?	11
Phoebe	Pickering, 1898	8,034,000	550	200 ?	14
SATELLITES OF URANUS					
Ariel	Lassell, 1851	119,100	2 12 29	600 ?	16
Umbriel	Lassell, 1851	165,900	4 3 28	400 ?	16
Titania	Herschel, 1787	272,000	8 16 56	1000 ?	14
Oberon	Herschel, 1787	364,000	13 11 7	900 ?	14
SATELLITE OF NEPTUNE					
Nameless	Lassell, 1846	220,000	5 21 3	3000 ?	13

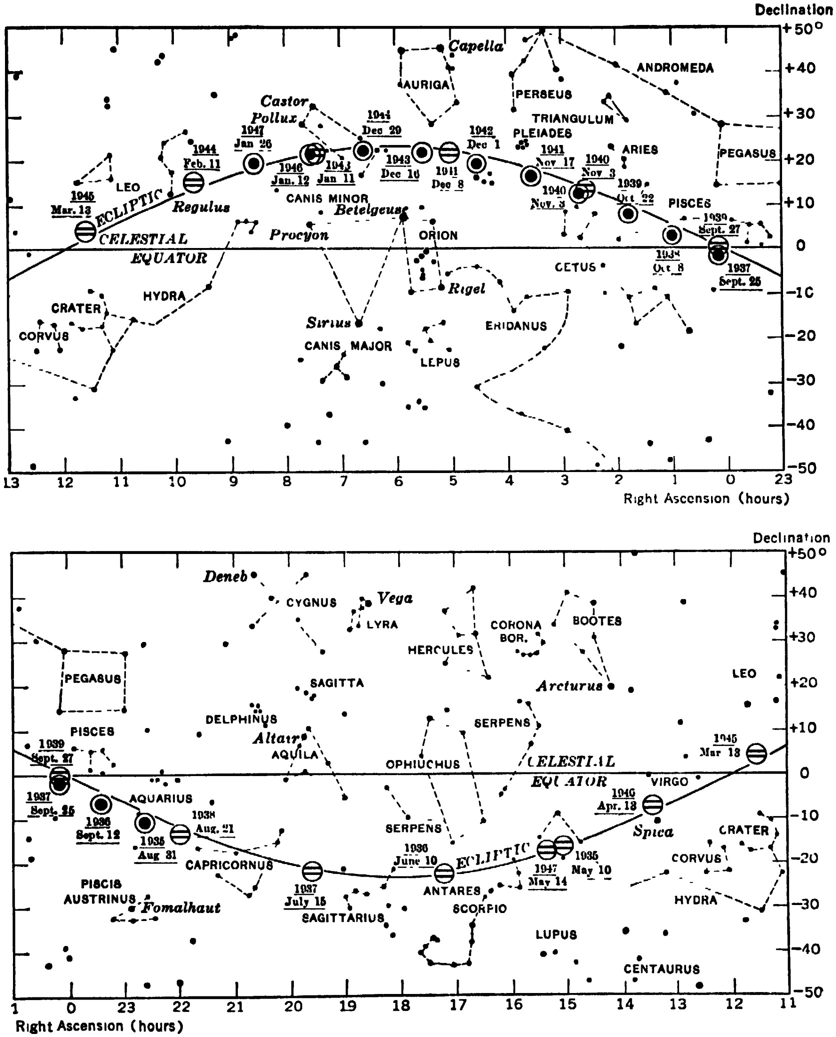


FIG. 7.18. Positions of Jupiter and Saturn at Their Oppositions, 1935-47. Barred disks represent Jupiter; disks with circles around them represent Saturn. (*Data by courtesy of the Director of the Nautical Almanac Office, U. S. Naval Observatory*)

that these planets are observed in the sky always near the ecliptic, and mostly within the boundaries of the zodiac.

The true periods of the revolutions, or *sidereal periods,* increase with distance from the sun in accordance with Kepler's harmonic law, from 88 days for Mercury to 248 years for Pluto. The *synodic periods* are given also in the Table. They are the intervals in which the faster moving inferior planets gain a lap on the earth, or in which the earth overtakes the slower moving superior planets.

7.19. Configurations of the Planets. The *elongation* of a planet is the difference between the planet's celestial longitude and that of the sun. Special values of elongation, as when the planet is passing the sun or is opposite the sun, have special names, and together are known as the *aspects* of the planet.

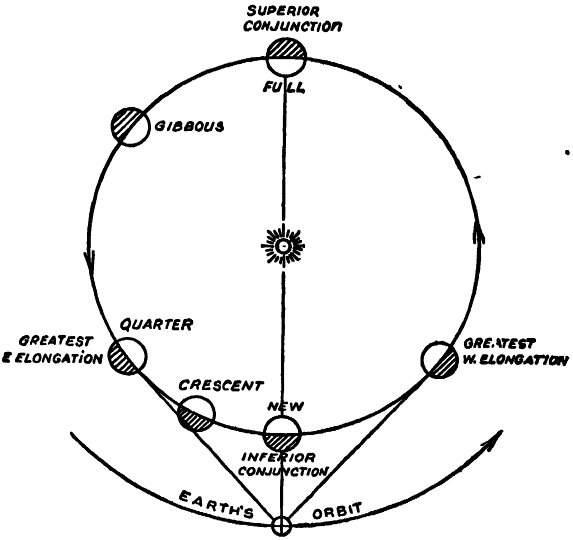


FIG. 7.19. Aspects and Phases of an Inferior Planet. The aspects differ from those of the moon; the phases are the same.

The inferior planets, Mercury and Venus, appear to us to oscillate to the east and west of the sun's place. From *superior conjunction* (elongation 0°) beyond the sun they move out to *greatest eastern elongation,* which does not exceed 48° from the sun for Venus and 28° for Mercury. Here they turn westward relative to the sun, and passing between us and the sun at *inferior conjunction,* when the elongation is

0° again, they move out to *greatest western elongation,* and then back toward the east behind the sun.

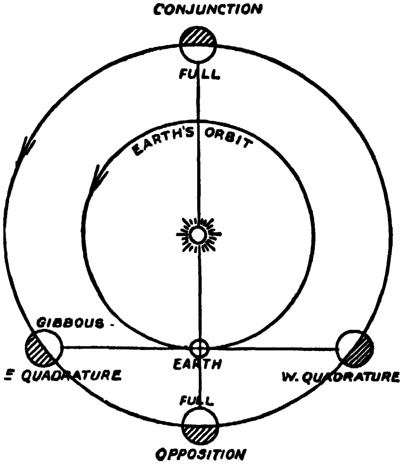


Fig. 7.19A. Aspects and Phases of a Superior Planet. The aspects are similar to those of the moon. The only phases are full and gibbous.

The superior planets, such as Mars and Jupiter, move continually westward relative to the sun's place. At *conjunction,* when the elongation is 0°, they pass the sun from the evening into the morning sky. At *western quadrature,* when they are 90° west of the sun, they are in the south at sunrise. At *opposition,* or elongation 180°, they are directly in the south at midnight; and at *eastern quadrature* when they are 90° east of the sun, they are in the south at sunset.

Notice in Figs. 7.19 and 7.19A, which illustrate the configurations of the planets, that the inferior planets turn their sunlit hemispheres in all directions relative to the earth; they show all the phases that the moon does, from new to full and back to new again.

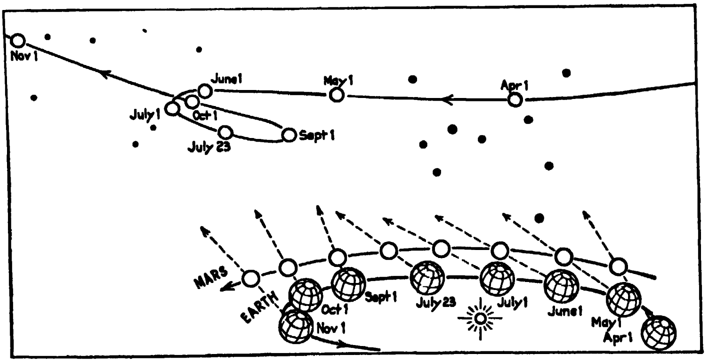


Fig. 7.20. Retrograde Motion of Mars Explained. The planet seems to move backward among the stars when the faster-moving earth sweeps by it.

The superior planets, on the other hand, never turn their dark hemispheres fully toward us. The planet Mars shows the gibbous phase noticeably near its quadratures. But the more remote of the superior planets show very nearly the full phase at all times.

7.20. Retrograde Motions Explained. This Chapter ends as it began, with a consideration of the looped motions of the planets against the background of the stars. These loops, which mystified the ancient astronomers and which promoted the complex machinery of the old Ptolemaic theory, are easy to understand now that the true motions of the planets are clearly before us.

Owing to the earth's swift movement in its orbit around the sun, the planets are shifted backward against the more distant background of the stars. It is the same effect that one observes as he drives along the highway; objects near the road fly past more rapidly than those in the distance. This effect combines with the planet's real eastward motion to produce the looped paths we have noticed.

A superior planet, such as Mars, retrogrades near the time of its opposition; for the earth then overtakes the planet and leaves it behind. An inferior planet, such as Venus, retrogrades near inferior conjunction. In general, a planet retrogrades, or apparently moves westward among the stars, when it is nearest the earth.

QUESTIONS ON CHAPTER VII

1. Would the problem of the planetary motions have been easier to solve if we had lived on another planet? On the sun?
2. Galileo's discovery that the planet Venus shows phases like the moon's disproved a part of the Ptolemaic system (Fig. 7.4). Explain.
3. In what respects did the Copernican theory differ from the Ptolemaic system? From present ideas?
4. How did the Copernican theory open the way to a fuller understanding of the vast distances of the stars?
5. In what respects did Kepler's laws disprove the Ptolemaic system?
6. Suppose that a planet circles around the sun once in 8 years. How does its distance from the sun compare with the earth's distance? (Use Kepler's third law.)
7. Suppose that two balls weighing 1 and 2 pounds respectively are dropped together from the same height. The force of the earth's attraction on the first ball is half of that on the second (7.11). Yet they reach the ground together, as Galileo is said to have shown by dropping objects of different weights from the leaning tower in Pisa. Explain.
8. Precisely what is meant by the statement (7.11) that the moon "falls" toward the earth?
9. State the dates of the next oppositions of Jupiter and Saturn, and where these planets will then appear among the stars.
10. Name the aspect of the moon when its phase is new; first quarter; full; last quarter

11. Which two of the principal planets have the longest synodic periods, and why?

12. If the sun is represented by a globe one foot in diameter, what are the diameters of the principal planets and their distances from the sun on the same scale?

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CHAPTER VIII

PLANETS AND THEIR SATELLITES

MERCURY AND VENUS — MARS, THE RED PLANET — THE ASTEROIDS — JUPITER, THE GIANT PLANET — SATURN, THE RINGED PLANET — URANUS AND NEPTUNE — PLUTO, THE MOST REMOTE PLANET

MERCURY AND VENUS

These two planets revolve inside the earth's orbit, Mercury once in 88 days, Venus in 225 days. They accordingly (7.19) oscillate to the east and west of the sun's place in the heavens and are never very far from it. Sometimes they come out in the west at nightfall as evening stars; at other times they rise before the sun as morning stars.

Mercury is nearest of all the planets to the sun and the smallest of the principal planets, with the possible exception of Pluto. Its diameter, 3100 miles, is only half again as great as the moon's, and is slightly exceeded by two of Jupiter's satellites.

Venus, the brightest of the planets, outshines all the other celestial bodies except the sun and moon. Our nearest neighbor among the principal planets, it comes within 26 million miles of the earth at inferior conjunction. Its diameter, 7700 miles, is only slightly less than the earth's diameter. Both Mercury and Venus, as we view them through the telescope, show the whole cycle of phases (Fig. 7.19) just as the moon does. Neither planet has a satellite.

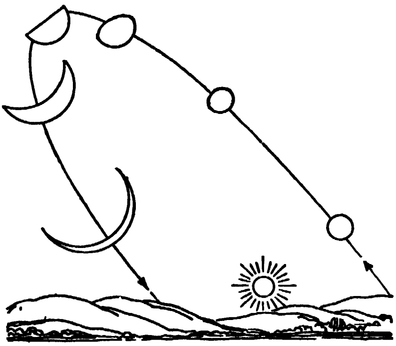

FIG. 8.1. Venus as Evening Star. Changing phase and apparent size of the planet as viewed through the telescope.

8.1. As Evening and Morning Stars. The inferior planets are best placed for observation with the naked eye around the times of their greatest elongations. On such occasions Venus is always remarkably conspicuous. Mercury, however, requires still other favorable conditions to render it clearly visible.

Mercury should also be near its aphelion. Owing to the considerable eccentricity of its orbit, the apparent distance of Mercury from the sun's place varies from 28°, when the planet is at aphelion, to as little as 18° at perihelion. Moreover, the line joining the planet to the sun should stand most nearly vertical; this important condition is fulfilled when Mercury is evening star in the spring and morning star in the autumn.

Mercury's synodic period is 116 days, the period in which the planet seems to go around the sun as viewed from the revolving earth. The synodic period of Venus is 584 days.

TABLE 8.1. DATES OF CONJUNCTIONS AND ELONGATIONS OF VENUS

Superior Conjunction	Greatest Elongation East (Evening Star)	Inferior Conjunction	Greatest Elongation West (Morning Star)
1939 Sep. 5	1940 Apr. 17	1940 June 26	1940 Sep. 5
1941 Apr. 19	1941 Nov. 23	1942 Feb. 2	1942 Apr. 13
1942 Nov. 16	1943 June 28	1943 Sep. 5	1943 Nov. 16
1944 June 27	1945 Feb. 3	1945 Apr. 15	1945 June 24
1946 Feb. 1	1946 Sep. 8	1946 Nov. 17	1947 Jan. 28
1947 Sep. 3	1948 Apr. 15	1948 June 24	1948 Sep. 3

Venus emerges slowly from superior conjunction behind the sun into the evening sky, requiring 220 days to reach greatest eastern elongation. Then in only 72 days it moves back to inferior conjunction between us and the sun and into the morning sky. In 72 days more it arrives at greatest western elongation, where it turns again and begins the leisurely return of 220 days to superior conjunction.

The greatest brilliancy of Venus as evening and morning star occurs about 36 days before and after inferior conjunction. Then the planet appears through the telescope in the crescent phase, a crescent between five and six times as great from horn to horn as the apparent diameter of the fully illuminated disk at superior conjunction over beyond the sun. Around the times of greatest brilliancy Venus becomes visible in full daylight, like a tiny star in the blue sky.

The terms "evening star" and "morning star" are applied more often to the appearances of the inferior planets after sunset or before sunrise. But they are employed for the bright superior planets as well, to designate that they set after or rise before the sun.

8.2. Mercury Resembles the Moon. The contrast between Mercury and Venus is fully as striking as that between the moon and the earth, and it arises from the same cause. Mercury does not greatly exceed the moon in size and mass, and consequently in surface gravity. The low velocity of escape (6.16) at its surface, 2.2 miles a second, would seem unfavorable to the retention of atmosphere.

Mercury reflects only seven per cent of the sunlight it receives, which suggests that its surface is dark, broken, and airless. The rapid increase in its brightness between the quarter and the full phase indicates that the planet's surface is at least as mountainous as the moon's.

The best views of Mercury through the telescope are obtained in the daytime when the planet is far above the horizon. While the different phases are easy enough to see, the markings on the tiny disk are difficult under the best conditions. Yet markings have been noticed by many astronomers. Observing with the 40-inch refractor of Yerkes Observatory, Barnard recorded "three or four large darkish spots very much resembling those seen on the moon with the naked eye." Unmistakable dark markings have been photographed in the daytime at Lowell Observatory.

Mercury appears to turn one face toward the sun always, just as the "man in the moon" turns his face always toward the earth. The Italian astronomer Schiaparelli reached this conclusion, in 1889, from his persistent observations of the hazy markings; he found that Mercury rotates on its axis in the same period, 88 days, in which it revolves around the sun. It should be added that librations, owing to the considerable eccentricity of Mercury's orbit, bring nearly a half of the other hemisphere into the sunlight at times.

We conclude that Mercury is an airless, lifeless world where there are marked extremes of temperature. The rocks on its sunward side are hot enough to melt lead; the part of the planet where eternal night prevails is intensely cold.

8.3. Venus, the "Earth's Twin Sister." In its size, mass, and distance from the sun the brilliant Venus of our evening and morning skies closely resembles the earth. Gravity at its surface is 85 per cent of its value at the earth's surface. The velocity of escape is high enough to retain an atmosphere. Indeed, there are definite indications that Venus has an atmosphere.

Twilight effects have been observed. The planet reflects 59 per cent of the sunlight that falls on it; such high efficiency as a reflector indicates usually, though not always, the presence of a cloudy atmosphere.

Pettit and Nicholson at the Mount Wilson Observatory find a uniform temperature of −10° F. for both day and night sides of Venus alike. So low a temperature for a planet so near the sun would be difficult to explain unless the radiation they have measured comes from high, cold levels of the planet's atmosphere. Another striking indication of the presence of atmosphere remains to be noticed.

Through the telescope the disk of Venus shows in addition to its conspicuous phases only the very faintest markings. Photographs through infra-red filters show no markings at all. Such photographs reveal the distant terrestrial landscape through the intervening air more clearly than the eye can see it, or the ordinary photograph can record it.

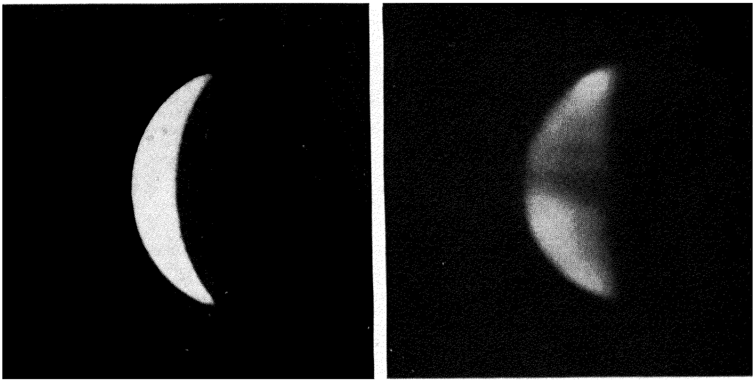

FIG. 8.3. Venus at the Crescent Phase. Photographed in the ordinary way and through an ultra-violet filter. (*Photographed by E. E. Barnard, Yerkes Observatory, and by F. E. Ross at Mount Wilson Observatory*)

But photographs through violet filters (Fig. 8.3), in the light that an atmosphere turns back most effectively, exhibit a variety of markings on the disk of Venus. They are cloud markings, which the eye at the telescope sees indistinctly, if at all. Ross infers from his photographs that the clouds are symmetrically arranged relative to the equator of Venus, and that they suggest a rotation period of the planet of something like 30 days.

While the conditions at its surface are unknown, the presence of life on the planet is doubtful. Free oxygen is not identified in the upper levels of the atmosphere, though carbon dioxide is abundant.

8.4. Transits of Mercury and Venus. The inferior planets occasionally *transit,* or cross directly in front of the sun at inferior conjunction. They then appear as dark dots against the sun's disk. Mercury is too small to be seen without the telescope at such times; but the transit of Venus is plainly visible to the naked eye.

About 13 transits of Mercury occur in the course of a century. Recent ones occurred on May 7, 1924, November 10, 1927, and May 11, 1937. The first of these was visible in the United States in its beginning; the third was only a partial transit. The beginning of the next transit, at 2:49 P. M. Central Standard time on November 11, 1940, will be visible in the United States, but the sun will set before the transit is completed. The following transit, on November 14, 1953, will be wholly visible here.

Transits of Venus are less frequent. They occur at present in pairs eight years apart at intervals of somewhat more than a century. There were two transits in June, 1761, and June, 1769, and two more in December, 1874, and December, 1882. The next two are scheduled for June 8, 2004, and June 6, 2012.

MARS, THE RED PLANET

Next in order beyond the earth, the planet Mars revolves once in 687 days at the average distance of 142 million miles from the sun, and rotates meanwhile on its axis once in $24^h\ 37^m$. Its diameter is 4200 miles, or slightly more than half the earth's diameter. Its atmosphere is not sufficiently extensive and clouded to hide its surface.

Mars is distinguished from the other planets by its red color. It is the only planet except our own whose surface is clearly revealed to us. Mercury's surface markings are extremely faint. Pluto is too remote to show a disk at all even through the largest telescopes. And the other principal planets are hidden underneath their atmospheres.

The fact that its surface is open to inspection and the often-mentioned possibility that it may be the abode of life have made Mars an object of particular interest, especially during its unusually close approaches.

8.5. Favorable Oppositions of Mars. A superior planet is nearest the earth, as a general thing, when it is opposite the sun. Mars comes to opposition at intervals of 780 days, or nearly two years and two months, its synodic period. But its distance varies greatly on these occasions owing to the considerable eccentricity of its orbit.

Favorable oppositions occur when the planet is also near its perihelion. At these close approaches, which always come in the late summer, the planet may be as near us as 35 million miles. Mars then becomes the most brilliant starlike object in the heavens, with the single exception of Venus.

The most remote oppositions, when the planet is near aphelion,

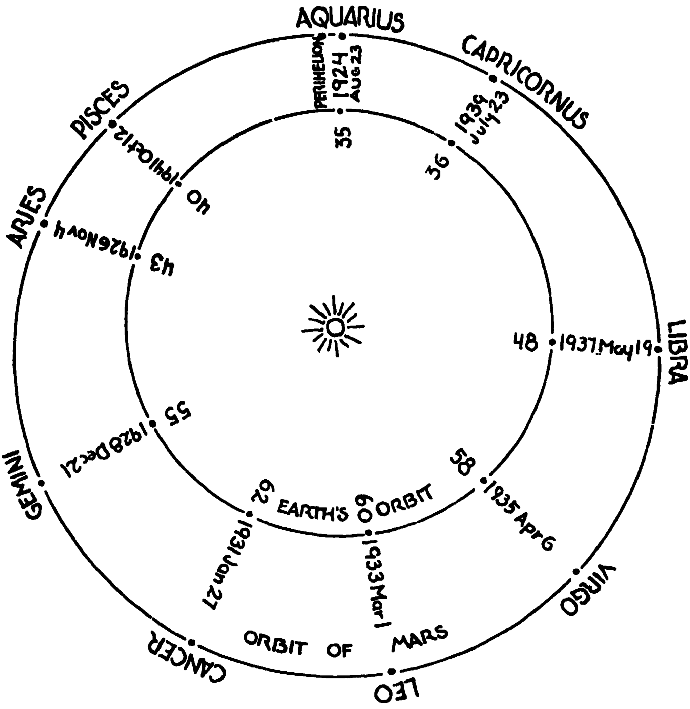

FIG. 8.5. Oppositions of Mars, 1924-41. Showing the date of each opposition, Mars' distance from the earth in million miles, and the constellation in which it appears. (*Data by courtesy of the Director of the Nautical Almanac Office, U. S. Naval Observatory*)

come in the late winter; then its distance from the earth may be as much as 63 million miles, and it ranks below Sirius in brightness.

Much of our knowledge of Mars has been gained around the times of the unusually close approaches, when the planet is seen at its best through the telescope. Favorable oppositions occur at intervals of 15, or sometimes 17, years. It was at the favorable opposition of 1877 that the two satellites and the canals of Mars were discovered. Each succeeding close approach has brought some addition to our information about Mars. The favorable opposition of August 23, 1924, was accompanied by a closer approach of the planet to the earth than will occur again for many centuries; opposition and perihelion were only a week apart (Fig. 8.5).

The most recent favorable opposition of Mars occurred on July 23, 1939; the closest approach to the earth, at the distance of 36,200,000 miles, came four days later. Mars was then far south, in Capricornus, and was accordingly too near the south horizon to be seen at its best through telescopes in the United States and Canada. At the following opposition of October 12, 1941, the red planet will be four million miles farther away from us, but it will be north of the equator, in Pisces, and therefore higher in the sky as seen from our northern latitudes.

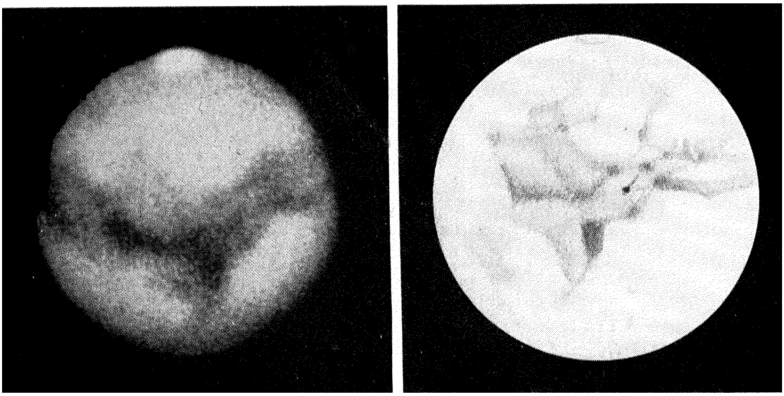

FIG. 8.6. Photograph and Drawing of Mars. The south polar cap is at the top. The prominent marking below the center is the Syrtis Major. (*Photograph, September 28, 1909, by E. E. Barnard, Yerkes Observatory. Drawing, September 29, 1926, by R. J. Trumpler, Lick Observatory*)

8.6. The Surface of Mars. Blue-green markings appear on the orange background which covers three fifths of the surface, and accounts for the planet's ruddy color in our skies. They are known by watery names which have survived, like the lunar "seas," from the old maps, though these markings are no longer regarded as water areas. Prominent among them is the triangular *Syrtis Major* (Fig. 8.6), the "Great Bog," which Huygens observed as early as 1659.

Finer dark markings were discovered by Schiaparelli at Milan, in 1877. He saw them as narrow streaks connecting the larger dark spots, and named them "canals" to match the other watery designations. The presence of the streaks, which traverse the dark areas as well, is amply confirmed; but observers today place little emphasis on the formerly suggested possibility that the "canals" of Mars might be artificial waterways.

White spots appear at the poles of Mars alternately as winter comes on in the two hemispheres, and gradually diminish with the approach of summer. These Martian "snow caps" behave as polar caps of ice and snow might be expected to do, except in one particular.

Photographs of Mars through infra-red filters, which should give the best views of its surface, bring out the blue-green markings clearly. Yet they show the polar caps indistinctly, or not at all. Photographs through ultra-violet filters, which should give the best views of details of the Martian atmosphere, reveal not only occasional bright patches of cloud, but the polar caps as well. It is suggested, therefore, that the polar caps we see are fog areas overlying the surface caps themselves.

A word of caution should be added. These features of Mars are not easy to see with a small telescope, as a usual thing. Even through a large telescope Mars is often a disappointing object to view, unless conditions are excellent.

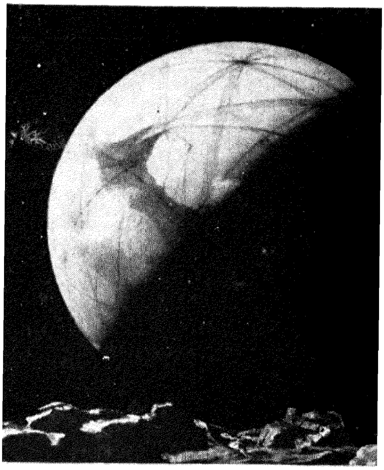

FIG. 8.7. Mars as Seen from Its Inner Satellite. From a painting by Howard Russell Butler. (*Courtesy of American Museum of Natural History*)

8.7. Possibility of Life on Mars. This question suggests first of all a consideration of the climatic conditions on Mars. Could life exist there? We refer to life as we know it, which requires air, water, and a narrow range of temperature.

An atmosphere is present. A twilight band 8° wide tempers the change from day to night. The surface markings fade toward the edge of the disk where they are viewed obliquely through a greater thickness of atmosphere. The photographs through filters are equally conclusive (8.6).

The Martian atmosphere is rarer than ours. The low reflecting power (0.15) and the distinctness of the surface features lead to this conclusion, while the smaller surface gravity (0.38 that of the earth) and the consequently lower velocity of escape (3 miles a second) give a reason for it.

Astronomers at Mount Wilson inform us, as the result of their spectroscopic examinations of the planet, that the amount of oxygen above the reflecting level of Mars can not exceed a thousandth part of the amount above an equal area of the earth at sea level, while the amount of water vapor is as low as five per cent. These restrictions on life appear to be serious.

Water is probably scarce on the surface as well as in the atmosphere. The blue-green areas are not bodies of water. Mars is a desert, in general.

The surface of Mars is above freezing at noon in the tropics. Pettit and Nicholson find that the temperature of the surface directly under the sun varies from 32° F., when Mars is at aphelion, to around 80° F. at perihelion. This in itself looks more hopeful for life. In addition, there are the seasonal changes.

Photographs by E. C. Slipher and others at Lowell Observatory show that the dark markings in a Martian hemisphere grow greener and more prominent in the late spring and early summer of that hemisphere. They fade to a chocolate brown as the fall season approaches. Since the equator of Mars is inclined 23½° to its orbit, the cycle of the seasons there resembles ours, except that it is longer.

These changes in the surface markings are such as would be expected, if they are produced by the growth and decline of vegetation. If this be the correct explanation, then there is life on Mars — vegetable life, at least. But some other explanation of the seasonal changes may come forth. It seems wisest to leave the whole question of life on Mars open for the present.

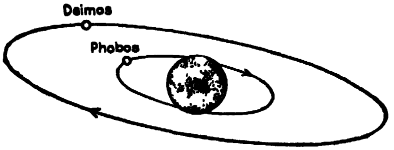

FIG. 8.8. Orbits of the Satellites of Mars as Viewed from the Earth.

8.8. Mars Has Two Satellites. They were discovered in 1877 by Asaph Hall at the Naval Observatory in Washington. Their names are Phobos and Deimos. Both are tiny bodies, perhaps not exceeding 10 miles in diameter; and they are so near the bright planet as to be quite invisible except with large telescopes at favorable times.

Phobos revolves eastward at the distance of only 3700 miles from the surface of Mars, once around in 7^h 39^m, or in less than one third of the period of the planet's rotation in the same direction. Viewed from the planet, therefore, Phobos rises in the west and sets in the east. *No other known satellite in the solar system revolves in a shorter interval than the rotation period of its primary.*

Deimos, the outer satellite, revolves eastward around Mars once in $30^h\ 18^m$. It is doubtless smaller than Phobos, because it is only a third as bright. This satellite rises in the east in the Martian sky, but it drops behind the rotating planet so slowly that it goes through its whole cycle of phases twice before it sets in the west.

THE ASTEROIDS

The *asteroids,* or *minor planets,* revolve around the sun mostly between the orbits of Mars and Jupiter. The majority have periods between 3½ and 6 years. Invisible to the naked eye, with the occasional exception of Vesta, they are "starlike" in the sense that few of them show disks even through powerful telescopes.

Ceres, the largest asteroid and the first to be discovered, is 480 miles in diameter. About a dozen have diameters exceeding a hundred miles. Some are not more than a mile across.

Small bodies in the solar system exhibit wide variations from the regularities we have noticed (7.18) in the movements of the larger members. All the asteroids revolve from west to east, to be sure. But some of these tiny planets have orbits so highly inclined that they venture far from the zodiac. Some have highly eccentric orbits; one asteroid, Hidalgo, has its aphelion as far away as Saturn, while others come at their perihelions nearer the sun than the orbit of Venus.

8.9. Discovery of the Asteroids. Toward the close of the eighteenth century, the German astronomer Bode invited his colleagues to share in a search for a planet between the orbits of Mars and Jupiter. He pointed out that a series of numbers which came to be known later as Bode's law (7.17) represented the distances of the planets remarkably well, with a single exception. No planet had been found corresponding to the number 2.8.

While the search was being organized, the missing planet was discovered quite by accident by Piazzi in Sicily, on the 1st of January, 1801. Its motion from night to night among the stars he was observing declared that it was not one of them. The mean distance of the new planet, which Piazzi named Ceres, proved to be almost exactly 2.8 times the earth's distance from the sun.

oppositions with the 100-inch telescope on Mount Wilson. All of these together would probably amount to not more than one or two per cent of the moon's mass.

8.10. Close Approaches of Asteroids. Seven asteroids are known, and others will doubtless be discovered, which make closer approaches to the earth than any of the principal planets (Venus at inferior conjunction is 26 million miles away). *Albert* can come within about 18 million miles. The least possible distance of *Eros* is slightly less than 14 million miles. Four tiny asteroids can approach still nearer.

From the time of its discovery, in 1898, until 1932, Eros was regarded as the most neighborly of all the planets, though its favorable oppositions, when Eros is also near its perihelion, are infrequent. Near its opposition in 1931 its least distance from the earth was 16 million miles. The next favorable opposition will occur in 1975. On such occasions only a small telescope is needed to observe this planet as a star of the seventh magnitude. Eros fluctuates in brightness, as do other asteroids. The period of its light variation, slightly more than five hours and a quarter, is the period of the planet's rotation. The amount of the fluctuation varies. Watson at Harvard Observatory finds that Eros is an irregular body whose length, about 20 miles, is three times its width and thickness. The greatest fluctuation in light occurs when the earth is in the plane of the planet's equator.

The asteroid *Amor*, discovered in 1932 by Delporte in Belgium, comes to perihelion 10 million miles outside the earth's orbit. It was found again at Harvard Observatory in 1936. Another opportunity to observe it will be offered in 1943.

Apollo, discovered by Reinmuth at Heidelberg in 1932, has its perihelion 8 million miles inside the orbit of Venus, and passes at two points within 3 million miles of the earth's orbit.

The perihelion of *Adonis*, discovered by Delporte in 1936, is only 5 million miles farther from the sun than Mercury's mean distance. This asteroid passes a little more than a million miles from the earth's orbit, and about the same distance from the orbits of Venus and Mars.

Hermes, discovered by Reinmuth in 1937, passed less than a million miles from the earth. These four recently discovered asteroids are something like a mile in diameter; they appear at best as very faint stars, requiring telescopes of moderate size to see them at all. They raise the question as to whether there is a dividing line between asteroids and meteors.

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JUPITER, THE GIANT PLANET

Jupiter is the *largest* planet. Its equatorial diameter, 88,640 miles, is eleven times as great as the earth's diameter. Its mass exceeds the combined mass of all the other planets. Though it is nearly five hundred million miles from the sun, Jupiter is the brightest starlike object in our skies, with the exception of Venus and occasionally Mars.

Even a small telescope shows its four bright satellites and dark cloud belts clearly. Jupiter has eleven known satellites; for the moment at least it has the *greatest number of satellites.*

Jupiter revolves around the sun once in nearly 12 years, so that it advances about one sign of the zodiac from year to year. Its period of rotation, around $9^h\ 50^m$, is the *shortest* among the principal planets.

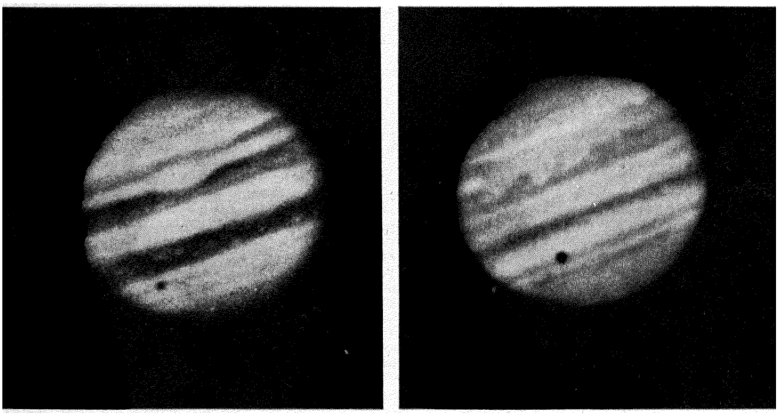


FIG. 8.11. Jupiter. The great red spot, an enlargement of the south tropical zone, is slightly above the center at the left. Jupiter's third satellite and its shadow appear in the photograph at the right. (*Photographed at Mount Wilson Observatory*)

8.11. Jupiter Enveloped in Clouds. The markings on the disk of this giant planet run parallel to its equator. Bright *zones* or *currents,* evidently regions of maximum cloudiness at the level we are observing, alternate with dark *belts.*

The broad *equatorial zone* is bordered by the dark *north and south equatorial belts,* the most conspicuous of the belts. Then come the *north and south tropical zones,* and beyond them the dark and bright streaks of the temperate and polar regions. Patches appear as well in a variety of colors and shades.

Jupiter's swift rotation on its axis accounts for the pronounced bulging at its equator which is whirling more than 27 times as fast as the earth's equator. The markings go around at different rates, owing to rapid horizontal movements of the clouds themselves. The equatorial zone rotates once in about $9^h\ 50^m$, while other parts of the disk turn once around in about $9^h\ 55^m$, with variations from this period.

The markings change in form, often quite rapidly, as we might expect cloud markings to do. Yet some of them are of surprisingly long duration. The *great red spot* is a famous example. An elliptical brick-red patch 30,000 miles long, it was first noticed in 1878, while the somewhat larger bright spot of the same shape, in which it is set, was recorded as early as 1831.

The red spot has faded, but has not entirely disappeared; its pinkish color has been remarked on by recent observers. The bright spot is still conspicuous as an enlargement of the south tropical zone.

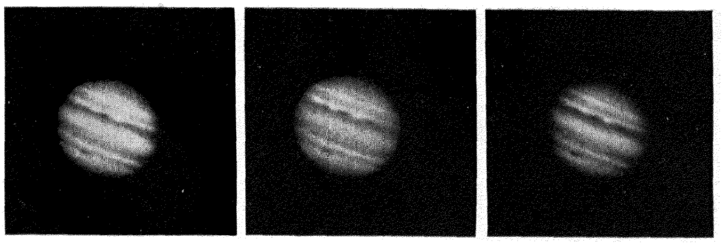


FIG. 8.11A. The Planet Jupiter. (*Photographed by Frank Schlesinger with the 30-inch Refractor, Allegheny Observatory*)

8.12. The Weather of Jupiter. Including its atmosphere, Jupiter averages only a third again as dense as water, and slightly less than the sun's density. This fact together with the great size of the planet promoted the idea of former times that Jupiter was a ball of hot gas throughout, though not hot enough to be appreciably self-luminous.

Measurements of the radiation show, however, that the temperature of the level of its atmosphere that we observe is 200° below zero Fahrenheit. This is about the temperature which would be expected, if the warmth of Jupiter comes from the sunshine alone. It seems more probable, therefore, that there is a great solid planet underneath, whose high surface gravity and low temperature have conspired to retain an extensive atmosphere around it.

It is not water vapor that condenses to form the cloud covering of Jupiter. Rather, it is some chemical compound that can evaporate under conditions where water is permanently frozen. V. M. Slipher's spectroscopic studies show the presence of constituents in the atmospheres of the great planets, which strongly absorb the orange and red of the sunlight.

More recently, Wildt at Göttingen, Dunham at Mount Wilson, and Slipher and Adel at the Lowell Observatory identified the absorption bands with those of ammonia and methane. Ammonia, which vaporizes at a higher temperature, is especially conspicuous on Jupiter, while the volatile methane is much the more prominent on the more distant, colder planets.

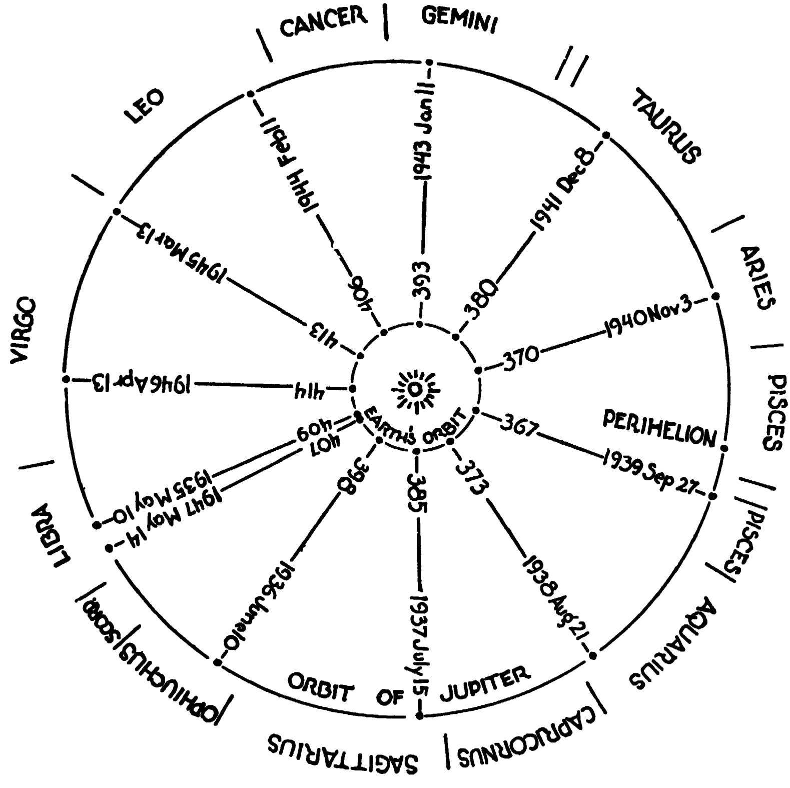


FIG. 8.12. Oppositions of Jupiter, 1935-47. Showing the date of each opposition, Jupiter's distance from the earth in million miles, and the constellation in which it appears. (*Data by courtesy of the Director of the Nautical Almanac Office, U. S. Naval Observatory*)

It is interesting to imagine how such compounds might take the place of water in the weather of Jupiter, rising from its surface as vapor, condensing into clouds, and coming down as rain to fill the streams. Speculating further, we might imagine a sort of life in which compounds like these enter instead of water to adapt it to the extremely frigid surroundings.

8.13. Jupiter's Eleven Satellites.

Next to our own moon the four bright satellites of Jupiter are the most conspicuous of all. They are bright enough to be glimpsed with the naked eye, if they were further removed from the glare of their planet. Galileo saw them with his new telescope, early in 1610.

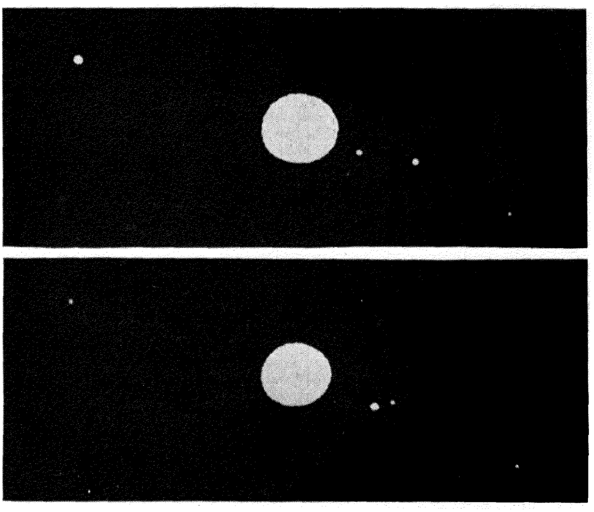


FIG. 8.13. Jupiter's Four Bright Satellites. The lower photograph was taken about three hours later than the upper one. (*Photographed, August 27, 1916, at Yerkes Observatory*)

The four bright satellites (Fig. 8.13) are numbered in order of distance from Jupiter; they have personal names, too, though these are not so often used. The first and second satellites are of about the moon's size. The third and fourth satellites are half again as great; they are the *largest of all satellites,* and surpass even the planet Mercury. Like our moon, they have equal periods of rotation and revolution.

These satellites revolve in nearly circular orbits, nearly in the planes of the planet's equator and of its orbit. Since their paths are turned not far from edgewise to the earth, they seem to us to swing back and forth from one side of the planet to the other.

The motions of the satellites add interest to the view of Jupiter through the telescope. Sometimes they disappear behind the planet's disk or into its shadow. At other times they pass across the disk; they are then usually visible with telescopes of moderate size, and the shadows they cast on the planet are visible also. The times of the occultations, eclipses, transits, and shadow transits of the satellites are predicted in the almanacs.

The other seven satellites of Jupiter are too small and faint to be easily seen even through large telescopes. They are designated by numbers in order of their discovery. The fifth satellite is nearest the planet, as Table 7.II shows. The eighth, ninth, and eleventh are the *most distant* of all satellites from their planets; they are further remarkable because *they revolve from east to west.*

SATURN, THE RINGED PLANET

Saturn is the most remote of the bright planets, and is therefore the most leisurely in its movements among the constellations. It revolves once in 29½ years at the mean distance of 886 million miles from the sun. A bright yellow star in our skies, it varies from equality with Altair to twice the brilliancy of Capella.

This planet ranks second to Jupiter in size and mass; its equatorial diameter is 74,100 miles. It has the *lowest density,* 0.7 times the density of water, and the *most prominent bulge at the equator* of any of the planets. Its *unique system of rings* makes it one of the most impressive celestial sights that the telescope shows.

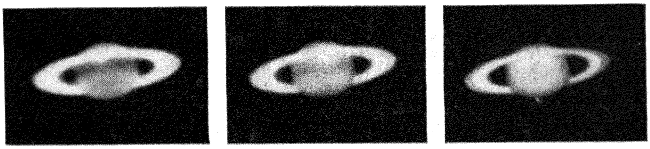
8.14. Cloud Markings of Saturn. Like Jupiter, and also Uranus and Neptune, Saturn is enveloped in cloud and mystery. From its broad yellow equatorial zone to its bluish polar regions this planet exhibits less detail than Jupiter, partly because it is nearly twice as far away.

Conspicuous spots have appeared rarely on Saturn. Hall, at Washington, observed a bright spot near the equator, in 1876, which went around once in $10^h\ 14^m$. This was in close agreement with the period of rotation of Saturn which William Herschel had determined, in 1794, by watching an irregularity in one of the belts. Barnard, in 1903, derived a period of $10^h\ 38^m$ from his observations of a spot in latitude 36° N.

As in the case of Jupiter, therefore, the atmosphere of Saturn turns around in a shorter period near the equator than in higher latitudes. But the difference here is almost beyond belief. The equatorial current runs ahead of the temperate zone at the rate of 21,000 miles a day!

The appearance of another large bright spot early in August, 1933, aroused much interest. This one was again in the equatorial zone. An elliptical spot at first, some 10,000 miles long, it rapidly spread out on the forward side, as the spot of 1876 had done, brushed out in this direction as if by a powerful wind.

Wright, who followed the development of this spot on his photographs at Lick Observatory through filters of different colors (Fig. 8.14), concluded that the spot was higher than the general level of the equatorial current. One may well wonder what unusual condition down below caused the excessive updraft that raised this great cloud so far aloft.



Ultra-violet Violet Yellow

FIG. 8.14. Bright Spot on Saturn. (*Photographed through filters, August 7, 1933 by W. H. Wright, Lick Observatory*)

8.15. Satellites of Saturn. Saturn has nine known satellites. Titan, the largest and brightest, was discovered by Huygens in Holland, in 1655. It is somewhat larger than our moon, and is visible in small telescopes as a star of the eighth magnitude.

Phoebe, the faintest and probably the smallest of Saturn's satellites, was discovered by W. H. Pickering, in 1898. The most distant from the planet, it revolves from *east to west*, like the three outermost satellites of Jupiter.

Six or seven of the satellites can be seen through telescopes of moderate size, like faint stars in the vicinity of the ringed planet. They are easy to identify by means of convenient tables in the *American Ephemeris and Nautical Almanac*.

8.16. The Rings of Saturn are invisible to the naked eye, and were therefore unknown until after the invention of the telescope. When

Galileo began watching Saturn through his little telescope, in 1610, he saw what seemed to be two smaller bodies in contact with the planet on opposite sides. These appendages disappeared two years later, and subsequently reappeared.

This changing appearance of Saturn remained a mystery until Huygens' discovery of the satellite Titan, in 1655, suggested to him the explanation that Saturn is encircled by a broad flat ring. In 1675, Cassini at the Paris Observatory noticed a dark line running around the ring, which eventually proved to be an actual division between two bright rings. It remained for the Bonds at Harvard Observatory, in 1850, to discover another, fainter ring nearer the planet. So there are three rings in all.

The entire ring system is 171,000 miles across. The width of the *outer bright ring* is 10,000 miles, while that of the *inner bright ring* is 16,000; it is brighter as well as broader than the outer one and is separated from it by the 3000-mile gap of the Cassini division. The *crape ring* is about 12,000 miles wide. Much fainter than the others, it is, nevertheless, easily visible through telescopes of moderate size.

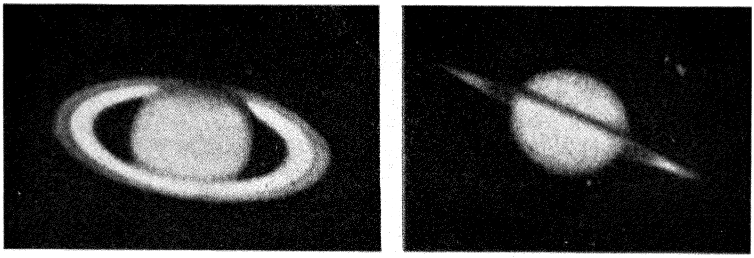


FIG. 8.16. The Rings of Saturn. Near their maximum opening, and nearly edgewise. (*Photographed by E. C. Slipher, Lowell Observatory*)

8.17. The Rings at Different Angles. Saturn's rings are inclined 27° to the plane of the planet's orbit, and they keep the same direction as the planet revolves. Accordingly, they present their northern and southern sides to us alternately. At intervals of about 15 years, or twice during the planet's sidereal period of 29½ years, the rings are edgewise to the sun; and on each occasion they are edgewise to the earth from one to three times. Their thickness is so small that they then appear as a very narrow bright line.

The rings were edgewise to the earth three times in 1920 and 1921.

Thereafter, the northern side came into view and opened out gradually to the greatest apparent width in 1928 and 1929, when the planet was far south in Sagittarius.

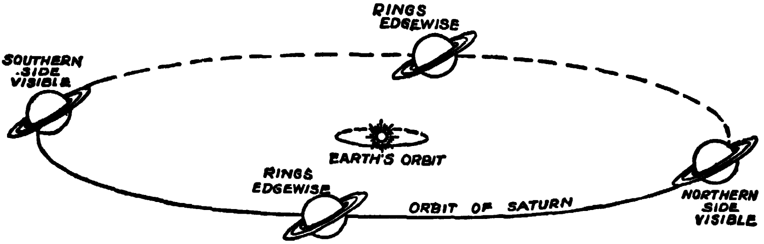


FIG. 8.17. Saturn's Rings at Different Angles. Twice in the course of Saturn's revolution its rings become edgewise to the sun. Each time the plane of the rings requires about a year to sweep across the earth's orbit.

The rings were edgewise to the earth again in February, 1937; their plane barely missed the earth early in July, 1936, and crossed the sun late in December, 1936. Their southern side is now presented to us.

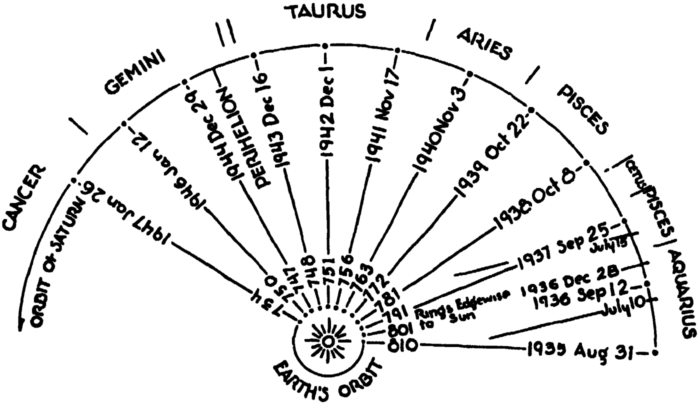


FIG. 8.17A. Oppositions of Saturn, 1935-1947. Showing the date of each opposition, Saturn's distance from the earth in million miles, and the constellation in which it appears. The plane of the rings was edgewise to the earth's orbit for about a year beginning July 10, 1936. *(Data by courtesy of the Directoi of the Nautical Almanac Office, U. S. Naval Observatory)*

At the next widest opening of the rings, around the opposition of December 16, 1943, Saturn will appear near the tip of the southern horn of Taurus, in fine position for observation from our northern hemisphere. It will be near its perihelion as well, and therefore at about its greatest possible brilliancy.

8.18. Saturn's Rings Are Composed of Many Pieces. They may be likened to a swarm of meteors, each member revolving like a satellite around the planet and reflecting a tiny spark of sunlight. It is because the separate bodies cannot be seen at this great distance that the rings have the appearance of continuous surfaces.

Keeler, at the Allegheny Observatory in 1895, was the first to observe that Saturn's rings are not solid surfaces. Employing the spectroscope, he saw that the speed of the rotation of the rings becomes less with increasing distance from the planet. This would be true for separate bodies revolving around the planet, in accordance with Kepler's harmonic law. If each ring were a solid surface, the outer edge would turn around faster than the inner one.

The outer edge of the outer ring has the longest period of rotation, $14^h\ 27^m$. The inner edge of the middle ring rotates once in $7^h\ 46^m$, while the material of the crape ring goes around in a still shorter time. Since the planet's equator turns once in $10^h\ 14^m$, it is evident that the outer parts of the ring system move from east to west across the Saturnian sky, while the inner parts go from west to east, like Phobos in the Martian sky.

URANUS AND NEPTUNE

8.19. Discoveries of Uranus and Neptune. The discovery of the planet Uranus, in 1781, was accidental and unexpected. William Herschel in England was examining a region in the constellation Gemini through the telescope when he noticed a greenish object which seemed to him somewhat larger than a star. Its movement among the stars soon declared conclusively that it was not a star.

Calculations showed eventually that it was a planet more remote than Saturn, and the name Uranus was assigned to it. The ways of the new planet perplexed astronomers for many years thereafter. It did not follow faithfully the course they expected it to pursue around the sun, the predicted orbit in which the disturbing effects of the other known planets had been carefully included.

At length, Leverrier in France reached the conclusion that the motion of Uranus was being altered by the attraction of a planet still more remote and as yet unseen. From his study of the discrepancies between the predicted and observed positions he succeeded, in 1846, in determining the position of the disturber in the constellation Aquarius.

Leverrier then wrote to Galle at the Berlin Observatory, where a map of the stars in this particular region of the heavens had been recently completed, telling him just where to search for the new planet. Galle directed the telescope toward this region, and soon noticed a star-like object which his map did not show in that place. It was the planet Neptune.

Meanwhile, another astronomer, J. C. Adams in England, had also solved the problem, and was indeed the first to deduce the position of Neptune; but he was not so successful in securing effective telescopic cooperation.

8.20. Uranus, the first planet to be discovered, revolves once in 84 years at 19 times the earth's distance, or nearly 1800 million miles from the sun. Barely visible to the naked eye as a star of the sixth magnitude, it shows through the telescope a tiny blue-green disk on which no markings are clearly discernible.

This planet is 32,000 miles in diameter, and is evidently cloud-enveloped, like Jupiter and Saturn. Its rotation period of 10.8 hours was determined spectroscopically by V. M. Slipher at Lowell Observatory.

Four satellites revolve around Uranus in nearly circular orbits which are inclined almost at right angles to the plane of the planet's orbit. Their orbits were edgewise to the earth in 1924, and will appear nearly as circles in 1945.

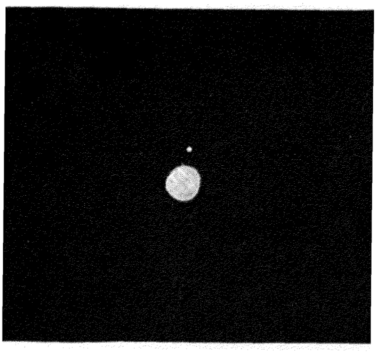


FIG. 8.21. Neptune and Its Satellite. (*Photographed, September 6, 1915, by E. E. Barnard, Yerkes Observatory*)

8.21. Neptune revolves once in 165 years at 30 times the earth's distance, or somewhat less than three thousand million miles from the sun. Always invisible to the naked eye, it appears through the telescope as bright as a star of the eighth magnitude. Its tiny disk shows no markings.

This planet is 31,000 miles in diameter, or about equal to Uranus. It is presumably cloud-covered, like the other three great planets. It rotates from west to east once in 15.8 hours, according to the spectroscopic studies of Moore and Menzel at Lick Observatory.

Neptune has a single satellite whose distance from the planet is slightly less than the moon's distance from the earth, and whose diameter is about half again as great as the moon's. This satellite revolves from *east to west,* contrary to the direction of the planet's rotation.

PLUTO, THE MOST REMOTE PLANET

8.22. The Discovery of Pluto was announced by Lowell Observatory on March 13, 1930, as the successful result of a long-continued photographic search for a planet beyond Neptune. The planet was first detected, by Clyde Tombaugh, on photographs taken late in January of that year; it was moving slowly among the stars in the constellation Gemini.

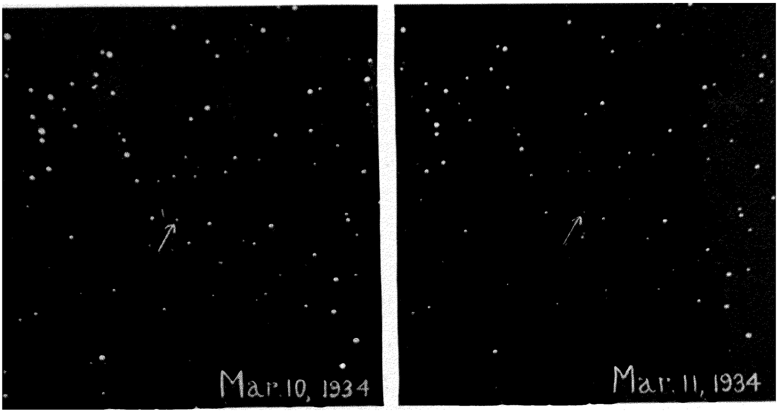


FIG. 8.22. Pluto. Showing its motion among the stars in one day. (*Photographed, March 10 and 11, 1934, at Yerkes Observatory*)

As early as 1915, Lowell had calculated the orbit of the trans-Neptunian planet from slight discrepancies between the observed and predicted movements of Uranus, which still remained after the discovery of Neptune. While the position of Pluto at its discovery was in reasonable agreement with the calculations, its mass seems too small to have caused the discrepancies on which the calculations were based.

Pluto is visible in large telescopes as a star of the fifteenth magnitude. It has a yellowish hue rather than the blue-green color of its nearest neighbors. Too small and remote to show a disk, its size can only be inferred from its brightness. It is probably inferior to the earth in size and mass; Bower finds that it is less than a tenth as massive as the earth, if it has the same density and reflecting power as Neptune's satellite.

8.23. The Orbit of Pluto. The most remote planet known, Pluto revolves at the average distance of 39.5 astronomical units, or 3670 million miles from the sun. It goes around the sun once in 248 years, which is almost exactly half again as long as Neptune's sidereal period.

Pluto's orbit is inclined 17° to the ecliptic, the highest inclination for any principal planet. At the time of its discovery Pluto was near its ascending node, and therefore close to the ecliptic. But it ventures at times well beyond the borders of the zodiac.

The eccentricity (0.25) of Pluto's orbit is the greatest for any principal planet. On this account and because of the huge size of its orbit, its distance from the sun varies enormously. At aphelion it is 1800 million miles beyond Neptune's distance from the sun, while at perihelion it is *35 million miles nearer the sun than Neptune's distance.* There is no immediate danger of collision; in their present orbits the two planets cannot approach each other closer than 240 million miles.

At the time of its discovery, in 1930, Pluto was near its average distance of 39.5 units from the sun, which is nearly 900 million miles greater than Neptune's distance. It will draw nearer the sun until it passes perihelion toward the end of the year 1989.

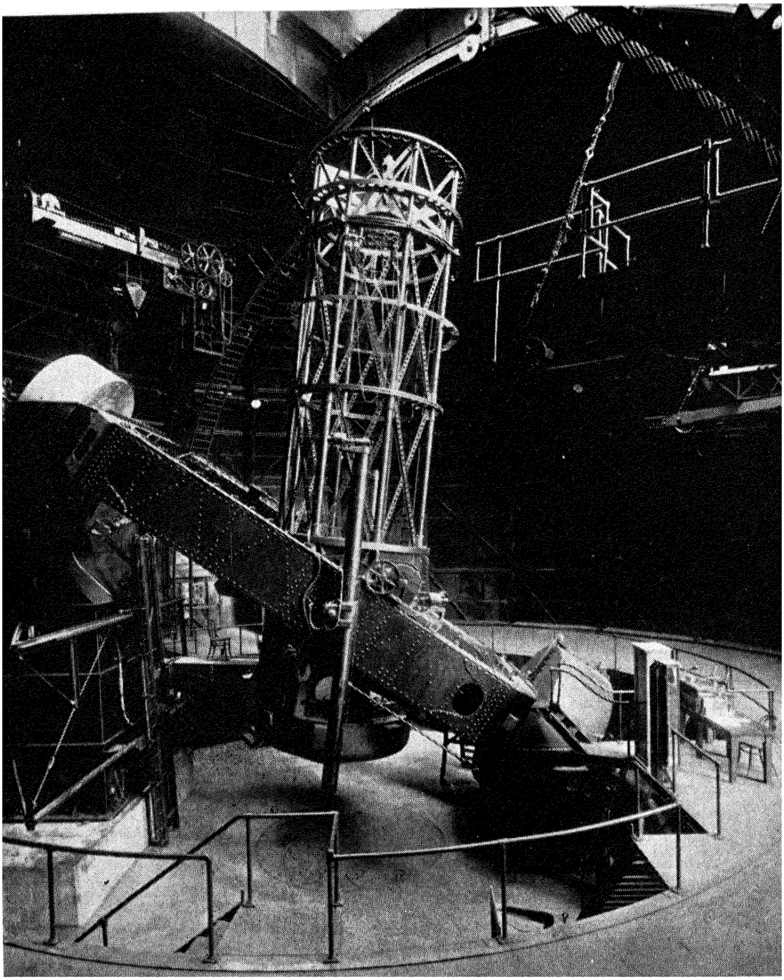
QUESTIONS ON CHAPTER VIII

1. Notice, in Table 8.I, that the dates of the conjunctions and elongations of Venus are nearly repeated after an interval of 8 years. Explain.
2. In what year will Venus be near its greatest brilliancy as evening star on Christmas Eve?
3. Why is Venus brightest at the crescent phase, and not at the full phase as in the case of the moon?
4. Why should photographs of Mars through infra-red filters give clearer views of the planet's surface than ordinary photographs?
5. Explain why photography is more effective than the eye at the telescope in the discovery of asteroids.
6. Jupiter's first satellite would appear slightly larger as viewed from the planet's surface than our moon does to us. How would it compare in brightness?
7. At intervals of 15 years the plane of Saturn's rings sweeps across the earth's orbit, taking a year to do so. Show that during that year the rings become edgewise to the earth from one to three times.

8. How could astronomers decide, in 1930, that the starlike object discovered in Gemini was a very remote planet, and not a relatively near-by asteroid?

9. Name the principal planets in order of their distance from the sun, and state an outstanding unique feature of each.

10. What conditions on each of the planets appear to be favorable or unfavorable to the existence of life?



The 100-Inch Reflecting Telescope, Mount Wilson Observatory.

CHAPTER IX

OTHER FEATURES OF THE SOLAR SYSTEM

COMETS — METEORS AND METEOR SWARMS — METEORITES AND METEOR CRATERS

In addition to the planets and their satellites, described in Chapter VIII, there are multitudes of small bodies in the solar system. We have noticed already the meteoric construction of the rings of Saturn. This Chapter is concerned chiefly with assemblages of such bodies in comets and meteor swarms, and with the meteors that the earth encounters. The description of the sun itself is left for Chapter X.

COMETS

Comets were looked upon by people of olden times as mysterious prowlers in the skies whose presence boded no good to mankind. Superstitious folk viewed them as omens of pestilence and war. In later times there was the fear that a comet might collide with the earth and destroy it. Nowadays, we watch the apparition of a great comet with admiration unmixed with any special alarm, as one of nature's most impressive spectacles.

A conspicuous comet has a head and a tail. The head consists of the hazy, globular *coma* which often has a star-like *nucleus* near its center. Bright *jets* project in various directions from the coma as though propelled by explosions from the nucleus. The luminous *tail,* growing wider as it recedes from the head, sweeps across the heavens in the direction opposite the sun.

Really spectacular comets appear rather infrequently. Donati's comet of 1858, the great September comet of 1882, and Halley's comet of 1910 gave noteworthy displays in recent years. The last-mentioned is without doubt the most famous of all comets.

9.1. Halley's Comet is named in honor of Edmund Halley, contemporary of Isaac Newton, who predicted its return. Halley calculated the orbit of the bright comet that appeared in 1682, and noticed its close resemblance to the orbits of the comets of 1531 and 1607, which he had also determined from the records of their observed positions. Deciding that these were three appearances of the same comet, Halley predicted that it would return again "about the year 1758."

The comet was sighted on Christmas night of that year, and reached its perihelion on March 13, 1759. It came around again to perihelion on November 16, 1835, and again on April 19, 1910. The first periodic comet to be recognized, it is the only conspicuous one among the many periodic comets known today which returns to view oftener than once a century.

Cowell and Crommelin at Greenwich have identified from the records 28 returns of this comet, as far back at 240 B.C. It was Halley's comet that appeared in 1066, at the time of the Norman conquest of England. The interval between returns to perihelion averages 77 years, varying several years owing to the disturbing effects of the planets. The present period of revolution is 75 years.

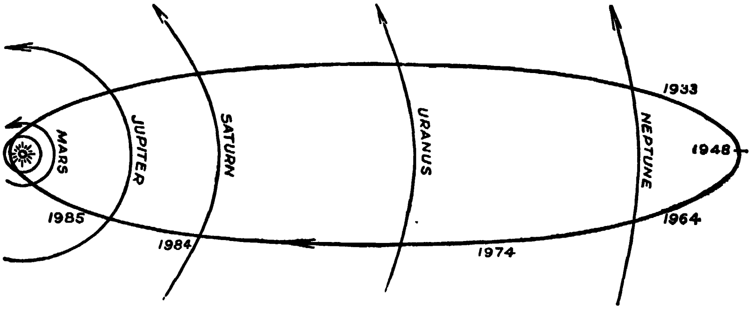
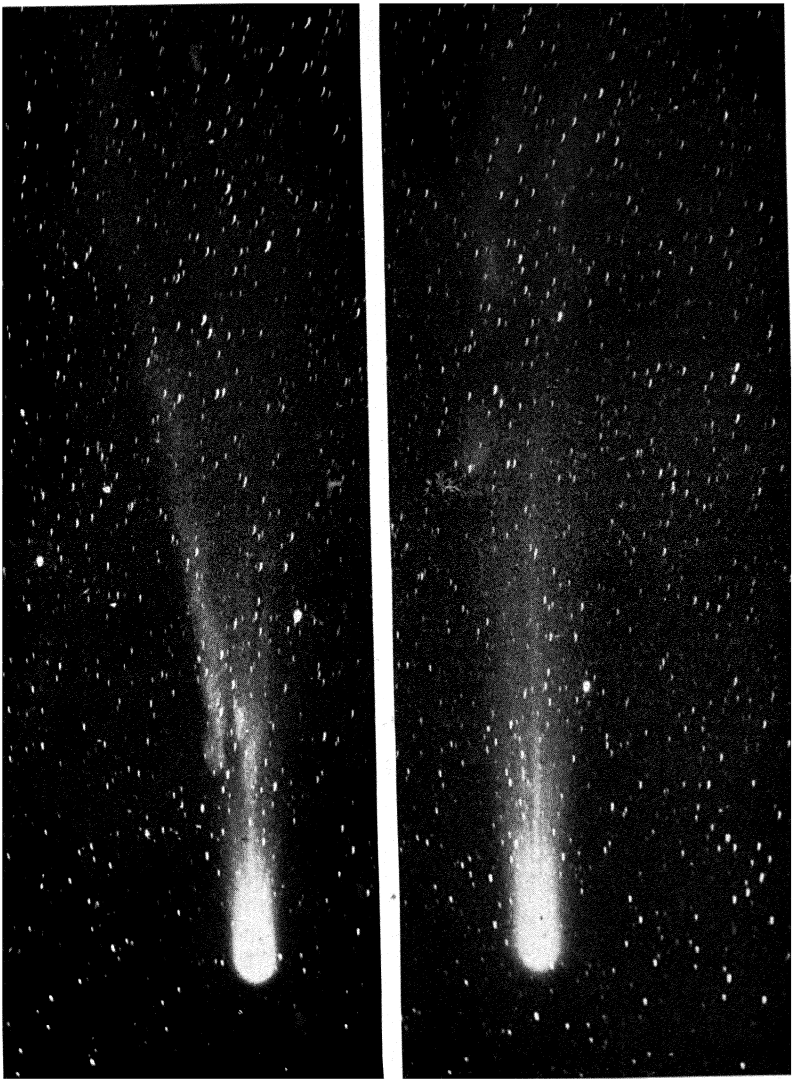


FIG. 9.1. Orbit of Halley's Comet. The comet remains for nearly half the time in the small part of its path which lies beyond the distance of Neptune. It will pass its aphelion in 1948, and will return to the sun in 1986.

Halley's comet revolves from east to west around the sun in a long orbit whose distance from the sun ranges from about half to more than 35 times the earth's distance. At present more remote than Neptune, it will turn back toward the sun in 1948, and will reach its perihelion in 1986.

9.2. Halley's Comet in 1910. The comet was first recognized by Wolf at Heidelberg as a faint speck on his photograph taken September 11, 1909; it was then in the asteroid zone, more than 300 million miles from the sun. It became visible to the naked eye about the middle of April, 1910, and remained so for two months and a half.

Growing gradually brighter, the comet was a fine spectacle in the east before dawn in early May. Its tail, increasing to as much as 28 million miles in length, stretched far across the heavens, filling an angle of more than 90° for a short time while it was in the earth's vicinity.



June 6 June 7

FIG. 9.2. Halley's Comet in 1910. (*Photographed by Heber D. Curtis at Lick Observatory*)

The comet's head passed directly between the earth and sun at the distance of 14 million miles from the earth; this occurred around 4 o'clock in the morning of May 19, Greenwich time, and therefore during the night throughout the United States. Ellerman, observing with the telescope in Hawaii, watched the sun closely at the predicted time of transit and saw nothing unusual. If there had been a solid body in the comet's head as great as 200 miles in diameter, it might well have been noticed.

Similarly, there was no certain evidence of any effect of the earth's encounter with the tail of the comet, which is supposed to have occurred a day or two after the transit. The comet appeared thereafter in the evening sky, growing fainter from night to night. Curtis at Lick Observatory saw it last with the naked eye on June 28, 1910. The comet remained within reach of the telescope until June, 1911, when it had passed beyond the distance of Jupiter.

In *Lick Observatory Publications,* volume XVII, Bobrovnikoff presents an instructive pictorial review of the changing aspects of Halley's comet during its most recent appearance. Among the spectacular developments was the parting of a streamer from the head of the comet (Fig. 9.2) and its increasingly rapid recession until it attained a speed of 60 miles a second.

9.3. Discoveries of Comets. Anyone who searches the heavens with a small telescope, particularly in the west after nightfall or in the east before dawn, may discover a comet. Amateurs have been the first to see many of them. The newly discovered comet is likely to appear as a little fuzzy patch, and its gradual movement among the stars soon shows that it is not a faint star cluster or nebula.

Having discovered a comet, the observer would do well to telegraph its position, direction of motion, and brightness to the Harvard Observatory which serves as a receiving and distributing station for such astronomical news.

As soon as three positions of the comet (its right ascensions and declinations) have been measured at intervals of several days, the orbit can be calculated. Many preliminary orbits are determined at the Students' Observatory of the University of California by methods developed by Leuschner and his associates. An examination of the records then shows whether the comet is a new one or the return of one that appeared before.

Five comets a year has been the average of discoveries in recent years, and about two thirds of these are new ones. Thirteen comets were discovered in 1932. The great majority are never more than faint, hazy, taïlless, telescopic objects.

They are designated at first by the year of discovery followed by a small letter to show the order in which they were found; thus the second to be discovered in 1935 is comet 1935 b. Later they are assigned Roman numbers in order of their passing perihelion. Accordingly, comet 1935 I was the first to pass perihelion in that year, though it was not necessarily discovered in that year.

A comet, especially a remarkable one, is often known also by the name of its discoverer or of the astronomer whose investigations have peculiarly associated his name with the object. Morehouse's comet and Halley's comet are examples.

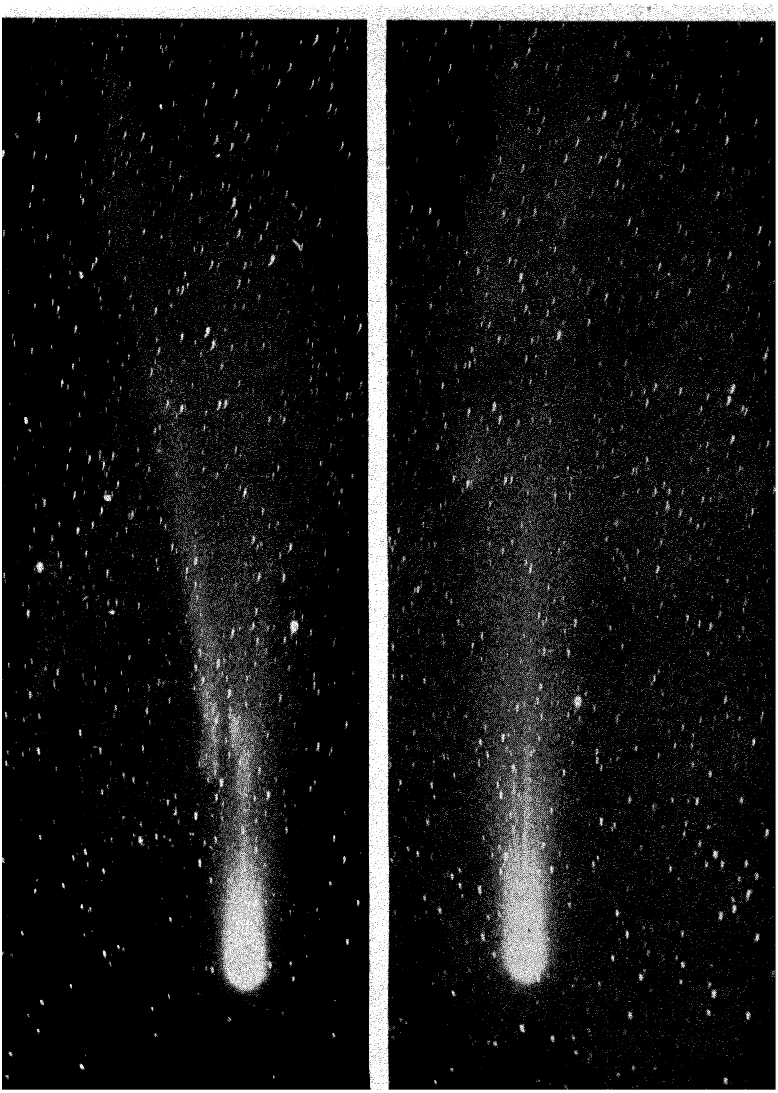
9.4. **The Paths of Comets** are so elongated that it is often difficult to decide whether they are open or closed on the side away from the sun. It is difficult because comets can be seen only while they are in the sun's vicinity. Few have been visible when they are more remote than Jupiter; the record so far is held by Stearns' comet of 1927, which was followed with the telescope until it had receded 200 million miles beyond the distance of Saturn.

Are all the comets that we observe permanent members of the solar system? Formerly, they were believed to be visitors to our system, rounding the sun only once unless their paths were shortened and closed by attractions of the planets. It is the general opinion today that practically all the comets that we see belong to the sun's family. Most of them withdraw so far from the sun before turning back that they return to view only after intervals of thousands of years.

Comets do not exhibit the regularities in their movements around the sun that we have noticed for the principal planets (7.18). The majority have nearly parabolic orbits which are inclined at various angles to the ecliptic. Some revolve from west to east, others from east to west. Only about a fourth of the orbits are known definitely to be elliptical.

The Schwassmann-Wachmann comet, discovered in 1927, is an interesting case. Its orbit is not far from a circle, and has a moderate inclination to the ecliptic. Revolving once in 16 years entirely between the orbits of Jupiter and Saturn, its distance from the sun varies only 170 million miles.

The great comets of 1668, 1843, 1880, 1882, and 1887, which passed remarkably close to the sun, constitute a *group;* their orbits are very east before dawn in early May. Its tail, increasing to as much as 28 million miles in length, stretched far across the heavens, filling an angle of more than 90° for a short time while it was in the earth's vicinity.



June 6 June 7

FIG. 9.2. Halley's Comet in 1910. (*Photographed by Heber D. Curtis at Lick Observatory*)

invisibility of Halley's comet during its transit across the sun's disk in 1910, and Van Biesbroeck's photograph of a star field right through the head of the Pons-Winnecke comet, in 1927, are examples of the evidence that the head of a comet is practically transparent.

The mass of the comet is very small compared with the masses of the planets. Orbits of comets have been greatly altered by attractions of planets; but there has not been the slightest observable effect on the movements of the planets and their satellites when comets have passed close by.


November 15 November 16

FIG. 9.6. Morehouse's Comet in 1908. The comet was moving toward the left and down with reference to the stars, as the directions of the star trails also show. Notice the remarkable change in the comet's appearance in a single day. (*Photographed by D. W. Morehouse, Drake University*)

The description so far could apply equally well to a swarm of meteors. But *the comet develops gases around it,* which make it visible out in space, while the meteor swarm does not.

As the comet draws nearer the sun, the emission of gases becomes greater, while explosions propel fine dust as well out into the coma. This light material is swept back by the pressure of the sunlight to form the tail which streams out, therefore, in the direction opposite the sun. The tail becomes wider as it recedes, because the diffusion of the matter is still going on, and it curves backward somewhat, too (Fig. 9.6A).

The comet shines with its own light, to a large extent, and not entirely by reflected sunlight as the planets do. The gases in the head and tail are set glowing by some action that is ascribed to the sun, perhaps the same that causes the auroral glow of our own atmosphere.

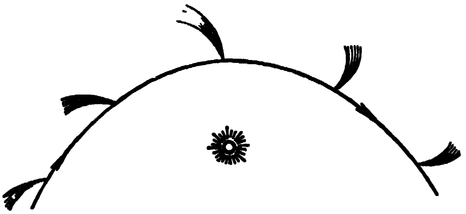


FIG. 9.6A. The Tail of a Comet is Directed Away from the Sun. It is usually curved, and is longest and brightest near perihelion.

Comets are often most active and brilliant after they have passed perihelion, owing presumably to a lag in these effects. Many comets remain inconspicuous at distances from the sun and earth where a few present fine spectacles. The difference may well depend on the supplies of materials they contain that vaporize under these conditions. So we may suppose that the comets of Jupiter's family are faint objects in our skies because they have already lost most of these materials in their frequent returns to the sun.

METEORS AND METEOR SWARMS

The bright streaks across the starlit skies, that we call "shooting stars," inform us of the fall of meteors through the air. *Meteors* are solid bodies of very small size, as a general thing. Too small to be visible by reflected sunlight, they speed through space unseen unless they chance to plunge into our atmosphere.

Impacts of the air molecules check the swift flight of the meteors, and thereby heat them so intensely that the meteors are mostly reduced to harmless gas and dust before they can reach the ground. In the short interval while they are being consumed, they leave blazing trails.

If the falling meteor is as bright as the brightest stars, it is called a *fireball.* If it explodes, it is a *bolide.* It becomes a *meteorite,* if it partly survives the consuming heat of its flight through the air. Very large meteors blast out great pits in the earth's surface that we call *meteor craters.*

9.7. Meteor Trails. It is estimated that a single observer can see an average of ten meteor trails in the course of an hour on clear, moonless nights throughout the year. If we suppose that one person can view the trails over a hundred thousandth of the earth's surface, then the meteors that are bright enough to be visible to the naked eye are falling at the rate of a million an hour over the whole earth.

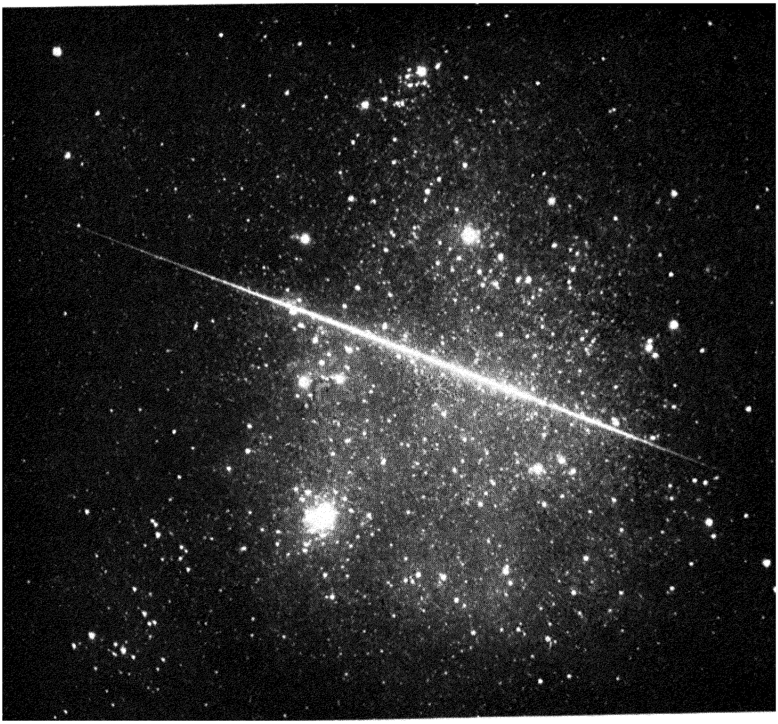


FIG. 9.7. Trail of a Brilliant Meteor. The meteor was brighter than the planet Venus. The left end of the trail is a little way south of Capella. The middle of the trail is nearly halfway between Algol and the Pleiades, and the right end is between Triangulum and the little triangle of Aries. The Hyades appear in the lower left corner. Photographed at the Oak Ridge station of Harvard Observatory. (*Courtesy of Wide World Photos, Inc.*)

This is the average rate of fall, according to the estimate, when no unusual displays are occurring. Doubtless it must be increased several times, if we include the fainter meteors visible only through the telescope. The frequency of the trails varies with the time of night, for one thing.

Twice as many meteors are likely to be seen in an hour's watch before dawn as appear in that interval after nightfall. In the morning we are on the forward side of the earth in its swift revolution around the sun, while in the evening we are on the rear, partly protected from the meteor storm.

Consider the effect of the earth's revolution on the speeds of meteors as we see them. Suppose that the meteors are travelling at the rate of 26 miles a second, which is about as fast as they can possibly go at this distance from the sun, if they really belong to the solar system (7.13). Since the earth's speed in its orbit is 18½ miles a second, the meteors of the morning with which we collide head-on can enter the atmosphere as fast as 44½ miles a second. Those that overtake us in the evening can come in as slowly as 7½ miles a second; these limiting speeds may be increased by 2½ miles a second owing to the earth's attraction. So in their swifter flight through the air the meteors that we see in the morning are subjected to more intense heat than the slower going meteors of the evening skies. Their trails are bluer, and the meteors themselves are less likely to penetrate as far as the ground.

9.8. The Paths of Meteors. A single observer sees only the directions of the meteor trails with relation to the stars. If two observers stationed several miles apart watch the same meteors, they can determine the heights of the trails in the atmosphere. Timing the durations of the flights, they can determine the speeds of the meteors.

On the average, small meteors appear at the height of 68 miles and disappear at 54 miles; the trails of fireballs are 87 miles high at the beginning and 31 miles at the end. These altitudes vary with the mass of the meteor and the time of night. The tops of the trails are often more than 100 miles high. Meteorites have continued to glow to within a very few miles of the ground.

Do the speeds of meteors, when they are corrected for the effect of the earth's revolution, ever greatly exceed 26 miles a second? If so, those meteors do not belong to our solar system; they have come in from outer space.

Hoffmeister, in Germany, reached the conclusion that the majority of meteors come from outside. The preliminary report of an expedition sent to Arizona, in 1931, to observe meteor trails seemed to confirm that conclusion. From his analysis of his own observations with the naked eye and of Boothroyd's with the telescope, Öpik found velocities relative to the sun up to 150 miles a second. Excluding members of well-known periodic swarms, the majority of the meteors observed by the expedition seemed to have come from outside the solar system.

Yet there is room for doubt. The orbits of a number of very bright meteors, as determined by Whipple at Harvard and Wylie at Iowa, have definitely closed orbits, in general. This may be true of the fainter meteors as well. The published speeds of meteors have sometimes been overestimated, as W. J. Fisher showed.

9.9. Swarms of Meteors. Multitudes of meteors which travel together constitute a *meteor swarm.* If the swarm is considerably strung out along its orbit, it is sometimes known as a *meteor stream* also. *Sporadic meteors* are those that do not belong to any recognized swarm.

Meteor swarms are invisible, like the individual meteors, except when they encounter the earth's atmosphere. Then a *meteor shower* occurs. The trails of the meteors in the shower are directed away from a small area in the sky, whose center is the *radiant* of the shower.

The members of a swarm are traveling together, so that their bright trails through the air are really parallel, except as meteors are deflected somewhat by the air from their original paths. The trails seem to spread out over the sky in the same way that the parallel rails of a track appear to diverge from a point in the distance. The place of the radiant in the sky and the speed with which the meteors enter the air, when allowance for the direction and speed of the earth's motion is made, permit the calculation of the orbit of the swarm around the sun.

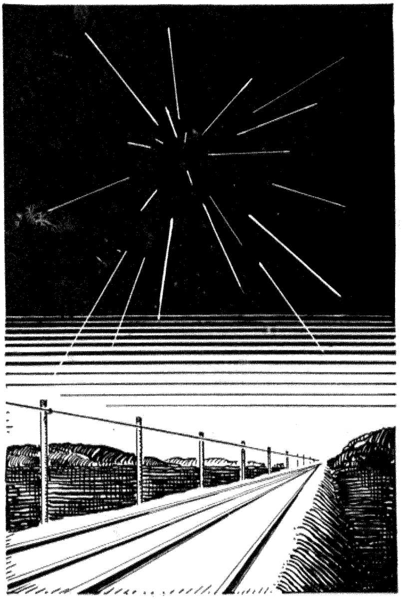


FIG. 9.9. The Radiant of a Meteor Shower.

Showers of meteors and the swarms that produce them are named from the positions of their radiants. Thus the trails of the Perseids seem to spread over the sky from their radiant in the constellation Perseus. Occasionally a swarm is known also by the name of the comet that travels in the same orbit; the Andromedes are the Bielids (9.5) as well.

Amateur astronomers are making important contributions to our knowledge of meteors. The American Meteor Society, under the direction of C. P. Olivier at the University of Pennsylvania, has been particularly active in the identification of the showers and in observing those that return periodically. A group under the guidance of C. C. Wylie at the University of Iowa investigates the numbers and heights of trails, and assembles records of especially brilliant ones. The more recently formed Society for Research on Meteorites is concerned especially with meteors that fall to the ground.

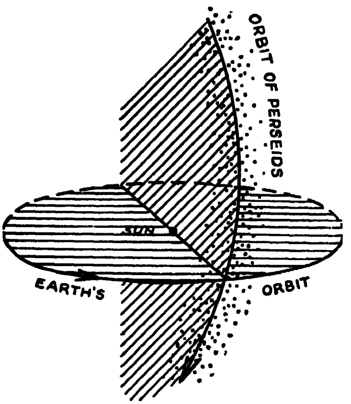


FIG. 9.10. Intersecting Orbits of the Perseid Meteors and Earth.

9.10. Showers of Meteors. Remarkable showers of meteors occur occasionally. Leonid showers of the nineteenth century were so brilliant as to terrify superstitious people. As recently as October 9, 1933, a shower having its radiant in the V-shaped head of Draco made a fine display in Europe. Meteors fell "as thickly as flakes of snow in a snowstorm." Peasants in Portugal were said to have taken refuge in churches, believing that the heavens were falling.

But most meteor showers are not spectacular enough to attract the attention of those who are not watching for them. Such showers are numerous. In the course of the year the earth crosses the orbits of hundreds of swarms. Some of these give showers every year while we are passing the intersections. Others that are more compact put on displays at longer intervals, when they and the earth come to the crossings at the same time.

Showers which recur periodically must be caused, of course, by swarms that revolve in closed orbits around the sun. A few of these, and the dates of the maximum displays, are:

The Lyrids (April 20). Small numbers are observed every year. Showers from this stream are recorded as early as 687 B.C. They have been brilliant at times.

The Perseids, or *August meteors* (August 11) are the most conspicuous of the annual showers, though they are never spectacular.

The Orionids (October 20) and the *Geminids* (December 10) are among the most faithful of the annual showers.

The Leonids (November 14), having their radiant in the well-known Sickle of Leo, appear at intervals of 33¼ years, the period of their revolution around the sun, for several years in succession at each appearance. First observed in A.D. 902, they gave especially remarkable displays in 1833 and 1866-1867. The returns of around 1900 and 1933 were less impressive, either because a considerable part of the swarm had been diverted meanwhile by the attractions of the outer planets, or because the earth did not happen to collide with congested regions of the swarm.

The Andromedes, or *Bielids* (November 24), traveling in the path of the lost Biela's comet, gave fine showers in 1872, 1885, and 1898. Only a few have been seen in recent years.

9.11. The Importance of Meteors. The evidence is accumulating that meteoric matter plays an important part in our solar system and in the universe generally.

The many swarms of meteors which are known to us because they happen to encounter the earth suggest that the whole number of swarms revolving around the sun must be very great indeed. The millions of sporadic meteors consumed in our atmosphere every day are surely mere handfuls in comparison with the vast numbers speeding all around us.

Meteoric matter is the chief building material of comets. Moreover, certain meteor swarms and comets travel in the same orbits around the sun. Since Schiaparelli, in 1866, discovered this relation between the Perseid meteors and Tuttle's comet of 1862, fully half a dozen other cases have been noticed.

The rings of Saturn are composed of meteoric matter. The dividing line between large meteors and small asteroids is not easy to define. The zodiacal light, next to be considered, is supposed to be sunlight reflected from meteoric material.

Finally, if the recent evidence that the majority of sporadic meteors have open orbits relative to the sun is substantiated, it extends their domain beyond the solar system. There is the possibility, too, that the cosmic clouds which cause the dark rifts in the Milky Way are assemblages of this same material that produces the "shooting stars" in our skies.

9.12. The Zodiacal Light. The faint triangular glow of the *zodiacal light* can be seen extending up from the west horizon after nightfall in the spring, and in the east before dawn in the autumn. Broadest and brightest near the horizon, it tapers upward, leaning toward the south, and fades into the sky perhaps as much as 90° from the sun's place. It lies along the ecliptic, and is most conspicuous, therefore, when the ecliptic stands most nearly vertical.

In the tropics, where the ecliptic is never far from vertical, the zodiacal light can be observed all year around. And here the faint glow has been seen extending as a narrow band completely around the ecliptic.

The zodiacal light is believed to be sunlight reflected from meteoric material within the earth's orbit. Russell points out that the light we see could be accounted for if the space inside our orbit contains particles a twenty-fifth of an inch in diameter and five miles apart.

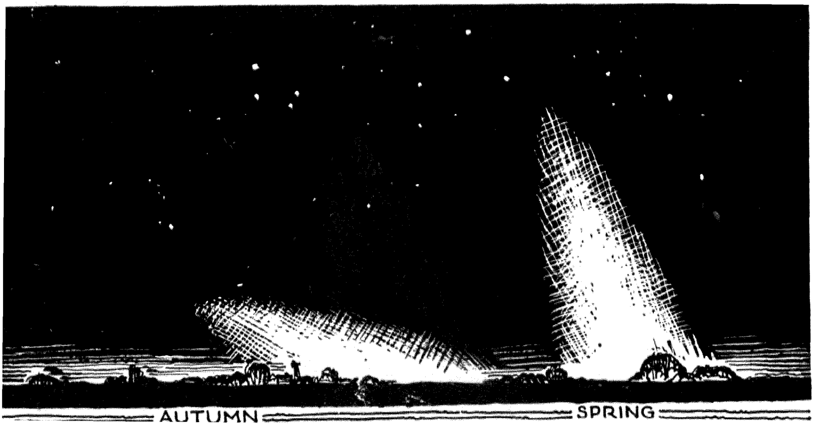


FIG. 9.12. The Zodiacal Light is Most Conspicuous in the Evening Around the Beginning of Spring, because the ecliptic is then most nearly vertical.

Opposite the sun the faint band of light brightens somewhat and widens into the oval *gegenschein*, or counterglow, some 10° or 15° long. First noticed less than a century ago, this hazy spot has since been frequently glimpsed and even photographed.

Elvey's studies of the gegenschein, at Yerkes Observatory in 1932, are noteworthy. Employing a sensitive photoelectric cell at the focus of the 40-inch telescope he found the oval glow fully twice as great as the eye could see. Its center was not far from the point directly opposite the sun. But the precise position of the center and the dimensions of the gegeschein seemed to him to change from night to night. Why the material congregates out there opposite the sun is an interesting problem for the mathematician.

METEORITES AND METEOR CRATERS

9.13. Stones from the Sky. Near noon one day in November, 1492, a month after Columbus first set foot in the New World, a number of stones came down in a field near Ensisheim, Alsace. The largest one, weighing 260 pounds, was placed in a church in that town; a piece of it may be seen in the Field Museum in Chicago. This is the oldest observed fall of meteorites on record, of which samples are still preserved.

The belief that stones fall from the sky goes back to very early times. There were stones preserved in some of the ancient temples which were doubtless of celestial origin. The famous black rock at Mecca is supposed to be a meteorite. These "stones from heaven" were often objects of veneration. Thus our Indians of the southwest revered and made offerings to great meteorites which lay in that region.

But in later times, all reports of stones falling from the sky came to be regarded with suspicion by the scientists. The stones seemed to choose remote places where there were no reliable observers. Doubtless, too, the accounts of terrified and perhaps highly superstitious spectators of some of the falls were so greatly exaggerated that no one could believe them.

Finally, in April, 1803, a shower of two or three thousand stones fell at L'Aigle, in France, and many people saw it. But the news spread so slowly that when three hundred pounds of stones came down near Weston, Connecticut, in December, 1807, the first recorded fall in the United States, most people did not believe the report at first.

9.14. Falls of Meteorites. Meteors which survive the intense heat of their flight through the air are larger, of course, than the general run. So their falls are more spectacular than the shooting stars. Sometimes they are brilliant even in full daylight, and they are followed by bright trains of melted stuff swept back by the rush of air. Often they are announced by blinding flashes of light and terrific crashes like thunder claps. Often, especially if they are composed of stony material, they are shattered into many fragments by impact of the air.

Brought almost to a full stop by air resistance while they are yet far from the ground, they drop the rest of the way under the earth's attraction alone, and quickly cool. The heat has not had time to reach far into their interiors; this is particularly true of stony meteorites which conduct heat slowly. The melted material that has not been swept away hardens into black crusts, and the meteorites come down usually cool enough to be handled comfortably.

Most meteorites are so reduced in speed when they land that they penetrate only a few feet into the ground, at the most. But the heavier the meteorite, the less it is impeded by the air. The really enormous ones strike at nearly full speed, and explode, blasting great holes in the earth and scattering destruction far and wide. It is fortunate that these do not come often.

Meteorites are named from the locality where they are found. Examples are: the Canyon Diablo meteorites; the Tucson meteorite.

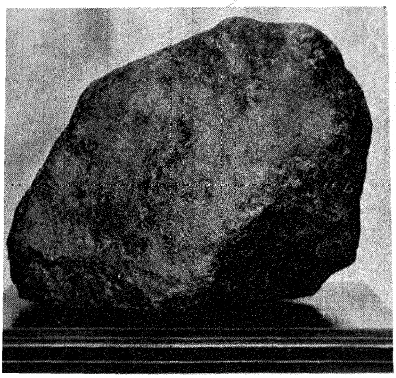


FIG. 9.15. Paragould, Arkansas, Meteorite. The largest single stone meteorite whose fall has been observed. (*Photograph by the Field Museum, Chicago*)

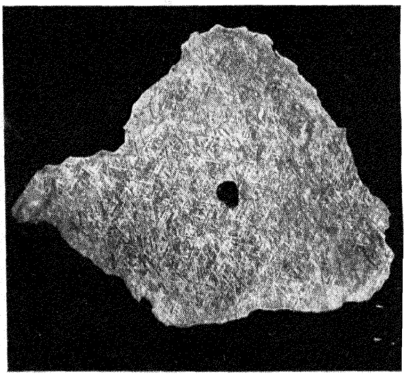


FIG. 9.15A. Etched Section of the Gibeon, South West Africa, Meteorite. (*Photograph by the American Museum of Natural History, New York*)

9.15. The Meteorites Themselves. These intruders from outer space are chiefly of two kinds: stony meteorites and iron meteorites. Inside their varnish-like black crusts, the *stony meteorites* are commonly grayish, appearing somewhat like the lighter colored native igneous rocks. But they are likely to be heavier than these, and to differ from them further by containing specks of nickel-iron.

The Long Island (Kansas) meteorite, found in 1891, is the heaviest stony meteorite, though it was broken into three thousand pieces just before it struck. Picked up within a space no larger than an ordinary room, these pieces weigh together 1244 pounds. The heaviest single stony meteorite (Fig. 9.15) is the largest of four which fell near Paragould, Arkansas, on February 17, 1930. It weighs 750 pounds, and is now in the Field Museum.

Iron meteorites are silvery under their blackened exteriors; they are composed mainly of alloys of nickel and iron. These alloys are affected by acids in different degrees. When they occur in crystal forms and when a section of such a meteorite is polished and treated with acid, the crystal structures show in striking patterns (Fig. 9.15A). The Grootfontein meteorite, the largest of all, which is one part nickel and five parts iron, does not show these patterns.

There are stony-iron meteorites, too; some are sponges of nickel-iron with stony fillings. The individuals of each fall have features different from those of other falls; and they are different enough from native rocks so that they are likely to attract attention whether they are "falls" or "finds" which were not actually seen to fall.

Individuals from more than a thousand falls of meteorites have been recovered and preserved. These are about half "falls," which are mostly stony meteorites, and half "finds," where the irons are most numerous, doubtless because they are more likely to be noticed, and because they crumble away less rapidly. Large collections of meteorites are exhibited in the Field Museum, Chicago, the American Museum of Natural History, New York, the National Museum, Washington, the British Museum, London, and in other places.

9.16. Showers of Meteorites. Because they are so often shattered in the flight through the air, and because they sometimes enter the atmosphere in groups, it frequently happens that many meteorites fall at the same time. This is a *shower of meteorites,* which must not be confused with a shower of meteors (9.10).

Several thousand individuals have come down in a single shower — a fine thing for the collectors. They scatter over an oval area often several miles long, whose lengthwise direction is the direction in which the group of meteorites came slanting to the ground. The heaviest individuals are likely to carry farthest, and so to land at the far end of the oval.

A shower of stones, preceded by blinding displays of celestial fireworks and by loud explosions, fell near Homestead, Iowa, February 12, 1875. Many thousands fell near Holbrook, Arizona, on July 19, 1912. Four terrific explosions announced a larger shower of stones in the vicinity of Johnstown, Colorado, in the afternoon of July 6, 1924. These are examples.

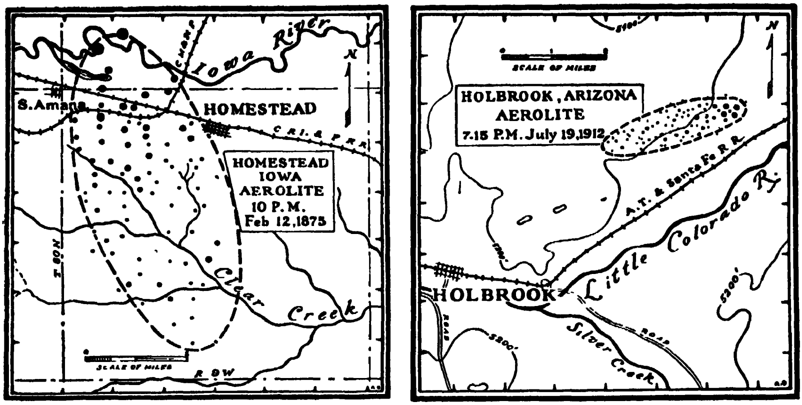


FIG. 9.16. The Homestead, Iowa, and Holbrook, Arizona, Showers of Meteorites. Showing the characteristic oval areas in which the meteorites were found, and how the heaviest individuals, represented by the largest dots, landed at the far ends of the ovals. (From *Natural History*, June, 1933)

9.17. The Great Iron Meteorites. All known single meteorites weighing more than a ton are masses of nickel-iron whose falls were not observed. They number somewhat more than a dozen. The heaviest of these monsters lies partly buried in the ground 12 miles west of Grootfontein, South West Africa, where it was found. Its upper surface measures 9 by 10 feet, and its thickness varies from 2½ to almost 4 feet,

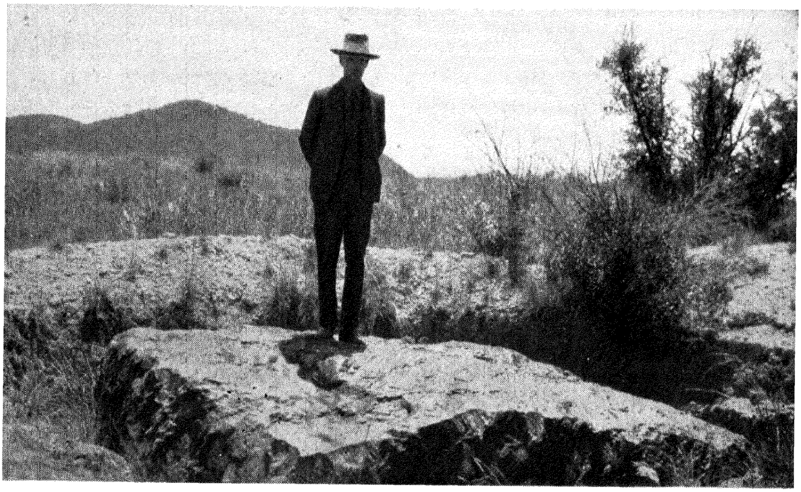


FIG. 9.17. The Grootfontein Meteorite. The largest known meteorite, a mass of nickel-iron weighing more than 50 tons. (*Photograph by W. J. Luyten*)

according to Luyten who visited the meteorite in 1929; its weight is estimated as more than 50 tons.

The largest of the Cape York meteorites, weighing 36½ tons, can be seen in the Hayden Planetarium in New York. It is 11 feet long, 5 feet wide, and 7 feet high. Brought back by the explorer Peary from an island in Melville Bay, Greenland, in 1897, it was christened "Ahnighito" in honor of his little daughter, the "Snow Baby." The Eskimos called it the "tent"; they had long known of this great meteorite and of three smaller ones in the same vicinity, which they called the "man," the "woman," and the "dog."

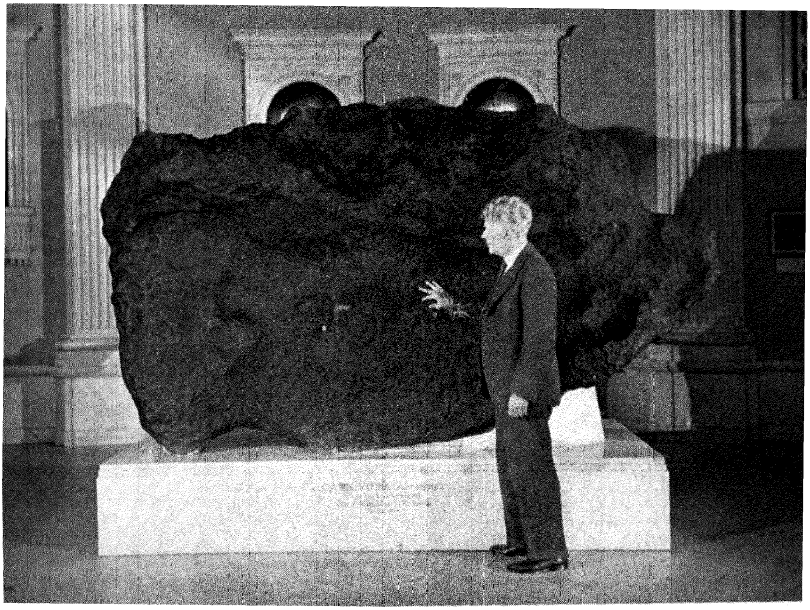


FIG. 9.17A. Cape York ("Ahnighito") Meteorite. A mass of nickel-iron weighing 36½ tons. (*Courtesy of the American Museum of Natural History, New York*)

The Willamette meteorite, also in the Hayden Planetarium, weighs 15½ tons. The largest single meteorite found in the United States, this cone-shaped mass of nickel-iron was discovered in 1902, nineteen miles south of Portland, Oregon.

A surprisingly large proportion of the great iron meteorites was found in Mexico. The largest one, weighing nearly 30 tons, is known as Bacubirito; it has not been removed from the place in Sinaloa, Mexico, where the American collector H. A. Ward unearthed it, in 1902. Five great irons are exhibited in the National School of Mines in Mexico City; these include Chupaderos, in two pieces which weigh together more than 20 tons, and the cone-shaped El Morito, weighing 11 tons. The Casas Grandes, a Mexican iron weighing nearly two tons, is in the National Museum in Washington. It was found wrapped in mummy cloth in a Montezuma ruin.

9.18. Meteor Crater in Arizona is a circular depression 4200 feet across and 570 feet deep. Its rim, which rises 150 feet above the plain outside, is composed of debris thrown out of the pit, from the finest rock dust to blocks of limestone and sandstone weighing thousands of tons apiece.

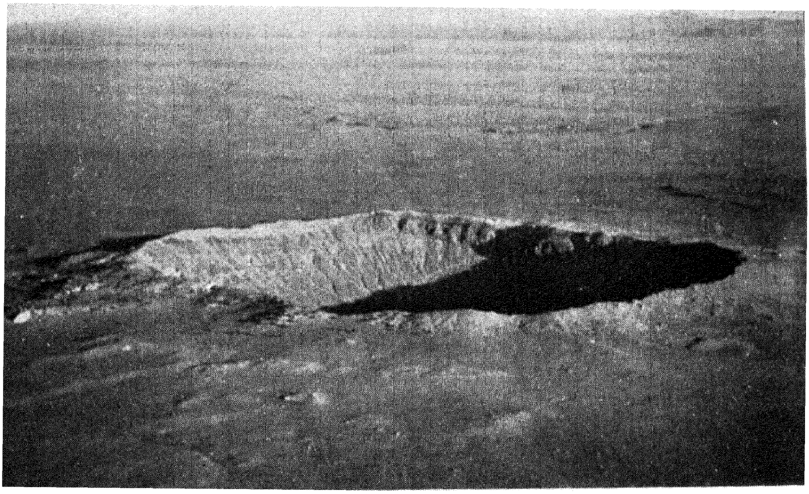


FIG. 9.18. Meteor Crater in Arizona. A great scar in the desert 20 miles west of Winslow, Arizona. Canyon Diablo and the San Francisco Mountains are in the background. (*Photographed from an airplane by Clyde Fisher*)

There is no doubt that this crater, near Canyon Diablo in northeastern Arizona, is the scar left by the fall of a great meteorite, or group of meteorites, many centuries ago. So massive that it was only slightly retarded by the air, it struck the earth a mighty blow. The enormous heat produced when the meteorite landed reduced the solid metal partly, or perhaps almost wholly, to gas.

The spreading of this gas was like the explosion of a gigantic charge of dynamite. It blasted out the great pit that we see, crushing the rocks for hundreds of feet below, and hurling rocks and fragments of the meteorite over the surrounding plain. Many of the iron meteorites that have been found in the vicinity of the crater, however, may have been companions of the main body. Borings have been made near the center of the crater and at its southern margin in the hope of locating a large meteorite underneath.

9.19. The Siberian Fall of 1908. The most destructive fall of meteorites recorded in modern times occurred on June 30, 1908, between the Yenissei and Lena rivers in north-central Siberia. A blast of intensely hot gases spread out from the place of the fall, devastating the country for miles around.

At 7 o'clock in the morning on that eventful day, a farmer was sitting on his porch in the settlement of Vanovara, fifty miles south of that place. He was amazed to see a great column of fire rising in the north. Heavy black clouds formed in that direction and spread quickly over the sky. Then came a terrific explosion. The man was hurled to the ground, and his house was badly damaged, according to the report.

A Russian scientist, Kulik, headed an expedition to this out-of-the-way part of the world, in 1927, and located the place of the fall. He viewed a scene of destruction over an area fully fifty miles across. The trees lay on the ground, stripped of bark and branches by the hot blast which felled them; they lay with their tops pointing away from the center of the area. In the center itself he found many craters which the meteorites had made. Some of the depressions are from 12 to 15 feet deep, and the largest is 150 feet in diameter.

This discovery of crater-like scars in the earth definitely associated with the fall of meteorites has drawn attention to similar pits in other parts of the world.

9.20. Other Meteor Craters are being recognized or at least suspected. In 1932, the English explorer Philby examined two large depressions at Wabar in the Arabian desert. He had heard from the Arabs a legend about a great city in that place, which had been destroyed by fire from heaven and buried in the sands. Philby identified the "buried ruins" as two meteor craters.

There is a circular pit 530 feet across near Odessa, Texas, which seems to be the work of a meteorite, for fragments of meteoric iron were found in the vicinity. There is a 650-foot pit near Henbury, in Central Australia, and a dozen smaller ones near by. More than a thousand pieces of meteoric iron were picked up in the neighborhood. There is a group of more than a dozen craters on the island of Oesel, in Estonia, recently visited and described by Clyde Fisher; the largest is 300 feet across. The Campo del Cielo craters in Argentina and a crater excavated by Ninninger near Haviland, Kansas, add to the growing list.

These great scars in the earth suggest a number of puzzling questions. Whence came the monsters that caused them? Were they enormous meteors, or comets, or perhaps stray asteroids? They bring to mind anew the theory that the lunar craters are scars left by falling meteors.

QUESTIONS ON CHAPTER IX

1. Why is Halley's comet the most famous of all comets? Name three other comets, and mention a specially interesting feature of each.
2. How would you answer the question: when will the next bright comet appear?
3. After a comet is discovered, how is it possible to decide whether it is a new one or the return of one that was seen before?
4. Distinguish between a family of comets and a comet group.
5. Can a comet's tail move in advance of its head?
6. If two observers stationed several miles apart watch the same meteors, they can determine the heights of the trails and the speeds of the meteors. Explain.
7. How is it possible to decide whether a meteor is a member of the solar system or comes from outer space?
8. Why is not the north pole a good place from which to view the zodiacal light?
9. Why should meteorites be cool, as a general thing, when they reach the ground?
10. Do you suppose that an enormous meteorite lies buried under Meteor Crater in Arizona? Why?

REFERENCES

H. H. Ninninger, *Our Stone-Pelted Planet* (Houghton Mifflin).

C. P. Olivier, *Comets* and *Meteors* (Williams and Wilkins).

Articles of current interest on meteors and meteorites by C. P. Olivier, C. C. Wylie, F. C. Leonard and others have appeared monthly in *Popular Astronomy*.

CHAPTER X

SUNLIGHT AND THE SUN ITSELF

THE SUN'S RADIATION — FEATURES OF THE SUN — THE SUN IN ECLIPSE

Finally in the description of the solar system we come to the sun itself. Containing almost 99.9 per cent of all the material in our system, the sun is therefore the most important member of the family; it holds the planets to their courses around it and provides them with light and heat.

The study of the sun is of interest to every one because of our dependence on the sun. Almost every kind of activity here on the earth can be traced back to the energy that comes to us in the sun's radiation. Power derived from the waterfall, from the wind, and from fuel and food has its origin in the great power plant of the sun.

The relative nearness of the sun to the earth makes it an object of special interest also because it is the only star whose features can be examined in detail. All the other stars are so remote that they appear only as points of light even through the largest telescope. In the study of the sun we are learning about a star.

We begin with the sunlight and the messages it brings concerning the sun itself. Then follow descriptions of the sun's surface, its atmosphere, and finally its filmy corona which comes into view when the sun is in total eclipse.

THE SUN'S RADIATION

10.1 The Spectroscope. When a beam of light passes obliquely from one medium to another, as from air into glass, it is refracted; its direction is altered. Since the amount of the change in direction increases progressively for different colors of the light from red to violet, the beam is sorted out by refraction into the *spectrum* of its constituent colors. Thus the rainbow is produced when sunlight is dispersed by raindrops or by the spray of the waterfall.

The *spectroscope* is employed for analysing light in this way. In its most common form it consists of a prism of glass toward which two small telescopes are directed. The light enters the first telescope through a narrow *slit,* and leaves through the *collimator* lens where it is transformed from a diverging to a parallel beam. The beam is then refracted and dispersed by the prism into a spectrum which is examined through the *view telescope.* For astronomical purposes the eyepiece of this telescope is usually replaced by a plate holder, so that the spectrum can be photographed.

If it is white light that is being examined, the spectrum is a continuous band of colors from red to violet. If the light consists of a limited number of colors, or better, wave lengths, the spectrum is a pattern of colored lines; and each line is an image of the slit in its particular color. So the narrow slit gives better selectivity, as a good radio set does. And so in general, the spectroscope shows what kinds of light are present in the beam.

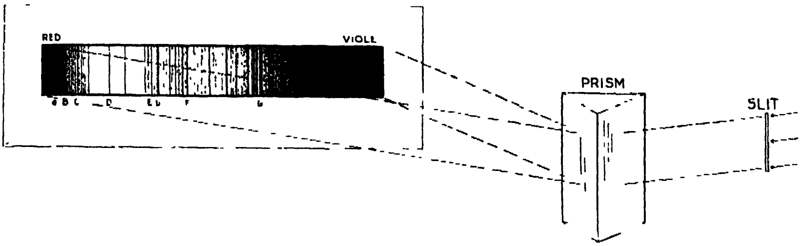


FIG. 10.1. The Spectrum of Sunlight. Prominent Fraunhofer lines are represented.

In the analysis of the light of the celestial bodies the spectroscope is attached at the end of the telescope, its slit where the light is brought to focus. For certain purposes the prism is of quartz or some other transparent substance instead of glass. Greater dispersion is effected by means of a train of prisms or else a *grating,* a piece of glass or metal on which many fine parallel grooves have been ruled. The objective prism spectroscope (11.11) has neither slit nor collimator; the prism is placed before the objective of the telescope itself which then takes the place of the view telescope.

10.2. Three Kinds of Spectra.

When the spectroscope is directed successively toward a variety of luminous objects both on the earth and in the heavens, it is found that spectra are of three kinds:

The continuous spectrum is an unbroken band of colors from red to violet. The source of the light is a luminous solid, liquid, or opaque gas. We are left in doubt in this case as to the chemical composition of the source. The filament of a lamp, a white-hot iron ball, the surface of the sun, all give continuous spectra.

The bright-line spectrum is a succession of colored lines, from red to violet, on a dark background. The source of the light is a glowing gas which broadcasts on a series of wave lengths like the radio stations of a network. Each chemical element glows in its particular selection of wave lengths and gives, therefore, its characteristic pattern of bright lines.

From such spectra the chemical composition of the source can be learned, whether the source of light is in the laboratory or far away in space. Some nebulae, such as the great nebula in Orion, have bright-line spectra. The spectrum of the sun's atmosphere, as it is viewed by itself during a total eclipse (10.14), is a pattern of bright lines. But most celestial bodies have spectra of the third kind:

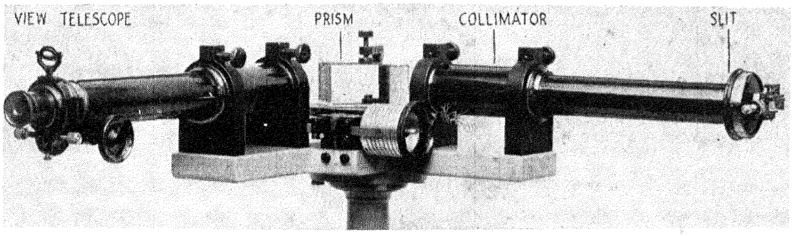


FIG. 10.1A. The Spectroscope. (*Courtesy of Adam Hilger, Ltd.*)

The dark-line spectrum is a succession of dark lines on an otherwise continuous background of the different colors. Cooler gas intervenes between the observer and the source of light which would otherwise give a continuous spectrum. The gas abstracts from the light the wave lengths that it emits itself. Thus the pattern of dark lines tells the chemical composition of the intervening gas.

The stars have dark-line spectra, as a general thing; the lines are produced while the light from the surfaces of the stars is filtering out through their atmospheres. Similarly, the spectrum of sunlight shows a pattern of dark lines, whether it comes to us directly or by reflection from the moon and planets.

10.3. The Spectrum of Sunlight is a band of colors from red to violet interrupted by thousands of dark lines. The lines do not show in the rainbow or in the spectrum formed by the prism alone. Fraunhofer was the first to see them clearly, in 1814, when he examined the sunlight with the spectroscope. He mapped 350 dark lines, and labeled the most prominent ones with letters of the alphabet beginning at the red end of the spectrum. These lines are still known by the letters which he assigned them.

Fraunhofer viewed them simply as a complex pattern of lines. And their meaning remained unknown until the physicist Kirchhoff explained, in 1859, that they are wave lengths abstracted from sunlight, for the most part by various gaseous chemical elements in the solar atmosphere. Miss Moore lists 64 chemical elements known to be present in the sun; these have been identified by comparing the solar spectrum with the spectral patterns of elements here on the earth.

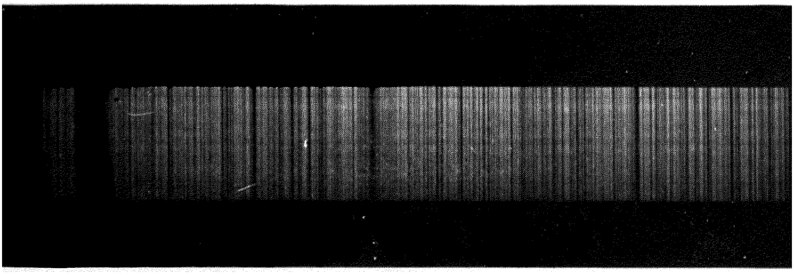


FIG. 10.3. Part of the Solar Spectrum. The two broad lines at the left are the H and K lines of calcium. (*Photographed by Frank Schlesinger at the Allegheny Observatory*)

The Fraunhofer C line in the crimson and the F line in the blue-green are due to hydrogen, the twin D lines in the yellow to sodium, the E line in the blue to iron, and the great H and K lines in the violet to calcium. The A and B bands in the red are caused by absorption of the sunlight in our own atmosphere; lines and bands such as these are easily distinguished from the truly solar lines by their increasing strength as the sun approaches the horizon, and in other ways.

The solar spectrum can be followed photographically into the ultra-violet, but only a little way before it is cut off completely by the ozone in our atmosphere. It is a fortunate arrangement indeed that the health-giving ultra-violet rays of the sun are allowed to reach us while the life-destroying ones of shorter wave lengths are prevented from doing so.

Beyond the reddest light the eye can see, the solar spectrum can be observed photographically to many times its visible length, and still farther into the infra-red by sensitive heat-detecting instruments. Here there are wide gaps caused by the obstructing action of water vapor and carbon dioxide in our atmosphere.

10.4. The Doppler Effect. *When the source of light is relatively approaching or receding from the observer, the lines in its spectrum are displaced respectively toward the violet or red end by an amount which is proportional to the speed of approach or recession.*

First announced by Doppler, in 1843, the principle was definitely applied to the spectrum by Fizeau, in 1848. Just as the pitch of the engine bell or of the fire chief's siren is abruptly lowered as it passes by, so the wave lengths of the lines in the spectrum of the source of light are diminished or lengthened by its approach or recession; and the lines are displaced accordingly toward the violet or red from their normal places.

The Doppler effect permits the astronomer to determine how the stars are moving toward or away from the earth (11.7), to observe their rotations, pulsations, and explosions, and to detect closely revolving pairs of stars which the telescope itself cannot separate. The principle is useful too in the studies of the rotations of the sun and planets, and in other ways.

10.5. Heat from the Sun. Only a part of the sun's radiation is perceived as sunlight. Much of it arrives in wave lengths too short or too long to make any visual impression. But all of it produces heat when it is absorbed. So the best way to measure the sun's radiation is by its heating effect.

Abbot and his associates at the different stations of the Astrophysical Observatory of the Smithsonian Institution have made precise measurements of the heat we receive from the sun. They inform us that energy equivalent to 4,700,000 horsepower would come to each square mile of the earth's surface where the sun is directly overhead, if our atmosphere were withdrawn.

Since a shell completely enclosing the sun at the earth's distance would contain more than 10^{17} square miles, it is evident that the total energy continually escaping from the sun is very great indeed; each square *yard* of the sun's surface contributes 70,000 horsepower. Less than a two-billionth of the vast amount is intercepted by the whole earth.

10.6. The Sun's Temperature. More heat is given by a hot radiator than by one that is only warm. But what precisely is the relation between the intensity of the radiation and the temperature of the radiator? Suppose that its temperature is doubled, for example.

The answer to this question is provided by *Stefan's law,* which states that *the rate of radiation is directly proportional to the absolute temperature of the radiator raised to the fourth power.* So if the temperature of the radiator is doubled, the rate of its radiation becomes 16 times as great as before. Here is a means of learning the sun's temperature. The rate of its radiation, per square yard or square mile, can be determined, as we have seen. Then it is possible to calculate by Stefan's law the average temperature of the levels in the sun from which its radiation comes.

Another way is to observe the color of the sunlight, or better, to measure precisely at what wave length the colored background of the sun's spectrum has the greatest strength. *Wien's law* states that *the wave length at which the radiation is the most intense varies inversely as the absolute temperature.* The bluer the light is all together, the higher is the temperature at its source.

By these and other known relations between the quantity or quality of the radiation and the temperature at its source, the sun's temperature is found to be 5750° K, or about 10,000° Fahrenheit. At the center of its disk, where we look deepest into the sun, the temperature is about 6000° K. (K, or Kelvin, denotes the temperature in degrees Centigrade above absolute zero.) The temperature diminishes above the radiating surface, and it rises rapidly with increasing depth below the surface to millions of degrees at the sun's center.

FEATURES OF THE SUN

As we view it ordinarily, the sun is a gaseous globe 864,100 miles in diameter, or 109 times the earth's diameter. The sun is therefore 1⅓ million times as large as the earth; and since its mass is a third of a million times as great, its average density is one fourth the earth's density, or 1.41 times the density of water.

The *photosphere* is this visible surface beyond which we cannot look any farther into the sun. Dark *sun-spots* appear here, and bright *faculae* at somewhat higher levels.

The *chromosphere,* or "atmosphere" of the sun, surrounds the visible surface to a height of several thousand miles. Its densest region within a few hundred miles of the photosphere is sometimes called the *reversing layer,* where most of the dark lines of the solar spectrum are abstracted from the sunlight. So-named because of its scarlet color, as we see when the sun is in total eclipse, the chromosphere is the base from which the similarly colored *prominences* rise at times to heights of hundreds of thousands of miles.

The *corona* is still more extensive. This pearly outer envelope is the most impressive feature of the total solar eclipse; its petals arch high above the prominences, and its equatorial streamers sometimes reach out millions of miles into space.

10.7. The Sun's Visible Surface. The sun is too bright to be observed steadily with safety in a clear sky, unless the eye is protected from its glare. Viewed through a dark glass it appears as a round disk, and a perfectly blank one ordinarily to the eye alone. Through the telescope the disk is enlarged, and its features are brought out more clearly.

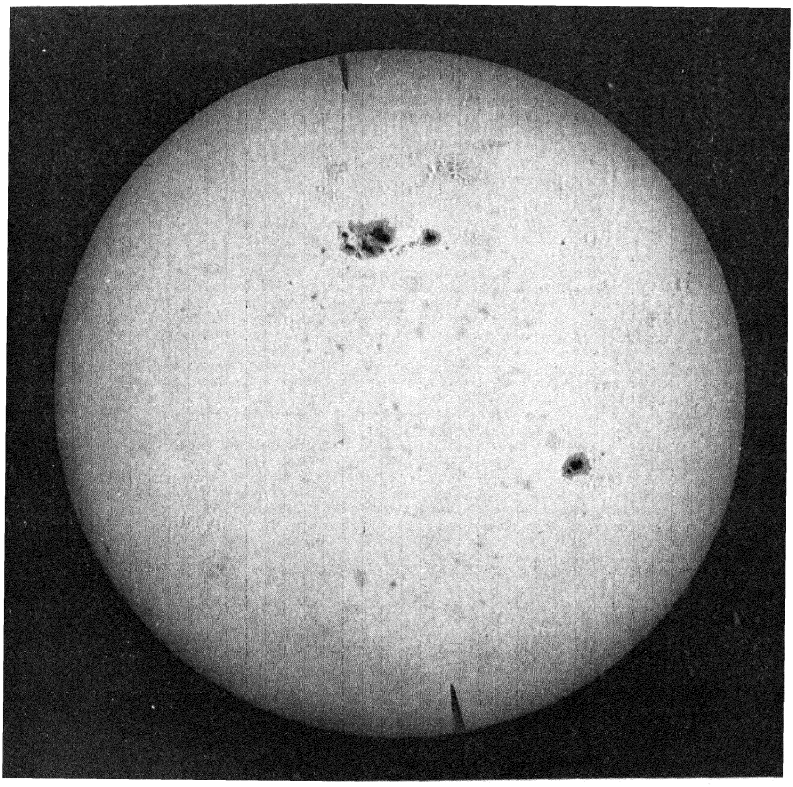


FIG. 10.7. The Sun, January 24, 1926. An exceptionally large group of sun-spots appears above the center of the disk. (*Photographed at Mount Wilson Observatory*)

We do not look directly through the telescope at the sun, of course, unless a special eyepiece is provided to divert most of the light and heat which the objective concentrates at its focus. A convenient way to observe the sun is to let the telescope project its image on a smooth white cardboard screen held a little way back of the eyepiece. The eyepiece must be drawn out somewhat farther than usual in order to focus the image sharply. In this way many people can observe the sun at the same time.

Through the telescope the sun presents a mottled appearance not unlike that of rough drawing paper. The disk is brightest at the center where we look vertically, and so deepest, into the sun. Near the edge where we look in obliquely, the view is arrested at higher, cooler, and accordingly less brilliant levels.

The sun's photosphere therefore represents a succession of layers of considerable thickness and of increasing height from the center to the edge of the disk. It is composed of gas hardly more than a ten thousandth as dense as our atmosphere at sea level. Yet it is opaque because it is so very hot.

The astronomers' studies of the photosphere, and of the more elevated regions of the sun as well, are largely photographic. The sun has been photographed at a number of observatories on every clear day for many years. And the majority of these researches have been concerned in one way or another with the dark spots on the sun.

10.8. Sun-Spots Show the Sun's Rotation. Galileo saw the sunspots in 1610, though he did not announce them until later. Meanwhile other early observers discovered them independently. They watched the spots come into view at the sun's eastern edge, move gradually across the disk from day to day, and disappear at the western edge; and they rightly concluded that the sun rotates on its axis from west to east.

The paths of the spots across the disk, which are of course parallel to the sun's equator, are usually curved; they are most curved early in March and September, while in early June and December the paths are straight (Fig. 10.8). It is because the sun's equator is inclined 7° to the ecliptic plane. The axis is directed toward a point in the heavens midway between Polaris and Vega. Its south pole is tipped toward us in March, its north pole in September, while its equator is edgewise to the earth in June and December.

Since the sun is gaseous, it is not surprising that different parts of its visible surface rotate in different periods. Spots near the equator go completely around in about 25 days, when they survive as long as that, though they seem to take a full four weeks to return to the middle of the disk because the earth has revolved partway around the sun in the meantime. In latitude 35° from the sun's equator, beyond which the spots are rarely seen, the true rotation period is about 27 days.

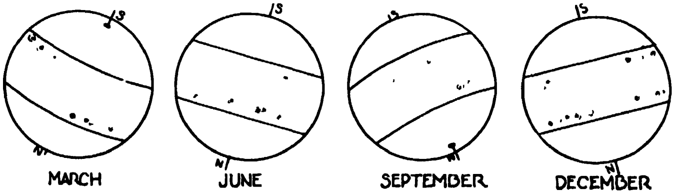
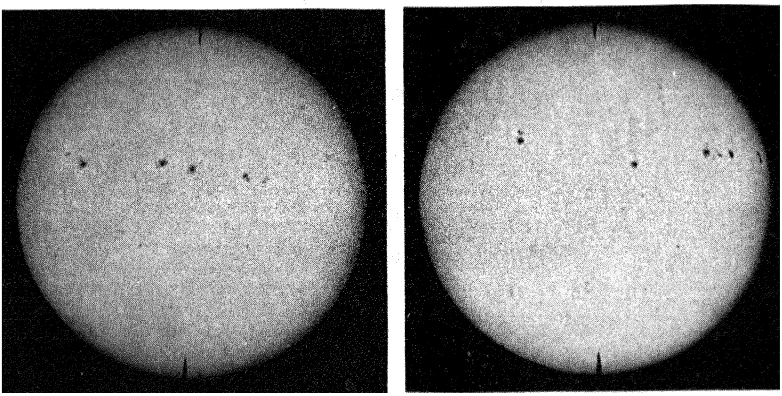


FIG. 10.8. Paths of the Spots Across the Sun's Disk at Different Seasons.

With the spectroscope it is possible to study the sun's rotation in different latitudes from the equator almost to the poles by comparing the Doppler effect at the approaching and receding edges. Adams found in this way, in 1908, a steady increase of the rotation period from 25 days at the equator to 34 days near the solar poles. The spectroscopically observed periods have varied considerably in the meantime; the variation may be caused, as St. John suggests, by the changing flow of the currents in which the dark lines of the sun's spectrum are formed.



October 10, 1926 October 14, 1926

FIG. 10.8A. Sun-Spots Show the Sun's Rotation. In the interval of four days the spots had moved toward the right. (*Photographed at Mount Wilson Observatory*)

10.9. Sun-Spots in Groups. Sun-spots are sharply divided into two parts: the *umbra,* the inner, darker part which comprises one sixth of the area of the whole spot, as a general thing, and the lighter *penumbra* around it. The sharp boundaries of these two regions are not well explained by the present theory of sun-spots, as Richardson has pointed out.

Nearly circular in their more stable states, they assume a variety of shapes in the processes of formation and dissolution, which are sometimes surprisingly rapid. They vary in diameter from a few hundred miles, the smallest ones which can be detected, to as much as 50,000 miles. They occur in groups which occasionally spread out over a sixth of the diameter of the sun's disk.

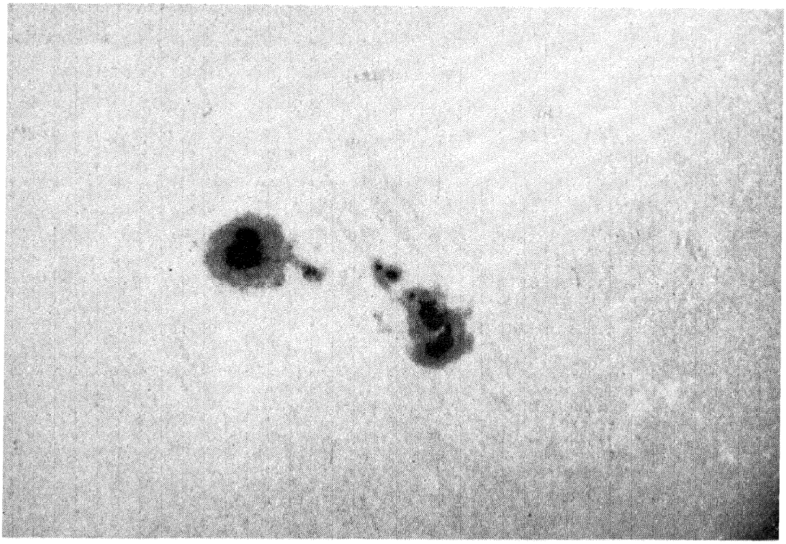


FIG. 10.9. Sun-Spot Group, September 17, 1926. The leading spot is at the left. (*Photographed at the Royal Observatory, Greenwich*)

The group is inaugurated by the appearance of two small spots in the same latitude, and three or four degrees apart in longitude. While these *principal spots* are rapidly growing, they draw apart to a difference of 10° or more in longitude; and in the meantime many smaller spots form in their vicinities. The *leading spot,* in the direction of the sun's rotation, becomes slightly the larger; it is also the more symmetrical of the two, and is subject to less rapid changes. At the end of a week the group attains its maximum area, and the decline sets in.

The *following spot* is the first of the principal spots to disappear, usually by repeated subdivision by brilliant "bridges." Presently the smaller spots vanish, and in a week or more after the maximum only the leader remains. This survivor of the group may remain for several weeks or even months; a spot observed in the years 1840–1841 lasted 18 months. Finally, all that are left to mark the region are bright faculae whose appearance was in fact the first indication of the disturbance which produced the group of spots.

10.10. Sun-Spots as Vortices. Sun-spots are dark only by contrast with the brighter regions around them. They are less luminous because they are cooler; their umbras have temperatures around 4800° K. Sun-spots are refrigeration projects on a vast scale. Areas of the sun's surface often far greater in diameter than the earth are kept for many days at a time a thousand degrees Centigrade cooler than their surroundings. By what process is it accomplished?

Comparable with the cyclones of our own atmosphere, they are regions where whirling columns of gases are ascending from below the sun's surface, and expanding as they reach the surface where the pressure around them is reduced. By expansion they are cooled and therefore darkened. At the same time, the gases in the sun's atmosphere above the spots are drawn down into the vortices; and they also whirl as they descend. This is the generally accepted theory.

Since Hale's discovery, in 1908, that sun-spots are magnets, much information about their magnetic characteristics has been revealed particularly by the studies of this astronomer and his associates at the Mount Wilson Observatory. That the spots are centers of magnetic fields is made evident by the broadening and even splitting of their spectrum lines, which is known as the "Zeeman effect." If these darkened regions are really vortices, then the spots are electromagnets owing presumably to the whirling of the electric charges they contain.

The descending gases far above the spots are whirling, as the spectroheliograms (Fig. 2.3) clearly show. They are turning in the counterclockwise direction in the sun's northern hemisphere and clockwise in the southern hemisphere, as a general rule. If the spots themselves are vortices, the usual rules of their turning are these, as their spectra show:

The leader and the following spot of a group whirl in opposite directions. Similar spots, leaders or followers, have opposite directions in the two hemispheres. And most remarkable of all, the directions of these lower vortices (more properly at present, their "polarities"

—the directions of their magnetic fields) are reversed with each succeeding sun-spot cycle.

10.11. The Sun-Spot Cycle. Sun-spots increase and then diminish in numbers in cycles of about eleven years. The discovery of this far-reaching fluctuation was made in 1843, by Schwabe, amateur astronomer of Dessau, Germany, after he had directed his small telescope to the sun on almost every clear day for nearly twenty years.

At the maximum of the cycle the sun's disk is seldom free from spots, and often it is speckled with a hundred or more. At the minimum it is not unusual for a week to pass without the appearance of a single spot. Wolf and his successors at Zurich have assembled the records of sun-spot counts from 1610 to the present time, and have drawn a curve to show how the area covered by the spots has varied.

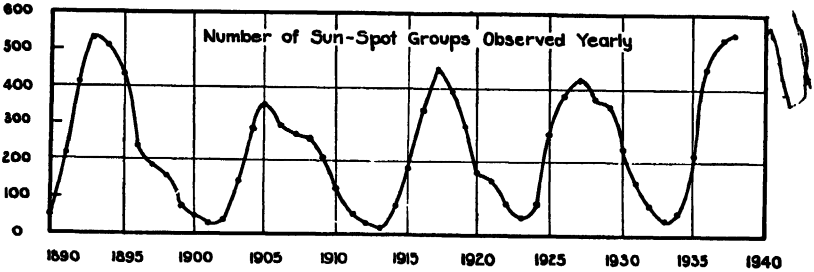


FIG. 10.11. The Sun-Spot Number Cycle. The point for each year represents the number of sun-spot groups observed during the year. The curve shows the roughly periodic variation in the numbers. (*From data by S. B. Nicholson*)

Nicholson's curve of the variation in the number of groups (Fig. 10.11) shows the character of the fluctuation equally as well. The intervals between the maximum spottedness average 11 years, varying mostly between 8 and 14 years. The rise to maximum is faster than the decline; and for a number of cycles in recent years the maximum numbers of groups have been alternately greater and fewer than their average.

Sun-spot minimum occurred toward the end of 1933, and the following maximum was reached in the fall of 1937.

10.12. The Shifting Sun-Spot Zones. Sun-spots are almost never found more than 45° from the sun's equator. They occur mostly within 30° of the equator; and they are not scattered at random within this band. The majority of the spots break out in two rather narrow zones at equal distances north and south from the equator, zones which shift equatorward as time goes on.

The two zones of activity have moved down to around latitude 16° when the spots are most numerous. As the time of minimum approaches, the zones of the declining disturbance have drawn in closely around the equator. Before the last spots of the old cycle have entirely vanished, perhaps a month or two before the minimum is reached, the first members of the new cycle make their appearance around latitude 30°.

The spots of the new cycle have the same aspect as the old ones. But when their magnetic characteristics are examined with the spectroscope it is found that their "polarities" are reversed. If the spots are magnets because they are vortices, then the rules about the rotations (10.10) are all turned around, though the directions of the whirling regions far above the spots remain the same as before. This remarkable reversal, first noticed by the Mount Wilson observers after the minimum of 1913, was verified in 1923 and again in 1933 when succeeding new cycles appeared. The first spot of the present cycle, in heliographic latitude +26°, was seen on October 10, 1933.

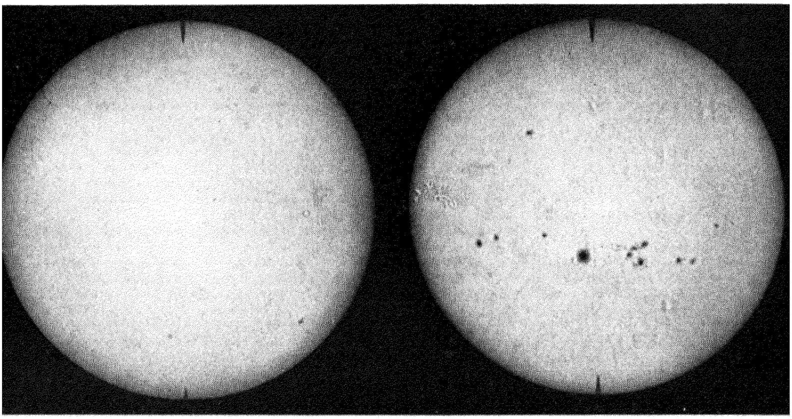


FIG. 10.12. Sun-Spots Vary in Numbers. Two views of the sun at different times. (*Photographed at Mount Wilson Observatory*)

Sun-spots are conspicuous manifestations of a fluctuating solar disturbance, perhaps in a true period of 22 years, whose effects extend from the sun's visible surface up to the outer reaches of its tenuous corona, and on to the earth itself. The bright faculae vary in numbers with the dark spots. The bright mottlings of flocculi revealed by the spectroheliograph vary likewise, as Hale and Fox demonstrated long ago. The red prominences (10.16) are most numerous and active around sun-spot maximum. The form of the corona (10.19) varies with the sun-spot cycle. Certain occurrences around us here on the earth show clearly the influence of this cycle.

10.13. Terrestrial Associations. The rapid and excessive gyrations of the compass needle which inform us that a "magnetic storm" is in progress occur most frequently and violently when sun-spots are most numerous. Displays of the aurora, or polar lights, are most frequent and spectacular around the times of sun-spot maximum.

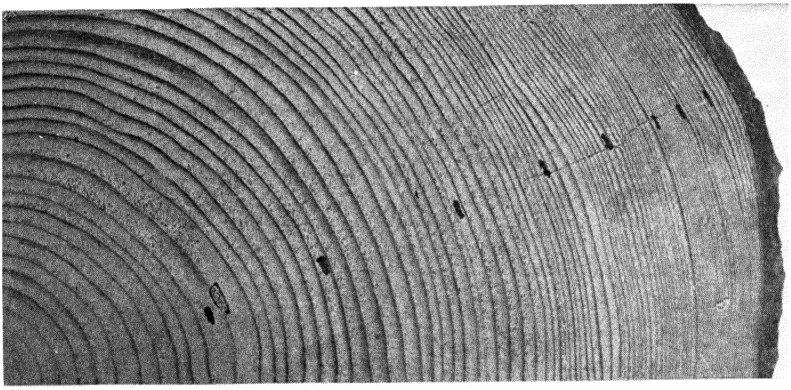


FIG. 10.13. Tree Rings. The dots mark rings formed at sun-spot maxima. (*Photographed by A. E. Douglass*)

These effects, and the impaired telegraphic and radio service which is likely to accompany them, vary with the 11-year cycle. Some, and perhaps all, of these variations can be ascribed to changing electrical conditions in the upper atmosphere under the influence of radiation from the sun varying in this cycle.

The total radiation we receive from the sun becomes a little more intense as the sun-spots increase in number, while the sun's ultra-violet radiation that we receive increases conspicuously. It might be imagined, therefore, that our weather and many things that depend on it would exhibit variations in the sun-spot cycle. Yet they do not do so in an unmistakable way, as a general thing. Correlations of the spot cycle with rainfall, temperature, and the ways of vegetable and animal life have usually been viewed with suspicion. One of these correlations is remarkable:

Douglass, of the University of Arizona, has studied the annual rings of ancient trees which abound in the southwestern country, viewing them in cross section when they are cut down. He finds that the spacing of the rings, which shows the increase of the tree's girth from year to year, varies in the 11-year cycle.

10.14. The Chromosphere, or "color sphere," surrounds the photosphere to a height of several thousand miles. This more tenuous layer of gases through which we look at the surface of the sun is also known as the sun's atmosphere. Its scarlet glow can be seen around the totally eclipsed sun, and the arrangement of its gases can be studied to advantage on these occasions.

These gases which cause the dark lines in the solar spectrum must give a similar pattern of bright lines when they are observed alone, according to the rules of spectrum analysis (10.2). Young was the first to see this *flash spectrum* at the eclipse of 1870; he so named it because the bright lines flash into view through the spectroscope in place of the dark ones near the beginning of the total eclipse.

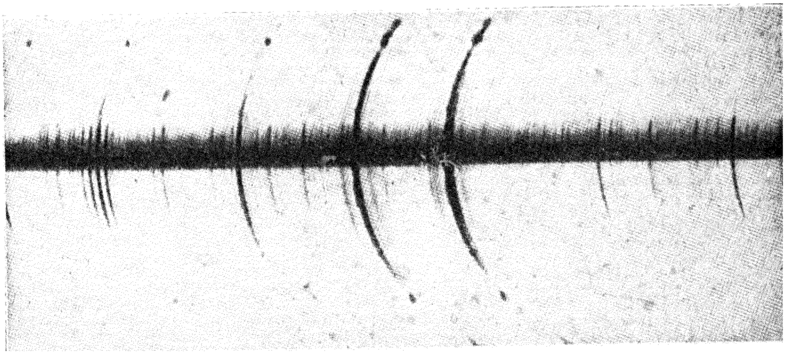


FIG. 10.14. The Flash Spectrum. A negative of the violet region of the spectrum of the chromosphere during a total eclipse of the sun. The two longest crescents are the H and K lines of calcium. (*Photographed by S. A. Mitchell, University of Virginia*)

As photographed with a slitless spectroscope near the beginning or end of totality, the flash spectrum (Fig. 10.14) appears as a succession of images of the narrow crescent of the chromosphere left uncovered by the moon's dark disk. The different lengths of the crescents show that some of the elements which produce them are effective at greater heights above the photosphere than others. Hydrogen, helium, and calcium give the longest crescents of all. On the other hand, the shortness of the majority of the crescents informs us that most of the chemical elements in the sun's atmosphere absorb the sunlight effectively only in the lowest levels which comprise the "reversing layer."

The flash spectrum is not an exact copy of the dark-line spectrum, it is true. The strong bright helium lines of the chromosphere, by which this useful gas was discovered in the sun long before it was found on the earth, are almost entirely missing in the ordinary solar spectrum.

Mitchell, of the University of Virginia, has determined the heights of elements in the chromosphere by measuring the lengths of the crescents of the flash spectrum, which he has photographed at a number of eclipses. Menzel has derived similar data from Lick Observatory photographs of the flash spectrum taken in a different way. Much of our knowledge of the sun's atmosphere has been obtained at other times than eclipses by means of the spectroheliograph.

10.15. The Spectroheliograph was invented in 1890, by Hale, then at his Kenwood Observatory in Chicago, and independently by Deslandres in France. An elaboration of the simple spectroscope, it is a device for photographing the sun in the light of a single line of its spectrum, and therefore in the light of whatever element produces the chosen line. The photograph is the *spectroheliogram.*

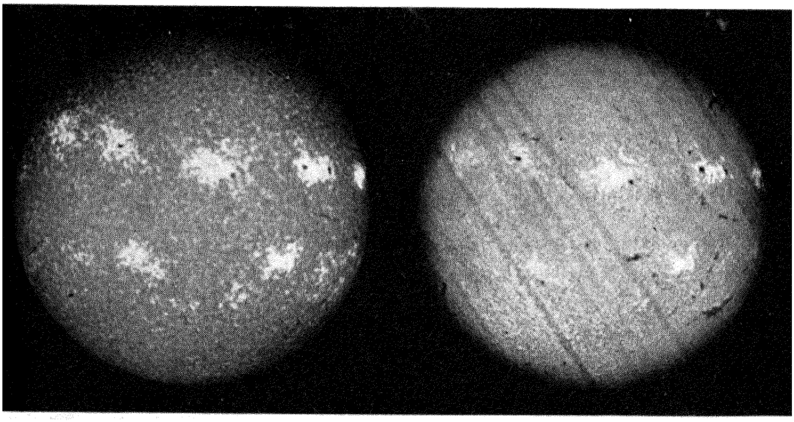
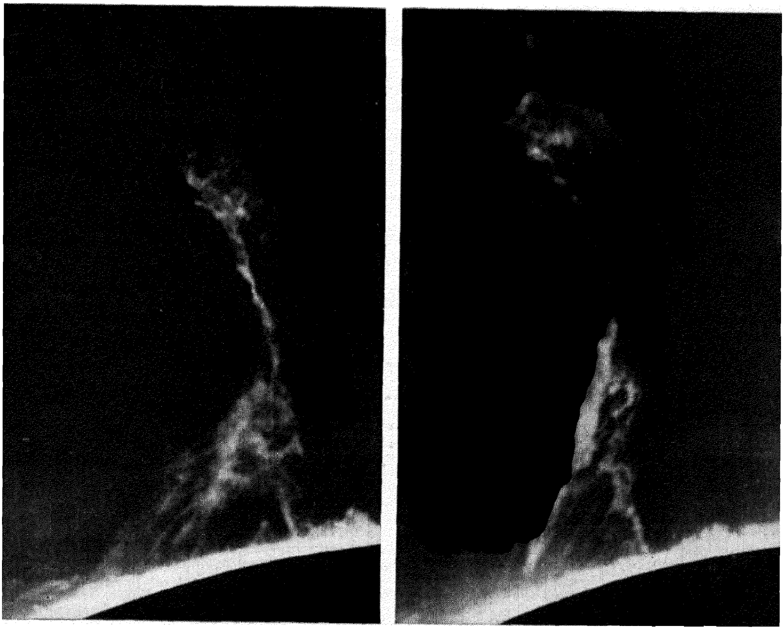


FIG. 10.15. The Sun in Calcium and Hydrogen Light. Spectroheliograms, October 14, 1926, taken with the K line of calcium (left) and the red hydrogen line (right). The direct view of the sun at that time is shown in Fig. 10.8A. (*Photographed at Mount Wilson Observatory*)

The K line of calcium and the red line of hydrogen are the ones most used. In the first case the photographs show great masses of calcium "flocculi" which are especially prevalent in the sun-spot regions (Fig. 10.15). In the second case they reveal mottlings of hydrogen masses which are spun out in the whirlpools above the spots, and the forms of prominences dark and sinister against the brighter background below. They picture also the prominences which reach out beyond the sun's edge.

Armed with this powerful instrument, astronomers have kept the activities of the sun's atmosphere under daily scrutiny for many years. In addition, the *spectrohelioscope,* which Hale perfected in 1924, permits these features of the sun to be observed visually as well.

10.16. Solar Prominences. Hidden ordinarily in the glare which our atmosphere diffuses around the sun's disk, the scarlet prominences come into view when the sun is eclipsed. Projecting then beyond the dark edge of the eclipsing moon, they owe their lurid hue chiefly to the



11:35 A.M.
Height 194,000 miles.

12:16 P.M.
Height 280,000 miles.

FIG. 10.16. The Rise of a Solar Prominence. Its height was increasing at the rate of 125,000 miles an hour. (*Photographed, August 6, 1931, by Edison Pettit at Yerkes Observatory*)

glowing hydrogen they contain; calcium and helium are also important constituents. Though they are ten thousand million times as rare as the air around us, their vast extension makes them clearly visible to the naked eye at these times.

Prominences were observed only during total solar eclipses until 1868, when a way was discovered of viewing them at other times through the widened slit of the spectroscope. Since 1890, they have been studied extensively outside eclipses with the spectroheliograph and spectrohelioscope. In 1930, Lyot contrived a special arrangement of the telescope, with which he and others have observed the prominences, and some features of the inner corona as well, outside eclipses. Motion pictures of the prominences by Lyot and at the McMath-Hulbert Observatory exhibit their spectacular behavior with remarkable clearness.

Many prominences appear as eruptions from the chromosphere. The rate of more than 100,000 miles an hour at which the prominence in Fig. 10.16 was ascending is not at all excessive. They reach enormous heights above the sun's surface, sometimes as much as half a million miles, and then either disperse or topple back. Some seem to be torn apart as they rise; some resemble fountains; some have the twisted appearance of tornadoes.

Often the prominences seem to originate in mysterious sources high above the chromosphere, and the material continues to rain down with no indication of how it is replenished at the sources. In contrast with such displays of violent activity, there are other prominences which remain suspended for days high above the chromosphere, almost unchanged in form.

Outside the chromosphere, the sun's corona remains almost entirely a feature of total eclipses. This brings us to the subject of eclipses of the sun in general. Lunar eclipses are described in Chapter VI.

THE SUN IN ECLIPSE

An eclipse of the sun occurs when the moon crosses directly between us and the sun. The moon at the new phase passes the sun about once a month, but usually far enough to the north or south so that it does not hide the sun at all. There can be an eclipse only when the sun is near one of the nodes where the moon's path intersects the ecliptic.

The sections of the ecliptic around the two opposite nodes where eclipses are produced are never so short that the sun can go over them before the moon returns. Two eclipses of the sun, one at each node, are inevitable in the course of a year. Five may occur: two at each node, and an additional eclipse if the sun comes around to the first node again before the year ends. But the greatest possible numbers of solar and lunar (6.19) eclipses cannot occur in the same year.

The minimum number of eclipses of both kinds in a year is two, of the sun; this is the case in 1940. The maximum number is seven, either five eclipses of the sun and two of the moon (1935), or four of the sun and three of the moon (1982).

10.17. The Moon's Shadow on the Earth. Sometimes the eclipse of the sun is not more than *partial* because the moon does not pass centrally across the face of the sun. Sometimes the eclipse is *annular,* or ring-form; though the moon is crossing directly between us and the sun, its disk appears slightly the smaller, so that a narrow ring of the sun remains uncovered around it.

Sometimes the eclipse is *total.* Then the dark umbra of the moon's shadow falls on the earth, but always so near its apex that the dot it forms on the earth's surface is never more than 167 miles across when the sun is overhead. Occasionally the umbra brushes the earth only when the sun is near the zenith; the eclipse begins as annular, changes to total near the middle of its path, and reverts to annular at the end.

The shadow-dot sweeps over the earth's surface in a generally eastward direction, tracing the narrow *path of the total eclipse.* Within this path the eclipse is total while the dot is passing; outside the path the partial eclipse is visible to a distance of two or three thousand miles. The speed of the shadow increases from a little more than a thousand miles an hour at the equator when the sun is overhead to as much as five thousand miles an hour in high latitudes when the sun is near the horizon. Evidently the little shadow-dot darkens any part of its path for a very short time. The greatest possible duration of total eclipse at any one place scarcely exceeds seven minutes and a half.

Two total eclipses occur every three years on the average somewhere in the world. But so narrow are the tracks that their visits to any particular place on the earth's surface are very rare indeed. Partial solar eclipses which are visible over much larger areas are less unusual sights.

10.18. The Sun in Eclipse. About an hour before the total eclipse is scheduled, the watcher within the path of totality sees a black notch appear at the sun's western edge. Gradually the moon encroaches more and more, and when only a thin crescent of the sun remains uncovered, the sky and landscape have assumed a pale, unfamiliar appearance; for the light from the sun's rim is redder than ordinary sunlight.

The sky darkens rapidly as the total eclipse approaches. There is a chill in the air; dew is likely to form; animals seem bewildered; birds seek their nests; some flowers close. The last sliver of the sun breaks into vivid "Baily's beads" and disappears as though by the snap of a switch. At that instant the filmy corona bursts into view, while red

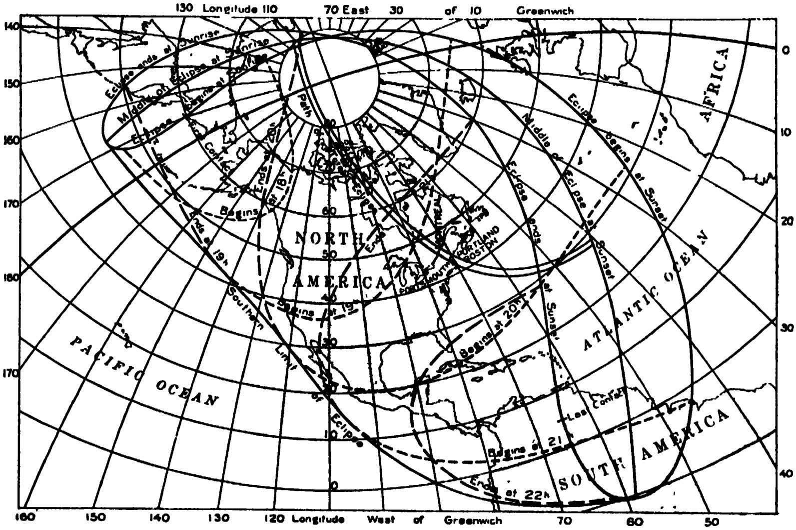


FIG. 10.18. Path of the Total Solar Eclipse of August 31, 1932. The umbra of the moon's shadow swept across northeastern Canada and New England. Elsewhere throughout North America the eclipse was partial. (From *The American Ephemeris and Nautical Almanac*)

prominences make their appearance close to the edge of the eclipsing moon. Bright stars and planets come out.

Totality ends as suddenly as it began. As though by another snap of a switch the sunlight returns, while the corona vanishes. Gradually the moon withdraws from before the sun, until after about an hour from the ending of the total phase the whole eclipse is over at that place.

A total eclipse of the sun is among the grandest of natural spectacles, a sight to be remembered always. Its scientific value is owing to the appearance on such occasions of things which are revealed less clearly, or not at all, at other times.

The appearance of the planets in the darkened sky around the eclipsed sun has made it possible to say definitely that there is no planet of any considerable size nearer the sun than Mercury's orbit. Precise measurements of the positions of the stars near the edge of the sun have shown that they are slightly displaced outward, just as they should be according to Einstein's theory of relativity. The observation of this effect at the total eclipse of 1919 and its verification at subsequent eclipses commended the new theory to scientists and the general public alike.

Some features of the chromosphere can be studied more effectively during total eclipses of the sun, and most details of the corona are visible only on these occasions.

10.19. The Corona. Far rarer than the best vacuum of the laboratory and shining all together not more than half as brightly as the full moon, this filmy envelope remains almost entirely a phenomenon of total solar eclipses. Half its light comes from the yellowish *inner corona* within 100,000 miles of the sun's surface, which Lyot has succeeded in view-

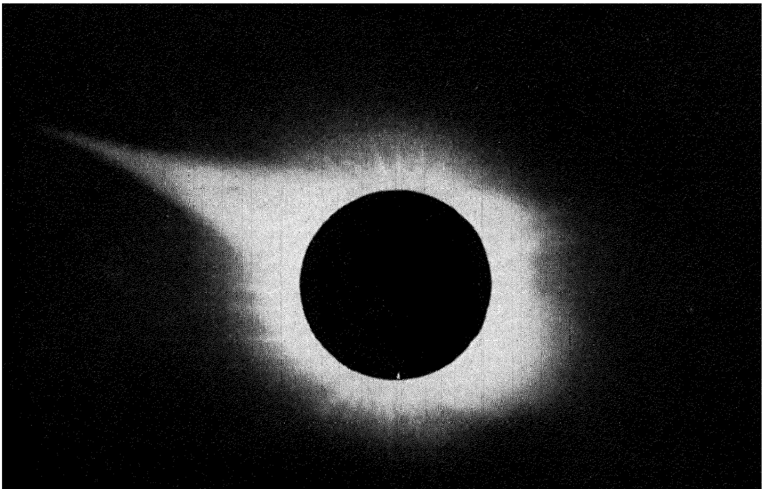


FIG. 10.19. The Sun's Corona. (*Photographed at the total eclipse of August 31, 1932, by Paul A. McNally, Georgetown College Observatory*)

ing through a special form of telescope outside eclipses. The *outer corona* is pearly white and approximately globular; the involved streamers are its conspicuous features.

This intricate structure varies in the sun-spot cycle, and depends at all times on the distribution of the spots on the sun's disk. Near sun-spot maximum it is roughly circular. Petal-like streamers arching above the prominences all around the disk give the corona the appearance which has been likened to a dahlia.

Near sun-spot minimum the corona is flattened in the polar regions where short, curved streamers symmetrical with the sun's axis of rotation remind the observer of the "lines of force" around the poles of a bar magnet. The equatorial regions are then far extended; long streamers reach out here to enormous distances.

10.20. The Total Eclipse of August 31, 1932, was the most recent of these impressive spectacles to be seen in the United States and Canada,

FIG. 10.20. Eclipse of the Sun, August 31, 1932. Showing different stages of the eclipse including the total phase. (*Photographed by William L. Hallowell at York, Maine*)

and the last one to appear in our part of the world for many years to come. Throngs of people were assembled along the more accessible part of the totality path on that day, including astronomers from many foreign lands. Clouds interfered in some places, while in others clear skies permitted fine views of the eclipse.

The moon's shadow touched the earth that morning near the north pole. It sped across Hudson Bay, Quebec and northern New England, and far out over the Atlantic Ocean where it left the earth at sunset. The shadow passed across Quebec and New England in the middle of the afternoon; there its path was slightly more than a hundred miles wide, and the duration of totality on the central line was about a minute and three quarters. Meanwhile the partial eclipse was visible throughout North America and as far as the northern part of South America.

10.21. Coming Eclipses of the Sun. Accurate predictions of solar eclipses, of when they will occur and where they will be visible, are published in the various almanacs a year of two in advance. The approximate times and places of eclipses from 1207 B.C. to A.D. 2161 can be found from tables in Oppolzer's *Canon der Finsternisse* which also contains maps showing the tracks of total and annular eclipses.

The predictions of eclipses are made possible by knowledge of the motions of the earth and moon. They are facilitated by a relation between the occurrences of eclipses which has been known from very early times.

The *saros* is the interval of 18 years 11⅓ days (10⅓ days if five instead of four leap years are included) in which eclipses are repeated. After this interval the relative positions of sun, moon, and node are nearly the same as before; the sun is about one diameter west of its former position relative to the node. Owing to the third of a day in the interval, the path of each eclipse in a series is displaced a third of the way around the earth from its predecessor. After three intervals, about 54 years and a month, the path returns to something like the same region as before, though it is farther north or south than before.

A dozen important series of total solar eclipses are now in progress. The one that includes the eclipses of June 8, 1937, and July 11, 1991, is remarkable because the durations of totality are not far from the greatest possible. The dates, durations at noon, and regions of coming total solar eclipses until 1950 are listed in the accompanying table. None of these is visible in the United States, with the single exception of the eclipse of July

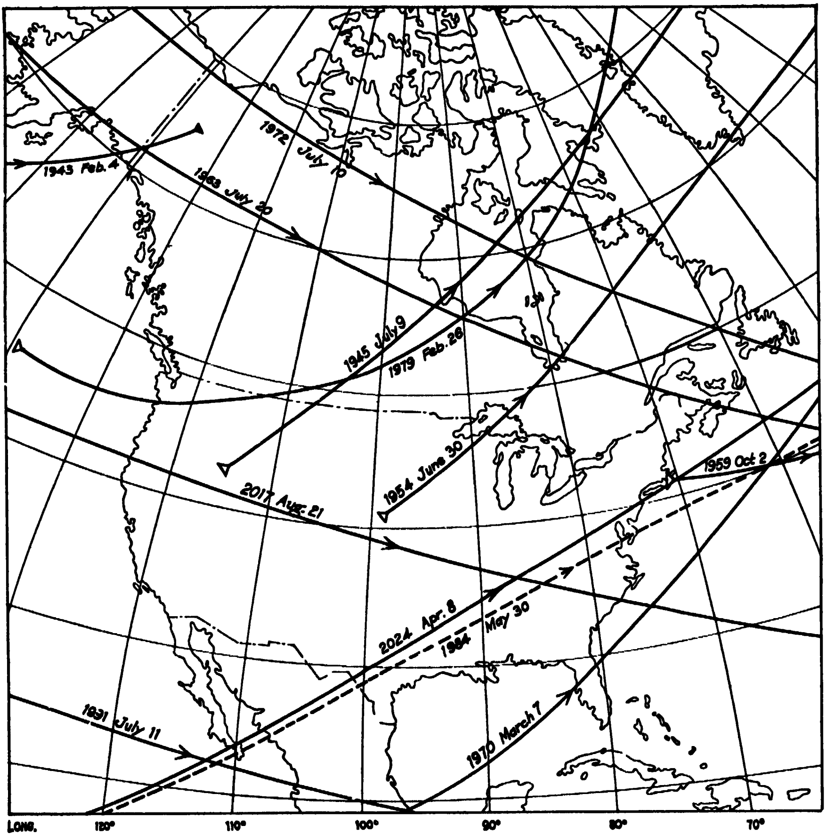


FIG. 10.21. Coming Total Solar Eclipses in North America.

9, 1945, which begins here at sunrise. Fig. 10.21 shows the paths of future total eclipses in North America (the eclipse of 1984 is annular).

TOTAL ECLIPSES OF THE SUN, 1936-1950

Date	Duration (minutes)	Region
1936, June 19	2.5	Greece, Central Asia, Japan
1937, June 8	7.1	Pacific Ocean, Peru
1940, Oct. 1	5.7	Colombia, Brazil, South Africa
1941, Sept. 21	3.3	Central Asia, China
1943, Feb. 4	2.5	China, Alaska
1945, July 9	1.2	Canada, Greenland, Norway
1947, May 20	5.2	Argentina, Central Africa
1948, Nov. 1	1.9	Central Africa, Congo

QUESTIONS ON CHAPTER X

1. What source of power on the earth cannot be traced to the sun's radiation?

2. How can the spectroscope help us to decide whether a comet shines by its own light or by reflected sunlight?

3. State two different ways of distinguishing the dark lines in the solar spectrum which are produced in our own atmosphere.

4. How is it possible to learn the chemical composition of the sun's atmosphere?

5. The sun rotates from west to east as the earth does. Yet the spots move across the sun's disk from east to west (10.8). Explain.

6. Show by a diagram that a complete rotation of the sun, as we view it, is performed in a longer time than the true period of the sun's rotation.

7. Enumerate the features of sun-spots which seem to be satisfactorily explained, and those which are left unexplained by the current theory of their nature.

8. In what years are the next maximum and minimum of sun-spot numbers most likely to occur (Fig. 10.11)?

9. Why do the solar prominences appear dark against the sun's disk, and bright when they project beyond it?

10. Can an eclipse of the sun appear total and annular at the same instant in different places? Total and partial?

11. Two total eclipses of the sun occur in the course of three years, on the average; yet many people have never seen one. Explain.

12. Describe an eclipse of the earth and an eclipse of the sun as one would view them from the moon.

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CHAPTER XI

THE STARS AROUND US

DISTANCES OF THE STARS — THE STARS IN MOTION — THE LIGHT OF THE STARS — STARS COMPARED WITH THE SUN

In the study of the stars as remote suns we look first to the nearer ones whose distances can be measured more dependably and whose movements are more clearly revealed. Though there are many telescopic stars among them, the nearer stars include, as a general thing, the brighter ones which form the familiar constellation figures.

DISTANCES OF THE STARS

The stars are great suns so far away that they are only points of light in the sky; no telescope is powerful enough to show them as disks. Yet their light is so spread that the brighter stars especially seem to have definite sizes whether they are viewed with the eye alone, the eye at the telescope, or in the photographs. We often speak of "big" stars and "tiny" ones in referring to their apparent brightness.

If a star should show a disk as much as 1′ in diameter, which would be too small for the unaided eye to see as a disk, and if it is really as great as our sun whose disk appears 30′ across in our skies, then it would be only thirty times as far away as the sun. This appearance as dots of considerable size led the early astronomers to suppose that the stars were nearer than they really are (7.7). It was not until about a century ago that the parallax of a star, and therefore its distance from the earth, was measured for the first time.

11.1. Parallaxes of the Stars. The nearer stars seem to swing back and forth slightly against the background of the more remote ones as the earth revolves around the sun. They seem to do so because we are viewing them from different places as we go around. The amount of the parallax (6.9) displacement, if it can be observed at all, informs us of the star's distance.

The effect is slight, to be sure. Even the very nearest star is displaced at the most only as much as the width of a penny a mile and a quarter away, which is also the width of the earth's orbit as viewed from the star. So small a displacement cannot be detected with the naked eye, and it can easily pass unnoticed through the large telescope unless accurate measurements are made. And this for the nearest star is the greatest displacement of all.

So it is not surprising that astronomers of early times did not observe the parallaxes of the stars which would have told them that the earth goes around the sun, and that the stars themselves are enormously far away. Not that they did not attempt to detect the parallaxes. They tried again and again as telescopes increased in size to prove the earth's revolution in this way. At length, in 1727, came the discovery of the aberration of starlight (3.2), a more conspicuous effect of our revolution around the sun. But more than a century went by after that noteworthy achievement before the parallaxes of the stars began to be observed.

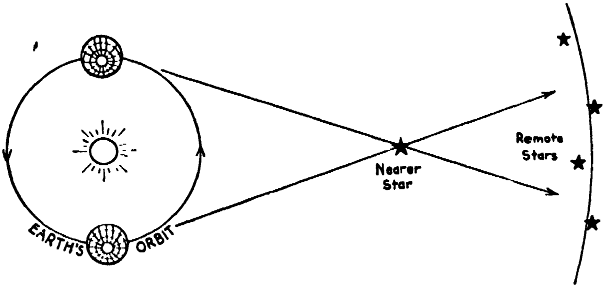


FIG. 11.1. Parallaxes of the Stars.

Bessel at Königsberg succeeded, in 1838, in measuring the parallax of the fast-moving 61 Cygni. The parallaxes of Vega and Alpha Centauri were announced soon afterward; and by the beginning of the present century the distances of sixty stars had become known in this way, though many of them were not very reliably established. In recent years, the accuracy of the measurements and the number of known parallaxes have been greatly increased by the substitution of the photographic plate for the eye at the telescope.

11.2. Parallaxes Determined by Photography. The modern era of parallax observing was inaugurated at Yerkes Observatory, in 1903, by Schlesinger, now the director of the Yale Observatory. The methods which he developed are employed today at observatories in various parts of the world which have joined in this exacting fundamental work.

The modern way of observing the parallax of one of the nearer stars is to photograph its region of the sky at intervals of six months, when the star is near the celestial meridian soon after nightfall, and again when it is there not long before dawn. Precise measurements of the photographs show how much the star's direction has altered relative to apparently neighboring stars which are probably too far away from us, as most stars are, to be noticeably affected by our revolution around the sun.

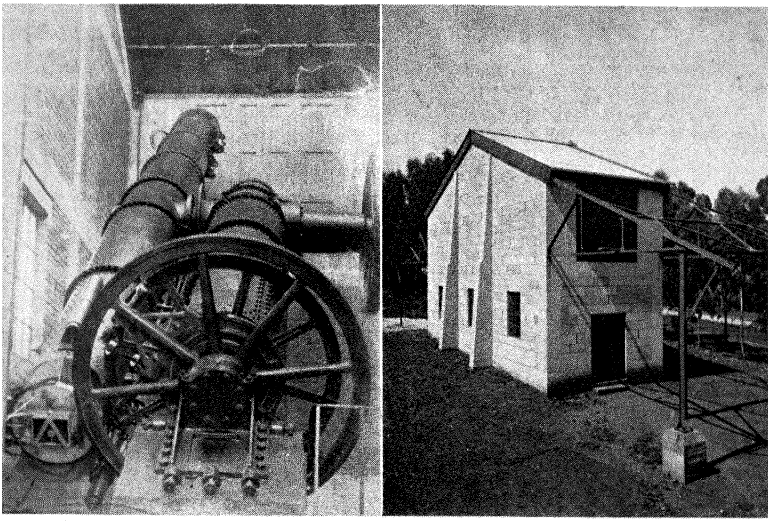


FIG. 11.2. The 26-Inch Photographic Refracting Telescope at the Southern Station of Yale Observatory, Johannesburg, South Africa.

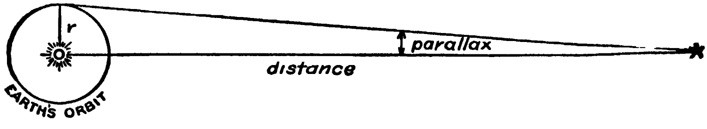


FIG. 11.2A. Heliocentric Parallax of a Star.

Part of the displacement that is observed is likely to be caused by the movement of the star itself. Accordingly, it is necessary to continue the photographs at six-month intervals until the yearly parallax swing can be disentangled from the straight-ahead motion.

The *parallax* of a star, as astronomers employ the term, is not far from half the greatest parallax displacement that is observed. It is the greatest difference in the star's directions as viewed from the earth and sun during the year, with a slight correction to bring the earth to its average distance from the sun.

When the parallax has been measured, the star's distance can be easily calculated, as we shall see. And this distance is often given in light years.

11.3. The Light Year. The discovery of the aberration of starlight called attention for the first time to the fact that the light does not come to us instantly; if it did, there could be no aberration displacement of the star at all, however fast we might be going. Scientists of former times, Galileo among them, had suspected that light might be traveling with finite speed; but they could think of no convincing way to prove it. Roemer in Denmark had demonstrated the finite speed of light as early as 1675 from his observations of the eclipses of Jupiter's satellites. But little attention was given to his important work until Bradley's discovery of aberration recalled it.

The speed of light is 186,270 miles a second, according to Pease's measurements of 1933 at the Mount Wilson Observatory. He was carrying on after the death of Michelson had interrupted the last of that distinguished physicist's attempts to determine the speed of light with the greatest possible precision.

This is the speed of light in a vacuum; the speed is reduced in a medium such as air or glass. It is always the same in empty space whether the star is approaching or receding from us, regardless of how fast the star is going.

Light travels 186,270 miles in one second. Since there are about 31½ million seconds in a year, light travels 5.88 million million miles in a year. This vast distance is the *light year*, a convenient unit to use in speaking of the distances of the stars.

11.4. Distances in Parsecs and Light Years. Two yardsticks are employed by astronomers in measuring stellar distances: the parsec and the light year.

The *parsec* is the distance at which a star would show a *par*allax of one *sec*ond of arc. One parsec equals 19.2 million million miles. Therefore (11.3), one parsec equals 3.258 light years.

So when the star's parallax has been observed, its distance is found by the rules:

Distance in parsecs = 1/parallax″
Distance in light years = 3.258/parallax″
Distance in miles = distance in parsecs × 19.2 million million
= distance in light years × 5.88 million million.

As an example, consider the bright star Arcturus whose parallax is 0″.086. Its distance in parsecs is 1/0.086, or 11.6 parsecs. Its distance in light years is 3.258 times as much, or 37.8 light years. Its distance in miles is 11.6 × 19.2 million million, or 223 million million miles.

To find the sun's distance from the earth in terms of the speed of light, divide 92,870,000 miles by 186,270 miles, the speed of light in one second, and you have 498.6 seconds; the sun's average distance is 8.3 light *minutes*. Similarly, the distance of Pluto, the most remote planet, averages five and a half light *hours*. The moon's distance is 1.3 light *seconds*.

11.5. "Proxima" is the Nearest Star, according to present information. Since the parallax of this eleventh magnitude star in the southern constellation Centaurus was announced in 1915, no nearer star has been found. Proxima is about two degrees from the brilliant double star Alpha Centauri which was formerly regarded as our nearest neighbor, and now appears to come second in the list.

The parallax of Proxima Centauri is 0″.762. Its distance is therefore 1.3 parsecs, or 4.3 light years. It must really be a faint star to shine as feebly as it does so close at hand. Brought as near us as the sun, Proxima would glow with a red light hardly more than 25 times as bright as the light of the full moon.

Three dozen stars are known to have parallaxes greater than 0″.2, so that they lie within 5 parsecs or a little more than 16 light years of our sun. It might be supposed that the list of the very nearest stars would include all the very brightest ones. Yet it contains only four of the brightest stars: Alpha Centauri, Sirius, Procyon, and Altair. And more than that, only one star in four in the list can be seen without the aid of the telescope.

Evidently there is such variety in the actual brightness of the stars that the splendor of any particular one in our skies tells us little of its distance. It will be evident also that the majority of the stars must be too dim to be seen even through large telescopes unless they are unusually near us.

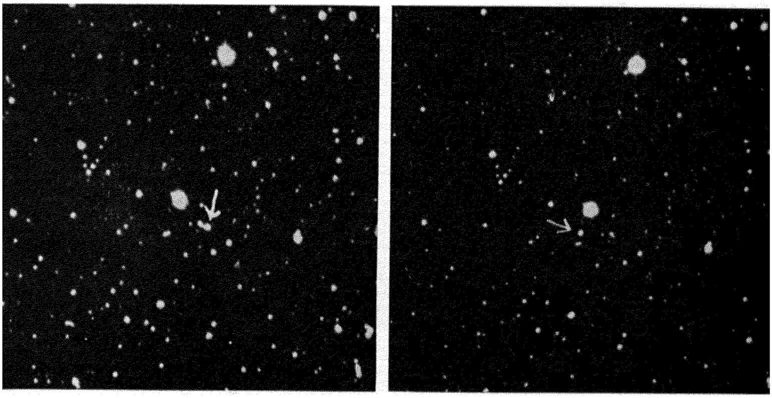
This direct method of determining the distances of the stars is limited to the nearer ones, though it establishes the scale for them all. At the distance of less than 200 light years, which is only a step into space, the parallaxes become too small to measure confidently. Other ways of gauging the distances of more remote stars will be described in their proper connections.

The Stars in Motion

The stars are not fixed on the globe of the heavens, we know today; the celestial sphere is only an illusion. The stars are widely scattered through space, and are speeding in various directions, though the vast distances that intervene make their movements seem very slow indeed. And our sun is moving forward swiftly relative to the stars around it.

Halley, whose name a great comet bears, was the first, in 1718, to demonstrate that the stars are not fixed. He observed that the bright stars Sirius, Betelgeuse, Aldebaran, and Arcturus had moved along about as much as the width of the full moon from the places assigned them in Ptolemy's catalogue.

11.6. Proper Motions of the Stars. The movements of the stars across the face of the sky relative to their fellows can be observed by comparing the records of their places on two occasions as far apart as possible, just as Halley did. The two places may be measured with the eye at the telescope or as they appear on the photographs.



August 23, 1894 May 30, 1916

FIG. 11.6. "Barnard's Star" Has the Fastest Proper Motion. In the interval of 22 years between the two exposures the star had moved an eighth of the apparent width of the full moon. (*Photographed at Yerkes Observatory*)

The *proper motions* of the stars are the rates at which they are changing their directions, when aberration, parallax, precession, and other effects of our own movements are allowed for; they are accordingly expressed as angles. As would be expected, the nearer stars have the greater proper motions as a general thing, while the very remote stars appear so nearly stationary that they make fine landmarks to show how the nearer ones are progressing.

"Barnard's star" (Fig. 11.6) has the greatest known proper motion of all. This tenth magnitude star in the constellation Ophiuchus moves among its neighbors at the rate of 10″.25 a year, or as far as the width of the full moon in 180 years. If such rapid displacements were not exceptional, the constellations would not hold together as well as they do. As it is, considerably less than fifty stars are known whose movements are great enough to be possibly detected with the unaided eye in the course of a lifetime; and the majority of these are visible only through the telescope.

11.7. Motions in the Line of Sight. The proper motions tell nothing, of course, of how the stars are angling toward or away from us as they go on. The speeds of the stars in the line of sight, or their *radial velocities*, are determined by means of the spectroscope. In the prismatic analysis the light of each star is spread into a band of rainbow colors, which is interrupted by dark lines as in the spectrum of sunlight, and sometimes by bright lines.

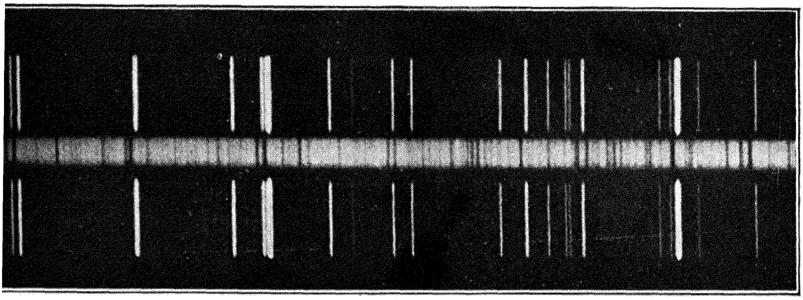


FIG. 11.7. The Spectrum of Procyon. The dark lines in the star's spectrum are displaced to the violet (left) with respect to corresponding bright lines in the comparison spectrum, above and below. At this time, Procyon and the earth were approaching at the rate of 18 miles a second. (*Photographed at Lowell Observatory*)

If the lines are displaced toward the violet end of the spectrum, the star is approaching us; if they are displaced toward the red end, the star is receding from us; and the amount of the displacement is proportional to the speed of approach or recession.

This Doppler effect, which has been mentioned before (10.4), shows how fast the stars are moving in the line of sight. The spectra of the stars are photographed, and the displacements of their lines are measured relative to stationary "comparison lines" which appear like pickets on the photographs above and below the spectra of the stars (Fig. 11.7). Effects of the earth's motions in the directions of the stars must be allowed for.

11.8. The Sun's Way. Since the stars are distant suns and suns in motion, our sun must be moving too. Accordingly, the motions of the stars that we observe are partly their own, and partly the motion of the scenery passing by in the opposite direction to the one our sun is taking. The stars should be opening out from the point in the heavens toward which the sun is moving, and closing in on the opposite point behind us. So reasoned Sir William Herschel, famous pioneer in sidereal astronomy.

From his study of the proper motions of 13 stars, which were the only ones known at that time, Herschel announced, in 1783, that the sun is moving toward a point in the constellation Hercules. This "apex of the sun's way" has been altered less than 10° by the elaborate modern analyses of thousands of proper motions and of radial velocities as well.

The sun and its family are moving at the rate of 12 miles a second in the direction of a point in Hercules scarcely more than 10° from brilliant Vega in Lyra. In the course of a year the whole solar system proceeds in this direction four times as far as the earth's distance from the sun.

This is the sun's way relative to the general average of the stars around us that are visible to the naked eye. It would have more than local interest if the stars were moving only at random throughout our galaxy. But there are definite communities of motion instead.

11.9. Common Motions of the Stars. Many stars travel in pairs, mutually revolving as they go. Many others proceed in the larger companies which we call star clusters, like fleets of ships bound on common errands; these will be described later. But one of the star-fleets is so near us that it does not resemble a star cluster in the ordinary sense.

As early as 1869, the English astronomer Proctor called attention to the fact that the stars of the Great Dipper, with the exceptions of Alpha, the northern one of the Pointers, and Eta, at the end of the handle, are moving in the same direction. Later, in 1909, Hertzsprung announced that other stars far from the Dipper in our skies, including brilliant Sirius and Gemma in the Northern Crown, are going along with the Dipper's stars.

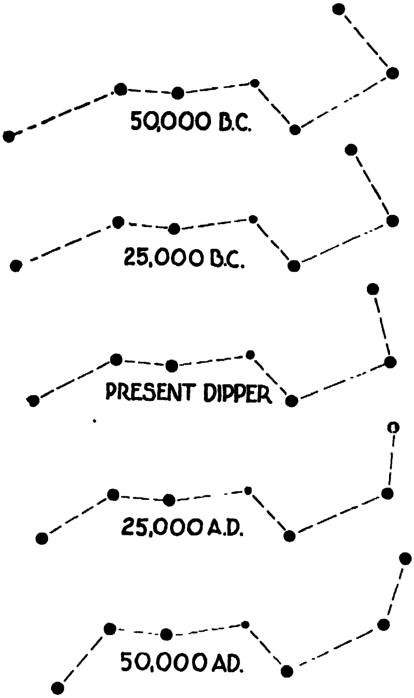


FIG. 11.9. Evolution of the Great Dipper. The stars at the two ends are not moving along with the others.

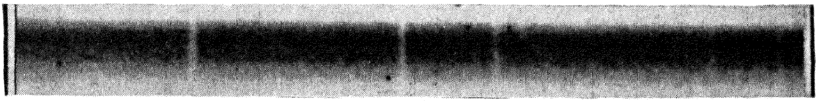
Our sun is in the midst of this moving cluster; that is why its stars are so widely scattered. But our sun is not a member of the company. Gradually these stars of the Dipper and their traveling companions will withdraw along paths which are really parallel and which seem therefore to converge in the distance, until they close up in the region south of Capricornus.

A large group of mostly blue stars which are traveling together spreads through Scorpius and Centaurus, while a similar group includes most of the bright stars of Orion except red Betelgeuse. It may be that the whole cloud of stars around us is whirling, and it is generally believed that the entire Milky Way is in rotation (13.15). In one way or another every star is associated with some of its fellows in some common movement.

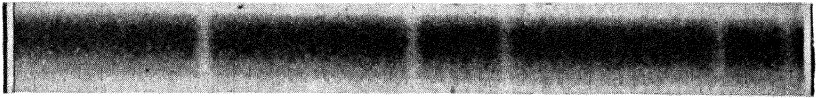
11.10. The Stars Rotate on Their Axes, as the sun does. While the sun's rotation has been known since Galileo and other early observers watched the march of the sun-spots across its disk, it was only in recent years that the rotations of the stars could be detected and studied.

Opposite sides of the sun's disk are moving in opposite directions in the rotation; one side is approaching us while the other side is receding, as the spectroscope shows (10.8). The stars exhibit the same effect to assure us that they also are turning on their axes. But since the stars appear as points of light instead of disks, this Doppler effect of the rotations becomes evident in a different way.

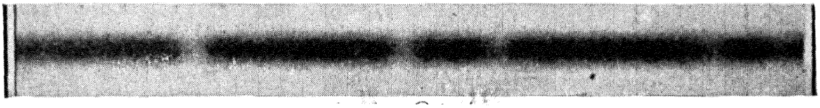
Unless the axis is directed toward us, the lines in the spectrum of every star are widened by the rotation because part of the starlight comes from a source that is receding and part from one that is approaching. And the faster the rotation, the greater is the widening of the lines. All stars are rotating, so far as is known.



Gamma Pegasi



Beta Canis Majoris



Epsilon Orionis

FIG. 11.10. Widening of Lines in Stellar Spectra. Negatives of the spectra of three stars showing progressive widening of the lines which is ascribed to the rotations of the stars. (*Photographed at Yerkes Observatory*)

THE LIGHT OF THE STARS

Starlight reveals by its directions the directions of the stars from which it comes. By its changing directions it tells of the distances and proper motions of the stars. Analyzed with the spectroscope it informs us of their motions in the line of sight and of their rotations as we have seen.

The quality of the starlight is next to be considered, as it is shown by the colors of the stars and by the patterns of lines in their spectra.

11.11. The Analysis of Starlight. Fraunhofer was not only the first to observe the dark lines in the solar spectrum (10.3), but he was also the first, in 1823, to view the spectra of the stars. Placing a glass prism in front of the objective of his telescope he saw the light of the stars drawn out in bands of rainbow hues, and noticed that these spectra are crossed by dark lines.

The number and arrangement of the lines vary with the color of the star, as Fraunhofer observed. In the spectra of blue stars such as Spica and Sirius the array of lines is simpler than that shown by yellow stars like the sun, while the red stars exhibit more complex patterns than the yellow ones. The spectra of some stars are crossed by bright lines as well.

In the extensive studies of stellar spectra at Harvard Observatory the objective prism is employed as it was originally used by Fraunhofer, except that the photographic plate replaces the eye at the telescope. It is much more effective for this purpose because the spectra of many stars are recorded on the plate with a single exposure.

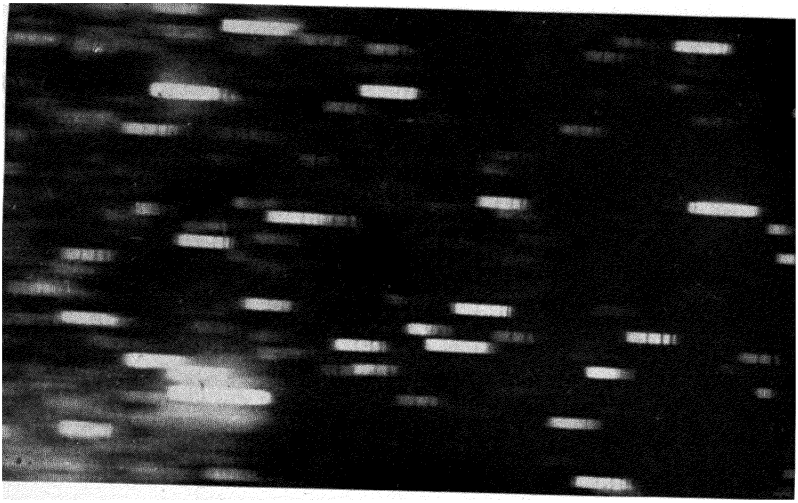


FIG. 11.11. Objective Prism Photograph of Stellar Spectra. (*Photographed at Harvard Observatory*)

The spectra of more than a quarter of a million stars have been observed on the Harvard photographs by Miss Cannon and her associates; and they have been classified according to the accepted plan (the Draper Classification, it is called) for which Miss Cannon is chiefly responsible.

11.12. Classes of Stellar Spectra. When the spectra of the stars are arranged in order of increasing redness of the stars themselves, their patterns of lines form a single unbroken sequence, as a general thing. This is the order of the Draper Classification whose most populous classes, or divisions, of the sequence are designated by the letters B, A, F, G, K, and M. Each class is divided into ten parts. The stars of class B, for example, are listed as B0, B1, B2, . . . B9; and the next step is A0.

Class B. Helium lines are prominent in the spectra of these blue stars, such as Spica and Rigel.

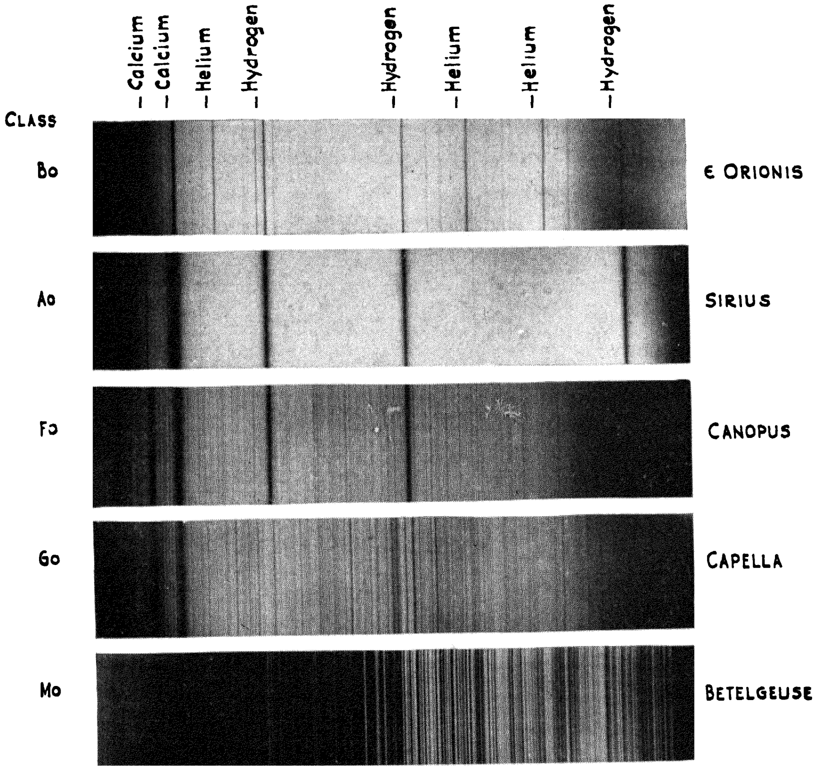


FIG. 11.12. Spectra of Representative Stars of Different Classes. (*Photographed at Harvard Observatory*)

Class A. Hydrogen lines, like a line of telegraph poles closing up in the distance, are most conspicuous in this class of blue stars, though they appear in all the other classes. Helium lines have disappeared. Examples are Sirius and Vega.

Class F. Yellowish stars such as Canopus and Procyon. Lines of the metals are increasing in intensity in their spectra, particularly the Fraunhofer *H and K lines of calcium.*

Class G. Lines of the metals, such as iron, are numerous and conspicuous in the yellow stars. Our sun and Capella belong to this class.

Class K. The *metallic lines are stronger* in the spectra of these orange stars. Arcturus and Aldebaran are examples.

Class M. Dark *bands* in the spectra in addition to the lines show the presence of chemical compounds, particularly titanium oxide, in the atmospheres of these red stars. Examples are Betelgeuse and Antares.

These six classes include 99 per cent of the stars whose spectra have been observed. The remaining stars belong to four other classes: Class O, which goes at the head of the list, contains the hottest stars. The spectra of the red stars of classes R and N show bands of carbon, while those of class S have bands which are produced by zirconium oxide.

11.13. "Hot" Stars and "Cool" Stars. The colors of the stars and the patterns of lines in their spectra are closely associated because both depend on their temperatures. Just as blue-hot metal becomes red-hot as it cools, so the blue stars are hotter than the red stars.

There are exceptions to the rule, to be sure. Our yellow sun sometimes appears red at its setting. Similarly, stars are reddened when their light passes through clouds of dust out in space.

The temperatures of the stars can be determined from their colors, if nothing intervenes to redden the starlight. They can be calculated from the amount of radiation the stars send us. They can be learned from the patterns of lines the spectra display. In these and other ways the temperatures of the stars have become known.

Class O stars have temperatures exceeding 20,000° K, or absolute Centigrade, though they are yellower than the cooler class B stars. Class A stars such as Sirius have surface temperatures around 10,000° K. Class G stars such as our sun have temperatures of about 6,000° K, or something like 10,000° Fahrenheit. The red stars range from around 3,000° to less than 2,000° K.

"Hot" stars are enormously hot. Even the "cool" stars are hot by ordinary standards; platinum would melt at the surface of the coolest red star. The atmospheres of the stars are somewhat cooler than their surfaces. With increasing depth below the surfaces the temperatures rise rapidly to perhaps millions of degrees at the centers of the stars.

11.14. The Colors of the Stars can be clearly seen in the brightest ones. Though they are less vividly colored than the stoplight at the crossroads, the bright stars are noticeably tinged with blue, yellow, orange, and red. Compare, for example, red Betelgeuse with blue Rigel diagonally across in the oblong figure of Orion. Astronomers determine the colors of the stars by comparing their photographic and visual magnitudes.

The magnitude of a star, as we have seen (4.13), is the measure of its brightness. It is indicated by a number which is larger as the star is fainter. Of two stars which differ by one magnitude exactly, one is about 2½ times (4.13) as bright as the other. But if the two stars differ in color, their difference in magnitude will not be the same on the photograph as it appears to the eye.

Notice how faint the red star Betelgeuse appears in the photograph of the constellation Orion (Fig. 5.32), though it looks almost as bright as blue Rigel in our skies. It is faint in the picture because the ordinary photographic plate is more sensitive to blue and violet light than to yellow and red light to which the eye is more sensitive.

11.15. The Apparent Magnitudes of the Stars are measures of their brightness as we see them. Their brightness in our skies depends on how bright the stars really are, on their distances from the earth, and of course on whatever intervenes to dim their light.

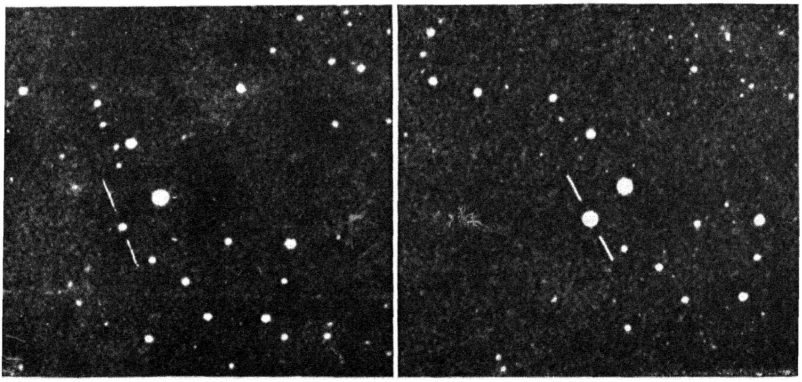


FIG. 11.14. A Red Star Appears Fainter in the Ordinary Photograph (left) Than to the Eye (right). (*Photographed by F. C. Jordan at Yerkes Observatory*)

The magnitudes of the stars are determined by comparing them with certain stars whose brightness has been measured with the greatest care and whose magnitudes are accordingly accepted as standards. The comparisons may be made with the eye alone, by photography, by directing the light of the stars successively on a photoelectric cell or thermocouple, or in other ways. With each method of reception there is a different relation between the magnitude of the star and its color.

11.16. Absolute Magnitudes. If all the stars were at the same distance from the earth, as was formerly supposed, their apparent magnitudes would represent their actual relative brightness, aside from any interference with the light on its way to us. When the distances of the stars are known, it is easy to calculate what their magnitudes would be if they were equally far away. Astronomers have placed this globe of their calculation at the distance where the stars would have a parallax of $0''.1$.

The *absolute magnitudes* of the stars are the magnitudes they would have at this distance of 10 parsecs, or 32½ light years. Most stars must be brought nearer than they are in order to be placed on the modern celestial sphere. The rule is:

$$M = m + 5 + 5 \log p'',$$

where M is the star's absolute magnitude, m is its apparent magnitude, and p'' is its parallax.

The sun's apparent visual magnitude is −26.7. Its absolute visual magnitude is +4.8. At this very moderate standard distance our sun would appear as a star only faintly visible to the naked eye. Placed there beside

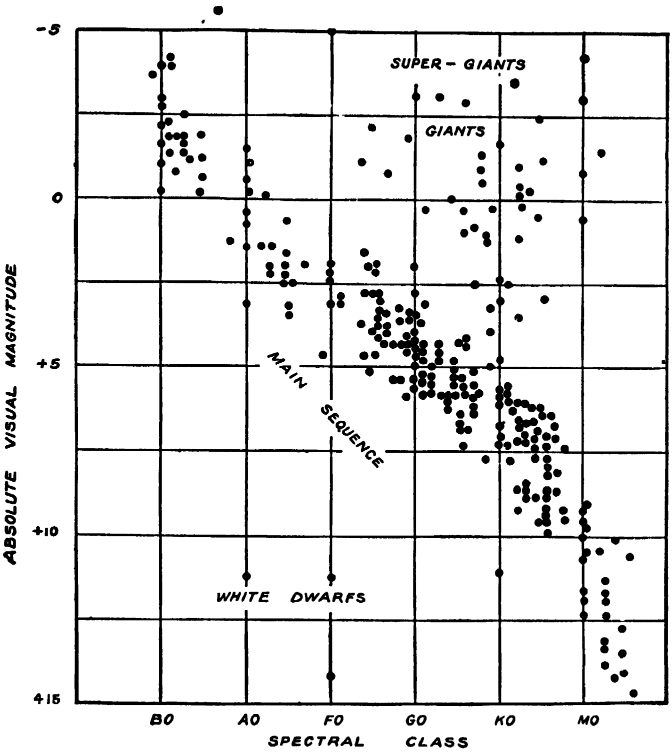


FIG. 11.17. Absolute Magnitudes of Stars Arranged with Respect to Their Spectral Classes. The point at absolute magnitude +4.8 and class GO represents our sun.

it, giant stars such as Canopus, Rigel, and Deneb would outshine our sun probably as much as ten thousand times.

Notice that the rule expresses a simple relation between three quantities, and that one of these, the apparent magnitude, can be readily observed. If the star's absolute magnitude can be found independently, then its parallax, and therefore its distance, is given by the rule. Here is a way of learning the distances of the stars, especially of remote ones whose parallaxes are too small to be measured directly (11.1); its use in determining the distances of Cepheid variable stars will be mentioned later (12.5).

STARS COMPARED WITH THE SUN

11.17. Stars of the Main Sequence.

In 1913, Russell at the Princeton Observatory called attention to a remarkable relation between the absolute magnitudes and spectral classes of the stars, which has guided many subsequent studies.

When the absolute magnitudes of the stars are plotted in order of their spectral classes, as in Fig. 11.17, the majority of the points lie along a narrow band which runs diagonally across the diagram, and which is known as the *main sequence*. With increasing redness these stars become fainter, and fainter too than can be accounted for by their lowered temperatures, which shows that they are becoming smaller as well.

TABLE 11.I. THE BRIGHTEST STARS

Name	Apparent Visual Magnitude	Spectrum	Parallax	Distance in Light Years	Absolute Visual Magnitude
Sirius	— 1.58*d*	A0	0″.373	8.7	+ 1.3
*Canopus	— 0.86	F0	.027	160	— 3.7
*Alpha Centauri	+ 0.06*d*	G0	.756	4.3	+ 4.4
Vega	0.14	A0	.124	26	+ 0.6
Capella	0.21	G0	.069	47	— 0.6
Arcturus	0.24	K0	.086	38	— 0.1
Rigel	0.34*d*	B8	.006	540	— 5.8
Procyon	0.48*d*	F5	.291	11.2	+ 2.8
*Achernar	0.60	B5	.049	66	— 0.9
*Beta Centauri	0.86	B1	.020	160	— 2.6
Altair	0.89	A5	.208	15.7	+ 2.5
Betelgeuse	0.92*v*	M0	.012	270	— 3.7
*Alpha Crucis	1.05	B1	.014	230	— 3.2
Aldebaran	1.06	K5	.057	57	— 0.2
Pollux	1.21	K0	.101	32	+ 1.2
Spica	1.21	B2	.018	180	— 2.5
Antares	1.22	M0	.013	250	— 3.2
Fomalhaut	1.29	A3	.125	26	+ 1.8
Deneb	1.33	A2	.007	460	— 4.4
Regulus	1.34	B8	.050	65	— 0.2

* Not visible in latitude 40° N.
d Double star with the telescope. The combined magnitude is given.
v Light varies through a range of half a magnitude.

Our sun belongs to the main sequence. Of class G0 and absolute magnitude +4.8, it is represented by a point in the diagram not far from the middle of the band.

If all the stars belonged to the main sequence, this band might be regarded as the life-track of the stars. It might be supposed to verify a theory of former times that the stars were blue and very brilliant in their youth, yellow and fainter in their middle age, and red and feebly glowing in their shrunken old age. But a number of dots in the diagram lie far above the diagonal band, as you see, while others fall far below it.

11.18. Giant and Dwarf Stars. *Giant stars* are much brighter than main-sequence stars of the same spectral class. Called "giants" for this reason by Hertzsprung, in 1905, they are giants in size as well. All stars of the same spectral class have nearly the same surface temperature and therefore nearly the same surface brightness *for each square mile.* So if one class M star, for example, greatly exceeds another in absolute brightness, its surface must contain many more square miles; its diameter must be the greater.

Evidently the dots near the upper right corner of the diagram represent the largest stars of all. Though these red stars are among the coolest and therefore the faintest per square mile of their surfaces, they are nevertheless among the absolutely brightest stars. They are *super-giants.* Red Betelgeuse in Orion is one of these.

The few dots near the lower left corner of the diagram represent the *white dwarfs,* the smallest stars of all. Absolutely faint despite the fact that their surfaces are bluer and hotter than the sun's, these dwarf stars are no larger than some of the planets in our solar system. Sirius' faint companion (12.10) is a famous example.

11.19. Our Sun Among the Stars. Our sun is a star, as we know. Its diameter is 864,100 miles, or 109 times the earth's diameter. It is nearly a third of a million times as massive as the earth. It averages 1.4 times as dense as water. How do the other stars compare in size and mass and density with our sun?

The stars vary enormously *in size.* Their diameters decrease, as a general thing, as we go to the left across the top of the diagram (Fig. 11.17), then down the main sequence, and across to the white dwarfs. The red super-giants at one extreme are at least as many times greater than the sun as the sun is greater than the earth, while the white dwarfs at the other scarcely exceed the earth in diameter.

The stars diminish *in mass* in this direction, though the variation is less pronounced. Most stars are not more than five times and not less than one fifth as massive as the sun.

In density, therefore, the stars vary enormously; their densities increase as we go along the diagram as before. The red super-giants average less than a thousandth as dense as the air around us, while the white dwarfs are tens of thousands times as dense as water.

In its size and mass and density our sun is a fair average of the visible stars. And if the small minority of giants and visible dwarfs is neglected, it does not differ greatly from the others in these respects. In surface temperature the sun has a middle place as well, as we have seen (11.13). It is composed of the same materials as the other stars, and in something like the same proportions. In its possession of a family of planets our sun may represent the average again, though nothing is certainly known about this.

If now we add the dwarf stars and the multitudes of small red main-sequence stars which are quite invisible except the very nearest ones, our sun may well exceed the average star in size. It is certainly not a "second-rate star," as has sometimes been said.

Questions on Chapter XI

1. How do the parallax and aberration displacements of a star differ in direction and amount?

2. A radio message travels through empty space with the speed of light. What would be the transmission time of a message to the earth from each of the other principal planets at its closest approach?

3. Suppose that the sun and the stars around it average a million miles in diameter and four light years apart. If they are represented by dots a hundredth of an inch across, how far are they separated on this scale?

4. The earth's revolution around the sun can be proved by observing the stars with the spectroscope. Explain.

5. The nearest stars have the greatest proper motions, as a general thing. If our sun belonged to a moving cluster, how could we recognize other members of the cluster?

6. If one star appears brighter than another, can we be sure that it is the nearer of the two?

7. Show that the star Regulus (Table 11.I) is really a hundred times as bright as our sun.

8. Why is a red giant star brighter than a red star of the main sequence?

9. Criticize a former theory of stellar evolution, which supposed that the stars shrink and become cooler as time goes on, changing from great blue stars in their youth to smaller red ones in their old age.

10. In what respects is our sun a fair average of the general run of stars?

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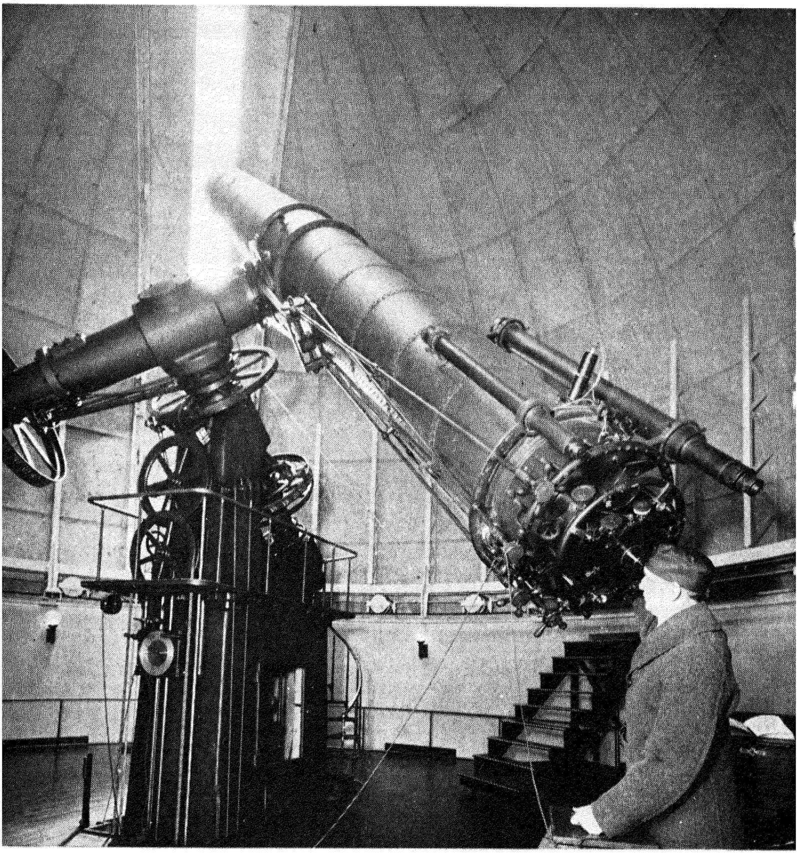
Harlow Shapley, *Flights from Chaos;* a survey of material systems from atoms to galaxies (McGraw-Hill).

Frank Schlesinger and Louise F. Jenkins, *Catalogue of Bright Stars;* containing all important data known in January, 1940, relating to all stars brighter than 6.5 visual magnitude, and some fainter ones (Yale University Observatory).



The 26-Inch Refracting Telescope of the U. S. Naval Observatory, Washington
(*Photographed by Underwood and Underwood, Washington*)

CHAPTER XII

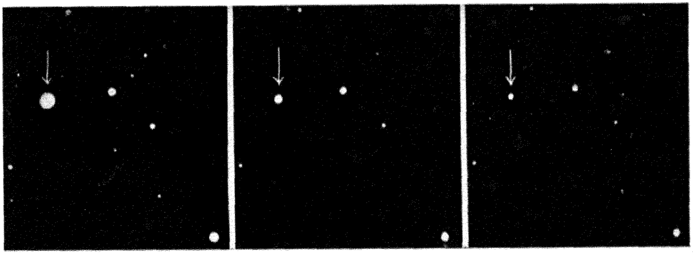
STARS AND NEBULAE

VARIABLE STARS — BINARY STARS — STAR CLUSTERS AND NEBULAE

VARIABLE STARS

Variable stars fall chiefly into four classes: eclipsing variables, Cepheid variables, long-period variables, and irregular variables. Novae, or temporary stars, constitute an additional and spectacular class of stars of variable brightness.

12.1. Light Curves of Variable Stars. When a variable star has been discovered, the next step is to learn how its light is fluctuating. This is done by comparing the variable from night to night, or repeatedly during the same night if the change is rapid, with neighboring stars of presumably constant brightness whose magnitudes are known.



August 26 Magnitude 8 — September 14 Magnitude 9 — October 13 Magnitude 10

FIG. 12.1. Variation in the Brightness of the Star RS Ophiuchi in 1933. (*Photographed by F. Quénisset*)

The observed magnitudes can be set down as points on a diagram with respect to the times; and the run of these points can be represented by a curved line, or *light curve*, which shows how the brightness of the star varies as time goes on. It resembles the curve in the daily paper which shows how the stock market fluctuates from day to day.

Amateur astronomers with small telescopes are making valuable contributions in this field, particularly in the studies of variable stars of large range in brightness. The American Association of Variable Star Observers, under the direction of Leon Campbell at Harvard Observatory, and a section of the British Astronomical Association are especially active in observations of variable stars.

12.2. Algol, the "Demon Star," is among the most famous of the variable stars; and it was one of the first to be discovered. In the snaky head of Medusa which Perseus held in one hand in the old picture book, Algol (β Persei) winked in a way that was quite mysterious until the reason for its winking came to be understood.

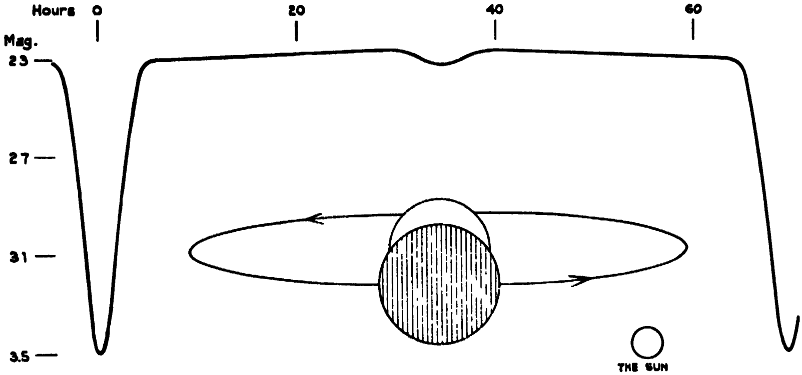


FIG. 12.2. Light Curve and System of Algol.

Algol is an eclipsing star. It is mutually revolving with a somewhat larger though yellower and therefore fainter companion once in about 2 days and 21 hours. Once in each revolution the companion passes between us and the brighter star partially eclipsing it for nearly ten hours, and reducing the light of the system to a third its normal brightness, at the most.

The brighter star is about three times as great as our sun. The fainter one is twenty per cent greater than its companion, and is three magnitudes the fainter. The centers of the two stars are 13 million miles apart, or slightly more than a third the average distance of the planet Mercury from the sun; so it is not surprising that no telescope can separate them. Their orbits are tilted 8° from the edgewise position relative to the earth.

12.3. Eclipsing Variable Stars, such as Algol, are double stars too close to be seen separately through the telescope at their great distances from us. Their orbits are so nearly edgewise to the earth that they mutually eclipse as they revolve. Viewed from another part of our galaxy these stars might well shine with constant brightness, while other close pairs whose light is invariable to us would there undergo eclipses.

Hundreds of eclipsing stars are recognized today. In addition to Algol, the stars β Lyrae, λ Tauri, and *u* Herculis are well known members of this class, whose periodic winking can be seen without the telescope.

The periods of the fluctuations vary from a few hours, when the two stars are very nearly in contact, to several months, as a general thing. In the very exceptional case of ε Aurigae the eclipses occur at intervals of 27 *years*, and they last about two years; the most recent minimum occurred in 1929. The blue fourth-magnitude ζ Aurigae, also in the little triangle near Capella, is totally eclipsed for a month once in 2 years 8 months by a fainter and much larger red companion.

Russell and Shapley have explained how to transform the light curve of an eclipsing variable into a picture of the double star itself, a picture in which the relative sizes of the two stars, their forms, their distances apart, and the tilt of their orbits are revealed. When the spectroscopic evidence is added, the dimensions are given in miles, and the masses and densities of the stars can be evaluated also.

Here is an impressive example of the power of astronomical inquiry; eclipsing stars can divulge by the manner of their winking remarkably complete descriptions of remote pairs of suns. An equally impressive example is given by another class of variable stars whose fluctuations inform us of their distances.

12.4. Cepheid Variable Stars. This class of variable stars takes its name from one of its earliest recognized members, Delta Cephei, in the little triangle which marks the southeast corner of the spire-like Cepheus in the northern sky. This star fluctuates with perfect regularity in cycles of 5 days and 9 hours, growing brighter, then fainter, then brighter again. Its light becomes bluer as it brightens, and redder as it fades.

Cepheid variables were formerly supposed to be double stars revolving in the periods of their light variations; for the lines in their spectra swing back and forth in these periods, farthest to the violet when the light is brightest and farthest to the red when the light is faintest. Theories were invented to explain why the stars should be brighter and bluer when they are revolving toward us, and fainter and redder when they are receding.

They are single stars, we believe today. Shapley, in 1914, showed that the double-star theory is unsatisfactory, and proposed the pulsation theory in its stead. In the simplest form of the new theory, Cepheids are single stars which are expanding and contracting rhythmically. Cooled by expansion they become fainter and redder; heated by compression they become brighter and bluer, though the stars do not attain their greatest brightness and bluest hue until they are expanding again most rapidly. And it is this surging of the gases to and fro on the sides of the stars that are turned toward the earth which causes the oscillations of the lines in their spectra.

Cepheids whose periods are around half a day are called *cluster variables*, because they are numerous in the globular clusters, as Bailey was the first to observe, in 1895. They are mostly blue stars, and no one of them is bright enough to be seen without the telescope. *Typical Cepheids*, such as δ Cephei and η Aquilae, have periods longer than a day, and are mostly yellow stars. Both increase in brightness more rapidly than they decline, as a general thing, though the difference becomes less noticeable as the periods are longer.

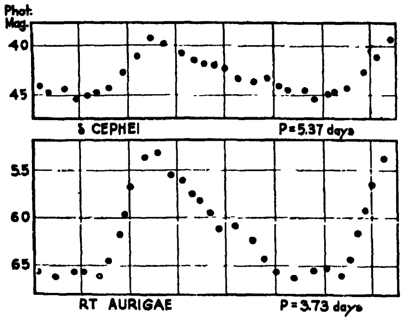


FIG. 12.4. Light Curves of Two Cepheid Variable Stars. (*From diagrams by L. V. Robinson, Harvard Observatory*)

The cause of Cepheid variation is not completely explained as yet. Meanwhile a remarkably useful relation between their periods and absolute magnitudes has been discovered.

12.5. The Period-Luminosity Relation. In 1912, Miss Leavitt at the Harvard Observatory noticed that the typical Cepheids in the Small Magellanic Cloud increase in *apparent* brightness as their periods increase.

Shapley, in 1918, was among the first to recognize the importance of this relation in sidereal explorations. Correcting for the distance of the Cloud, he published a curve which shows how the *absolute* median magnitudes of the Cepheids increase with the periods of their light variations.

The *median* magnitude of a variable star is the average of its magnitudes at maximum and minimum brightness.

If the period is half a day, the median absolute photographic magnitude is 0.0; a period of 1 day corresponds to magnitude −0.3; of 10 days to −1.8; of 50 days to −3.0; of 100 days to −4.6. When the period of the light variation has been observed, the absolute magnitude is derived at once from Shapley's curve.

When the absolute magnitude of the Cepheid has been learned in this way, and when its apparent magnitude has been measured, the star's distance from us can be readily calculated by the rule which has been mentioned before (11.16). Thus wherever a Cepheid variable is found, its distance can be learned, and so the distance of the assemblage of which the star is a member.

12.6. Mira, the "Wonderful," was the first variable star to be discovered, aside from a few remarkable novae. In 1596, the amateur astronomer Fabricius saw it as a star of the third magnitude in a place in the constellation Cetus where no star was marked on the charts; and he regarded it as another "new star." Its true character as a fluctuating star was not recognized until 1638. Meanwhile, Bayer (4.12) had observed Mira at one of its maxima, and not being aware of its variability had lettered it o Ceti on his chart.

This red star fluctuates in the average period of 330 days; the intervals between its maxima have varied as much as a month. It averages magnitude 3.5 at its brightest, and magnitude 9 at its faintest, when it is accordingly invisible to the naked eye.

Mira is a red super-giant, two or three hundred times as great as our sun. It is more massive also than the sun, but in nothing like the same proportion, so that its gaseous material is spread out on the average probably as much as a thousandth as thin as the air around us. If you weigh 150 pounds here on the earth, you would weigh only a few ounces at the surface of Mira. There, things are light and airy indeed.

The "Wonderful Star" in Cetus is one of the numerous class of *long-period variables* whose periods range from a few months to more than two years, and average about 300 days. These red stars fluctuate in a roughly periodic way that reminds us of the sun-spot cycles (10.11). Their light varies often through several magnitudes; in extreme cases such as χ Cygni the range exceeds eight magnitudes. Yet the variation of their total radiation averages only one magnitude, as Pettit and

Nicholson have found from their measurements of the amounts of heat these stars send us.

Long-period variables are pulsating stars, we believe today. Whether they are expanding and contracting as a whole or whether the effect is a superficial one, consisting perhaps only of the rise and fall of the levels from which their radiation escapes, is not yet completely revealed. In their approach to regularity they come between the punctual Cepheids and the irregular variables.

12.7. Irregular Variable Stars. Many red stars vary in light within narrow limits, seldom more than half a magnitude, in ways that are not readily predictable. Alpha Herculis is an example.

Betelgeuse, the brightest of the irregular variables, sometimes approaches the splendor of its blue neighbor Rigel, and at other times is scarcely more than a third as bright.

There are irregular variables of other colors which show a degree of uniformity in their variations, and are divided on this basis into three or more groups. Most faithfully observed of them all is the star known as SS Cygni. Campbell at Harvard Observatory has published a record of its variations from the time of its discovery, in 1896, a record of more than 44,000 observations, most of them by American and British amateur astronomers.

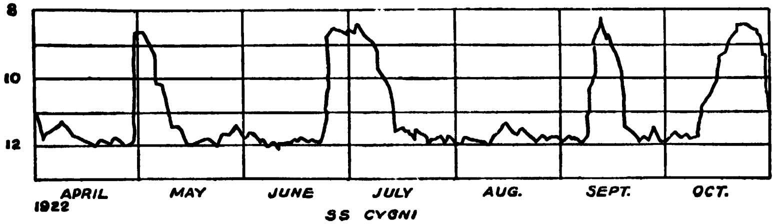
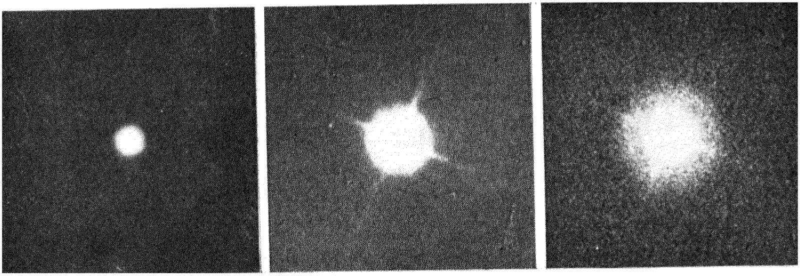


FIG. 12.7. Light Curve of the Variable Star SS Cygni.

Around the twelfth magnitude for most of the time, SS Cygni rises at intervals of 50 days on the average to between the eighth and ninth magnitudes. The maxima of the light curve are alternately wide and narrow, as a rule. The spectrum bears considerable resemblance to that of the "new" stars, according to Adams and Joy.

12.8. Novae, or *temporary stars,* burst out from relative obscurity sometimes to remarkable grandeur and then gradually decline. More than fifty have been recorded in our galaxy alone. It is estimated that as many as twenty novae brighter than the ninth magnitude make their appearance here each year, though most of them escape notice. They are designated by the word "Nova" followed by the possessive of the constellation name. Nova Aquilae is an example.



July 20, 1922 Sept. 3, 1926 Aug. 14, 1931

FIG. 12.8. Expanding Nebula Around Nova Aquilae of 1918. (*Photographed with the 100-inch telescope, Mount Wilson Observatory*)

The brightest nova on record was observed by Tycho Brahe. It appeared in Cassiopeia in November, 1572, and remained visible to the naked eye until May, 1574. It attained a brightness equal to that of Venus at greatest brilliancy. Kepler and Galileo were among those who watched the fine nova which flared out in Ophiuchus, in 1604; it rivaled the planet Jupiter, and remained visible to the naked eye for eighteen months.

Nova Aquilae, in 1918, was second in brightness to Sirius. Nova Persei, in 1901, was a little brighter than Capella. Nova Pictoris, visible in the southern hemisphere in 1925, was about as bright as Spica, while Nova Cygni, in 1920, was not much inferior to Deneb. Nova Herculis at its brightest on December 22, 1934, was about equal to Deneb. Previous to their amazing outbursts, these five stars were not brighter than the eleventh magnitude.

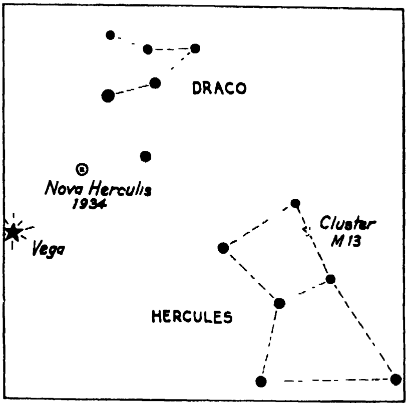


FIG. 12.8A. Region of Hercules. Showing positions of the Nova of 1934 and the cluster Messier 13.

These stars explode. Their outer layers are propelled outward at terrific speeds. Nine years after the explosion of Nova Aquilae the gaseous envelope around it was still growing in diameter at the rate of a hundred million miles a day (Fig. 12.8).

BINARY STARS

Two stars which appear close together in the sky may happen to lie in nearly the same direction, one far behind the other; or they may form a physical system. In 1802, William Herschel made the distinction between "optical doubles" and the "real doubles" which we call *binary stars* — pairs that are moving through space together and mutually revolving as they go.

Visual binaries are so close together that a telescope is needed to separate them. *Spectroscopic binaries* are even closer; single stars through the telescope, they are revealed as revolving pairs by the oscillation of their spectral lines.

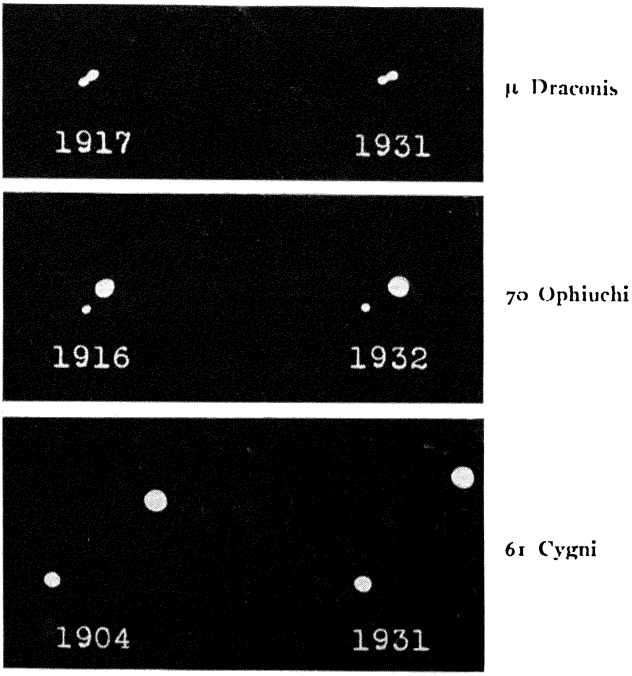


FIG. 12.9. Three Binary Systems. Showing their revolutions. (*Photographed at Yerkes Observatory*)

12.9. Visual Binary Stars. Mizar, at the bend in the Great Dipper's handle, was the first to be recorded, in 1650, as separated into two stars with the telescope. A few other conspicuous pairs, including Castor and Alpha Centauri, were noticed later. It remained for William Herschel, who began a systematic search for them in 1779, to discover that telescopic double stars are very numerous indeed, and that some of these pairs are mutually revolving.

The orbits of visual binaries are more eccentric than the planetary orbits, as a general thing. Their periods vary from a few years to hundreds and thousands of years, and their real separations vary from less than Jupiter's distance from the sun to many times Pluto's vast distance. Only a few have made complete revolutions since their discovery, and not more than one pair in ten has yet revolved far enough to show that it is really revolving.

Among the many visual binaries we select the brightest of all as a particularly interesting example.

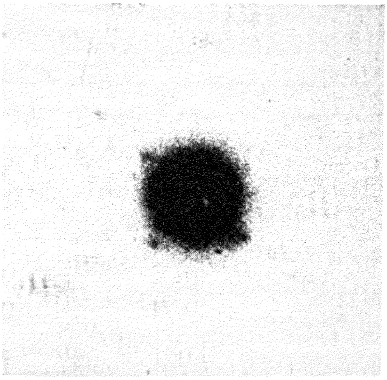


FIG. 12.10. Sirius and Its Companion. The large dot in this negative is the image of Sirius. The companion appears as a small dot immediately below it and to the left. Fainter images in the diagonal line were formed by a wire screen placed before the telescope objective. (*Photographed by A. Vyssotsky, Leander McCormick Observatory*)

12.10. The Companion of Sirius. One of the nearest stars, the brilliant Dog Star of our winter skies has a conspicuous proper motion. In the course of a thousand years it changes its place in the heavens as much as three quarters of the width of the full moon. More than that, it is proceeding in a wavy course, as Bessel was the first to notice, in 1834; it is not moving straight ahead as a single star would do. Sirius has a traveling companion.

The faint companion of Sirius was first seen in 1862, by the telescope maker Clark who was testing a new 18-inch lens, now the objective of the refracting telescope of the Dearborn Observatory at Northwestern University. The companion revolves in an orbit of considerable eccentricity around a common center with the bright star once in 50 years. For a few years around periastron, the closest approach of the two stars, which occurs next in 1944, the companion is invisible with present telescopes. At other times it can be clearly seen through large telescopes despite the glare of the bright star (Fig. 12.10).

Shining as a star of the eighth magnitude, only a ten thousandth as bright as Sirius itself, the companion is nevertheless not very much yellower than its brilliant primary, so that its radiation per square mile is not greatly different. The important difference is that it is very much smaller than Sirius.

The companion is one of the mysterious class of white dwarf stars. In diameter it resembles a planet, such as Uranus or Neptune, rather than a star. Yet its mass is as great as the sun's, and its density is accordingly something like 30,000 times that of water; a sample of its gaseous stuff no larger than a golf ball would weigh a ton here on earth. And a person who weighs 150 pounds here would weigh nearly 2000 tons at the surface of this remarkable star.

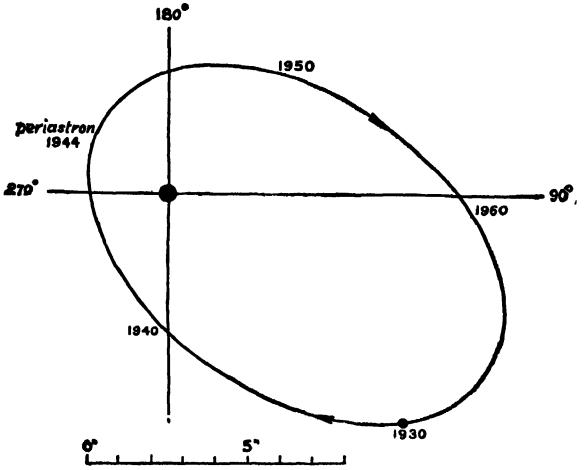


FIG. 12.11. The Orbit of Sirius. As determined by R. G. Aitken. The stars will be closest in 1944.

The light of the companion of Sirius loses so much of its energy in escaping from the powerful attraction of the star that the lines in its spectrum are plainly displaced to the red from their normal positions. Adams at the Mount Wilson Observatory observed this effect, in 1925, showing thereby that the companion is enormously compressed, and supporting Einstein's general theory of relativity which predicts such a redward shift of the spectral lines in a case of this sort.

12.11. Weighing the Stars. Double stars can tell us of their masses, the quantities of material they contain. The rule for determining the masses is found in the general statement of Kepler's harmonic law (7.14).

Let one pair of mutually revolving bodies be a visual binary, and let the other pair be the earth and sun. If our units of measurement are the combined mass of the earth and sun, the mean distance between the earth and sun, and the sidereal year, this law can be written:

The combined mass of the pair of stars equals the cube of their mean distance apart divided by the square of their period of revolution.

By means of this rule, which requires a knowledge of the orbit of the binary star and of its distance from the earth as well, astronomers have succeeded in "weighing" a number of stars with the result which we have noticed before. The masses of the stars vary less widely than their diameters. Relatively few stars have masses exceeding five times or less than one fifth the sun's mass. In addition, the studies of R. C. Huffer show that the brighter star is usually, though apparently not always, the more massive.

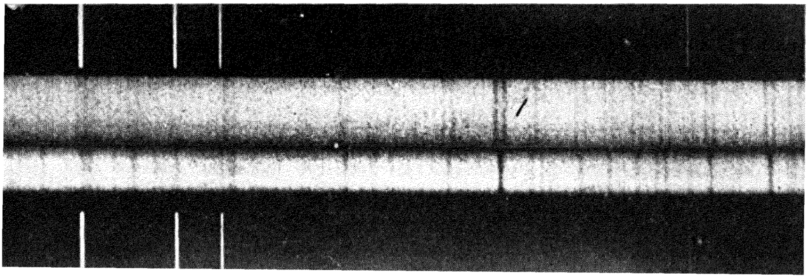


FIG. 12.12. Spectrum of Mizar. The dark lines of the two components of the spectroscopic pair are separated in the upper spectrum and superposed in the lower one. (*Photographed at Mount Wilson Observatory*)

12.12. Spectroscopic Binary Stars are mutually wheeling pairs which the telescope cannot separate. They are made known to us by the oscillations of the lines in their spectra — the Doppler effect (10.4) as the stars alternately approach and recede from the earth in their revolutions, and also by their periodic winking, if their orbits are nearly edgewise to us.

Mizar was the first spectroscopic binary to be discovered, just as it was the first telescopic pair to be recorded. In the annals of double stars this star in the Dipper's handle is doubly famous. Pickering at Harvard Observatory announced, in 1889, that the lines in Mizar's spectrum appeared double in some of the photographs, and single in others when the two sets of lines were superposed (Fig. 12.12).

More than a thousand spectroscopic binary systems are known today, chiefly among the stars visible to the naked eye, whose spectra are the easiest to photograph. Capella, Spica, Algol, and the two telescopic components of Castor are examples. If the fainter star is less than about a third as bright as its companion, which is true of the majority, its spectrum does not show ordinarily; its presence is revealed by the oscillation of the lines of the brighter star's spectrum.

Not all oscillating lines indicate revolving pairs, it is true. The spectra of Cepheid variable stars exhibit this effect clearly, as we have seen, which suggests that these single stars are pulsating. Indeed, the lines in the spectra of all the stars swing back and forth in the course of the year as the earth alternately approaches and recedes from them in its journey around the sun. This annual effect in the spectra, itself a convincing proof of the earth's revolution, is readily allowed for.

STAR CLUSTERS AND NEBULAE

12.13. Nebulae, in the original sense, are cloudy patches in the heavens. A few are dimly visible to the naked eye, and accordingly have been known for a very long time. When Galileo observed through his little telescope that the "nebula called Praesepe" is really a cluster of stars, and as other foggy celestial objects came to be resolved into stars by the telescopes, it seemed reasonable to believe that the unresolved nebulae were likewise masses of stars.

Though he shared this belief at first, William Herschel reached the conclusion, in 1791, that some nebulae are not of a starry constitution, but are composed instead of "a shining fluid of a nature entirely unknown to us." His conclusion did not receive complete acceptance until Huggins, in 1864, discovered that the spectra of certain nebulae show only the bright lines which characterize the spectrum of a glowing gas.

Star clusters and nebulae have been listed together in the catalogues because of the difficulty in former times of distinguishing between them. And among the "nebulae" are still listed the foggy patches which are recognized today as other galaxies far beyond our own; these are the *extragalactic nebulae,* while the clouds of gas and dust in our own galaxy are *galactic nebulae.*

The very brightest of all these dissimilar objects are often designated by their numbers in the catalogue which the celebrated comet-hunter Messier prepared for the *Connaisance des Temps* of 1784. They are designated also, along with some thirteen thousand other clusters and nebulae, by their running numbers in Dreyer's *New General Catalogue* (NGC) of 1887, and its extensions in 1894 and 1908 known as the *Index Catalogue* (IC). Thus the fine cluster in Hercules is Messier 13, or NGC 6205.

The star clusters themselves are of two kinds: the less populous and less compact *open clusters,* which are also called *galactic clusters,* and the great balls of stars known as *globular clusters.*

12.14. The Open Clusters. The Hyades cluster, at the distance of 120 light years, is the nearest of the open clusters. The Coma Berenices

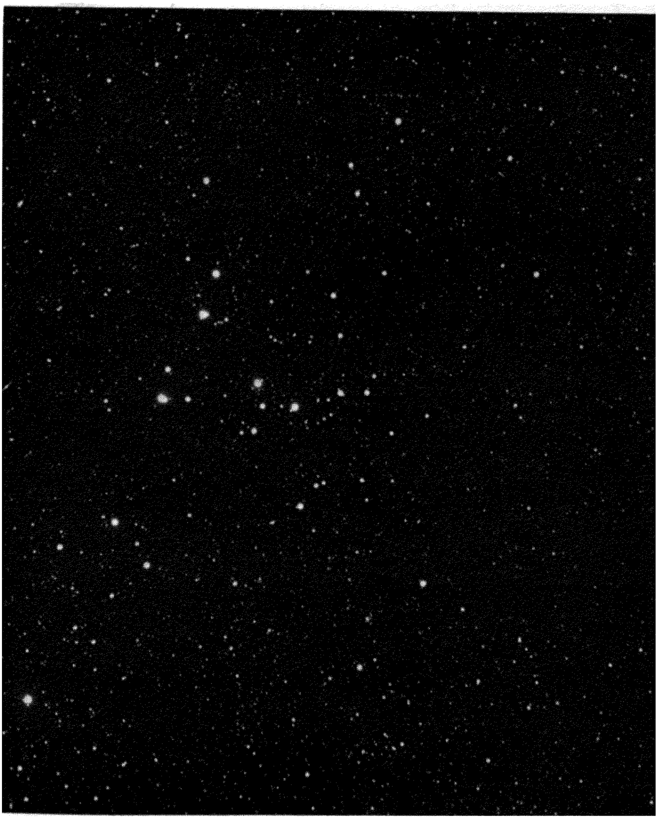


FIG. 12.14. Coma Berenices Cluster. (*Photographed by E. E. Barnard, Yerkes Observatory*)

(260 light years) and the Pleiades (nearly 500 light years) clusters come next in order. These three are near enough to show their brighter stars to the naked eye. Praesepe in Cancer (500 light years), the more distant double cluster in Perseus, and some others appear to the naked eye as foggy patches which are resolved into stars with slight optical aid. The majority of the clusters are invisible without the telescope.

More than three hundred open clusters are recognized. They lie within or close to the Milky Way, except the very nearest ones; the extreme exception is the Coma Berenices cluster (Fig. 12.14) near the north *pole* of the Milky Way. In membership they vary from thousands of stars in the Perseus clusters to so few that it is not easy to decide whether the grouping is real or accidental.

The so-called "moving clusters" are simply the nearer ones whose motions are more noticeable. The Ursa Major cluster has been mentioned before (11.9) as an unusual example; its stars are widely scattered over the heavens because we are in its midst. The Taurus cluster, containing the stars of the Hyades and its vicinity with the exception of Aldebaran, passed nearest the sun some 800,000 years ago at the distance of 50 light years, and since then has been angling away toward the east.

12.15. Globular Clusters. Two globular clusters are plainly visible to the unaided eye as stars of the fourth magnitude; they were designated as stars before their true character was revealed through the telescope. One is Omega Centauri (Fig. 12.15), the grandest of them all, near the northern edge of the Milky Way in the vicinity of the Southern Cross. The other is 47 Tucanae, west of the Small Magellanic Cloud and only 17° from the south pole of the heavens.

The great cluster in Hercules (Fig. 5.11) is the best known of the globular clusters to those who observe in middle northern latitudes. Nearly overhead in the early evenings of summer in the United States, it is a favorite showpiece through the telescope and a truly amazing assemblage of stars as it is revealed by photographs with great telescopes and long exposures.

Four other globular clusters are barely visible to the naked eye in the clearest skies, and are therefore easily located with slight optical aid, though a telescope of moderate size is needed to show that they are really globular clusters. These are Messier 22 in Sagittarius, Messier 5 in Serpens, Messier 55 in Sagittarius, and Messier 3 in Canes Venatici. The Hercules cluster itself is also known as Messier 13.

The nearest clusters appear something like two thirds as great as the full moon. Most of their stars lie within 30 light years of their centers, though some members are found as far as 100 light years from the centers. The clusters are not exact spheres; they evidently rotate on their axes, and bulge therefore at their equators.

Any one of the nearest clusters contains at least 50,000 stars bright enough to be observed, though the stars around the center are too congested to be separately seen. These are giant stars and the blue stars of the main sequence. Stars no brighter than our sun are quite invisible through the largest telescope at the great distance of even the nearest globular cluster.

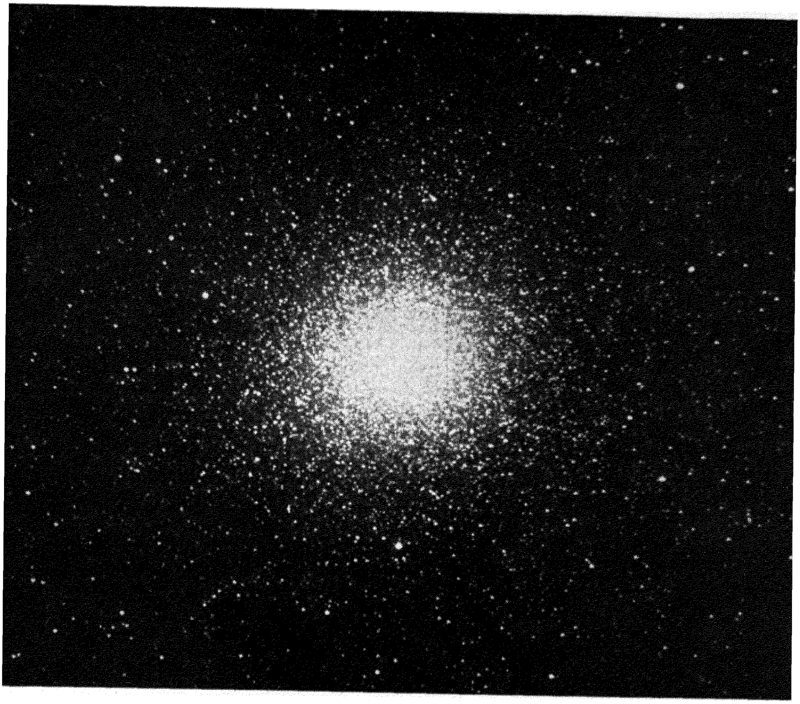


FIG. 12.15. Globular Cluster Omega Centauri. (*Photographed with the 60-inch Reflector at the Boyden Station of Harvard Observatory, in South Africa*)

Ninety-five globular clusters are recognized in our galaxy. The majority have been known to astronomers since the times of the Herschels, though not all of them were assigned at first to this particular class. Globular clusters are rare as compared with open clusters; it is their far greater luminosity that makes their observed number of the same order as that of open clusters.

12.16. The Great Nebula in Orion surrounds the middle one of the three stars in Orion's sword (Fig. 12.16). This star is resolved by the telescope into a little trapezium of four stars, while around them the nebula glows with a pale greenish light. It is the nearest and brightest of the cloudy patches of gas and dust along the course of the Milky Way, which we call *diffuse nebulae.*

Few of them except the Orion nebula are spectacular sights to the eye at the telescope. Many are spectacles indeed in the photographs with large telescopes and long exposures.

The whole region of Orion is a nebulous one, as the long-exposure photographs show. Stars of the Pleiades are entangled in cloudy stuff; the shredded nebulosity around Merope is particularly impressive, suggesting the fibrous cirrus clouds of fair weather.

FIG. 12.16. The Great Nebula in Orion. It surrounds the middle star of the three in Orion's sword. *(Photographed at Harvard Observatory)*

The North America Nebula near Deneb in the Northern Cross (Fig. 5.18) bears a striking resemblance in the photographs to the continent for which it was named by its discoverer, Wolf, at Heidelberg; yet it is quite invisible to the eye at the telescope. And near the end of the eastern arm of the Cross, the Network Nebula reminds one of frostwork on the windowpane, while the neighboring Filamentary Nebula marks the opposite side of a loop of nebulosity still spreading from a central point where a great explosion long ago propelled it outward.

The Trifid Nebula in Sagittarius might seem to be breaking apart, if we did not know that the streaks across the glowing mass are lines of dark nebulosity. These are a few examples. The diffuse nebulae present a variety of forms.

Why do these nebulae glow? They are too tenuous to be incandescent; the stuff of which the Orion nebula is composed can scarcely have a trillionth the density of the air around us. And why do some nebulae glow while others seem quite unlighted?

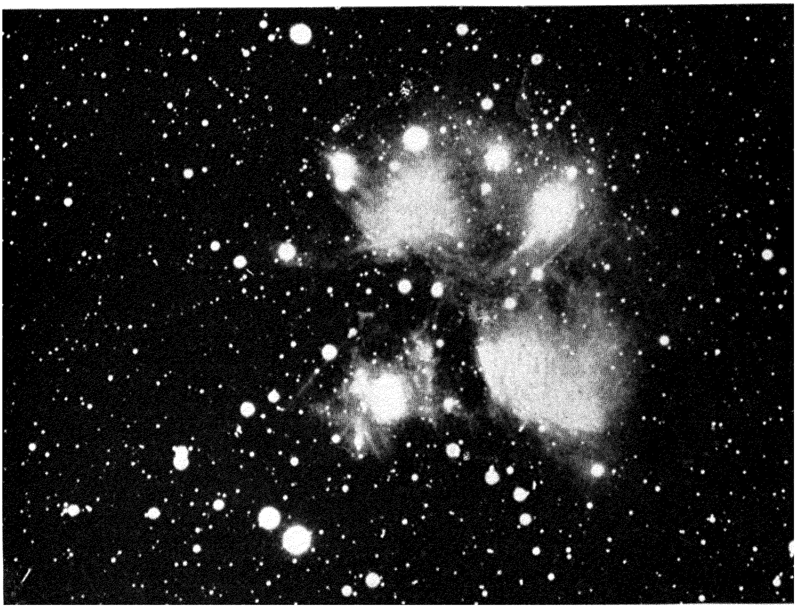


FIG. 12.17. Nebulae Surrounding Stars of the Pleiades. (*Photographed by E. E. Barnard*)

12.17. The Light of the Nebulae. The spectrum of the great nebula in Orion is a pattern of bright lines, such as a glowing gas ordinarily gives. Indeed, the bright-line spectrum was believed to be characteristic of all true nebulae until V. M. Slipher's discovery, at the Lowell Observatory in 1912, that the spectra of the nebulosities surrounding Merope and Maia in the Pleiades are crossed by dark lines, precisely like the spectra of the stars themselves.

Hubble, at Mount Wilson in 1922, made the next advance. He discovered that the nebulae are lighted by neighboring or actually involved stars. If the associated star is hotter than class B1, the nebula has a bright-line spectrum; in such cases the gaseous stuff is set glowing by the star, in perhaps the same way that our atmosphere is illuminated with auroral light by a stimulation coming from the sun.

If the associated star is cooler than class B1, the spectrum of the nebula is crossed by dark lines. Slipher suggested that the nebular light is then simply reflected starlight. Struve, Elvey, and Keenan at Yerkes Observatory find that the light of the nebula surrounding the Pleiades is not enough bluer than the starlight to be scattered by gas alone, as the scattering of sunlight by our atmosphere produces the blue sky. The greater part of the nebular light must be reflected by solid particles. So they confirm the thought of Russell and others that nebulae are assemblages of gas and dust, and doubtless of larger solid pieces as well.

The brighter the stars that are responsible for the light of the nebulae, the greater are the distances from them at which the nebulous stuff is still illuminated. Beyond limited distances from the stars the nebulae do not shine at all, or at least not enough to make them visible in this way. Thus there are many dark nebulae as well as bright ones. We shall notice in the following Chapter some obscuring effects of the dark "dust clouds" by which they are revealed.

12.18. Planetary Nebulae are so named because many of them appear as somewhat flattened disks through the telescope. Slightly more than a hundred are recognized in our galaxy, and not one of them is visible to the naked eye. The nearest of all, the helical nebula in Aquarius, appears half as great as the full moon, while the most distant ones look no larger than stars. Aside from some of the nearest ones, they crowd closely around the middle line of the Milky Way.

Curtis' photographs of these objects, at Lick Observatory (1918), made clear many of their characteristics. Their oval disks are brighter toward the circumference, and so decidedly brighter in some cases that the nebulae have the appearance of rings; the Ring Nebula in Lyra (Fig. 5.12A) is a famous example. Some, like the Dumb-bell Nebula in Vulpecula (Fig. 12.18), are less luminous at opposite sides of their bulging equators. Some are marked with complex patterns in bright and dark. Almost without exception the planetary nebula has a star at its center.

The resemblance of planetary nebulae to the nebulae expanding around some of the novae (Fig. 12.8) is conspicuous enough to promote the opinion that the planetaries originated in the explosions of their central stars. Duncan's photographs at Mount Wilson of one of these, the Crab Nebula in Taurus, show that it is still expanding. Mayall's spectroscopic study of this nebula at Lick Observatory shows that its radius is increasing daily more than half the distance from the earth to the sun. If the rate of expansion has been constant from the beginning, the explosion occurred around the year 1100. The loop of nebulosity in Cygnus (12.16) may well be considered a planetary near the end of its visible career. Whipple at Harvard Observatory estimates the average life of a planetary nebula at 30,000 years.

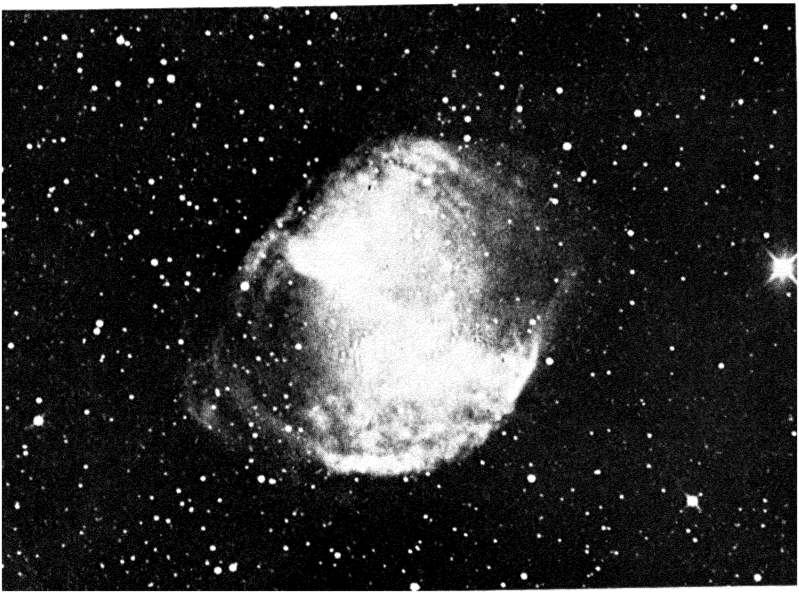


FIG. 12.18. Dumb-Bell Nebula in Vulpecula. *(Photographed July 11, 1931, by F. E. Ross at Mount Wilson Observatory)*

QUESTIONS ON CHAPTER XII

1. If you wished to discover a variable star, how would you proceed? Having discovered one, how could you then decide to what class it belonged?

2. Explain the slight drop in the light curve of Algol (Fig. 12.2) halfway between the principal eclipses.

3. Suppose that two Cepheid stars appear equally bright; the first one fluctuates in a period of five days, the second one in ten days. Which is the more remote?

4. Give directions for locating the variable star Mira. When is the region of this star favorably placed for observation in the early evening?

5. In what sense is a nova a "new star"?

6. How is it known that the companion of Sirius is a very small star?

7. The double star Alpha Centauri revolves in a period of 80 years, and its average separation is 23 times the earth's distance from the sun. Show that the combined mass of the pair is about twice the sun's mass.

8. Distinguish between open clusters and globular clusters. Name an example of each kind.

9. Many nebulae which are spectacular objects in the photographs are unimpressive sights to the eye at the telescope. Explain.

10. If our solar system should pass through a nebula such as the one in Orion, would we be likely to notice anything unusual?

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CHAPTER XIII

THE GALACTIC SYSTEM

The *galactic system* is the whole assemblage of stars and nebulae around us whose most impressive feature, as we look out from within the system, is the girdle of the Milky Way (5.17; 5.35). In studies which relate to the structure and extent of the galactic system it is often convenient to describe the positions of the celestial bodies with reference to a set of circles based on the Milky Way.

13.1. Galactic Longitude and Latitude. The north and south *galactic poles* are the two opposite points of the celestial sphere which are farthest from the central line of the Milky Way. The north galactic pole is in right ascension $12^h\ 40^m$, declination + 28° (1900), in Coma Berenices where we have noticed (Fig. 12.14) a fine open star cluster. The south galactic pole is situated in the constellation Sculptor. Halfway between the galactic poles, the *galactic equator* runs about a degree north of the central line of the Milky Way, which suggests that the sun may be somewhat north of the central plane of the system.

The galactic equator is inclined 62° to the celestial equator, and crosses it from south to north in the constellation Aquila. From this unnamed intersection, in right ascension $18^h\ 40^m$, *galactic longitude* is measured in degrees toward the north along the galactic equator. *Galactic latitude* is measured in degrees perpendicularly from the galactic equator. Tables and graphs are available for converting the equatorial coordinates of a star into galactic coordinates.

13.2. Early Studies of the Galactic System. Previous to 1775, when William Herschel in England began his celebrated "review of the heavens," astronomers had confined their attention chiefly to the members of the solar system. The significance of the Milky Way had been practically unknown until Galileo, about 1610, viewed it as "a mass of innumerable stars planted in clusters." Thomas Wright of Durham, England, and the philosopher Kant at Königsberg, about the middle of the eighteenth century, had suggested that the appearance of the Milky Way might well be produced by a much-flattened assemblage of stars in which the sun occupied a fairly central position. Herschel was the pioneer in systematic explorations of the star fields. One of his

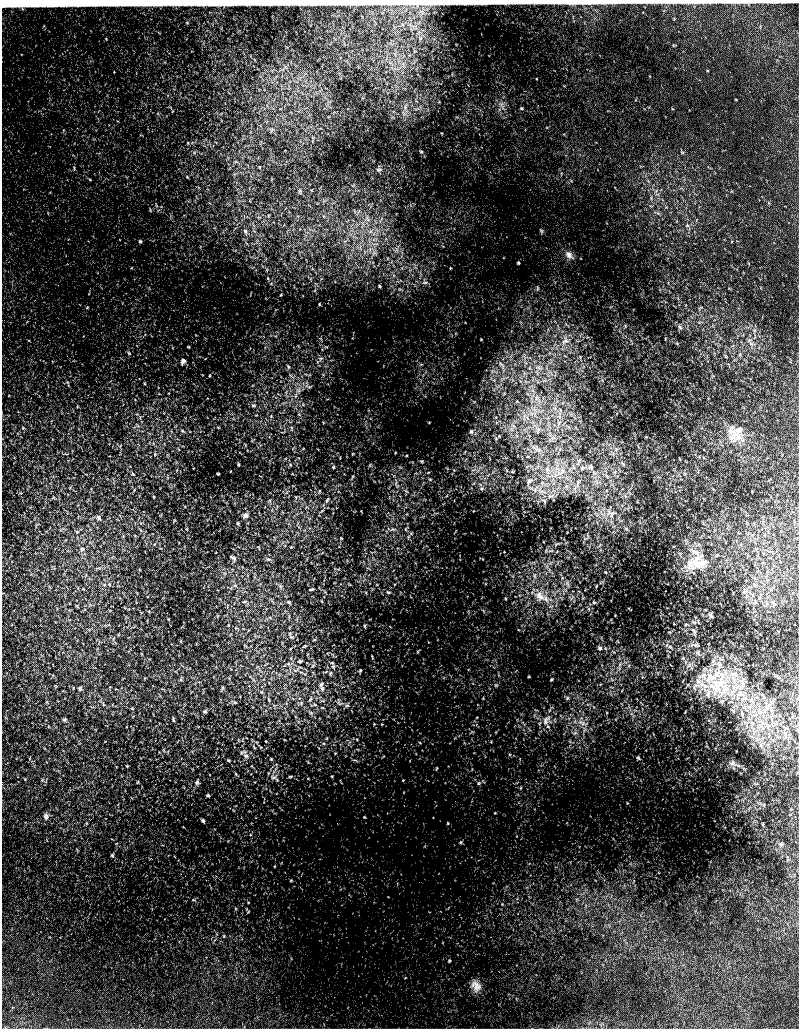


FIG. 13.2. The Milky Way from Scutum to Northern Sagittarius. The Scutum cloud is near the top. The northern edge of the Sagittarius cloud appears in the lower right corner, and to the left of it the globular cluster Messier 22 is seen. (*Photographed by F. E. Ross at Mount Wilson Observatory*)

principal projects was to determine the form and extent of the galactic system.

Herschel's "star gauges" consisted in counting the numbers of stars he could see in the field of view, when the telescope was directed successively to different parts of the heavens. This particular telescope was 20 feet long and 19 inches in aperture, and the area of the sky it showed at one time had half the apparent diameter of the moon. He examined 3400 regions; in some he saw only a few stars, while in others near the Milky Way he counted hundreds.

Herschel assumed that the distance to which the stars extend in any direction was proportional to the cube root of the number of stars he could see in that direction. If, for example, he counted 8 stars in one area and 64 in another, he concluded that the stars extended twice as far in the second direction as in the first. He was assuming for convenience that the stars were scattered uniformly through the system, and that he could see through to its edge.

The resulting model of the galactic system, which he published in 1784, had a much-flattened irregular form; it was cut in deeply toward the center in places where the dark rifts appear in the Milky Way. William Herschel's method was too simple, as pioneer methods are likely to be; but his counts and those of his son, John Herschel, in the southern hemisphere remained the principal data for subsequent investigations of galactic structure for nearly a century. With improvements in the procedure the analysis of star counts has remained to the present time a profitable approach to the problem of the structure of the galactic system.

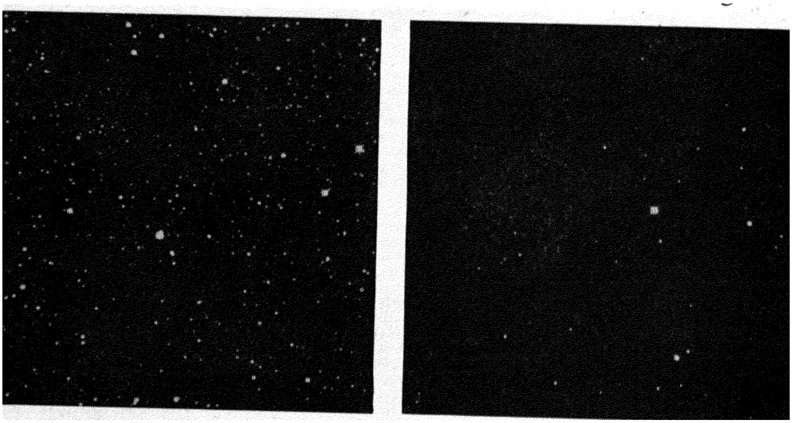
13.3. The Plan of Selected Areas. Herschel's method of determining the distribution of the stars in all parts of the heavens by counts in many small areas was elaborated by the Dutch astronomer Kapteyn in his plan of Selected Areas inaugurated in 1906. He chose 206 areas scattered uniformly over the whole sky, and invited astronomers to determine photographically the magnitudes and other data for the stars in these areas. The counts were now to be made with respect to magnitude.

Two noteworthy contributions to this project are the *Mount Wilson Catalogue* and the *Bergedorfer Spektral-Durchmusterung*. The former, published in 1930, contains the photographic magnitudes to around $18^{m}.0$ in 139 of the Areas as far south as declination $-15°$; they are squares 15′ or 20′ on a side. The latter, which is still incomplete, contains the photographic magnitudes and spectral classes of stars to around

$13^m.0$ in fields 3½° on a side centered in the original Areas. Counts of stars from the former catalogue and from other somewhat less reliable catalogues giving the magnitudes of stars in the southern Areas and of the brighter stars in larger fields were employed by Seares at Mount Wilson and by van Rhijn at Groningen to derive the surface distribution of the stars over the whole sky.

The object of the plan of Selected Areas is to solve the problem with a minimum of time and effort. The fields of the *Mount Wilson Catalogue* cover less than a twenty-fifth of one per cent of the whole sky. The plan is completely successful only if the small Areas are fair samples of the regions around them. Far from the Milky Way the Areas seem reasonably representative. But within the complex structure of the Milky Way itself the Areas give little information as to the character of their surroundings. A more recent and comprehensive plan of counting the stars in and near the Milky Way will be mentioned later (13.9).

13.4. Flattening of the Galactic System. The stars crowd toward the Milky Way. This is one of the most obvious features of the galactic system, as we look out from within the system and see it spread over the face of the sky. From the dull regions near the galactic poles,



In the Milky Way — Near the Galactic Pole

FIG. 13.4. The Stars Crowd Toward the Milky Way. Two equal areas of the sky, in the Milky Way and near the galactic pole. The faintest stars shown in both regions are of the eighteenth magnitude. (*Photographed at Mount Wilson Observatory*)

Auriga, where we look the shortest way out along the galactic equator. It seems probable that the sun's distance from the edge in the latter direction is less than its distance from the center of the system.

13.6. The Galactic System as a Spiral. The first characteristic of the galactic system to be recognized was its great extension in the plane of the galactic equator (13.4). Investigations of the system of globular clusters (13.5), in 1918, established the eccentric position of the sun and the direction of the center of the system in Sagittarius. The discovery, in 1924, that the extragalactic nebulae are systems exterior to the Milky Way and the frequency of the spiral structure in these systems suggested that the galactic system might have the spiral form as well. From counts of stars in Selected Areas and from other available data, Seares at Mount Wilson, in 1928, presented a tentative picture of the galactic system which was widely adopted as a basis for further inquiry. It was about as follows:

The galactic system is a vast organization resembling the spiral nebula Messier 33 (Fig. 13.14) though probably larger. Its center in galactic longitude 325° lies in an enormous condensation of stars that is mostly hidden behind the great dust cloud of Ophiuchus. The diameter of the system exceeds 200,000 light years, if it is coextensive with the system of globular clusters. The sun is near the plane of the galactic equator and some 60,000 light years from the center. The sun is situated in the local system, a flattened assemblage of many millions of stars, which is presumably a star cloud in one of the arms of the spiral. The diameter of the local system is around 20,000 light years and its center is in galactic longitude 230°, in Carina.

Further studies have altered some features of the earlier picture, as might well be expected. The diameter of the system is now estimated at 100,000 light years or even less, and the other dimensions are correspondingly reduced. The existence of the large local system is not verified. The part of the system that we can observe is not so broken into discrete star clouds as was formerly supposed. Most of the alterations have resulted from a better understanding of the obscuring effects of dust clouds in the system.

13.7. Star Clouds and Dust Clouds. Early investigators of the galactic system regarded the familiar rifts in the Milky Way as relatively vacant spaces between the star clouds through which they looked into the blackness of outer space. Barnard at Yerkes Observatory and Wolf at

Heidelberg, about 1910, presented the current interpretation that the rifts are caused by dark nebulae; these are clouds of dust which obscure the more distant stars. It was shown later (12.17) that the bright diffuse nebulae are parts of the dust clouds that are illuminated by involved or neighboring stars.

The longest dark rift is produced by a succession of dust clouds which extend from the Northern Cross nearly as far down as the Southern Cross, dividing the Milky Way into two streams over a third of its course. It is punctuated at one end by the conspicuous transverse slash north of Alpha Cygni and at the other by the famous "Coal Sack" near the Southern Cross. Examples of very large obscured areas are found in Ophiuchus and in Cassiopeia and Cepheus where the influence of the dark cloud extends northward beyond the celestial pole.

FIG. 13.7. **Rifts in the Milky Way. Region of southern Ophiuchus and northern Scorpius. A part of the great Sagittarius cloud appears in the lower left corner. The lower of the two bright spots near the right edge is Antares in Scorpius.** (*Photographed by F. E. Ross at Flagstaff, Arizona*)

The dark nebulae that are responsible for the Coal Sack and the rifts in Taurus and Auriga are something like 500 light years from the sun. The dark cloud of Ophiuchus is around 800 light years away. The cloud of Orion, one of whose illuminated parts is the great nebula in Orion, is at the distance of 1000 light years. The clouds of Cygnus and Cassiopeia are at distances around 2500 light years. All the conspicuous vacancies in the Milky Way are obscuring effects of relatively near-by dust clouds.

13.8. The Hypothesis of a Dusty Layer. After the recognition of the dust clouds in the vicinity of the Milky Way, it was generally believed that interstellar space was otherwise practically empty. Certain lines were observed in the spectra of stars, for example, the H and K lines of calcium in the spectra of blue stars, which evidently arose not in the atmospheres of these stars but during the long journey of the starlight to the earth. Yet the material that produces these *interstellar lines* could be so tenuous as not to appreciably dim or redden the starlight. Astronomers went on with their explorations of the galactic system, unaware that a widespread dusty medium in space was making some of the distances they measured come out too great.

FIG. 13.8. Spiral Nebula NGC 5746, in Virgo, Nearly on Edge. Like our own galactic system, the exterior systems have clouds of absorbing material along their principal planes. (*Photographed at Mount Wilson Observatory*)

Trumpler, at the Lick Observatory in 1930, gave definite warning that the dimming of starlight by dust was not restricted to the conspicuous rifts in the Milky Way. Having measured the distances of a hundred open star clusters, such as the double cluster in Perseus, with the assumption that the intervening spaces were perfectly transparent, he found that the clusters seemed to increase progressively in linear diameter with increasing distance from the earth. This could come about if their brightness was being reduced in proportion to their distances by a hazy medium in space; the sizes of the clusters would be magnified along with the distances more and more with increasing distance from the earth. This conclusion called for a review of all stellar distances which depended on the observed brightness of the stars.

To simplify the new problem as far as possible, Trumpler proposed the hypothesis of a uniform layer of dust something more than a thousand light years in thickness spread along the principal plane of the galactic system, like the filling of a sandwich, and containing the sun. If the effect of the layer on starlight traversing it vertically could be learned, its effect on the light of a star in any direction and at any specified distance from the earth could be calculated. Intended to simplify the correction for the obscuring medium, this hypothesis has been often employed by investigators of the galactic system. There is evidence, however, that the dust is patchy and that its effect in each part of the Milky Way must be determined by separate explorations.

13.9. Present Counts of Stars. The attempts to determine the distribution of the stars in all parts of the heavens by counts in small areas have been least successful in the vicinity of the Milky Way. Here the complexity is such that the investigations of two separated areas gives little information of conditions between the areas. A satisfactory exploration of a region of the Milky Way requires counts of stars over the entire region, at least to distances great enough to reach beyond the dust clouds which are responsible for the observed complexity of the scene.

Bok at Harvard Observatory and his associates in the enterprise are making counts of stars over the entire course of the Milky Way in order to reach this first objective. The counts are made on photographic plates; many of these are taken with 4-inch Ross cameras and show stars somewhat fainter than the fifteenth magnitude. The counts are made with respect to magnitude, so that ultimately the observer can determine how many stars per square degree in any particular area of the Milky Way are brighter than the ninth magnitude, brighter than the tenth magnitude, and so on to the fifteenth magnitude. Thus arranged, the star counts provide the data for the space analysis of that area. The general plan of the analysis is described in the following Section.

The analyses of these and other star counts are giving the positions in space of the different dust clouds and the amounts in magnitudes that they dim the stars behind them. They suggest that in the absence of intervening obscuring material the Milky Way would appear fairly regular, diminishing smoothly in brightness with increasing distance from the galactic equator. They show that the stars thin out with increasing distance from the sun in the plane of the equator. Thus the sun is situated in a region where the stars are more concentrated than they are in the regions immediately surrounding it. This assemblage of stars around the sun, however, is far smaller than the "local system" of the original analysis of the Selected Areas (13.6).

13.10. Analysis of the Star Counts. If the stars were uniformly distributed through space, if they were equally luminous, and if space itself were perfectly transparent, then the relative distance of any star could easily be determined from its observed magnitude. Consider, for example, a star of the ninth magnitude and another of the tenth magnitude. The first star is 2½ times (4.13) as bright as the second. Since the brightness of a star varies inversely as the square of its distance, the second star is 1.58 times as far away as the first. Under the assumed conditions, therefore, the number of stars brighter than a given magitude is 1.58^3, or nearly 4 times, greater than the number brighter than the next smaller-numbered magnitude. This relation is the basis for the analysis of the star counts.

If the counted numbers of stars to the successive limiting magnitudes in an unobscured area of the sky increase by a factor greater than 4, the stars are becoming more concentrated in that direction; if the factor is less than 4, the stars are thinning out with increasing distance. It will also be evident that a comparison of the counts in an obscured area with those in a corresponding unobscured area should show the distance and degree of obscuration of the dust cloud in the former area.

The assumption that the stars are all equally luminous is, of course, unwarranted. Since the absolute magnitudes of the stars differ widely (11.17), it is necessary to know what proportions of the stars at the various distances from the sun contribute to the total number counted at each successive apparent magnitude. This information is available, though it may still not be as accurate as could be desired.

So the star counts furnish the data for the space analyses which chart the distribution of the stars and dust clouds in the various directions as far from the sun as the counts extend, and prepare the way for more extensive explorations of the galactic system.

The evidence from the counts can be supported by observations of extragalactic nebulae. Wherever the exterior systems appear in profusion, it can be safely supposed that there is little obscuration of the stars in that direction. As a general thing, the exterior systems are most numerous far from the galactic equator and are rarely seen near that equator. The irregularity of the "zone of avoidance" (Fig. 13.10) and the existence of "windows," through which some exterior systems can be glimpsed very near the central line of the Milky Way, are not consistent with the hypothesis of a uniform dusty layer (13.8).

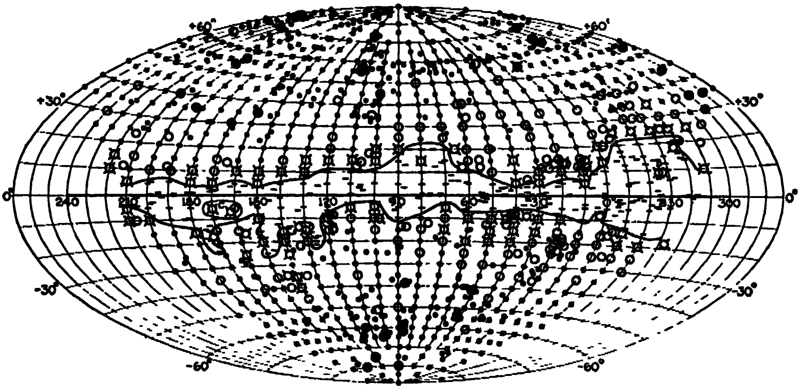


FIG. 13.10. Obscuring Material in and Around the Milky Way Hides the Extragalactic Nebulae Beyond. In this representation of the celestial sphere the numbers around the edge are galactic latitudes. Large dots indicate regions where the nebulae are more numerous than average, circles where they are less numerous than average, and dashes where they are not seen at all. The nebulae are entirely hidden in the irregular band along the galactic equator, and are partly hidden for some distance north and south of this "region of avoidance." (From a diagram by Edwin Hubble in *Contributions from the Mount Wilson Observatory, No. 485*)

Further support of the evidence from the star counts is provided by the degrees of reddening of the stars beyond their normal colors.

13.11. Reddening of Starlight by the Dust Clouds. Just as the normally yellow sun sometimes appears deep red at its setting, so the stars are reddened by intervening dusty material in the galactic system.

In order to determine the amount of this reddening in the case of any star, one must know the spectral class (11.12) of the star. The normal color of a star of each spectral class is well known and is often expressed numerically by the *color index*, that is to say, the difference between the photographic and visual magnitude of the star; the color index is taken as zero for a class A0 star, such as Sirius, and is something like a magnitude and a half for red stars such as Betelgeuse.

The procedure is to measure the color index of a star, perhaps by comparing its magnitude on an ordinary photographic plate with that on a red-sensitive plate exposed behind a red filter. When appropriate correction is made, the *color excess* of the star, or the amount that the observed color index exceeds the normal color index for that particular spectral class, is a measure of the reddening of the star by the intervening dust.

The distance and effectiveness of a dust cloud can be determined by measuring the color excesses of stars at different distances in that direction. If, for example, the stars in a certain area show no color excess to the distance of 1000 light years and an excess of half a magnitude beyond that distance, there is a dust cloud in this area at the distance of about 1000 light years from the sun. The *photographic absorption* of the cloud, which is the amount in magnitudes that the stars behind the cloud are dimmed on the ordinary photographic plate, is considerably greater than the color excess.

Stebbins, Huffer and Whitford have determined with the photoelectric cell the color excesses of class O and class B stars to about the tenth magnitude that are observable from Madison and Mount Wilson. Measures of color excess are in progress in different parts of the Milky Way. There is urgent need of spectral classes of fainter stars than are now available, so that the color excesses of more distant stars can become known.

13.12. Reddening of Globular Clusters. Particularly interesting in this connection are the measurements of the colors of the globular clusters which Stebbins has made with the photoelectric cell at the focus of the 100-inch telescope on Mount Wilson. He finds that the clusters are reddened more and more, in general, as they are nearer the central line of the Milky Way.

In the original investigation of the system of globular clusters (13.5) the effect of intervening dust was neglected, because its existence was then unknown. The diameter of the magnified cluster system in the plane of the galactic equator, where the system seemed to be much extended, was given as exceeding 200,000 light years. Since the cluster system was supposed to constitute the superstructure of the galactic system as a whole, the diameter of the system of the Milky Way itself was estimated at 200,000 light years.

With allowance for the dimming of the light of the clusters by the dusty medium, the clusters near the galactic equator are reduced to a fourth of their distances as originally given, while four fifths are brought within 50,000 light years of the center of the galactic system. The system of the visible clusters shrinks in the present view to half its former diameter, while something like a spherical boundary replaces its earlier much-flattened aspect. Moreover, its original status as the superstructure of the galactic system is now in question, according to Stebbins; fully two thirds of the clusters are within the region along the course of the Milky Way in which no glimpse can be had of the exterior systems. Here presumably we cannot see through to the other side of the galactic system.

13.13. Rotation of the Galactic System. The sun's motion toward a point in Hercules, which has already been mentioned (11.8), represents its drift through the star fields immediately around us. Relative to the globular clusters and other remote objects in the system, the sun is moving toward Cepheus, as Strömberg at Mount Wilson was the first to show, in 1923. This motion at right angles to the direction of the center of the galactic system is owing to the rotation of the system around its center. Speeding at the rate of 175 miles a second, the sun is circling around the center once in something like 200 million years.

If the material in the galactic system were fairly uniformly distributed, all parts of the system would go around in the same period. If most of the material is concentrated near the center, the period of the rotation increases with distance from the center in accordance with Kepler's harmonic law (7.8). The stars that are nearer the center than the sun's distance are gaining on us, just as Venus gains on the earth in the revolution around the sun. The stars that are farther from the center than the sun's distance are falling behind us.

Oort, at Leiden in 1927, showed that the stars in the sun's neighborhood are moving in accordance with the second plan. Plaskett and Pearce at Victoria found this effect of the galactic rotation displayed not only in the motions of the stars, but also in the drifting by of the cosmic material that produces the interstellar lines (13.8) in their spectra.

Berman has observed a similar effect in the motions of the planetary nebulae.

13.14. The Present Picture of the Galactic System is still far from complete. The study of its structure and extent is proceeding in at least three ways:

(1) *By counts of stars.* This method, employed since the time of William Herschel, is giving information as to the distribution of the stars in the region around the sun. (2) *By photometric measurements of distances.* Less simple than it may have seemed a few years ago because of outstanding uncertainties concerning the obscuring effects of dust clouds in the various directions, this method (12.5) can reach farther than the first one. It has already shown how the visible open clusters and globular clusters are arranged. (3) ***By observations of exterior systems.*** Features of the galactic system which are obscure to us who dwell within it might become clear enough if we could observe our

FIG. 13.14. Spiral Nebula Messier 33, in Triangulum. The nearest of the spiral nebulae, it has been selected as a possible example of the appearance of our galactic system to a very distant observer. (*Photographed at Mount Wilson Observatory*)

system from outside. Some of these features may well be revealed in the views of the exterior systems (Chapter XIV).

Most of the material in the galactic system is assembled in a relatively thin layer along the central plane of the Milky Way, though widely scattered stars are found at great distances in the directions of the galactic poles. This assemblage of stars and nebulous stuff is frequently supposed to have the form of a double-armed spiral, like the majority of the exterior systems; but there is no certainty as yet that it is so. The diameter of the lenticular system is estimated at present as of the order of 100,000 light years.

The center of the system is in the direction of Sagittarius, in galactic longitude 325°. The sun is something like two thirds of the way from the center toward the edge in the direction of Auriga; it seems to be set in a region where the stars are more concentrated than they are in the regions immediately surrounding it. The system is rotating around its center, once around in about 200 million years at the sun's distance.

Although the diameter of the system, as it is generally accepted for the present, is far less than the original estimate, the current value is open to suspicion because it is still greater than the diameter as yet assigned to any exterior system and greatly exceeds that of the average system (14.10). The suggestion that the galactic system may constitute a group, each member of which should be compared with the exterior systems, has not seemed to solve the difficulty.

QUESTIONS ON CHAPTER XIII

1. What are the right ascension and declination of the south galactic pole? What star marks this point approximately?

2. What are the reasons for believing that interstellar space is not empty?

3. Show that the distances of stars from direct measures of their parallaxes are not affected by intervening dust.

4. Show that distances of Cepheid variable stars (12.5) are measured too great if a dusty medium intervenes and is not allowed for.

5. How is it possible to decide whether a red star is really red or has been reddened by intervening dust?

6. If the stars around us were uniformly distributed and equally luminous, how would the expected increase in the counted numbers to successively fainter magnitudes (13.10) be affected by a thin dust cloud slightly more remote than the stars of the ninth magnitude?

7. Again supposing the stars uniformly distributed, though not equally luminous (11.17), how would the expected increase in the counts be affected by a thin dust cloud at a certain distance from the sun?

8. Enumerate the different kinds of celestial objects which make up the galactic system, naming an example of each.

9. What is the evidence that the galactic system is a much-flattened structure?

10. What are the reasons for supposing that the galactic system has the spiral form?

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CHAPTER XIV

THE EXTERIOR SYSTEMS

Nearly two centuries ago, the philosopher Kant imagined that the small hazy patches we see among the stars might well be other milky ways beyond our own. He was partly right, as we know today. While some of the original "nebulae" have proved to be either real nebulosities or else star clusters within the galactic system, others are themselves exterior systems.

Even before they were known to lie far beyond the galactic system, the spirals and associated structures were called *extragalactic nebulae*, because they seem to avoid the Milky Way, while the galactic nebulae are concentrated in this region. Now they have assumed their true role as extragalactic objects in their distribution through space as well as over the face of the sky. They are also known as *galaxies*.

Here again, as we have noticed in the galactic system itself, the building blocks of the universe fall into a limited number of general patterns. Judging from the nearer objects whose forms are more clearly delineated in the photographs, the millions of extragalactic nebulae are of three general types: spiral nebulae, elliptical nebulae, and irregular nebulae.

14.1. Spiral Nebulae. Three fourths of the exterior systems have the spiral form, at least among the nearer ones. The majority of these are sometimes called *normal spirals*. From opposite sides of a central nucleus two streams of stars emerge and coil around it in the same direction and in the same plane. The normal spirals can be arranged in a sequence, from those having thin arms tightly coiled around a massive nucleus to those having massive arms loosely coiled around an inconspicuous nucleus.

About one third of the spiral nebulae are *barred spirals*, first studied and described by Curtis at Lick Observatory. The two coils start abruptly from the ends of a narrow bright bar which projects straight out from opposite sides of the nucleus. These can be arranged in a sequence as well. Barred spirals are not more mysterious than the normal type, because the significance of neither form is as yet completely explained.

These flat spirals are presented to us in a variety of ways. Turned flatwise to the earth they appear nearly circular. Messier 51 (Fig. 14.1) is an example, though this particular one is unusual in having a large knot at the end of one arm. Partly tilted, as in the case of the Andromeda nebula (Fig. 14.2), the spiral appears elliptical. In the edgewise view (Fig. 14.3) the nebula has the shape of a spindle.

Messier 81, in Ursa Major — Messier 51, in Canes Venatici

FIG. 14.1. Spiral Nebulae. (*Photographed at Mount Wilson Observatory*)

The nucleus of the spiral is all that is likely to appear to the eye at the telescope. The arms are not usually seen at all, except in the edgewise position where their light is concentrated; but they appear clearly in the photographs. It is therefore not surprising that little was known about the spirals until astronomers began to photograph them.

14.2. The Great Nebula in Andromeda. Messier 31 is the brightest of the spirals, and the only one clearly visible to the naked eye. It appears in the constellation Andromeda (Fig. 5.22) as a hazy patch about as long as the width of the full moon and half as wide. Through the telescope it remains an indefinite glow like that of "a candle shining through horn," as an early observer described it.

It is the nucleus that appears to the naked eye and for the most part to the eye at the telescope. Fainter surrounding parts come out clearly in the photographs where the nebula is shown in its true character as a flat spiral tilted 15° from the edgewise position. As it appears in the photographs with large reflecting telescopes, the nebula is an oval 2° 40′ long and 40′ wide.

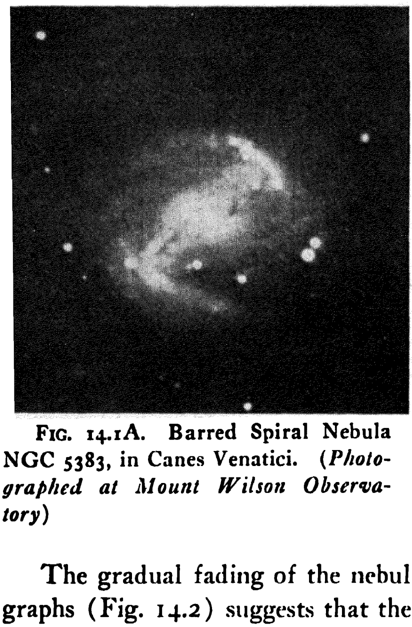


Fig. 14.1A. Barred Spiral Nebula NGC 5383, in Canes Venatici. (*Photographed at Mount Wilson Observatory*)

The distance of the Andromeda nebula is 800,000 light years; the real diameter of the conspicuous part of the spiral is accordingly nearly 40,000 light years. Many of the stars which Hubble's photographs show in the arms of the nebula are variable stars. More than a hundred novae have been discovered there as well, while more than a hundred fuzzy objects tentatively identified as globular clusters surround the spiral, making the diameter of the whole system considerably greater than that of the conspicuous part of the spiral alone.

The gradual fading of the nebula at its edges in the reflector photographs (Fig. 14.2) suggests that the dimensions of the spiral are greater than those originally assigned. Indeed, the observations of Stebbins and Whitford at Mount Wilson with the photoelectric cell increase the diameter fully 25 per cent. Measurements on small-scale photographs at Harvard Observatory show that the bright oval of the nebula is surrounded by a more nearly circular glow as much as 4½°, or 63,000 light years, in diameter. It is inferred that the flat spiral of Messier 31 is the brightest part of a nearly globular assemblage which includes not only the globular clusters around the spiral but also its two elliptical companions.

14.3. Edgewise Spirals. The details of the arms are concealed in the edgewise view of the spirals; for the arms are so nearly in the same plane that they become little more than narrow lines when they are seen on edge—bright lines having the bun-shaped nuclei near their middle points.

On the other hand, the dark absorbing stuff they contain becomes more conspicuous as the nebulae are presented to us more and more nearly on edge. Scarcely noticeable in the flatwise position, as a general thing, as we see in the case of Messier 51, the dark material bordering

FIG. 14.2. Great Nebula in Andromeda, Messier 31. One elliptical companion, Messier 32, appears directly above the nucleus; the other, NGC 205, is near the lower left corner. (*Photographed by G. W. Ritchey with the 24-inch reflector, Yerkes Observatory*)

the nuclear equator and the arms is plainly visible in the tilted Andromeda nebula. It constitutes a characteristic and spectacular feature of the edgewise spirals, sometimes seeming to cut them completely in two.

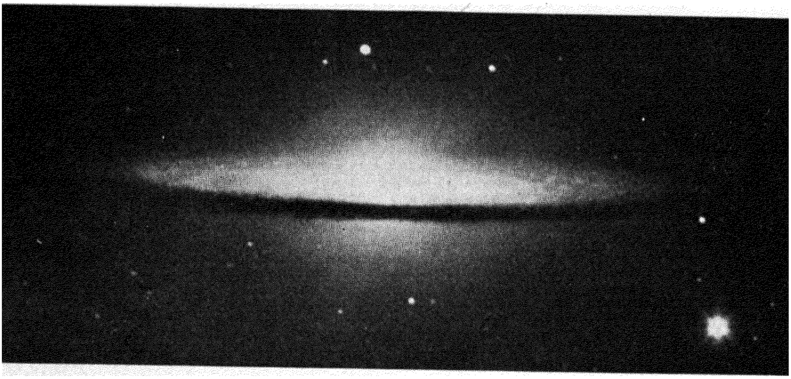
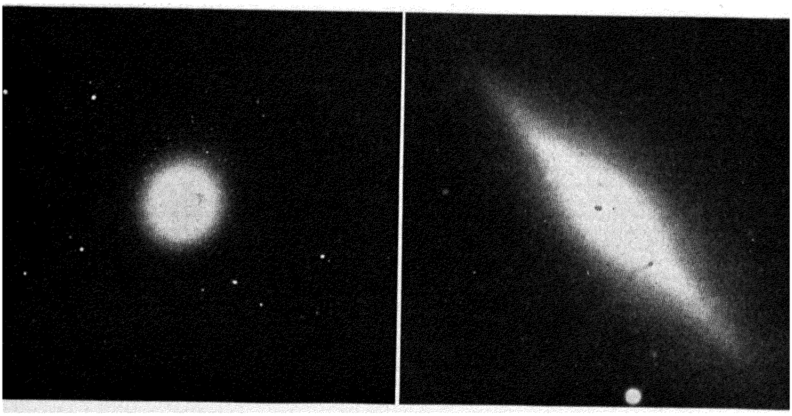


FIG. 14.3. Spiral Nebula Viewed Edgewise. NGC 4594, in Virgo. (*Photographed at Mount Wilson Observatory*)

The spiral nebulae are rotating, as their flattened forms suggest. This was demonstrated by V. M. Slipher at Flagstaff and by Max Wolf at Heidelberg, who photographed the spectra of the nearly edgewise NGC 4594 (Fig. 14.3) and the inclined Messier 81 (Fig. 14.1) re-



NGC 4486. NGC 3115.

FIG. 14.4. Extreme Types of Elliptical Nebulae. NGC 4486, in Virgo, has a nearly circular disk. NGC 3115, in Sextans, is among the most flattened of the elliptical nebulae. (*Photographed at Mount Wilson Observatory*)

spectively, bringing the images of the nebulae lengthwise along the slits of their spectroscopes; and they found that the dark lines run slanting across the prismatic bands. In each case one side of the nebula is approaching the earth and the other is receding in the rotation.

14.4. Elliptical Nebulae. Less spectacular than their spiral associates, the elliptical nebulae differ one from another only in apparent brightness and size, and in degree of flattening presumably at the poles of rotation. They fade gradually from their nuclei to indefinite edges which enlarge with increasing exposure times, while the shapes remain unchanged. Though their dark-line spectra suggest that they are assemblages of stars, they are not resolved into stars in the photographs, with a single doubtful exception. Examples are the two companions of Messier 31 (Fig. 14.2). Extreme types are shown in Fig. 14.4.

Hubble has arranged the elliptical nebulae in a sequence in order of

FIG. 14.5. The Magellanic Clouds. (*From Harvard Observatory photographs*)

increasing flattening, from the globular type, such as NGC 4486, to the extreme lenticular type, such as NGC 3115. Here, with the aid of an intermediate type in which the arms are supposed to be forming, he attaches the two parallel sequences of the normal and the barred spirals.

14.5. Irregular Extragalactic Nebulae. Two or three per cent of the exterior systems whose forms can be observed show no evidence of rotational symmetry. Their true frequency may be greater than it seems to be. Smaller and less brilliant than the spirals, the irregular nebulae must be nearer us in order to attract equal attention. The two Magellanic Clouds (Fig. 14.5), both visible to the unaided eye, are the brightest and nearest examples. They are in fact the nearest of all the exterior systems and are often regarded as satellites of the galactic system. Neither one is visible from any part of the United States.

Early voyagers into the southern hemisphere brought back reports of two white clouds in the heavens, which seemed like detached pieces of the Milky Way, though they are far from that luminous stream. Magellan described them, and in his honor they are named.

The Large Magellanic Cloud, centered about 20° from the south celestial pole in the constellation Dorado, stands above that pole in the early evenings of February. Its distance is 85,000 light years. The main assemblage, some 7°, or 10,000 light years, in diameter, contains a long, large star cloud and groups of smaller ones. It is surrounded by more widely scattered stars over a region whose diameter is twice as great.

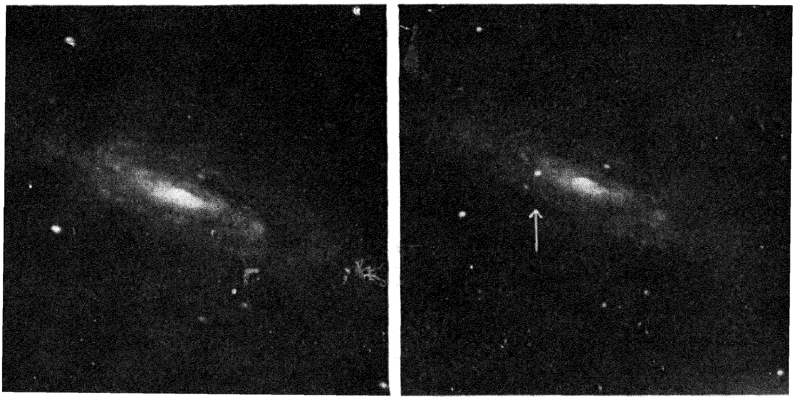
The Small Magellanic Cloud, in the constellation Tucana, is slightly nearer the south celestial pole and appears above that pole in the early evenings of November. Its distance is about 95,000 light years. About half as great as the Large Cloud in the ordinary view, its brighter region is 6000 light years in diameter, while its suburbs can be traced on small-scale photographs over a region whose diameter is twice as great.

Detailed investigations of the Clouds on Harvard Observatory photographs have revealed a variety of stars, star clusters and nebulae comparable with those in the Milky Way, though some of the blue stars appear to be of unusual intrinsic brightness.

14.6. Novae and Supernovae in Exterior Systems. Novae of the familiar type (12.8) are found in some of the nearer exterior systems. More than a hundred have been identified in the Andromeda nebula alone. It is estimated that twenty or thirty appear yearly in this system, which is about their estimated frequency in the galactic system; and their absolute brightness at maximum is about the same in the two systems.

The *supernovae* are of a different and more spectacular type. They attain a brightness that is a considerable fraction of the total brightness of the entire systems in which they make their appearance. The maximum absolute magnitude of the average is around -14.3. Placed beside the sun at the distance where the sun would appear as a star barely visible to the naked eye, the average supernova would shine five times as brightly as the full moon.

The first supernova on record appeared in 1885 near the center of the Andromeda nebula as a star of the eighth magnitude. About two dozen have since been discovered (1939) in extragalactic nebulae by comparing photographs of these objects taken at different times; the majority of these were found as the result of systematic search programs at Mount Wilson and Mount Palomar. Zwicky estimates that each system displays a supernova at the rate of one in 600 years. The suggestion that Tycho's nova of 1572 was actually a supernova in the galactic system is weakened by the lack of knowledge of the distance of that object.



May 8, 1901 April 16, 1915

FIG. 14.6. A Supernova in the Spiral Nebula NGC 4527. The arrow points to the nova. (*Photographed by Heber D. Curtis at Lick Observatory*)

In their rapid rise to greatest brilliancy and their subsequent gradual fading, the supernovae resemble the ordinary novae. The bands in their spectra differ from those of ordinary novae chiefly in their greater width, which implies more violent explosions. Whipple suggests that a supernova may arise from the collision of two stars.

14.7. Distances of Extragalactic Nebulae. Photographs with large reflecting telescopes in the early years of the present century revealed a hitherto unexpected profusion of spiral nebulae. They did not definitely resolve any of the spirals into separate stars, however, with the exception of a few novae of two distinct types (14.6), and there was uncertainty as to which of the two should be compared with the familiar novae in our own system. So the distances of the spirals remained unknown. Were they relatively near by and therefore relatively small objects, or were they enormous in distances and dimensions—other systems beyond the Milky Way?

The status of the spirals and other extragalactic nebulae was finally established in 1924. Hubble's photographs with the 100-inch telescope on Mount Wilson showed some of the brighter stars in the nearer nebulae. He observed that many of these stars are Cepheid variables, and determined their distances by means of the period-luminosity relation (12.5). These nebulae proved to be other systems exterior to the galactic system.

The distances of extragalactic nebulae are determined in the following ways: (1) *By Cepheid variable stars.* These stars, which give the most reliable distances, appear in the photographs with the 100-inch telescope in spiral and irregular nebulae within the distance of about a million light years. Some stars still brighter than the Cepheids can be detected in systems still more remote.

(2) *By novae of the ordinary type and the very brightest stars in the nebulae.* These stars, which give fairly dependable distances, are visible in some of the extragalactic nebulae as far as seven million light years. Their average absolute magnitudes are respectively −5.5, at maximum brightness, and −6.1. If the average absolute magnitude, −14.3, can be taken for the individual supernovae, these most luminous of all stars can give the distances of systems far more remote.

(3) *From the total brightness of the nebulae.* It is reasonable to suppose that the observed brightness of nebulae of the same general type diminishes with increasing distance. Distances so determined are useful for statistical purposes. If a dusty medium intervenes, the distances as determined in all these ways come out too great.

(4) *By the velocity-distance relation.* The distances of extragalactic nebulae can be determined from photographs of their spectra (14.13).

14.8. The Nearer Extragalactic Nebulae. The galactic system is a member of a group of a dozen or more systems occupying an ellipsoidal volume of space whose longest diameter is a million light years. Our system is near one end of this diameter, and Messier 31 is near the other end. The distances separating the members of the *local group* are less than the average distance between the exterior systems generally, which is two million light years. By this fortunate arrangement examples of all types of exterior systems, except the barred spirals, are near enough to us for relatively minute inspection on photographs with large telescopes.

The local group includes the two Magellanic Clouds, irregular systems at distances somewhat less than 100,000 light years, the irregular nebulae NGC 6822 and IC 1613 at the distances 600,000 and nearly a million light years respectively, the great spiral Messier 31 with its two elliptical companions (800,000 light years), and the spiral Messier 33 (800,000 light years). Some members of the group are so near the Milky Way that their light may be dimmed by intervening dust. There are perhaps others entirely hidden behind the dust clouds.

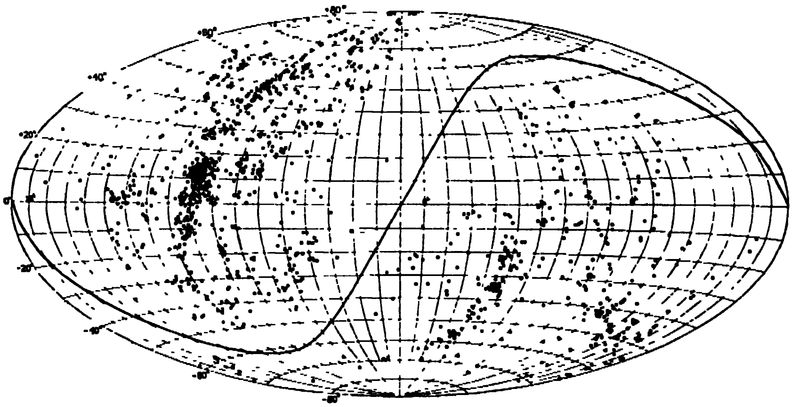


Fig. 14.9. Distribution of Extragalactic Nebulae Brighter Than the Thirteenth Photographic Magnitude. The entire celestial sphere is represented, with the north celestial pole at the top. The heavy curved line is the galactic equator. The positions of the nebulae are shown by dots. (From *Harvard Observatory Annals, Vol. 88*)

14.9. Surface Distribution of Extragalactic Nebulae. The survey by Shapley and Miss Ames at Harvard Observatory of the 1025 exterior systems brighter than the thirteenth photographic magnitude brings out clearly some characteristics of their distribution over the face of the heavens:

(1) *The exterior systems seem to avoid the vicinity of the Milky Way.* Few appear within 10° of the galactic equator, which is represented by the somewhat heavier curved line of Fig. 14.9. This "region

of avoidance" has been mentioned before (13.10). The obscuring effects of dust clouds are made evident as far as galactic latitude 30° by the reduced numbers of extragalactic nebulae observed in these low latitudes as compared with the numbers found near the galactic poles.

(2) *The exterior systems are assembled in clusters.* The nearest of the great clusters of extragalactic nebulae, the Virgo cluster, is conspicuous at the left in the Figure. Centered near the northern border of the constellation Virgo, it extends northward into Coma Berenices and southward beyond the celestial equator.

(3) *The exterior systems are not uniformly distributed* over the celestial sphere. Even when allowance is made for the obscuration of those near the Milky Way and for the conspicuous clusters, their distribution is still patchy, according to the Harvard observers. The approach to uniformity seems close enough, however, so that counts of the exterior systems which appear on the photographs of any area of the sky can inform us of the degree of obscuration by a dusty medium in that area.

14.10. Neighboring Systems Compared with Our Own. The nearer spiral nebulae which can be partly resolved in the photographs with great telescopes display about the same kinds of objects that make up our own system. They contain stars of the different colors, variable stars of the familiar types, novae, open and globular star clusters, and galactic nebulae both bright and dark.

The spiral nebulae constitute the majority of the exterior systems. They are much-flattened structures like our own system, and are also in rotation. Viewed nearly edgewise, they are crossed by narrow dark bands, presumably of the same sort of obscuring material that causes the rifts in the Milky Way. An observer within one of the spiral nebulae would see a milky way around his sky, probably broken by rifts. Analogies such as these encourage the belief that the galactic system has the spiral form, though definite proof is still lacking.

The outstanding difficulty in these comparisons is that the galactic system seems to be larger than any of the exterior systems. The diameter of the galactic system is of the order of 100,000 light years, according to the recent estimates. On the other hand, the great nebula in Andromeda, a giant among the spirals, measures at most scarcely more than 60,000 light years in diameter. The average of the more open spirals is only 10,000 light years in diameter, according to Hubble, while the average irregular and elliptical nebulae are still smaller.

An interesting and perhaps significant discrepancy between the rotations of the galactic system and Messier 31 is shown by Babcock's recent studies of the latter at Lick Observatory. While the period of rotation of the galactic system in the sun's neighborhood increases with distance from the center of the system (13.13), the plan of rotation of the Andromeda nebula seems to be different. The nucleus rotates at a constant angular rate, once around in 11 million years. The outer arms, beyond the radius of 20′ from the center, also rotate at a constant rate, once around in 92 million years.

14.11. Clusters of Extragalactic Nebulae. Associations of exterior systems are similar to associations of stars in the galactic system. The percentage of *double systems* is comparable with that of double stars. One in every twenty-five nebulae on the long-exposure Harvard plates is a component of a double whose separation at the nearest edges does not exceed the diameter of either nebula. *Multiple systems* are not uncommon. Associations like those of the Magellanic Clouds with the galactic system and of the two elliptical nebulae with the great spiral in Andromeda are frequently observed. The local group (14.8) is an example of somewhat larger grouping.

FIG. 14.11. Cluster of Extragalactic Nebulae in Coma Berenices. (*Photographed at Mount Wilson Observatory*)

Clusters of systems are still larger assemblages, each containing about 500 members. Some twenty such clusters are now recognized. These resemble open star clusters in population and in the slight concentration toward the center. They do not vary greatly in size, so that their relative distances are reliably determined from their apparent diameters. There is no known example of far greater clusters of nebulae that might be compared with the globular star clusters.

The Virgo cluster is the nearest, and therefore the apparently brightest and largest, of the clusters; it was the first of them to be recognized. At the distance of 7 million light years, it is near enough so that the structures of its members and the very brightest stars in some of them can be discerned in the photographs. This cluster is valuable in investigations of the relations between the different types of extragalactic nebulae. Since the differences in the distances of its members can be neglected in comparison with the distance of the whole cluster, ratios of apparent size and brightness of these nebulae are ratios of real size and brightness.

14.12. Space Distribution of Extragalactic Nebulae. Counts of nebulae to a succession of limiting magnitudes furnish the material for space analyses of the nebulae. An extensive survey to about the 18th photographic magnitude is in progress at Harvard Observatory on long-

FIG. 14.12. Extragalactic Nebulae in a Region in Pisces. (*Photographed at Mount Wilson Observatory*)

exposure photographs with the 24-inch Bruce telescope near Bloemfontein, South Africa, and the 16-inch Metcalf refractor at the Oak Ridge station. A second survey in small areas as far as the twentieth magnitude is being made on photographs with the Mount Wilson reflecting telescopes. The usable field of the 100-inch telescope for this purpose is equal to the apparent area of the full moon. Counts in 1283 such sample areas have already been completed.

The distance of the faintest exterior systems shown in the photographs with the 100-inch telescope is 500 million light years, according to Hubble, and the total number of systems within this radius is 100 million. He finds the distribution of the systems fairly uniform in the long run; the average separations are 2 million light years.

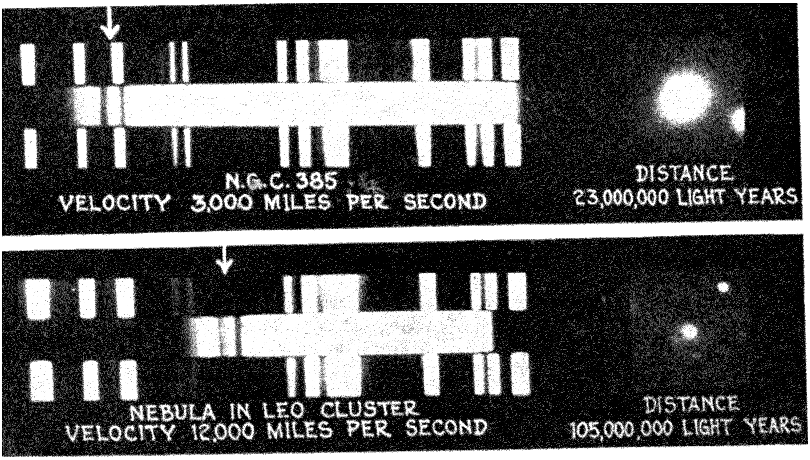


FIG. 14.13. The "Red Shift" in the Spectra of Extragalactic Nebulae. The greater the distance of the nebula, the greater is the displacement of its spectrum lines toward the red. (*From photographs by Edwin Hubble and M. L. Humason, Mount Wilson Observatory*)

In regions of the sky unobscured by dust clouds of the galactic system, the total number of systems per square degree brighter than a specified magnitude is nearly four times the number brighter than the next lower-numbered magnitude. This ratio, which is expected (13.10) if the space distribution is uniform, continues to the very faintest nebulae that can be observed. There is no certain evidence as yet of any thinning out of the systems toward the boundary of the visible universe, which might give a clue as to the dimensions of the vast aggregate of the extragalactic nebulae.

14.13. Motions of Extragalactic Nebulae. Owing to the vast distances of the exterior systems, it is improbable that their proper motions can be observed, at least for a long time to come. The only way of learning about their movements is by observing the displacements of the lines in their spectra. Since an extragalactic nebula is an assemblage of stars, its spectrum is a composite of stellar spectra of the different classes; it is chiefly a dark-line spectrum, somewhat like the spectrum of the sun.

The dark lines run slanting across the spectra of those spirals whose equators are presented nearly edgewise to the earth, as we have noticed (14.3), showing that the spirals are rotating. In addition, the lines in the spectra of the exterior systems generally are displaced from their normal positions. *The remarkable feature of these displacements is that they are toward the red end of the spectrum,* except in a very few cases. The exceptions, where the lines are displaced toward the violet, are in the spectra of the very nearest systems.

Having corrected the nebular radial velocities for the effect of the sun's motion in the rotation of the galactic system, Hubble showed, in 1929, that the redward shift of the lines in their spectra increases steadily as the distances of the nebulae are greater. If it is a true Doppler shift (10.4), then the exterior systems are receding from us faster and faster as their distances are greater; their speeds of recession increase more than a hundred miles a second for each million light years that is added to their distances.

Hubble and Humason have derived speeds of recession for some of the more distant systems, which seem almost fantastic. For example, a cluster of extragalactic nebulae in Ursa Major at the distance of 235 million light years seems to be withdrawing from us at the rate of 26,000 miles a second.

This *velocity-distance relation* is extremely valuable as a means of obtaining the distances of remote exterior systems. If the systems are still bright enough so that their spectra can be photographed, the distances can be learned from the amounts of the red shift of the lines.

14.14. The "Expanding Universe." Suppose that in addition to Newton's law of gravitation every body in the universe also repels every other body with a force which varies directly as their distance apart. The repulsive force could be practically negligible among the celestial bodies more immediately around us, and yet become the predominent factor for the widely separated extragalactic systems.

Einstein, in 1917, proposed the addition to Newton's law of a term equivalent to this repulsive force, and in order to balance it assumed a uniform medium throughout space which would produce an attractive force varying directly as the distance. Lemaître, in Belgium in 1927, showed that Einstein's mathematical universe would be unstable; it must collapse or expand. He analyzed the latter case.

According to this idea, the whole assemblage of the galactic system and the exterior systems is expanding; the separate systems are drawing apart. From the earth or any other point of observation at all the systems would recede from the observer with speeds directly proportional to their distances from him.

Are these spectacular red shifts in the spectra of the extragalactic nebulae really Doppler effects caused by the recession of the nebulae? Or are they other effects on the light of these remote objects—effects so minute in the light of the near-by celestial bodies that they have passed unnoticed? This question remains an open one for the present.

14.15. Concluding Remarks. Our study of astronomy has taken us a long way from home. We began with the earth and the sphere of the stars around it, and noticed particularly the apparent motions of the starry scenery that are caused by the various movements of the earth. The moon was then examined. Next we ventured a little farther from the earth to the planets and their satellites and the other bodies which likewise revolve around the sun. The discussion of the sun as a typical star led to considerations of the stars themselves and of the vast galactic system in which they are assembled. Finally, we looked beyond the Milky Way to survey the exterior systems.

We have ended with a picture of the visible universe spread out around us to the distance of 500 million light years, for the present. The radius may well be doubled when the great telescope of the Hale Observatory on Mount Palomar is in operation. A review of the different features which have been studied will now show more clearly than before the place of each one in the picture.

QUESTIONS ON CHAPTER XIV

1. What is meant by the statement that the spiral nebula Messier 31 is "in the constellation Andromeda"? Give directions for finding the nebula in the sky.

2. Describe the appearance of the heavens as viewed from somewhere in the arms of the Andromeda nebula.

3. Can you decide which side of the tilted Andromeda nebula (Fig. 14.2) is toward the earth?

4. The absolute magnitude of the average supernova at its brightest is nearly 20 magnitudes brighter than the sun's absolute magnitude. Compare the actual brightness of the two.

5. Suppose that the average extragalactic nebula contains 1000 million stars. Calculate the number of stars in the visible universe.

6. Many of the problems which confronted the astronomers when they began to explore the galactic system are repeated in the explorations of the exterior systems. Explain.

7. Nothing, except the imagination, can travel faster than the speed of light. Imagine that you are speeding away from the earth a million times as fast as light travels. How long will it take you to reach the planet Pluto? The outer edge of the Milky Way? The Andromeda nebula? The remotest exterior system that has been photographed?

8. State five former problems of astronomy which now seem to be solved, and five problems as yet unsolved.

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