THE NATURE OF VARIABLE STARS

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THE NATURE OF VARIABLE STARS

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PREFACE

In preparing this little book my purpose has been not only to outline our knowledge of variable stars, but also to assist the non-technical reader to a comprehension of the general nature of modern astrophysical studies. I hope it will help him to understand the sort of thing with which astronomers are occupied, and why their work has so many points of contact with other sciences.

Part of the material has been taken from a series of articles in Popular Astronomy.

I take this opportunity to thank Dr. F. H. Seares for reading the manuscript and suggesting numerous improvements.

P. W. M.

Pasadena, Calif.

CONTENTS

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CHAPTER I

INTRODUCTORY

THE NATURE OF STARS IN GENERAL

AT some point in his astronomical education, perhaps after he has heard for the first time that a planet is *not* a star, nearly everyone asks, "Just what is a star, anyway?" Assorted answers are:

1. A distant sun
2. A mathematical point
3. A citizen of the universe
4. A red-hot vacuum

Every one of these answers is incomplete but none is facetious. Probably the best single categorical answer is the first one; let us consider it in two ways—a distant *sun,* and a *distant* sun.

A distant SUN. All the fixed stars are enormous globes of glowing gas, shining brilliantly by their own light. Our beneficent sun, ruler of the planets, is a somewhat undersized specimen. Great and glorious as he seems swinging across the blue sky, nevertheless from a cosmic view point he is negligibly small and unimportant. Feeble and insignificant in comparison with his stellar compatriots, he still manages to present the earth with a billion dollars worth of light and heat every second, and to send out in other directions more than two billion times as much. Certain giant stars radiate a thousand times as much energy as the sun; if measured in units of horse-power the staggering total would be 5 followed by 26 ciphers. This incessant outpouring of tremendous quantities of radiant energy at a steady rate calls for a balanced interplay of forces almost inconceivably great. The effective radiating layers near the surface must continually be receiving from somewhere, presumably from the star's interior, supplies of energy exactly equivalent to those emitted. This amounts to 100,000 horsepower, more or less, per square yard of the star's surface. Its regular delivery must be independent of railroad and coal strikes, decisions of the Interstate Commerce Commission, and repairs to the elevator. Fulfillment of the requirements of regularity is the rule, however, rather than the exception, for the great majority of all stars, including the faint telescopic stars as well as those visible to the naked eye, shine continually with a steady light. The brightness of most stars is either perfectly uniform or so nearly so that any slight variations which may occur have not been detected. This must mean that in general the stars are stabilized bodies whose internal mechanisms are so nicely adjusted that the outflow of visible energy has been maintained at a substantially constant rate over the whole period covered by available records.

A DISTANT sun. Certain curious properties of the stars such as their extremely small angular diameters (see next paragraph) and their apparent fixity in the sky, arise from their vast remoteness. The distance to even the nearest fixed star is so great that it entirely transcends all our ordinary experience and is totally impossible for anyone to visualize: it is in all literalness inconceivably great. By building up a sufficiently large unit we can of course express stellar distances in small figures and say, for example, that the distance to the nearest fixed star is only 4¼ light-years, but this is about like explaining to a child the meaning of the word atom by telling him that it is something made up of electrons and protons. Our best method of illustrating considerable distances on the earth's surface is to state the time required to travel by train, e.g., three days from Pasadena to Chicago. This method does not do so well when applied to astronomy but here are the results. To our sun, which is really very, very near, the railway journey would require 200 years and the cost of a one-way ticket would be $2,000,000. To the next nearest star, for the sun is itself a star, would require 55,000,000 years. The calculated fare is too large to mention but the tip to the porter at only twenty-five cents per day would amount to five billion dollars. Probably no astronomer, at least no professional astronomer, will ever feel that he can afford the trip. The above illustrations are for a star 4.3 light years from the earth. Many of the naked-eye stars are hundreds of light years distant. Remember that light travels 186,000 miles per *second.*

A mathematical point. A star offers perhaps the finest available illustration of a mathematical point. For all observations, except certain highly specialized ones with a large stellar interferometer having mirrors many feet apart, a star has no appreciable dimensions: through a telescope as to the naked eye, it presents no true disk. Seen through a good telescope, the apparent image, called the "spurious disk," is minute with high magnifying powers, and its size bears no relation at all to the actual size of the star but depends rather on the seeing (optical steadiness of the air) or if the seeing is fine, on the size and excellence of the optical parts of the telescope. The larger the instrument and the more perfect the workmanship, the smaller does the star's image appear to be.[1]

A citizen of the universe. In the cosmic world, spiral nebulae or galaxies are nations; star clusters are states and cities; stars are adult citizens; planets are children; while satellites, including our moon, are puppies and kittens—the children's little playmates. We must therefore understand fairly well the nature of stars before we can hope to make much progress in the more general problems of cosmogony or the structure of the universe. To

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[1] This of course does not apply to the planets which under high magnification appear as large disks.

this end astronomers have devoted much time to classifying the stars and studying their physical properties. Of the various types of stars, variables are among the most interesting. The facts concerning them bear on an amazingly wide range of astronomical and physical problems.

A red-hot vacuum. This answer is particularly applicable to those stars with which this book is largely concerned—the long-period variables. Stars are of two races, giants and dwarfs. The giants are large, bright, and tenuous; the dwarfs small, faint, and condensed. Our sun is a dwarf but all long-period variables are giants, as are also nearly all the well known naked-eye fixed stars. One of these giants bears somewhat the same relationship to the sun that a soap bubble six inches in diameter bears to a globule of gold one thirty-second of an inch in diameter. We might call a giant star a fiery soap-bubble, but its density is really much less than that of the air in a bubble—probably only one-hundredth, or even in extreme instances such as long-period variables, one-thousandth as great. In the physical laboratory a volume of gas at this density would be regarded as a vacuum.

If some astronomical Rip Van Winkle, for example Hipparchus, having gone to sleep two thousand years ago, should awake tonight and glance at the sky, he would not rub his eyes in wonder at the changes, for the ancient constellations would be shining in their familiar aspects. He might soon discover that the earth's axis has undergone a change in direction, but he would be a keen observer if he detected any changes in the stars themselves. This age-long persistence would, however, scarcely be inferred from a brief inspection of the night sky. The twinkling stars look so minute and unsubstantial that an inexperienced beholder might expect one after another to vanish from its place.[2] Is it not strange that these slight flickering sparks should have such a tenacious hold on luminosity that they not only remain visible for hours, but appear, practically without change, night after night for centuries?

But if the enduring constancy of the stars is impressive to the casual and naive observer, it is more profoundly so to the student who has an inkling of their actual nature. Instead of infinitesimal points of light whose beams find their way, with some difficulty, through the earth's unfriendly atmosphere, he visualizes them as giant globes of incandescent matter pouring forth energy at so terrific a rate as to stagger the imagination. The contrast between the apparent and the real is the most stupendous in all human experience.

The laws of physics tell us that the outer layers of a star (the only ones we can see) would cool

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[2] When a meteor darts across the sky is it not a common conception that a fixed star, suddenly eluding the forces which have held it fast, is making a wild dash for liberty, only to be quickly extinguished by its rapid motion?

off and become less brilliant very quickly if their relatively small stores of energy were not continually replenished.[8] As noted in a previous paragraph, this replenishment is adequately accomplished in most stars, and we perceive no variation in the intensity of their light.

How does the interior of the star manage to supply the enormous amount of energy radiated in all directions from its surface? The central portions are extremely hot and the vast reservoir of energy constituted by the intense heat and radiation throughout the star's great bulk could contribute to the spendthrift layers at the surface for thousands of years or even perhaps for a few millions, but the actual duration of a star's life is conceded to be hundreds of millions of years at least, probably very much longer. Investigators, therefore, are agreed that the release of some highly concentrated form of pent up energy must occur inside the stars. In other words, stars are not merely hot bodies cooling off; they are automatic heat engines keeping themselves hot by some mysterious process carried on in secret beneath the opaque outer layers. The process must be *sub-atomic* for the simple reason that no rearrangement of whole atoms (such as moving in toward the star's center, or that which occurs in any ordinary chemical reaction) could

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[8] For the same reasons an electric light goes out almost instantaneously when the current is turned off. The star's surface would not fade quite so quickly, but nevertheless, if shut off from the interior, would become dim in a very short time.

supply enough energy. The tremendous forces existing in the close interplay of the ultimate electrical particles, positive and negative, must somehow be let loose.

An analogy may illustrate the argument. Imagine a warehouse piled high with dynamite bombs. If the bombs were poorly stacked, some of them might occasionally come tumbling down, and the motion would generate a limited amount of sound and vibration; but the explosion of even a single bomb would produce far greater results. Thus if resounding detonations accompanied by shocks felt miles away occurred continually for days, the conclusion would certainly be, not that the bombs were merely rearranging themselves under the force of gravity, but that one after another was exploding. A bomb represents an atom and an explosion corresponds to the annihilation of sub-atomic mass or electrical particles, with results far more violent than any the atom as a whole could produce. The exact manner in which sub-atomic energy is released in stars is at present unknown, but astronomers and physicists are working persistently to discover it. Variable stars are of interest in this connection because the changing conditions at their surfaces, accessible to observation, may supply clues to the underlying source of stellar energy. Data on variable stars have in fact a bearing on many important problems in both astronomy and physics.

This is one reason why the study of variables is so fascinating and so fruitful.

One of the features of modern science is the close union which has sprung up between astronomy, physics, and chemistry. Problems in atomic structure, for example, are dealt with by investigators in any one of the three branches. Thus variable stars are of interest not only as distant, telescopic bodies, but also as welcome adjuncts to the physical laboratory, where atoms may be studied under a wide range of conditions not feasible to produce on earth. It is when energy is transformed in some way that we have opportunity of learning the properties of nature; and unusual transformations, or those involving unusual conditions, are especially worth investigating.

In appraising the value of detailed investigations of the stars we must remember that much of the useful technical knowledge of today lay yesterday in the realm of the remote and obscure. No one can doubt that facts and theories now at the frontiers of scientific exploration will later be brought into the practical service of the world. Mankind would not part with what has been learned about light and electricity in the past fifty years for many, many times what that knowledge cost; but as the essential facts were being developed they doubtless seemed totally disconnected from practical application. In this connection it is interesting to note that observations of sun-spots and of certain stars whose atmospheres contain helium were important in the early development of definite theories of the electron as a physical entity, and thus hastened the day of radio and other recent devices dependent on the control of electrons.

We cannot expect ever to travel to the stars or to make them do our bidding, but we may hope to learn from them phases of truth about matter, electricity, light, and gravitation which will profoundly benefit the human race.

CHAPTER II

VARIETIES OF VARIABLE STARS

VIEWED from Mount Wilson at night, Pasadena, Los Angeles, Hollywood, and other Southern California cities form mundane constellations of sparkling beauty. Most of their tiny lights shine throughout the evening hours with unchanging brightness, but here and there may be noted a neon sign flashing on and off, or a revolving air beacon visible only at intervals. Similarly among the celestial constellations most of the stars shine always with a sensibly steady light, but a few do change.

These changing objects are known as *variable* stars, the adjective being restricted by usage to designate changes in *brightness* only; changes in position or other characteristics are not included. Hence a star is not known technically as variable unless its apparent or observed brightness changes, no matter what other phenomena it may exhibit.

The changes in brightness are large in some stars, small in others, but in nearly all a certain orderliness prevails. Many variables have been carefully watched for decades, a few for centuries; in practically all, the fluctuations have remained within fairly well-defined limits, without any apparent tendency toward cumulative alteration. In typical variables the brightness fluctuates about an average value which remains the same year after year. Surprisingly few stars are known to have suffered permanent changes at any time, or to be growing progressively brighter or fainter. The reason that progressive variations are practically unknown is that the period of time covered by astronomical records is too small to allow secular or evolutionary changes to manifest themselves: the history of astronomy spans too brief a portion of the life-time of a star. We cannot watch the stars grow old nor do we read in human records any observational account of stellar evolution. What we know about this intriguing subject comes from inference rather than from direct observation. The study of variable stars is important in this connection for in these objects we are privileged to observe within the course of a few hours, days, or months, changes which in non-variable stars may require thousands upon thousands of years.

In most variable stars there prevails also another type of orderliness which refers to the times of greatest and least brightness. The fluctuations of most variables repeat themselves at equal or nearly equal intervals of time. Such stars are said to be "periodic," the average interval between times of maximum brightness being called the "period." The observed periods for various stars range from 1 hour 28 minutes for a faint variable in the constellation Aquarius, known as CY Aquarii, to 950 days for VW Aquilae.[1] Some stars waver irregularly back and forth between fairly well defined limits of brightness or are subject to sudden short changes from a habitual level; and a few examples of other, nondescript, kinds of change are known. Most sensational of all variables are the new or temporary stars which occasionally flare up. They constitute a class by themselves with highly specialized characteristic properties.

To systematize the study of variable stars some sort of classification is essential. The first step is to distinguish between repeating and non-repeating stars. Variables which repeat, and these are decidedly the more numerous, may do so at regular intervals in a predictable cyclical maner: in this case they are called periodic. Others repeat approximately the the same behavior again and again but at irregular intervals. Of the non-repeating variables, novae are the most notable; a few other objects vary irregularly in a totally unpredictable fashion. A preliminary classification of variables is therefore as follows:

- Repeating Variables
  - Periodic
  - Non-periodic

- Non-repeating Variables
  - New stars
  - Miscellaneous

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[1] The bright star ε Aurigae varies in a period of 27 years, but it is an eclipsing star not intrinsically variable in this period.

PERIODIC VARIABLES

Among the periodic variables are (a) those which actually vary in their intrinsic light and would appear variable from any direction in space; and (b) those which are really constant but whose light as seen from the earth is partially shut off at times by a close companion star which in the course of its orbital motion passes at regular intervals in front of the so-called variable. These are the famous "eclipsing" variables of which Algol, the Demon star in Perseus, is the best known. Viewed from most points in space these objects would not vary at all. The intrinsic variables are further subdivided according to their periods as indicated in Table I. The limiting periods indicated are not the extreme limits but those beyond which only a few scattering examples are found.

TABLE I

CHIEF TYPES OF PERIODIC VARIABLES

NAME	TYPE STAR	NO. KNOWN 1935	PERIOD IN DAYS		
			Lower Limit	Most Frequent	Upper Limit
Cluster . .	RR Lyrae	620	0.2	0.56	0.9
Cepheid . .	δ Cephei	287	3.	5.6	32.
Long Period	Mira Ceti	2144	32.	280.	560.
Eclipsing* .	Algol	873	0.2	2.8	30.

*Not intrinsically variable.

Some confusion exists in regard to the naming of the first two groups. Numerous examples of the first group were found years ago among the faint stars in the great globular star clusters. They thus became known as cluster-type variables. Some astronomers object to this designation, however, because many similar variables are now known which have no connection with clusters, and prefer the term "RR Lyrae stars" after the prototype, a seventh magnitude star, invisible to the naked eye, in the constellation Lyra. Other authorities call both groups cepheids and refer to long- and short-period cepheids. Shapley calls the long-period cepheids, "classical" cepheids.

Cluster Type or RR Lyrae Variables

These eager little objects are both resilient and punctual. Coming to maximum light twice every day (most frequent period 0.56 day) they faithfully repeat their cycles year after year with almost clock-like regularity. They are not so well known as they deserve to be because not a single one is bright enough to be visible to the unaided eye. They are remarkable for their violent motions, darting about our galaxy with speeds that range up to 200 miles per second. Slight variations in the motion recurring in step with the light changes suggested to observers years ago that they move in small quick orbits, but this deduction is now considered incorrect. It is more probable that the observed phenomena are caused by alternate inward and outward motions of the star's surface layers—a sort of volume pulsation of the star as a whole.

CEPHEID VARIABLES

These resemble the first class in some respects, but their periods are ten times as long, averaging about six days. They exhibit similar surface pulsations but their bodily motions through space, in great contrast to those of the RR Lyrae variables, are very slow. In these contrasting velocities we have one of the great puzzles of modern astronomy about which more will be said in another chapter. The prototype is δ Cephei, a naked-eye star in the northern constellation Cepheus, discovered to be variable by Goodricke in 1784. Its period is 5.4 days. Cepheids are famous as yardsticks of the universe. They have been used by Shapley to establish the scale of our Milky Way system and by Hubble to measure the distances to the great spiral nebulae or island universes.

LONG-PERIOD VARIABLES

Of all classes, the ponderous long-period variables are the most numerous and the most thoroughly observed. They are characteristically yellow or red, while the periods are much longer than those of the cepheids, 280 days being a typical value. The range of brightness is astonishingly great, the typical star being nearly 100 times as bright at maximum as at minimum. One star is known to have an extreme range of 10,000 times. Imagine our sun behaving in that manner! Their motions show certain remarkable features which will be described in detail in another chapter. These objects are worth investigating, not only astronomically but from a purely physical standpoint as well. The application of the spectroscope to the analysis of their light has disclosed many surprising features, some of which have not yet been matched in any light source studied in the laboratory. The type star is Mira Ceti (also known to astronomers as omicron Ceti). Its variability was discovered by Fabricius in 1596, fourteen years before the invention of the telescope. It is visible to the naked eye when brightest, invisible when faintest.

The very extensive data concerning the light variation of long-period variables are due in no small degree to the efficient co-operation of numerous amateur astronomers. Probably more persons have been active in the determination of the light curves of long-period variables than in any other field of astronomical investigation.

ECLIPSING VARIABLES

An eclipsing variable can usually be distinguished from other types by the fact that it remains most of the time at a constant brightness, being dimmed temporarily at intervals as if some object were passing in front of it. This object, one might guess, is a dark companion star swinging around in a small orbit. Spectroscopic observations confirm this guess in a remarkable manner; they show clearly that the bright star moves in an orbit, and that it is on the *far* side of its orbit (in the proper position to be occulted) when the dimming occurs. No doubt now remains that the light decreases when the variable is partly hidden behind its companion, and that the period of variation is merely the orbital period in which the two stars revolve about their common center of mass. Eclipsing variables are therefore true double stars, but not all doubles will appear variable—only those whose orbital planes (extended in imagination through space) chance to pass very near the earth. The reason the periods are short, averaging about three days, is that the longer orbits are also larger and the bodies farther apart; the chance of occultation as seen from the earth is therefore smaller. Sometimes the companion star, B, is nearly as bright as the principal one, A, and the combined light dims appreciably not only when A is behind B, but also when B is behind A. In this case the light dips twice in each complete orbital revolution. Sometimes, as in the well known variable β Lyrae, the bodies are so near each other that the occultation of B begins almost as soon as that of A ceases, and there remains practically no time when the light is constant.

Eclipsing variables are important because the size, density, and surface brightness of the component stars may sometimes be determined with fair accuracy. They are, of course, in an entirely different class from all other variables. Since they are essentially double stars and do not present the same physical problems as individual stars which are intrinsically variable, they are not extensively discussed in this book.

Pickering's Classification

A classification of variable stars of great historical importance, proposed in 1880 by Director E. C. Pickering of the Harvard College Observatory is as follows:

I. New or temporary stars (Novae)
II. Long-period variables
III. Irregular variables
IV. Short-period variables (Cepheids)
V. Eclipsing variables (Algols)

A more detailed classification with ten subdivisions, compiled a few years ago by the German astronomer H. Ludendorff, is proving useful to research workers.

Variable stars have been under investigation for more than three centuries, and have been intensively studied for about sixty-five years. The resulting accumulation of data concerning these remarkable objects has called forth extensive discussion and speculation, but in spite of this it is for the eclipsing stars only that the underlying cause of variability is satisfactorily established. Working hypotheses of great value have, however, been suggested for some of the other types.

Like spectators of a silent and mysterious drama whose plot is fascinatingly difficult to grasp, laymen and astronomers have taken a keen delight in observing the behavior of hundreds of variable stars. To watch a tiny red star outshine its companions for a few weeks and then fade to invisibility while the others remain unchanged, is enlivening to the curiosity and the romantic imagination with which the human race is blessed. More searching investigations of the light of variable stars serve but to enhance their appeal to man's interest.

CHAPTER III

DISCOVERY AND CATALOGUING

THE first astronomical problems to attract attention were those connected with the apparent motions of the heavenly bodies. The daily rotation of the celestial sphere; the monthly motion of the moon and the changes in her appearance; the annual motion of the sun; the complicated motions of the major planets; these were all observed by the ancients, and their interpretation occupied a major part of the time of astronomers for centuries. Satisfactory explanations in terms of geometrical and physical laws finally became available through the combined labors of Hipparchus (190–125 B.C.), Ptolemy (about 140 A.D.), Copernicus (1473–1543), Tychò Brahe (1546–1601), Kepler (1571–1630), Galileo (1564–1642), Newton (1642–1727), and many others.

Systematic investigation of the brightness of the stars did not become a very important part of astronomy until the days of the German astronomer Argelander (1799–1875), but this does not mean that the subject had been wholly neglected before his time. Hipparchus and Ptolemy had classified hundreds of stars in six "magnitudes" according to their brightness. It is believed that the need of a star catalogue was suggested to Hipparchus about 130 B.C. by the sudden appearance of a new star in the constellation Scorpio. But if variable stars were known and studied in ancient and medieval times, no records, aside from a few references to novae, have come down to us.

About twenty long-period variables visible to the naked eye at times of greatest brightness are now known, but apparently only one, *o*, or Mira, Ceti was discovered before the invention of the telescope. Its variability was noticed in 1596 but the periodicity was not recognized until 1639. Several of the twenty stars barely reach naked-eye visibility at maximum and require good conditions to be seen, but others are fairly conspicuous at times, and one wonders whether the variations in *o* Ceti, R Leonis, L_2 Puppis, R Carinae, R Hydrae, and χ Cygni could have been entirely overlooked for centuries. It seems more reasonable to believe that the variations actually were noticed but that records of the observations were not made, or were not preserved, because their importance was not realized. We must remember that records could not formerly be made and distributed with the same facility as today. Moreover, we cannot be certain that we are really doing any better at the present time, for it is probable that in the year 3000 A.D. students will marvel at our failure to observe certain things and to perceive the potential interest of some of the things we do observe.

Variable stars have generally been discovered by detecting changes in their brightness as compared with neighboring stars. The exact measurement of the light of an individual star, observed as an isolated object, is beset with so many practical difficulties that comparatively few stars have ever been observed in this way, and a large proportion of those so investigated were already known to be variable. But the determination of the *relative* brightness of a number of stars within a small area of the sky is very much easier. If every star in the sky should suddenly brighten by twenty per cent, most astronomical observations would not be capable of revealing this astonishing occurrence, but if only one star out of every ten should do so, astronomers would stand a good chance of detecting many of the variables. This is but one illustration of the very general fact that differential measurements are simpler and more certain than absolute ones. For the most part, then, the light of the stars has been studied by differential or relative methods.

Until the latter part of the nineteenth century, variable stars were found either by general observation of the sky or in connection with the formation of star charts and catalogues. But with the application of the photographic plate and the spectroscope to astronomical research, efficient systematic methods of detecting variables became available and have produced rich results. These methods are by far the most important now in use, but the history of

TABLE II

THE FIRST SIXTEEN VARIABLES DISCOVERED

	R. A. 1900 h m	DEC. 1900 ° ′	MAG.	PERIOD DAYS	DISCOVERER	DATE
1. *o* Ceti*	2 14.3	− 3 26	1.7– 9.6	331.7	Fabricius	1596
2. β Persei	3 1.7	+40 34	2.1– 3.2	2.9	Montanari	1669
3. χ Cygni*	19 46.7	+32 40	4.0–13.5	406.0	Kirch	1686
4. R Hydrae*	13 24.2	−22 46	4.0– 9.8	425.2	Maraldi	1704
5. R Leonis*	9 42.2	+11 54	4.6–10.5	312.8	Koch	1782
6. η Aquilae	19 47.4	+ 0 45	3.7– 4.5	7.2	Pigott	1784
7. β Lyrae	18 46.4	+33 15	3.4– 4.1	12.9	Goodricke	1784
8. δ Cephei	22 25.4	+57 54	3.7– 4.6	5.4	Goodricke	1784
9. α Herculis	17 10.1	+14 30	3.1– 3.9	Irreg.	W. Herschel	1795
10. R Coronae	15 44.4	+28 28	5.5–12.5	Irreg.	Pigott	1795
11. R Scuti	18 42.2	− 5 49	4.8– 7.8	Irreg.	Pigott	1795
12. R Virginis*	12 33.4	+ 7 32	6.4–12.1	145.5	Harding	1809
13. R Aquarii*	23 38.6	−15 50	6.2–11.0	387.2	Harding	1811
14. R Serpentis*	15 46.1	+15 26	5.6–13.	357.2	Harding	1826
15. S Serpentis*	15 17.0	+14 40	7.8–14.0	368.5	Harding	1828
16. R Cancri*	8 11.0	+12 2	6.0–11.3	362.	Schwerd	1829

* Those marked with an asterisk are typical long-period variables. Data largely from *Annals Harvard College Observatory,* Volume 56.

the subject will be better displayed if we postpone their consideration until the older work has been described.

The great changes in brightness characteristic of long-period variables make the discovery of these objects relatively easy. Their redness is also a factor in attracting the attention of observers and in raising an *a priori* suspicion of variability. Thus it happened that of the first sixteen variable stars to be discovered, nine are typical long-period variables. (See Table II.)

The first four long-period variables to be discovered, *o* Ceti, χ Cygni, R Hydrae, and R Leonis are well known to astronomers and laymen. All were found prior to the year 1800 and thus long before the development of the photographic and spectroscopic methods. These four objects, moreover, are the only long-period variables discovered before 1800, whereas during the nineteenth century, 223 were found, 131 of them during the last decade.

o CETI (MIRA)

On the night of August 13, 1596, Fabricius[1] noticed that a star in Cetus (later to be called *o* Ceti), was brighter than *α* Arietis, a yellow star of magnitude 2.2. He observed it again during the first few days of September and followed it until it vanished from sight sometime in October. As it was in excellent observing position at this time, the observed decrease of light was doubtless real. Apparently all his observations were made while the light was diminishing. Maximum probably occurred about the end of June, 1596. The next fact seems to us a strange one. It is that twelve years elapsed before the next recorded observation. According to the record, Fabricius next saw Mira on February 15, 1609. Whether he looked for it during this long interval we do not know. Mira is in the most favorable position for observation during the autumn of each year, coming to opposition[2] during

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[1] David Fabricius (1564–1617), a German clergyman.

[2] On the meridian at midnight, therefore observable all night long.

the last days of October. As the period between its light maxima is about eleven months, it would have been faint during the autumn for several years following 1596 so that if Fabricius looked for it, he might have been unable to see it, and perhaps entertained no idea of the recurrence of its visibility. It should have been easy to observe, however, during the years 1602 to 1605.

The next recorded observation was in 1631. On October 14 of that year Schickard saw the variable as bright as α Ceti, a neighboring red star of magnitude 2.8. In December, 1638, the variability was discovered independently by Holwarda and Fullenius. Since that time observations have been made nearly every year. This star occurs in Bayer's famous star chart "Uranometria" published in 1603. Bayer, ignorant of its variability, assigned it the Greek letter *o* (omicron) by which it is still known. Hevelius later used the special name Mira,[3] given to it originally by Fabricius because of its wonderful changes in light. Observations made about 1780 by the great English astronomer Sir William Herschel are quoted in Chapter IV.

χ CYGNI

In July, 1686, G. Kirch[4] looked at the new star in Vulpecula which had been discovered in 1670,

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[3] Latin word for wonderful.

[4] A German astronomer (1639–1710).

and took the occasion to compare the surrounding part of the sky with the charts of Bayer and Hevelius. In this way he noticed the absence of a star in Cygnus which had been marked χ by Bayer. He kept the region under continued observation and on October 19, 1686, was rewarded by finding the star to be of the fifth magnitude, thus discovering its variability. He and other members of his family followed the star until 1738.

R Hydrae

This star does not occur in the regular edition of Bayer's chart (1603) but Montanari put it in by hand in his copy, as of the fourth magnitude. His observations were made in April, 1670. Still earlier observations by Hevelius on April 18 and 19, 1662, had caused him to include this star in his catalogue, assigning it to the sixth magnitude. Neither of these observers appears to have recognized any changes. The credit for discovering the variability seems to belong to Maraldi.[5] He saw Montanari's record on the Bayer chart and searched for the star in 1702 but failed to find it. He saw it for the first time in 1704 as of the fourth magnitude, and between then and 1712 he observed several appearances and disappearances.

[5] Italian astronomer (1665–1729).

R Leonis

The following is a translation of part of a letter dated January 14, 1785, from D. Koch of Osnabrück to J. E. Bode, Astronomer of the Berlin Observatory, published in 1785 in the Berliner Astronomisches Jahrbuch for 1788.

"I take the liberty, sir, to communicate to you several observations which I have made, in various years, of the 420th star in Mayer's Zodiacal Star Catalogue (106 Leonis in my own complete star catalogue) which seem to me to be of some importance. This star, whose right ascension for 1756.0 in Mayer's Catalogue is 143° 36′ 50″ ($9^{h}\ 34^{m}\ 27^{s}.3$), declination +12° 33′ $4''.1$, has exhibited very considerable variation of its apparent magnitude. In the year 1780 when I first looked at it in a telescope I estimated it to be of the seventh magnitude, and it was then noticeably fainter than the neighboring star Mayer 419, which is identical with 19 Leonis according to Flamsteed. In February, 1782, it was of the sixth magnitude and visible to the naked eye. At the end of April, 1783, it was of the ninth magnitude, and at the beginning of April, 1784, of the tenth. At present, however, it is so faint that I am unable to recognize it with a good 16-inch Gregorian telescope. This telescope is the best which has served for my observations. To be sure, I possess a better one but on account of its length I have not been able to use it as yet. It would be agreeable to me, sir, if in connection with the observations of this star you would take a few moments to ascertain to what extent it is visible in better telescopes than the one mentioned."

A footnote added to the letter says, "On February 27 and 28, 1785, I directed my three and a half foot Doll.[6] telescope toward the position of the star Mayer 420 (R Leonis) but could see no trace of a star."

Table III contains a list of all variables definitely recognized to have long periods, which were discovered prior to 1860.

TABLE III

LONG-PERIOD VARIABLES DISCOVERED PRIOR TO 1860

	R. A. 1900 h m	DEC. 1900 ° ′	MAG.	PERIOD DAYS	DISCOVERER	DATE
1. R Androm.	0 18.8	+38 1	6.0–14.9	410.7	(Bonn)	1858
2. S Piscium	1 12.4	+ 8 24	8.2–<14.7	404.3	Hind	1851
3. R Piscium	1 25.5	+ 2 22	7.6–13.5	344.2	Hind	1850
4. R Arietis	2 10.4	+24 35	7.5–13.7	186.6	(Bonn)	1858
5. o Ceti	2 14.3	− 3 26	1.7– 9.6	331.7	Fabricius	1596
6. R Tauri	4 22.8	+ 9 56	8.0–14.0	325.	Hind	1849
7. S Tauri	4 23.7	+ 9 44	9.5–14.6	365.	Oudemans	1855
8. R Orionis	4 53.6	+ 7 59	8.7–13.5	378.5	Hind	1848
9. R Leporis	4 55.0	−14 57	6.1– 9.7	436.1	Schmidt	1855
10. R Gemin.	7 1.3	+22 52	6.4–13.8	370.2	Hind	1848
11. R Can. Min.	7 3.2	+10 11	7.2–10.0	337.7	(Bonn)	1855
12. S Can. Min.	7 27.3	+ 8 32	7.0–12.2	330.3	Hind	1856
13. S Gemin	7 37.0	+23 41	8.2–14.5	294.	Hind	1848
14. T Gemin.	7 43.3	+23 59	8.1–<13.5	288.1	Hind	1848
15. U Gemin.	7 49.2	+22 16	8.9–14.0	893.	Hind	1855
16. R Cancri	8 11.0	+12 2	6.0–11.3	362.	Schwerd	1829
17. U Cancri	8 30.0	+19 14	8.4–<14.0	305.0	Chacornac	1853
18. S Hydrae	8 48.4	+ 3 27	7.5–13.0	256.	Hind	1848
19. T Hydrae	8 50.8	− 8 46	7.0–13.1	288.8	Hind	1851
20. T Cancri	8 51.0	+20 14	8.0–10.8	482.	Hind	1850
21. R Leonis	9 42.2	+11 54	4.6–10.5	312.8	Koch	1782
22. R Urs. Maj.	10 37.6	+69 18	7.0–13.5	302.1	Pogson	1853
23. S Leonis	11 5.7	+ 6 0	9.0–13.5	189.5	Chacornac	1856
24. R Com. Ber.	11 59.1	+19 20	8.0–15.0	361.8	Schönfeld	1856

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[6] Dollond?

TABLE III (*Continued*)

LONG-PERIOD VARIABLES DISCOVERED PRIOR TO 1860

	R. A. 1900 h m	Dec. 1900 ° ′	Mag.	Period Days	Discoverer	Date
25. T Virginis	12 9.5	− 5 29	8.7–13.5	339.5	Boguslawski	1849
26. S Urs. Maj.	12 39.6	+61 38	7.3–12.5	226.5	Pogson	1853
27. U Virginis	12 46.0	+ 6 6	7.5–13.5	206.9	Harding	1831
28. V Virginis	13 22.6	− 2 39	8.0–14.0	250.5	Goldschmidt	1857
29. R Hydrae	13 24.2	−22 46	4.0– 9.8	425.2	Maraldi	1704
30. S Virginis	13 27.8	− 6 41	5.6–12.3	376.9	Hind	1852
31. R Camelop.	14 25.1	+84 17	7.9–13.7	269.5	Hencke	1858
32. R Boötis	14 32.8	+27 10	6.6–12.9	223.3	(Bonn)	1858
33. S Serpentis	15 17.0	+14 40	7.8–14.0	368.5	Harding	1828
34. R Serpentis	15 46.1	+15 26	5.6–13.	357.2	Harding	1826
35. R Librae	15 47.9	−15 56	9.2–<13.	242.4	Pogson	1858
36. R Herculis	16 1.7	+18 38	8.6–14.8	317.7	(Bonn)	1855
37. S Scorpii	16 11.7	−22 39	9.1–15.	176.7	Chacornac	1854
38. R Scorpii	16 11.7	−22 42	9.5–16.	224.1	Chacornac	1853
39. S Ophiuchi	16 28.5	−16 57	8.3–<13.	233.8	Pogson	1854
40. S Herculis	16 47.4	+15 7	7.3–12.6	308.3	(Bonn)	1856
41. R Ophiuchi	17 2.0	−15 58	7.1–13.6	302.2	Pogson	1853
42. T Herculis	18 5.3	+31 0	7.2–13.6	165.0	(Bonn)	1857
43. R Aquilae	19 1.6	+ 8 5	5.8–<12.	355.0	(Bonn)	1856
44. R Sag.	19 10.8	−19 29	6.9–12.3	269.0	Pogson	1858
45. R Cygni	19 34.1	+49 58	6.6–13.9	425.9	Pogson	1852
46. χ Cygni	19 46.7	+32 40	4.0–13.5	406.0	Kirch	1686
47. R Cap.	20 5.7	−14 34	9.0–<13.	344.	Hind	1848
48. R Delph.	20 10.1	+ 8 47	7.6–13.0	284.4	Hencke	1851
49. U Cap.	20 42.6	−15 9	10.2–14.	202.5	Pogson	1857
50. R Vulpec.	20 59.9	+23 26	7.5–12.1	136.8	(Bonn)	1858
51. T Cap.	20 16.5	−15 35	8.8–13.5	269.2	Hind	1854
52. S Cephei	21 36.5	+78 10	7.9–13.1	485.8	Hencke	1858
53. S Aquarii	22 51.8	−20 53	8.0–14.2	279.7	Argelander	1853
54. R Pegasi	23 1.6	+10 0	7.5–13.2	377.5	Hind	1848
55. R Aquarii	23 38.6	−15 50	6.2–11.0	387.2	Harding	1811
56. R Cass.	23 53.3	+50 50	5.3–12.8	431.6	Pogson	1853

Data from *Annals Harvard College Observatory*, Volume 56.

With the introduction of photography as a method of star charting, the discovery of variables was greatly facilitated. The images of hundreds or even thousands of stars may appear on a single negative and the intensity of each one can, by means of a special optical comparator, be quickly compared with that on another plate of the same region taken at a different time. Moreover, it was not long after the general adoption of the photographic plate as a standard astronomical tool that a remarkable new method of detecting long-period variables by a single observation was discovered. This method depends on the fact that a particular type of spectrum is a positive indication of long-period variability. Its importance may be realized from the fact that present catalogues contain hundreds of objects whose variability could be predicted by an expert from a glance at the photographed spectrum. And in other instances the spectrum would raise a suspicion of variability.

The Harvard College Observatory has been the great pioneer institution in the systematic discovery of variable stars, chiefly by photographic and spectroscopic methods. The earliest Harvard discoveries were, however, made visually. The first variable discovered at Harvard was T Orionis (1900 R.A. 5^{h} $30^{m}.9$; Dec. —5° 32′; Mag. 9.0–13.0; Period irregular) found in 1863 by Professor George P. Bond in connection with his extensive study of the region of the Orion nebula. The second and third, U Puppis (1900 R.A. 7^{h} $56^{m}.1$; Dec.—12° 34′; Mag. 8.5–14.5; Period 315 days; Spectrum M5e) and R Ursae Minoris (1900 R.A. 16^{h} $31^{m}.3$; Dec. +72° 28′; Mag. 8.6–10.5; Period 320 days; Spectrum M7) were found in 1881 by Professor E. C. Pickering. For both of these the variability was at first suspected from the character of the spectrum, which was observed visually. About 1886 a program for the wholesale photography of stellar spectra was inaugurated by Professor Pickering. His method, reverting to that of Fraunhofer, was to photograph the sky through a large prism placed in front of the object glass of the telescope. Each star is thus photographed not as a point image but as a narrow spectrum half an inch or so long.

The first star to be identified as a long-period variable from a photograph of its spectrum was U Orionis (1900 R.A. $5^h\ 49^m\!.9$; Dec. $+20°\ 10'$; Mag. 6.0–11.8; Period 372.2 days; Spectrum M6e). Upon its discovery by Gore on December 13, 1885, it was first thought to be a nova, but on December 16 a photograph of its spectrum taken at the Harvard Observatory showed a strong similarity to that of o Ceti, photographed for the first time only five days previously, and it was accordingly assigned to the long-period class of variables. The first star for which variability was inferred from the character of the photographed spectrum is R Caeli (1900 R.A. $4^h\ 37^m\!.0$; Dec. $-38°\ 26'$; Mag. 8.3–13.0; Period 394 days; Spectrum M6e) found in 1890 by Mrs. Fleming at the Harvard Observatory. Thus the Harvard College Observatory has to its credit the following pioneer achievements in the spectroscopy of long-period variable stars:

Year	*Star*	
1881	U Puppis and R Ursae Minoris	First stars for which variability was inferred from the character of the spectrum observed visually.
1885	*o* Ceti	First photograph of the spectrum of a long-period variable.
1885	U Orionis	First variable assigned to the long-period class from the character of its photographed spectrum.
1890	R Caeli	First star for which variability was inferred from the character of its photographed spectrum.

The facts concerning the discovery of individual variables, together with references to all recorded observations up to the end of 1915 are collected in a monumental work by G. Müller and E. Hartwig under the auspices of the Astronomische Gesellschaft, "Geschichte und Literatur des Lichtwechsels der bis Ende 1915 als sicher veränderlich anerkannten Sterne nebst einem Katalog der Elemente ihres Lichtwechsels" (History and Bibliography of the Changes in Brightness of all Stars Recognized before the end of 1915 as Certainly Variable, with a Catalogue of Data Concerning their Variations), Leipzig, 1918. A second edition by R. Prager covering the literature of the years 1916–1933 is partially completed. These volumes are indispensable to anyone who wishes to look up in detail the observations of a particular variable.

The historical progress in the discovery of variables may be seen from the number of stars contained in the successive catalogues in the following list:

CATALOGUES OF VARIABLE STARS

Year	*Compiler*	*No. of Stars*
1786	Pigott	12
1844	Argelander	18
1850	Argelander	24
1854	Pogson	53
1865	Chambers	113
1875	Schönfeld	143
1884	Gore	191
1888	Gore	243
1893	Chandler	260
1896	Chandler	393
1903	Pickering	701
1907	Cannon	1380
1915	Müller and Hartwig	1687
1926	Prager	2906
1927	Prager	3026
1928	Prager	3218
1929	Prager	4031
1930	Prager	4581
1931	Prager	5461
1932	Prager	5826
1933	Prager	6081
1934	Prager	6221
1935	Prager	6776
1936	Schneller	6968

These catalogues contain variables of all types with short as well as long periods. In the recent lists more than one-half of the stars probably belong in the long-period group.

DESIGNATIONS OF VARIABLE STARS

Argelander, prior to 1850, introduced the use of the capital Roman Letters R to Z as designations of variable stars in order of discovery in each constellation. Thus the first variable discovered in Aquarius is R Aquarii, the ninth, Z Aquarii. For stars previously named, however, he did not assign new designations but retained the old ones, e.g., o Ceti, β Persei, χ Cygni, η Aquilae. Discovery of additional variables soon exhausted, in certain constellations, the nine available symbols, and in 1881 Hartwig proposed using the double letters RR, RS . . . RZ, SS, ST . . . SZ, etc. This added 45 symbols and remained adequate until about 1904 when a further extension was made. At that time double letters beginning at the first of the alphabet were employed, thus AA, AB . . . AZ, BB, BC . . . BZ, etc. The letter J is omitted throughout. This provided 280 additional symbols, or 334 in all. In six constellations (Aquila, Centaurus, Cygnus, Ophiuchus, Sagittarius, Scorpius) the number of catalogued variables now exceeds 334; those after QZ (number 334) are listed in order as V335, V336, . . . etc., followed by the constellation name. The complete system is as follows:

DESIGNATIONS OF VARIABLE STARS IN EACH CONSTELLATION

1.	R	55.	AA
2.	S	56.	AB
–		–	
–		–	
9.	Z	79.	AZ *
10.	RR	80.	BB
11.	RS	81.	BC
–		–	
–		–	
18.	RZ	334.	QZ
19.	SS	335.	V335
20.	ST	336.	V336
–		–	
–		–	
26.	SZ	∞	V ∞
–			
–			
54.	ZZ		

* The letter J is omitted throughout.

In 1888 Chandler suggested that the designations of variable stars be one-tenth of the right ascension, expressed in time-seconds, for the equinox 1900.0. Thus

Variable	*R.A. 1900.0*	*Chandler No.*
o Ceti	$2^{h}\ 14^{m}\ 18^{s} = 8058^{s}$	806
R Leonis	9 42 11 = 34931	3493
χ Cygni	19 46 44 = 71204	7120

These "Chandler numbers" are found on the Hagen charts and in many of the older lists of variables but are now seldom used.

In the so-called "Astronomischen Nachrichten"[7] system, variables are designated by a current number preceding the year of discovery. Thus the stars discovered in 1910 were listed 1.1910, 2.1910, 3.1910, etc. These designations are regarded as provisional and temporary and are not in general use.

The variables found at the Harvard Observatory have been given the designation HV1, HV2, HV3, etc., in order of discovery. Many of these are later assigned constellation letters according to the standard system, but for faint variables in special regions the HV numbers may serve as the permanent designations.

A convenient means of finding the numerous aliases under which a particular variable may appear has been provided by a publication in 1927 by R. Prager of the Berlin-Babelsberg Observatory, entitled "Tabellen zur Nomenkatur der veränderlichen

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[7] "Astronomical News," a German technical publication.

Sterne."[8] (Tables for the Designations of Variable Stars.)

A method devised at the Harvard Observatory many years ago to give in compact form the approximate position of a variable has proven very convenient and is now widely used. Six figures are employed to give the position for 1900.0. The first two give the hour of right ascension; the second two the minute of right ascension; and the last two the degree of declination.[9] Thus for R Leonis (1900 R.A. 9^{h} $42^{m}.2$; Dec. + 11° 54′) the designation is 094211. If the declination is south, the number is italicized. Thus o Ceti (1900 R.A. 2^{h} $14^{m}.3$; Dec. —3° 26′) *021403*. It has recently become the practice to italicize the figures for the declination only, thus 0214*03*.

The Vade Mecum of observers dealing extensively with variable stars is a volume published annually under the auspices of the Committee for Variable Stars of the Astronomische Gesellschaft. The exact titlè is "Katalog und Ephemeriden veränderlicher Sterne für (1936). Kleinere Veröffentlichungen der Universitätssternwarte zu Berlin-Babelsberg. Nr (15)." It gives in several convenient tables the up-to-date list of recognized variables with their accepted designations, together with the position and annual precession, the period, predicted times

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[8] Kleinere Veröffentlichungen der Universitätssternwarte zu Berlin-Babelsberg Nr. 2.

[9] *Right ascension* of a star, measured easterly from a certain point in the sky corresponds to terrestrial longitude; *declination,* measured north or south from the celestial equator, corresponds to latitude.

of maximum, limiting magnitudes, and spectral type.

The most recent catalogue devoted exclusively to long-period variables is the "Harvard Catalogue of Long-Period Variable Stars," by Sidney D. Townley, Annie J. Cannon, and Leon Campbell, Annals Harvard College Observatory, Vol. 79, Part 3, 1926, which gives, in systematic form, extensive data for 1760 stars.

At the present time the lists of variables are reasonably complete only for the brighter stars, including the eighth or perhaps the ninth magnitude. Below the ninth, and especially below the tenth magnitude, relatively few are known, though thousands upon thousands are doubtless awaiting discovery. Shapley and Waterfield estimate that only about one-half of the variables brighter than the eleventh magnitude have been found, while for fainter magnitudes the proportion is, of course, far less.

The importance of discovering additional faint variables while perhaps not very obvious, is nevertheless really considerable. It is true that only the brighter objects can be studied in detail by spectroscopic and precise photometric methods and that variables already known furnish extensive opportunity for work of this kind. But it is possible that among future discoveries will be found new or abnormal types of variability of especial interest, for example stars with longer periods or greater ranges than any now known. Some of the new long-period stars might prove to have lower surface temperatures than any stars so far studied. If such very cool stars exist it is clearly very important to find and study them for their bearing on the problems of stellar evolution.

The discovery of variables, moreover, is now being emphasized in a totally different connection, namely, for the assistance they may render in determining the distance of special objects such as Milky Way clouds, star clusters, and spiral nebulae, which are too far away to yield to ordinary parallax methods. We have recently gained a fairly accurate knowledge of the average intrinsic brightness of variables of various periods, and by comparing this average with the observed brightness of a particular variable an approximate determination of its distance is at once obtained. The faintest stars are of the most interest because they are probably the most distant. This method is being extensively applied by Dr. Harlow Shapley and the staff of the Harvard College Observatory to the star clouds in the Milky Way, and by Dr. E. P. Hubble of the Mount Wilson Observatory to the distant spiral nebulae.

CHAPTER IV

LIGHT CURVES

OUR most precious data concerning variables are the records of their variations in brightness during past years. A partial orderliness prevails in the behavior of these objects, but many display no clock-like regularity and are not as yet subject to precise calculation. To find out *why* they vary, we must first know exactly *how* they vary, and this we cannot learn except by watching them for a long time. Observations over a short term of years will not give us mastery of the difficult problems involved. Hence the great value of a knowledge of the past behavior of these objects.

For many years after the discovery, in 1596, of the fluctuating brightness of Mira Ceti, the study of variable stars was casual and desultory. Even by the time of Sir William Herschel, nearly two centuries later, the behavior of Mira was apparently not at all well known, and Sir William thought it worth while to report the details of his own rather scattering observations to the Philosophical Society of Bath. Parts of Herschel's reports are worth quoting not only because of their historical interest, but also because they present so vivid a picture of the phenomena of stellar variability.

ASTRONOMICAL OBSERVATIONS ON THE PERIODICAL STAR IN COLLO CETI.[1]

By Mr. William Herschel, of Bath; communicated by Dr. Watson, Jun. of Bath. F.R.S.

Read May 11, 1780

This remarkable star, we are told, "was first observed by David Fabricius, the 13th of August, 1596, who called it the stella mira, or wonderful star; which has been since found to appear and disappear, periodically, seven times in six years, continuing in the greatest lustre for fifteen days together, and is never quite extinguished."

My own observations on this wonderful star are but few, yet sufficiently verify the surprising appearances that have been ascribed to it. I shall transcribe them from my astronomical journal in the order they were made.

October 20, 1777, I looked out for the periodical star in Collo Ceti, but it was not visible. If its period is 312 days I may expect to see it about Christmas, not being visible at present.

Dec. 18, 1777, I saw the periodical star in Collo Ceti. It appeared in the very place where, about a fortnight ago, I imagined (but was not sure) there was a faint appearance of it. It was in magnitude about equal to ζ, but not so large as δ.[2]

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[1] Bayer's character for this star is ο.

[2] The comparison stars mentioned by Herschel in this and the following papers, with modern determinations of their magnitudes, are as follows:

α	Ceti	2.8	ν	Ceti	5.0	
β	Ceti	2.2	α	Arietis	2.3	
γ	Ceti	3.6	α	Piscium	3.9	
δ	Ceti	4.0	γ	Orionis	1.7	(Bellatrix)
ζ	Ceti	3.9	α	Tauri	1.1	(Aldebaran)

Jan. 26, 1778. The periodical star was larger than δ, but less than γ. Being taken up with other observations, I paid no more attention to it during the rest of this period.

Sept. 18, 1779. The periodical star was visible to the naked eye, when I first looked for it.

Oct. 6, 1779. The periodical star was exceedingly bright this evening. It exceeded α and β Ceti; which latter, I must here observe, is considerably larger than the former, and affords a proof of the change in the magnitude of the fixed stars; as we can hardly suppose Bayer should have made a mistake in the magnitude of the two first stars of this constellation.[3]

Jan. 4, 1780. The periodical star is very much diminished.

Feb. 7, 1780. The periodical star was invisible to the naked eye. I was but little prepared to look a long time for it with the telescope; but suppose I shall be able to find it another time.

ON THE PERIODICAL STAR IN COLLO CETI

Read Feb. 2, 1781

Last year I presented to this Society a Memorandum of the uncommon lustre of the periodical Star in Collo Ceti. It is somewhat remarkable that the succeeding Period should be distinguish'd by the very reverse of the former. The subject is so involved in obscurity that I shall attempt little more than to deliver my observations accompanyed with a few conjectures, leaving it to

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[3] This remark refers to Bayer's custom of calling the brightest star in each constellation α, the second brightest β.

future Observers to frame some plausible theory, when many succeeding periods may have furnished means to direct the thoughts in this pursuit.

A star (a Sun I should say), perhaps surrounded with a system of Planets depending upon it, undergoes a change, which, were it to happen to *our* Sun, would probably be the total destruction of every living creature! What an amazing alteration from the first magnitude down to the 6th, 7th or 8th! But let me not take up a time in admiration which may perhaps be more philosophically imployed in reciting plain matters of fact.

The observations I have been able to make upon this wonderful star are this time fewer than I could wish to have made; yet are sufficient to deserve to be mentioned as they are so far connected with the former, that we may presume to conjecture the remarkable want of brightness in this period to be some natural consequence of the super-abundant light in that immediately preceeding.

Observations in 1780

August 3^d 2^h $35'$ in the morning.

The periodical star is not to be found with the naked eye. The night uncommonly fine.

Aug. 8. 2^h in the morning.

I looked with a compound eye piece that takes in a very large field of view, and examined every very small star near the place of the periodical star but could not find it. I also looked with the power of 222 without success.

Sept. 8. I could just discover the periodical star with the naked eye, tho' with some doubts; but on applying the Telescope I saw it perfectly well and the small star which follows it.

The colour was very remarkable, being a darker red, (or rather garnet colour) than any I remember to have seen before among the fixt Stars.

Sept. 19. The periodical Star is considerably increased, being nearly equal to δ Ceti.

Nov. 7. The periodical star is hardly so large as δ.

Nov. 24. The periodical Star is less than it was, instead of being encreased as I expected. 11 o'clock.

Dec. 15. *o* Ceti is diminished since I saw it last.

Dec. 17. *o* Ceti is hardly visible to the naked eye tho' δ is bright enough.

Dec. 23. I can not find the periodical star.

. . . . .

ON THE PERIODICAL APPEARANCE OF *o* CETI

Read December 22, 1791

The changeable star in the neck of the Whale, *o* Ceti, continues its variations as usual, but with some considerable irregularities of brightness.

In the year 1779, as we have seen, it excelled *a* Arietis so far as almost to rival Aldebaran; and continued in that state a full month.

In 1780, its greatness brightness was only like that of δ Ceti.

In the year 1781, it did not come up to the brightness of δ.

In 1782, this star increased to the size of β Ceti, and continued bright for more than twenty days.

In 1783, it did not only vanish to the naked eye, as usual, but disappeared so completely, that I could not find it with a telescope, which permitted not a star of the 10th magnitude to escape me. When it increased again, it did not amount to the brightness of δ.

In 1784, I saw it only of the 8th magnitude in a twenty-feet reflector, but as I did not continue to observe it regularly, it might possibly change as usual.

In 1789, it arrived to the brightness of α Piscium, or rather excelled it.

In 1790, the greatest brightness was almost equal to that of α Ceti.

In the present year, I have seen it only of the magnitude of γ Ceti nearly; or between γ and δ; but, as bad weather has occasioned many interruptions, it may possibly have been larger.

The period of 333 days, assigned by BOUILLAUD, does not agree with present observations compared to those of FABRICIUS made on the 13th of August, 1596, when this star was in its greatest lustre. M. CASSINI also found, that his observations, in the beginning of August, 1703, when the star was brightest, did not agree with the interval of 333 days; and therefore, supposing the star to have changed 117 times since the epoch of FABRICIUS, he gave it a period of 334 days. This will, however, not agree with the present time of the changes; and it appears now that M. CASSINI ought to have assumed 118 instead of 117 variations; which would have pointed out a period of 331 days, and some hours.

That this is, probably, very near the real time of the star's variation, will be seen when we admit it to have undergone 214 changes between the 13th of August, 1596, and the 21st of October, 1790; by which long interval we obtain the period of 331 days, 10 hours, 19 minutes. It will, indeed, be necessary, in order to reconcile all observations, to admit of some occasional deviations in the appearance of the star, amounting almost to a month; but that this is no more than we may allow, is pretty evident from the variations I have taken notice of within the last 14 years; besides, a period of 334 days could not be admitted without totally giving up all regularity in the returning appearance of the star.

I have taken the epoch of the 21st of October, 1790, as one of the best ascertained, modern appearances I have been able to obtain; and believe it to be more proper for settling the period, than that which might be deduced from a brilliant blaze of the star, such as took place in 1779, owing to causes that are not regular, and therefore may be apprehended to disturb the general order of the change.

The history of the changing light intensity of a variable star is ordinarily exhibited by a graph known as a light curve. A time scale is laid off from left to right along a horizontal line, every point of which corresponds to a particular instant. The observed brightness at any time is represented by a point whose vertical distance above the horizontal line is a measure of the brightness [4] on some pre-determined scale, usually that of stellar magnitudes.[5] A non-variable

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[4] Strictly speaking, brightness refers to the visual sensation, but no great confusion seems to arise from the common practice of using it for either the visual sensation or the physical light intensity.

[5] In mathematical language, rectangular Cartesian co-ordinates are employed in which time is taken as the abscissa, brightness or magnitude as the ordinate.

star is represented by a horizontal line; one increasing in brightness by a line sloping up toward the right; one decreasing in brightness by a line sloping down toward the right. The steepness of the line indicates the rate at which the brightness is changing. A vertical segment would mean an instantaneous change.

The universal method of reckoning the brightness of stars is by the stellar *magnitude* scale which has an ancient and honorable history. Ptolemy and other ancient astronomers divided the naked-eye stars into six classes according to their brightness, calling the classes the first, second, . . . sixth magnitudes, in order of *decreasing* brightness. Thus the magnitude scale is an inverted one, i.e., the brighter stars have the smaller numbers. This system has continued in use until the present time but has been extended both in range and accuracy. For centuries there existed no logical definition of the scale, and various observers differed considerably in the numbers assigned to the same stars. This was particularly true of magnitude estimates of telescopic stars between the years 1610 and 1885. About 1830, measurements by Sir John Herschel showed that the average first magnitude star is about one hundred times as bright as one of the sixth magnitude, and in 1850 Pogson suggested that this ratio be made, by definition, the basis of the magnitude scale. This means that the ratio between two successive magnitudes raised to the fifth power, to pass from magnitude six to magnitude one, shall equal

100, or in other words that the ratio of brightness between two successive magnitudes shall be the fifth root of 100, or slightly more than 2.512. For an approximation easy to remember, we may say that each magnitude is two and one-half times as bright as the next fainter one. Pogson's proposal finally found general acceptance and the zero point of the scale was fixed in the first place by adjusting the first six magnitudes to conform as nearly as possible to those assigned by Argelander in his great star catalogue, the Bonn Durchmusterung. The zero point is now defined in a more precise way, the rather involved details of which are not important for the practical use of the system.

In the magnitude scale each step represents not a certain quantity or unit of light, but a certain *ratio* of intensities.[6] This gives a scale whose properties are quite different from those of the scales with which we are most familiar such as those of length or weight, but which is much more convenient for many purposes. It is well adapted, for example, to deal with the enormous range in the apparent brightness of observable stars. The brightest stars are many hundred million times as bright as the faintest which can be photographed with large telescopes, but it would be awkward, and wholly unnecessary from the standpoint of attainable accuracy, to use nine figures to express the brightness of any star. This

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[6] The mathematician would call such a scale logarithmic or exponential.

is avoided by the magnitude scale, which is so compressed that a difference of 20 corresponds to an intensity ratio of 100,000,000 to 1. Moreover, the magnitude scale automatically presents an appropriate unit for use with a star of any brightness. The smallest amount of light which is physically important is not a fixed unit of light intensity, but something that depends on the brightness of the star under consideration; it is in fact a certain proportion of the star's light, however great or small that may be. For example, if the light of a very faint star should increase twenty-five per cent the change would be observable and important but the same actual amount of light added to that of a very bright star would be utterly insignificant and undetectable. The convenience of the magnitude scale for visual observation is founded upon a psychological relationship formulated in Fechner's famous law, as follows: The least observable increase in a stimulus is proportional to the stimulus itself.[7]

If I_s is the light intensity of a star of magnitude s, and I_t that of a star of magnitude t, then the relative intensity of the two stars, I_s/I_t, is given by the equation

$$I_s/I_t = 2.512^{(t-s)} \qquad \text{or } \log_{10} I_s/I_t = 0.4\ (t-s)$$

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[7] Alternative statements of Fechner's law are: Sensation is proportional to the logarithm of the stimulus; or, in order that the intensity of a sensation may increase in arithmetical progression, the stimulus must increase in geometrical progression.

From this equation we may compute the apparent relative brightness of two stars, whose magnitudes differ by any given amount. Table IV gives a good idea of the relationship between the two quantities.

TABLE IV

RELATIVE LIGHT INTENSITY CORRESPONDING TO A GIVEN DIFFERENCE IN MAGNITUDE

Difference in Magnitude	*Relative Intensity*	*Difference in Magnitude*	*Relative Intensity*
0.00	1.000	2.0	6.31
0.01	1.009	2.5	10.00
0.1	1.096	3.0	15.85
0.2	1.202	3.5	25.12
0.3	1.32	4.0	39.81
0.4	1.45	5.0	100.00
0.5	1.58	6.0	251.2
0.6	1.74	7.0	631.0
0.7	1.91	8.0	1,585.
0.8	2.09	9.0	3,981.
0.9	2.29	10.0	10,000.
1.0	2.51	15.0	1,000,000.
1.5	3.98	20.0	100,000,000.

If the light range of a variable does not exceed one or two magnitudes, the light curve looks about the same whether plotted in actual intensity or in stellar magnitudes, but if the range is five or more magnitudes, as is frequently the case in long-period variables, the appearance of the two curves is very different. Figure 1 shows the mean light curve of χ Cygni (1902–1905) on both systems. Table V gives the data from which Figure 1 was constructed. The magnitudes of the mean light curve were taken from *Harvard Annals*, *57*, 195, 1907. It is obvious that the *magnitude* curve is the more convenient of the two. The *intensity* curve is awkward to plot because of its large numerical range: if the scale be so chosen that the differences near minimum are clearly shown, the maximum rises to an undue

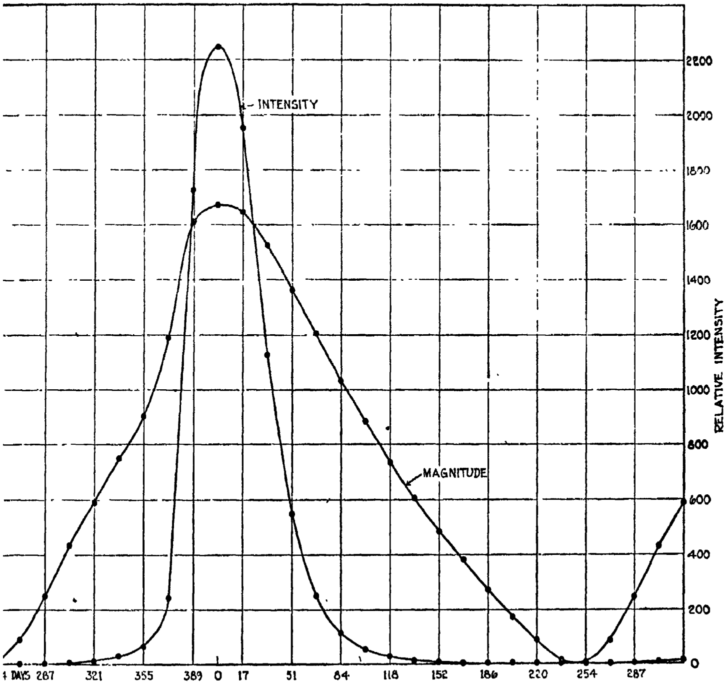

FIG. 1. Mean light curve of χ Cygni, 1902–1905, in magnitudes, and in amount of light (intensity or candlepower) relative to that at minimum. (*Popular Astronomy*)

height; while if the scale is made smaller to give a reasonable height to maximum, a large portion of the curve near minimum is so compressed as to appear flat. The *magnitude* scale is not subject to this difficulty and for this as well as for other reasons is regularly used for practical purposes; in fact, curves of the other type are seldom seen.

TABLE V

MEAN LIGHT CURVE OF χ CYGNI, 1902–1905

Phase	*Magnitude*	*Magnitude Difference*	*Relative Intensity*
0 days	4.69	8.37	2229.
17	4.83	8.23	1959.
34	5.43	7.63	1127.
51	6.21	6.85	549.5
68	7.05	6.01	253.5
84	7.87	5.19	119.1
101	8.64	4.42	58.61
118	9.37	3.69	29.92
135	10.04	3.02	16.14
152	10.64	2.42	9.290
169	11.15	1.91	5.808
186	11.69	1.37	3.532
203	12.19	0.87	2.228
220	12.63	0.43	1.486
237	12.98	0.08	1.076
254	13.06	0.00	1.000
270	12.61	0.45	1.514
287	11.80	1.26	3.192
304	10.88	2.18	7.447
321	10.09	2.97	15.42
338	9.36	3.70	30.20
355	8.53	4.53	64.86
372	7.08	5.98	246.6
389	4.97	8.09	1722.
406	4.69	8.37	2229.

The brightness of a variable star is nearly always determined by referring it to nearby stars of known magnitudes. For long-period variables this has usually been done by direct visual estimates. Felix de Roy has outlined most concisely the methods thus employed to give a numerical result.[8] "As is well known, two methods of determining the brightness

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[8] *Memoirs British Astronomical Association, 28,* p. XIX, 1929.

of variables under observation are in general use: (1) the Fractional Method, by which the brightness is estimated as a fraction of the light interval between a pair of comparison stars, the fraction being either a simple one (General Method), or a decimal one (Pickering's Decimal Method); and (2) Pogson's Step-Method, by which the variable is estimated as so many "steps" brighter than one comparison star, and so many "steps" fainter than another, the step being assumed to be $\frac{1}{10}$ of a magnitude.

"It should be understood that, strictly speaking, Pogson's method is, in many cases, a fractional method, or a combination of the fractional method and Argelander's original "step" method. An observer comparing a variable with two comparison stars, knowing that $a = 9^{m}.0$ and $b = 9^{m}.5$, and estimating it $a - 2$, $b + 3 = 9^{m}.2$, is performing a fractional operation in which the denominator of the fraction (in this case 5) is always made equal to the number of tenths of magnitude between the two comparison stars. When, as frequently occurs, the observer uses one comparison star only, and makes some comparison such as $a + 3 = 8^{m}.7$, he is falling back upon the true "step" method, though it may be supposed that, from practice and knowledge of adjacent intervals, the interval "3," in this case, will not differ much from $0^{m}.3$."

Many details concerning star charts and other matters connected with actual observing are explained in an excellent book by Miss Furness, "An Introduction to the Study of Variable Stars,"[9] and in Hagen's German treatise "Die Veränderliche Sterne." Here we cannot deal further with the methods of determining magnitudes of variables but must hasten to a consideration of the results.

A typical variable of long period completes its cycle of change in 280 days. During this interval a typical RR Lyrae variable makes no less than 500 fluctuations, while a cepheid runs through 50 cycles. Our typical long-period variable is 63 times as bright at maximum as at minimum, while this ratio for cepheids is only 2.1. For easy comparison, these figures are brought together in Table VI.

TABLE VI

COMPARISON OF VARIOUS TYPES OF VARIABLES

KIND OF VARIABLE	PERIOD	NUMBER OF CYCLES IN 280 DAYS	LIGHT RANGE (TYPICAL)	
			Mag.	Ratio of Max. to Min. Brightness
Long-period	280 days	1	4.5	63.
Cepheid	5.6	50	0.8	2.1
Eclipsing	2.8	100	1.0	2.5
RR Lyrae	0.56	500	1.0	2.5

The data of Table VI are displayed graphically in Figure 2, which should make it easy to remember the general behavior of the different types of variables. In Figure 3 is shown the light curve of a typical eclipsing variable.

[9] Houghton Mifflin Co., 1915.

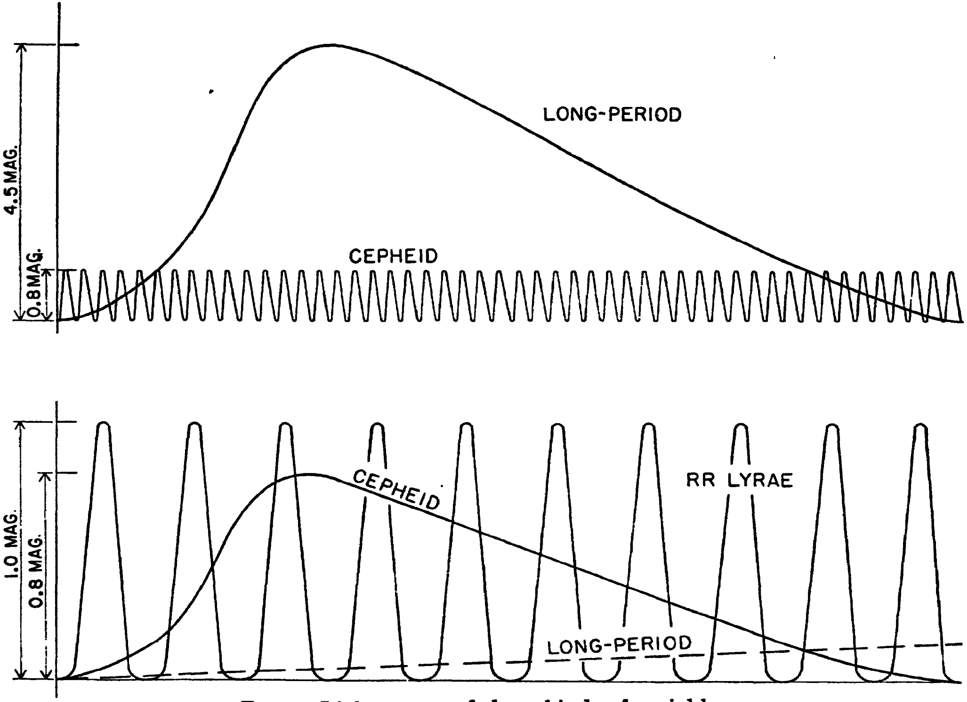

FIG. 2. Light curves of three kinds of variables.

We come now to a brief discussion of the numbers of known variables of various periods. The long-period variables far outnumber the others, but in recent years the proportion of RR Lyrae stars has been increasing, while the cepheids are a poor third. A complete survey of the present situation is afforded by Figure 4, which should perhaps have been exhibited in Chapter II, as it shows the logical basis for the classification of variables. In this diagram the periods from one-eighth of a day to one thousand days are laid off along the horizontal scale; at any value of the period the distance the curve rises above the zero line at the bottom indicates the number of variables having that period. Technically it is a frequency curve of periods. If one were to pick variable stars at random out of a catalogue, the curve shows just the relative frequency with which he would come across variables of the different periods. The fact that the main curve has

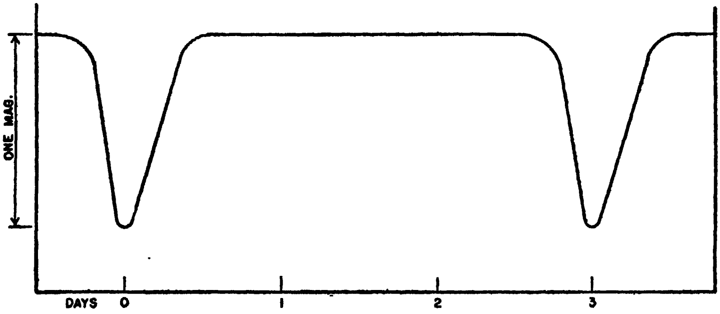

FIG. 3. Light curve of a typical eclipsing variable.

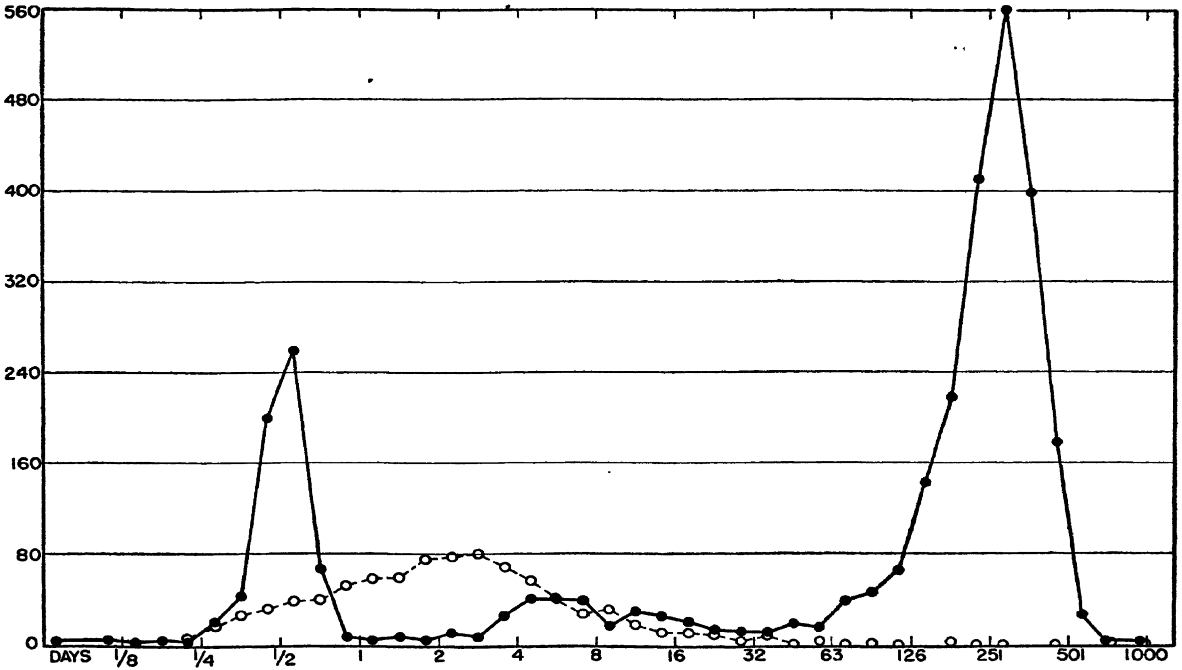

FIG. 4. Numbers of variable stars having various periods. Open circles represent eclipsing variables; solid circles, all other variables.

three maxima and falls nearly to zero between them shows that the division of variables into the three groups described in Chapter II was not arbitrary but had a definite physical basis. In other words the groups are natural ones, with few intermediate specimens, and all the astronomer has done is to recognize that fact. It is like a manufactured product which comes only in one, two, and five-pound packages. It's no use asking for a one and a half pound package—the store keeper will not have it. We can be sure that this conclusion corresponds to a reality of nature and is not an accidental result arising somehow from the astronomer's methods of searching for variables, because the other kind of variables, the eclipsing stars, are found to be most numerous at the very periods lying in the gap between the RR Lyrae variables and the cepheids. See Figure 4. This fact forces us to believe that if the missing variables were in the sky astronomers would find them.

Why, one may well ask, are there numerous variables, the RR Lyrae type, having periods about half a day, and a goodly number, the cepheids, with periods from four to eight days, but so few with periods of one, two, or three days? Further along, the diagram exhibits a paucity of stars of periods between 20 and 60 days, especially striking compared to the great numbers between 60 and 500 days. Even the little notch at 9 days appears to be real, although this has not been recognized as the dividing point between different types of variables. How does all this come about? Does nature's star factory have some kind of packaging machinery for variables, which is set for periods of 0.56, 5.6 and 280 days; and allows a certain tolerance on either side of the preferred periods, but which cannot be stretched to produce variables of widely different periods? Or do stars for their own personal reasons (good physical reasons, let us hope, not mere whims) decline to vibrate with certain periods which they consider unsuitable or inconvenient? When these questions can be answered satisfactorily we will know more about stars and about stellar evolution than we do now.

Light Curves of Long-Period Variables

χ Cygni, one of the best known long-period variables, was discovered in 1686 by G. Kirch, who with other members of his family kept track of its brightness until 1738. During this interval observations were made also by Maraldi, Cassini and Halley. Before 1842 the observations were pretty scattering, but since that date the general course of the light curve can be plotted, while since 1905 the curve has been adequately recorded even in its fainter parts. Figure 5, from data compiled by Mr. Leon Campbell of the Harvard College Observatory, and made available through the courtesy of Director Shapley, shows the light curve from 1842 to 1930 as completely as it can be determined from all known observations. Inspection shows that the mag-

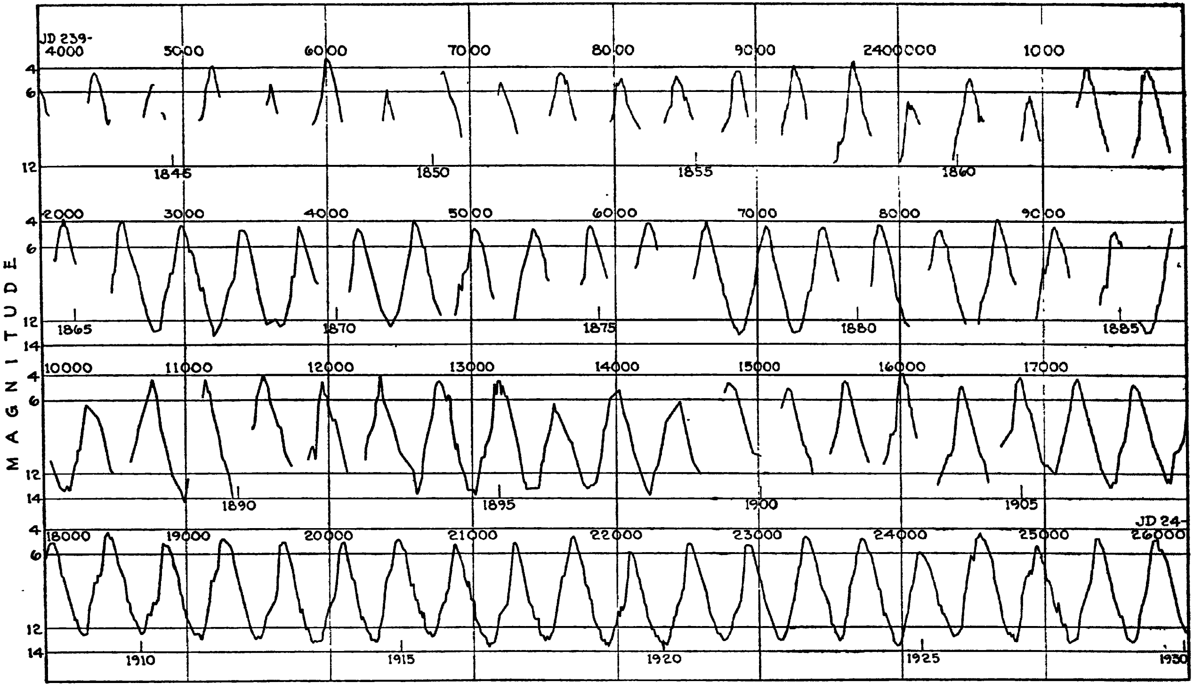

FIG. 5. Light curve of χ Cygni, 1842–1930. (*Popular Astronomy*)

nitude at maximum varies from 3.5 (1847) to 7.0 (1859). The minimum magnitudes seem more consistent; nearly all that are well determined lie between 12.5 and 14.0 while the extremes are about 12.2 and 14.5. The total range from the faintest minimum to the brightest maximum exceeds 10 magnitudes or a brightness ratio of 10,000 to 1! A being on a hypothetical planet revolving about χ Cygni, having to contend with these great extremes, must lead a weird, precarious existence. Perhaps he thinks life on our earth would be pretty tame and uneventful.

The curves of other well-known variables shown in Figures 6 and 7 have also been supplied by Mr. Campbell. For the lengths of their periods and other data see Table VII.

TABLE VII

DATA CONCERNING VARIABLES WHOSE LIGHT CURVES ARE SHOWN IN FIGURES 6 AND 7

Variable	*Designation*	*Magnitude*		*Period*	*Spectrum*
		Max.	*Min.*	*Days*	*at Max.*
X Camelopardalis	043274	8.2	12.8	142.3	M3e
R Serpentis	154615	6.9	13.0	357.2	M7e
T Cephei	210868	6.1	10.1	387	M7e
R Hydrae	132422	4.2	9.5	405	M7e
T Cassiopeiae	001755	8.2	11.9	443	M8e
S Ursae Majoris	123961	7.9	11.5	225.3	Se
S Cassiopeiae	011272	8.3	14.5	612.5	Se
RV Centuari	133155	7.0	9.5	460	N3
S Cephei	213678	8.1	11.3	485.8	M8e
χ Cygni	194632	5.1	13.3	406.6	M6pe

Raised to a high plane of accuracy and reliability by Argelander[10] in the middle of the last century, the

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[10] Director of the Observatory at Bonn, Germany, 1837–1875.

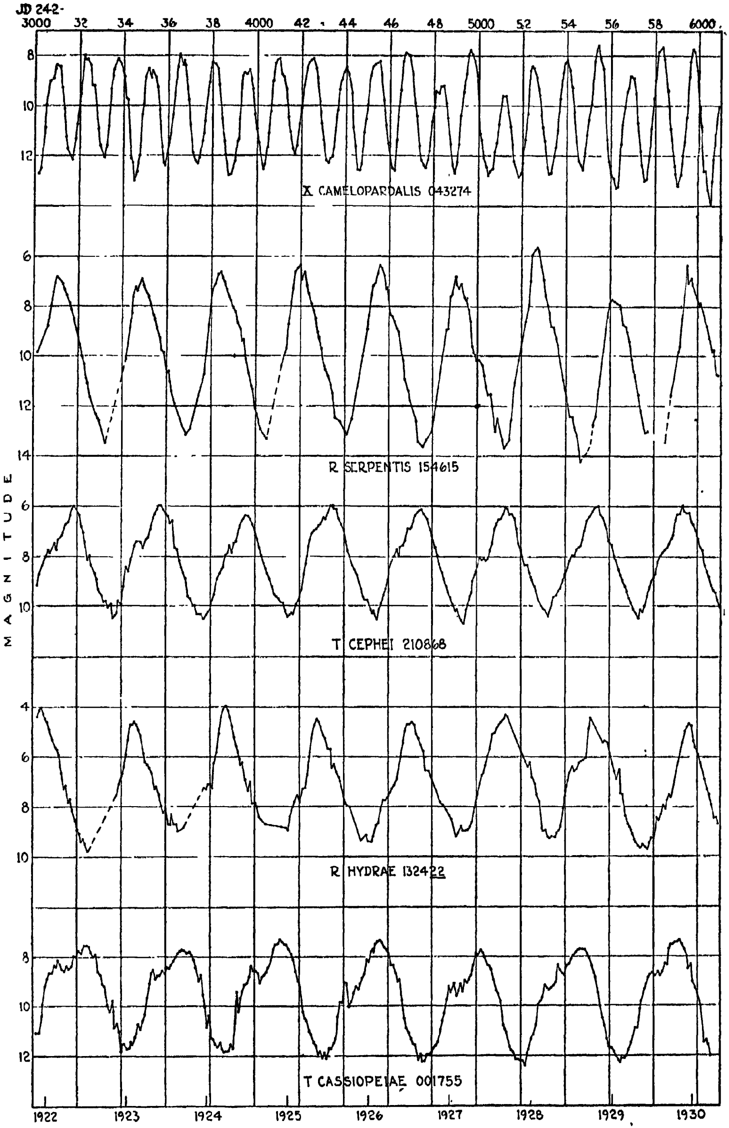

Fig. 6. Light curves of five long-period variables, 1922–1930. (Spectra of class Me.)
(Popular Astronomy)

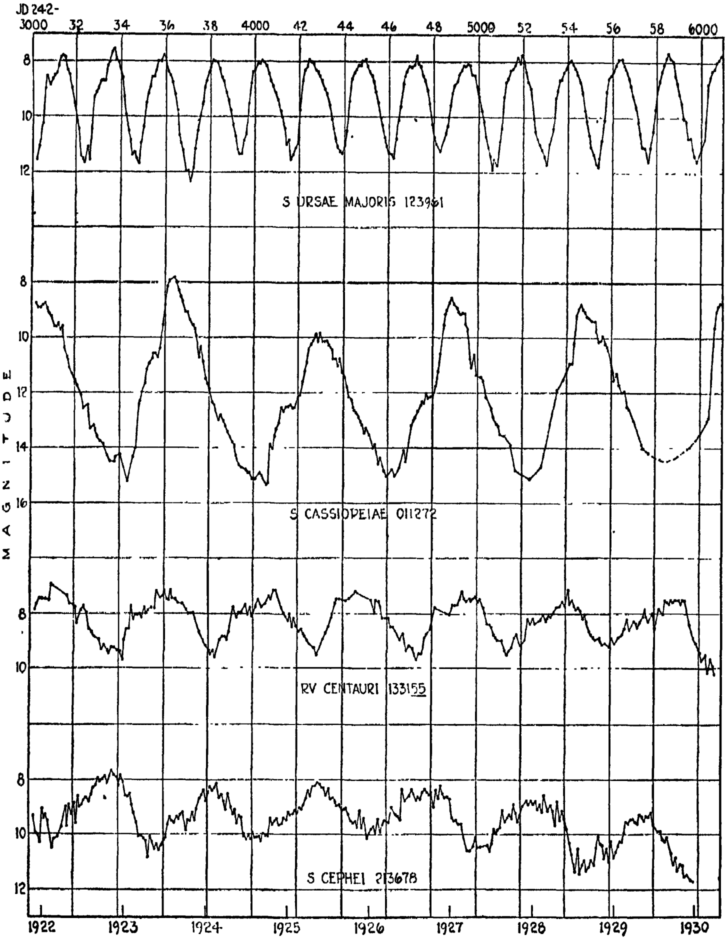

FIG. 7. Light curves of four long-period variables, 1922–1930. (Spectra of classes Se and N.) (*Popular Astronomy*)

systematic observation of variations of brightness is now more advanced than any other branch of the study of long-period variables. The reason is largely that this kind of work may be satisfactorily carried out with small telescopes and inexpensive equipment, and is thus well adapted to amateur astronomers, many of whom have made splendid use of their opportunities. Probably more persons have participated in the determination of the changes of brightness of long-period variables than in any other type of astronomical investigation. The Variable Star Section of the British Astronomical Association, the American Association of Variable Star Observers, and similar organizations in other countries have done and are doing work of great importance in keeping track of numerous variables and in arranging for the systematic compilation of the observations. Any amateur astronomer seeking a useful job would do well to consider variable star observing, and if interested should write to some observatory[11] for advice and assistance.

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[11] In the United States, to the Harvard College Observatory, Cambridge, Massachusetts.

CHAPTER V

PHYSICAL PROPERTIES

LONG-PERIOD variables are among the largest of all stars, their only serious rivals being certain super-giant red stars such as α Orionis (Betelgeuse) and α Scorpii (Antares). Were we placed as far from the center of a typical long-period variable as we are from the sun, we would find ourselves well within its vast bulk, in fact only one-third of the distance from the center to the circumference—decidedly on the inside but not looking out, for the deep strata above us, even though formed of tenuous gas, would be quite opaque. The largest long-period variables are probably larger compared to the sun than is the sun compared to the earth: the sun's diameter is 110 times that of the earth, its volume 1,300,000 times, while the diameter of a long-period variable may be as much as 300 times that of the sun, its volume 25,000,000 times.

Nevertheless one must not expect to see long-period variables, much less other types of variables, as sizable disks even in the most powerful telescope. The tiny disks which stars present in the telescope are incidental optical phenomena of one kind or another and give no indication that the stars are more than luminous points. For all practical observations, with the exception of those made with the stellar interferometer, variables, like all other fixed stars, actually behave like luminous points and must be studied as such. A comparable limitation in the study of a laboratory light-source, such as an electric arc, would ensue if the arc were placed behind an opaque screen through which a tiny pin-hole allowed light to escape. To make the analogy more complete, imagine the pin-hole covered with ground glass which, by thoroughly mixing light from all parts of the arc, would prevent any image of the pin-hole from yielding direct information concerning the size and shape of the luminous portions of the arc. The physicist would then be obliged to study the arc without *seeing* it at all in the ordinary sense.

Yet, even under the unfavorable circumstances similar to those just described, the astronomer has been able, chiefly through the power of the spectroscope, to learn much concerning the physical properties of the various types of stars. Thus we know many facts concerning the size, density, temperature, composition, etc. of variable stars. Many items result from straightforward observations of individual stars, while portions of our knowledge arise from statistical considerations often based in a rather involved manner on vast accumulations of various kinds of data.

It is most convenient and most significant to describe certain properties of variables by comparing them with the general run of ordinary or non-variable stars. For this reason several important facts which would otherwise be mentioned here are, to avoid repetition, reserved for discussion in Chapter VIII which deals with the general relationship of variable stars and the stellar system.

COLORS OF VARIABLES

To make a visual estimate of the brightness of a variable star the observer must first identify it with certainty. Mistakes are very annoying. One can scarcely have a satisfactory interview with Mr. A. unless he feels sure it really is Mr. A. to whom he is talking. After pointing the telescope with care to the known position of the variable, a competent observer will be reasonably safe in assuming that the desired object is in the field of view. But when he looks in, a dozen or more stars may meet his eye. Which is the right one? If he is searching for a *long-period* variable the answer is usually simple and unambiguous. Among the stars in the field of view one will usually be set apart from all the others by its marked red or deep orange color; that one is very probably the variable sought. If there happen to be two or more red stars the observer will have to glance at his chart. If the variable is one of short-period, however, he will generally not be able to distinguish it by its color but will have to rely wholly on the chart. The reason for this is that the short period stars are white or yellow in color just like the vast majority of all stars. In 1888, Chandler stated the relationship between period and color as follows: "The redness of the variable stars is, in general, a function of the lengths of their period of light variation. The redder the tint, the longer the period."

CLOSER STUDY OF THE LIGHT OF VARIABLES

Thus far we have talked about star-light, in particular the light of a variable star, as if it were a single homogeneous entity having but two properties, namely intensity or brightness, and a somewhat secondary property, color. The classification of variables, their discovery and cataloguing, and their light variations have all been discussed on this basis. Now as a matter of fact the light of a star is *not* a simple thing, but a most complex bundle of vibrations of different wave-lengths or colors. In all ordinary observations, however, the component vibrations are not sorted out but are presented to the eye or to the photographic plate in a small heterogeneous heap called the "image." The integrated effect upon the eye is the visual brightness, and it is this sensation that is measured by the light curve. Similarly a photographic plate upon which the image of a star falls, responds by presenting, when developed, a single round black spot in which are combined the contributions of many different vibrations. With certain types of modern panchromatic or color-sensitive emulsions the relative effectiveness of the various colors upon the plate is nearly the same as upon the eye. With the old-fashioned or "ordinary" emulsions, however, it is very different: violet light is relatively more effective than blue, while green, yellow and red produce no result at all. These colors knock on the plate but nothing happens; it takes the sharper, quicker raps delivered by blue and violet light to call forth a response.

It is apparent from what has just been said that the complexity of light is not utilized in ordinary types of observation, but may actually be a difficulty in achieving accurate and definite results. Since different eyes, and especially different photographic emulsions, are not equally sensitive to all colors, there is too often considerable uncertainty in the intercomparison of observations made by different persons or with different kinds of apparatus. Small technical difficulties arising from the nonhomogeneous nature of light enter into precise observations at almost every turn.

Imagine, on the other hand, how interesting it is to separate the numerous vibrations in a beam of star-light, and then to focus them side by side in a neat row where each can be examined by itself. The neat row is of course the *spectrum* and the instrument which produces it is the *spectroscope*.[1] Now it is

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[1] A spectroscope adapted to take photographs of spectra is called a spectrograph; the photographed spectra, spectrograms. A brief and very elementary description of the action of the spectroscope, with a simple mechanical analogy for illustration, will be found in volume one, page 169 of the "Leaflets" published by the Astronomical Society of the Pacific, San Francisco, 1934. A more complete popular exposition is "The Spectroscope and its Work," by H. F. Newall, Society for Promoting Christian Knowledge, London, 1910.

from a close study of the individual vibrations, or narrow portions of the spectrum (usually called spectral lines) that we obtain our greatest insight into the physical properties of the stars. Great numbers of details become apparent, each of which has its chemical and physical meaning. With an ease that seems almost magical we can recognize with certainty the existence in stellar atmospheres of chemical elements precisely similar to those known on earth. We can tell whether the stars, with their gaseous atmospheres, are approaching the earth or receding. We can even probe inside stellar atoms and ascertain what certain constituent parts, the electrons, are doing,—whether they remain regularly in place forming complete uncharged atoms, or whether some of them habitually stay away from home, leaving the parent atoms electrically upset because of their absence. Such is the power of the spectroscope.

Except for general attrition caused by its struggle with the inverse-square law, not much happens to star-light in its long passage through the abysmal depths of interstellar space. In other words practically the only effect of the enormous distances of variable stars is greatly to diminish the intensity of their light. The *character* of each individual ray appears to be unchanged by its long journey. Light that is red or blue when it leaves a star, arrives at the earth, perhaps centuries later, unchanged in color; even the minutest spectral details are accurately preserved. The mechanism by which light is transmitted evidently is very exact, being able to carry a beam at the terrific speed of 186,000 miles per second for centuries on end without altering in the slightest its intricate structure. Thus the light of an unthinkably remote star may be analyzed just as if it came from a laboratory source ten feet away.[2] In this respect the immense distances of the stars give rise to no difficulty except that the light becomes inconveniently faint. The astronomer's defense against stellar faintness lies in large telescopes with their great light grasp, and in long exposures on the most sensitive photographic plates.

The fascinating story of the development of the science of spectroscopy and of its application to astronomy is too long to relate here, but a few items will serve for historical orientation. It is now (1937) two hundred and sixty-five years since Sir Isaac Newton discovered the visible spectrum. The first hundred years were the hardest. In fact it was not until 1859 that, thanks to Kirchhoff and Bunsen, the principles of spectrum analysis became sufficiently well understood to make possible the satisfactory interpretation of celestial spectra. After that date progress was rapid. In 1863, Father Secchi made a splendid contribution by carefully examining and classifying the spectra of thousands of stars. His own

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[2] Effects, usually slight, caused by tenuous interstellar clouds of dust or gas are present in the light of the more distant stars; but these effects are negligible in the study of most variables. Light from external galaxies is reddened but it is doubtful if the reddening is introduced during transit.

description (quoted below) of the four types into which he divided the stars furnishes an excellent introduction to the vast subject of stellar spectra.

SECCHI'S DESCRIPTION OF STELLAR CLASSIFICATION

Extracts from an article entitled "On Stellar Spectrometry" by Padre Secchi, *British Association Reports,* Vol. 38, p. 166, 1868.

All the stars in relation to their spectrum can be divided into four groups, for each of which the type of spectrum is quite different.

The first type is represented by the stars Sirius, and Vega or α Lyrae, and by all the *white* stars, as α Aquilae, Regulus, Castor, the large stars in the Great Bear, α excepted, etc. The spectra of all these stars consist of an almost uniform prismatic series of colors, interrupted only by four very strong black lines. Of these black lines the one in the red is coincident with the solar line C of Fraunhofer; another, in the blue, coincides with the line F [8] ; the other two are also in the sun's spectrum, but they have no prominent place. These lines all belong to hydrogen gas; and the coincidence of these four black lines with those of the gas has been, by careful experiments, already proved by Mr. Huggins, and also lately by myself. In α Lyrae the coincidence is found to be perfectly accurate. Mr. Huggins, however, finds a little difference in the spectrum of Sirius, for which we account in another way, as I will explain presently.

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[8] The modern designations of the Fraunhofer lines C and F are $H\alpha$ and $H\beta$ respectively.

Stars of this first type are very numerous, and embrace almost one-half of the visible stars of the heavens. We observe, however, some difference in individual stars; so that in some the lines are broader, and in others narrower; this may be due to the thickness of the stratum which has been traversed by the luminous rays. The more vivid stars have other very fine lines occasionally visible, but which are not characteristic of the type-form. In this type the red rays are very faint in proportion to the blue, violet, and green, so that the color of the star tends to the blue hue, and occasionally to the green. Of this last kind is the group of the large constellation Orion and its neighborhood.

The second type is that of the yellow stars, as Capella, Pollux, Arcturus, Aldebaran, α Ursae Majoris, etc. These stars have a spectrum exactly like that of our sun—that is, distinguished by very fine and numerous lines. These stars give occasionally a continuous spectrum when the state of the atmosphere is not good; but in general the lines may be distinguished very easily. A fuller description is unnecessary, since the spectrum of the sun is very well known. The only thing which deserves particular attention is that in this class occasionally the magnesium lines are very strong, so as to produce very strong bands, and the iron lines in the green are in some very distinct. These stars can be distinguished even without the prism by the difference of color, a rich yellow, which contrasts strongly with that of the first type. Stars of this second type are very numerous, and embrace almost the other half of the stars.

The third and very remarkable type is that of orange or reddish stars. These have as a prototype the stars α Herculis, α Orionis, Antares, ο Ceti, β Pegasi. The spectra of these stars show a row of columns at least eight in number, which are formed by strong luminous bands alternating with darker ones, so arranged as to represent apparently a series of round pillars, closely resembling a colonnade. α Herculis is exceedingly remarkable in this respect; the other stars are more or less clearly divided into pillars; but it is quite impossible to describe the beauty of the appearance which is visible in a telescope on a fine night.

Now it is a very remarkable fact that these types seem to differ from one another not in the metallic lines, but in the nebulous bands. Thus, for instance, the spectrum of Arcturus and Aldebaran represent the same metallic lines as α Orionis, but this has bands in addition; the feature, however, is altogether so peculiar that a different type must be constituted. It is to be remarked also that all the pillars have their luminous sides toward the red, while the shadowed sides are toward the violet; this difference is very substantial, as we shall see presently.

The fourth type is not less remarkable. This is the result of a laborious research on the telescopic stars of a red color. Some of these are very small; and none of them exceed the sixth magnitude. This is the reason why in my first memoir I limited the spectra to three types only, being engaged on larger stars only. The spectrum of this type consists of three large bands of light, which alternate with dark spaces so distributed as to have the most luminous side towards the violet.

Amateur astronomers should find it of much interest to attach simple spectroscopes to their telescopes and acquaint themselves with Secchi's four types. The spectra of long-period variables are especially beautiful.

The scheme of stellar classification now universally employed by research workers is the Henry Draper or Harvard classification developed at Cambridge, Massachusetts, about 1890. To designate the various classes, it utilizes the letters of the alphabet from A to S, but for technical reasons which are now of historical interest only, certain letters are missing, and curiously enough the sequence does not begin with A but either with B or O depending on the degree of completeness required. The chief classes, with the colors of the stars to which they correspond, are shown in Figure 8. The range of color from white or bluish for the hotter stars to red for the cooler ones is similar to that exhibited by a very hot piece of metal in cooling, although the hotter stars have surface temperatures exceeding any available in the foundry. The stellar sequence is indeed one of de-

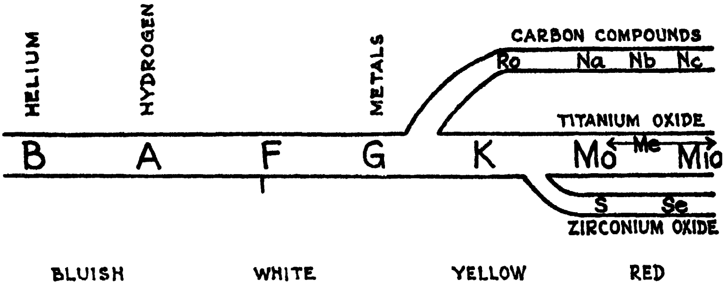

FIG. 8. The various classes of stellar spectra. (*Popular Astronomy*)

creasing temperature, and a very fair estimate of a star's temperature can be made by noting its color. The vast majority of stars have surface temperatures between 30,000° and 2,000°. These temperatures are reckoned on the Centigrade scale from absolute zero. The corresponding Fahrenheit degrees would be 53,500 and 3140 respectively.

The actual grouping of the stars into numerous spectral classes depends, however, on something more definite and easier to determine with precision than color, namely the narrow spectral lines, many of which stand out in the photographed spectra as plainly as pencil marks on a strip of paper. Each has its chemical significance, and the astrophysicist can interpret nearly all of them. Thus in the A stars (see Fig. 8) the common element hydrogen is predominant. In the hotter B stars hydrogen yields to helium, while in G stars, of which our sun is an example, metals like iron, nickel and vanadium steal the show. The red stars are cooler, and chemical compounds form in their atmospheres,—something that cannot occur at higher temperatures. Here we have a three-fold diversity. The "carbon" stars, class N, exhibit indubitable evidences of *carbon* molecules and also of that poisonous combination of carbon and nitrogen known as *cyanogen*. The M stars, comprising the great majority of red stars, are boldly marked by the heavy flutings of *titanium oxide*. In the closely related group of S stars the characteristic bands are those of *zirconium* oxide. Chemists have discovered the close similarity of the elements titanium and zirconium and apparently the stars too are aware of it. In the illustration facing p. 78 are shown examples of the spectra of the three main types of red stars. Inspection of these photographs will indicate the richness of the observational material upon which astrophysical studies are based.

The vast majority, eighty-eight per cent to be exact, of long period variables belong to type M; five per cent belong to type S, and five per cent to type N. The remaining two per cent are of types K or R. The short period variables on the other hand have "earlier" spectra, i.e. those corresponding to the colors white and yellow instead of red. RR Lyrae variables are of types A and F; cepheids very largely of types F and G.

A remarkable feature of the light of long-period variables distinguishes their spectra from those of non-variable stars of the same types, namely the presence of bright lines of the gas hydrogen. In most stars, the sun for example, the gases of the outer atmosphere, although themselves incandescent, nevertheless absorb or stop some of the light from the lower layers and cause the spectrum to be crossed by (relatively) *dark* lines. If, however, the atmospheric gases are unusually extensive or for any reason sufficiently brilliant, they may add to the star's light instead of subtracting something from it. In this case *bright* lines will be seen in the spectrum, a condition illustrated by the first four spectra

EXPLANATION OF PHOTOGRAPHS OF SPECTRA

In each of the six photographs there are actually three spectra, one of the star in the center with the "comparison" spectrum of iron above and below. The comparison spectrum is introduced at the time of observation by reflecting into the spectrograph alongside the beam of star light, the light from an electric arc burning between iron electrodes. The colors are violet at the left end, blue-green at the right, but the original negatives, as well as these positive reproductions are ordinary photographs in black and white. The photographs were taken with a one-prism spectrograph attached to the 100-inch telescope on Mount Wilson. For a detailed study one should have a chart of the iron spectrum. The only conspicuous lines of other elements in the comparison spectra are λλ4031–33–34 of manganese. The following key may be useful to those who are not chemists:

H,	hydrogen	Ca,	calcium
Sr,	strontium	Cr,	chromium
Mn,	manganese	Ba,	barium
TiO,	titanium oxide	ZrO,	zirconium oxide
K,	potassium	CN,	cyanogen

Swan, bands of carbon

The photographs are in pairs, two each of types M, S, and N. In the second example of each pair the characteristic features are more pronounced, and the spectra are said to be more "advanced." This really indicates a lower temperature of the stellar gases.

Class M: In comparing the second spectrum with the first, note (a) the increased strength of the titanium bands and the appearance of additional band-heads; (b) the increased intensity of certain "low-temperature" lines notably λ4227 Ca, and λλ4254–75–90 Cr; the absence of the Hβ line (apparently smothered by the strong titanium bands), and the increased intensity of bright Hδ compared to Hγ.

Class S: Bright Hβ is much stronger than Hγ or Hδ. λ4554 *Ba* II and the neighboring line λ4536 (probably a blend of titanium and zirconium) form a fairly conspicuous pair of dark lines. In the second spectrum the zirconium bands are stronger than in the first, and the titanium band head at λ4955 is distinctly seen, illustrating the fact that titanium and zirconium bands frequently occur in the same spectrum.

Class N: Notice that, as observed by Secchi (Type IV), the bands face oppositely to those in class M (Type III). The "Swan" bands of carbon are much more prominent in the second spectrum.

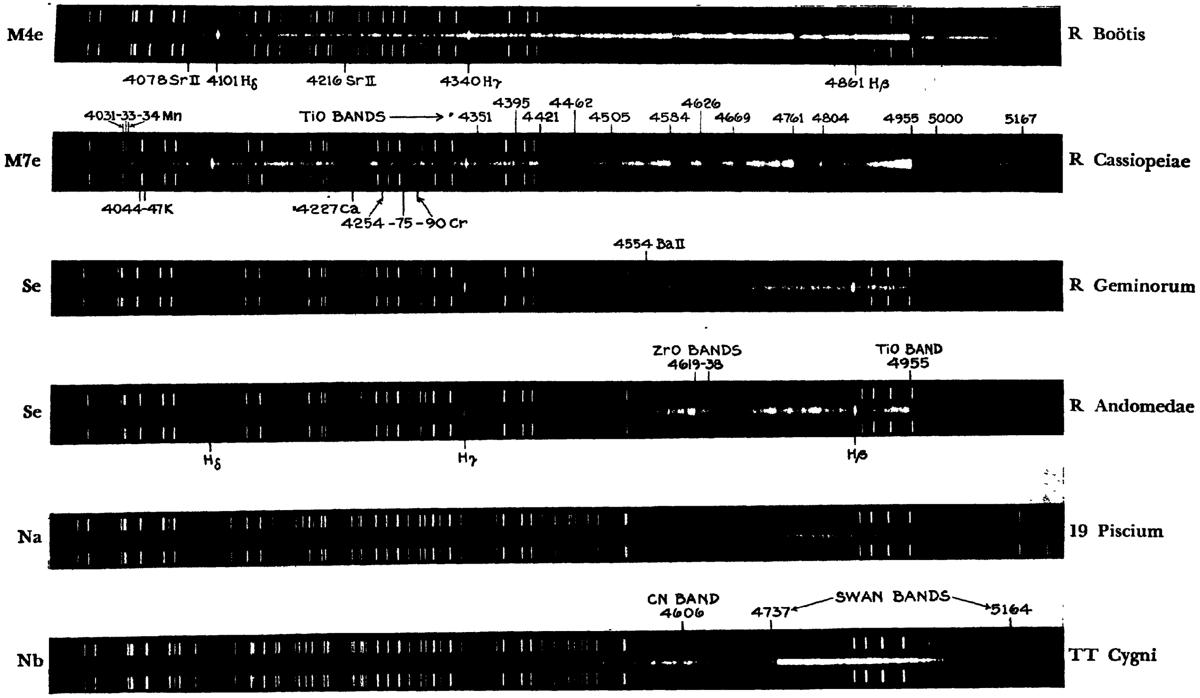

PLATE I. Typical spectra of red variables. (*Popular Astronomy*)

in Plate I, where the lines of hydrogen are bright. The presence of glowing hydrogen in cool red stars offers a serious physical difficulty, because to induce them to shine, hydrogen atoms require more stimulation than a red-hot body has to offer. Investigators are actively studying this anomaly at the present time hoping to find, possibly in connection with the formation or dissociation of titanium oxide molecules, a source of sufficient energy. One student has suggested that cosmic rays may be responsible.

It is well known that the eye is sensitive to a small section only of the whole range of vibrations of radiant energy which nature has provided. Those radiations, called visible light, which affect the retina and thus give us sight, are of intermediate wave-lengths. There exist in addition to visible waves, ultra-violet waves too short, and infra-red waves too long, to be seen. Imagine a smooth strip of metal a foot long, at room temperature except for the central inch which has been heated over a gas flame. A finger passed lightly over the rod will experience little sensation except at the heated section. This analogy to light waves is misleading in suggesting that the reason we see certain wave-lengths and not others lies in the greater energy of those perceived. In general this is quite untrue, for in many common sources the invisible infra-red rays are far more energetic than any we can see. Let us seek a better illustration. Imagine the metal strip scored with shallow grooves at right angles to its length, the grooves at one end being so closely spaced as to be visible only under a microscope. At the other end the grooves are drawn out to wide rounding hollows an inch or two apart, while in between is a continuous progression in the spacing. The grooves are all well rounded and of the same depth, differing only in width. If a finger is passed along the rod it cannot readily detect the crowded grooves at one end or the wide flat grooves at the other, but will feel distinctly those of intermediate spacing, resembling a file, near the center. Thus the eye responds to certain intermediate wave-lengths only. In both instances the results depend on the structure and properties of our bodies, in short the selection is physiological. We have, moreover, to take vision as nature provides it for, unlike radio, we cannot tune our eyes at will to various wave-lengths. The only modification we can make is to shut out part of the natural range, e.g. by looking through a colored glass.

The above paragraph is introductory to the statement that the radiations by means of which we see a star are not the only ones it sends to us. The visible radiations may in fact carry but a very small fraction of the total energy, most of which may come in wave-lengths to which the eye is not sensitive. One of the most important observational data concerning a star is the total radiant energy, ultraviolet, visible, and infra-red, that we receive from it, or in simpler language, the amount of heat in a beam of star-light. The measurement of this quantity is, however, beset with considerable difficulty. Stellar radiation received at the earth is feeble and can be recorded accurately only by sensitive physical agents. Now it happens, unfortunately, that the most sensitive of these, namely the photographic plate and the photoelectric cell (the electric eye of industry), like the human eye, respond to but a fraction of the whole range of wave-lengths, and are thus unsuited to measure total radiant energy. Recourse must be had to so-called "non-selective" receivers that react equally to a given amount of radiant energy, no matter what its wave-length. This appears not to be true of any chemical or electronic process. It is well known, however, that all radiation falling on a dull black (non-reflective) surface is transformed into heat, and the resulting rise in temperature is a measure of the intensity of the incident radiation. The problem thus resolves itself into detecting and measuring very small changes in temperature.

A very small blackened receiver at the focus of the 100-inch telescope on Mount Wilson may be heated as much as 0°.015 Centigrade (0°.027 Fahrenheit) by the image of Betelgeuse. For fainter stars the measured increase in temperature is often but a few millionths of a degree. These small temperature differences have been successfully measured by three different devices: (1) the thermocouple, (2) the bolometer, (3) the radiometer. In the thermocouple the heat is conducted from the receiver to a small area of contract between two suitable metals and there generates a minute electric current, which is measured with a sensitive galvanometer. In the bolometer, the change in electrical resistance of a small metal strip exposed to the stellar radiation is measured. The action of the radiometer depends upon the rotation of a delicately suspended vane, caused by the increased rebound of the molecules of the surrounding gas when one side of the vane is warmed by starlight.[4] Curiously enough the sensitivity of these three instruments, which measure the rise of temperature in entirely different ways, is nearly the same. Measurements of stellar radiation by the three methods have been made by various observers as follows: The thermocouple—Pfund at Allegheny, Coblentz at Lick and Flagstaff Observatories, Pettit and Nicholson at Mount Wilson Observatory; the bolometer (originally developed by Langley for measurements of the sun's heat)—Abbot at Mount Wilson Observatory; the radiometer—Nicols at Yerkes Observatory, Abbot and Smith at Mount Wilson Observatory.

The application of these instruments to the observation of long-period variables is of special interest because much of the radiation of these objects is in the long, infra-red wave-lengths, which cannot be photographed or observed in any other way. Table VIII shows how greatly the distribution of

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[4] The stellar radiometer is merely a more delicate version of the revolving vane instrument occasionally seen in a glass bulb in a store window.

energy among various spectral regions varies with the temperature of the source.

TABLE VIII

PERCENTAGE OF RADIATION IN VARIOUS SPECTRAL REGIONS

Temperature	*Ultra-Violet* λ *0–4000A*	*Visible* λ *4000–7600A*	*Infra-Red* λ *7600A–∞*
1,800 ° C. Abs.	0.0	0.7	99.3
2,300	0.0	3.4	96.6
5,000	6.7	37.8	55.5
10,000	48.3	35.7	16.0
20,000	85.7	11.3	3.0

The first two temperatures, 1800° and 2300°, are those of typical long-period variables at minimum and maximum light respectively.

Pettit and Nicholson, measuring with a thermocouple the heat of various stars collected by the 100-inch telescope on Mount Wilson, have discovered certain remarkably interesting facts concerning the behavior of long-period variables. They found for six objects the mean range in total energy to be only 0.9 of a magnitude, whereas the visual range is 5.9 magnitudes. In other words, in passing from minimum to maximum the brightness of these stars is multiplied by 230, while the total heat radiated is only slightly more than doubled. They also found the energy maximum to occur 50 days (about one seventh of the cycle) later than the light maximum, at a time when the brightness has decreased by 1.5 magnitudes (i.e. to one-fourth of the maximum brightness). The importance of such facts in the physical study of long-period variables as immense gaseous globes of fluctuating brightness is very great.

INTERNAL CONSTITUTION

We can see but a very small fraction of the radius into any star, even a highly tenuous long-period variable. Thus the only portions accessible to direct observation are the extreme outer layers. The only way to learn about the interior is by what Eddington has called an "analytical boring machine," which is supposed to bore mathematically into the interior and bring up a sample. The trouble is that the drill takes down some of the engineer's ideas and hypotheses and these so color the material brought up that we are a bit uncertain as to its original properties. Technical journals are filled with elaborate papers on conditions in the interiors of model gaseous spheres, but these discussions have, for the most part, the character of exercises in mathematical physics rather than astronomical investigations, and it is difficult to judge the degree of resemblance between the models and actual stars. Differential equations are like servants in livery: it is honorable to be able to command them, but they are "yes" men, loyally giving support and amplification to the ideas entrusted to them by their master.

Concerning certain features of the internal constitution of long-period variables there can, however, be little doubt.[5] The density, for example, must be

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[5] For a general account of conditions in the interior of stars see the first chapter of "Stars and Atoms" by Sir Arthur Eddington. The book is delightful reading.

extremely low. The volume of a typical long-period variable such as *o* Ceti is about 25,000,000 times that of the sun. No direct determination of the mass has been made but the order of magnitude is probably ten times that of the sun; 25 times the solar mass would be considered a high estimate. The mean density is therefore probably less than a millionth that of the sun. The solar density, 1.4 on the ordinary laboratory scale in which water is 1.0, is about 1000 times that of air at sea-level. Hence a long-period variable as a whole is only one thousandth as dense as the air we breathe. In the physical laboratory a volume of gas at this density would be considered a vacuum. Thus we may call a long-period variable a red-hot vacuum!

In the outer portions of the variable where the observed spectral lines and bands are produced, the density is, of course, much less than the mean density, and at the center of the star it is much greater, but the exact values are not known. The temperature also increases, at an unknown rate, from about 2300°C. at the photosphere (at a time of maximum light) to a very high value, perhaps 15,000,000° at the center.

CHAPTER VI

NEW OR TEMPORARY STARS

NEW stars, the most bizarre and spectacular of all variables, are badly named. The adjective new seems to imply that having recently joined the heavenly host, they have come to stay. As a matter of fact, this is not their customary behavior. One of their recognized characteristics is, following the hectic rise to great brilliance, a gradual but persistent decline to obscurity. After a luminous splurge lasting for weeks or months, the decline may occupy several years, but on the cosmic time scale these exhibitions are about as permanent as the flash of a rocket. The adjective *temporary* would therefore better convey the correct notion. The Latin word for the new, *nova,* applied centuries ago to these astonishing objects is, however, now the standard technical designation in use by astronomers. A particular star is named after the constellation in which it appears, together with the year of appearance. Thus the official designation of the new star discovered in the constellation Hercules in December, 1934, is Nova Herculis 1934.

Temporary stars appear suddenly and unexpectedly, and by preference in or near the Milky Way. Some are sufficiently conspicuous to alter the general appearance of the constellation they visit. Practically all that become visible to the naked eye are discovered by amateur astronomers rather than by professionals. The reason for this is that the amateurs are more numerous and they watch larger areas of the sky. The professional astronomer, busy with a planned research program, has little time for general reconnaisance. Moreover his work usually does not require a detailed knowledge of the constellations. The amateur who observes variable stars with a small telescope, and especially the one who is constantly using star charts in plotting the paths of meteors, often acquires a superior working knowledge of the constellations and is quick to recognize a strange object. More power to him!

If you, dear reader, chance to see a star-like object which you suspect of being a new star, your correct procedure is as follows:

1. *Carefully compare the part of the sky in question with an adequate star chart* (i.e. one showing all stars as bright as the one under suspicion) to make sure the star is not on the chart.

2. *Satisfy yourself it is not a planet.* Planets move about and may fool even the experienced observer if he is not on his guard. The five bright planets, Mercury, Venus, Mars, Jupiter, and Saturn, must be checked over and accounted for. The possible positions of these objects are quite limited: they can never be far from the ecliptic, the great circle through the sky traced by the annual motion of the sun. Venus, the brightest of all, has another limitation,—

it can never be more than 48° from the sun; Mercury never more than 28°. Moreover, while the planets shift about rather quickly, they cannot move great distances from one night to the next. These general facts may serve to eliminate planets from consideration, but if there is the slightest question, look up their current positions in an almanac or some current guide for amateur observers.

3. If you are sure it is neither a charted star nor a planet, *telephone the nearest observatory at once.* It is important that observations of new stars be started as promptly as possible. The loss of even a single night would be unfortunate.

Since the beginning of the present century, nearly 50 new stars have been discovered, of which about a dozen were bright enough and were discovered soon enough to be studied in some detail. Two of the brighter novae appeared to have some connection with eclipses of the sun: Nova Aquilae 1918 was discovered the night after a solar eclipse, Nova Lacertae 1936, the night before one. Since there cannot be the slightest physical connection between eclipses and new stars, the agreements in date are purely fortuitous coincidences which seem even more striking when we realize that the stellar outbursts actually occurred some two thousand years before we observed them.

After the first impetuous rise in luminosity, most temporary stars find that the new scale of expenditure is quite beyond their means, and begin at once to curb their extravagance. Their brilliance declines rapidly at first, then more slowly, sometimes with a series of fluctuations. After a few months the decline becomes very gradual and 15 years may elapse before the original state is regained. The light curve of Nova Lacertae 1936, in Figure 9, is typical, although the drop in light is perhaps somewhat more abrupt than usual. In a few exceptional instances, notably Nova Herculis 1934, a persistent decline did not set in for several weeks, and the first maximum was only slightly higher than some which followed.

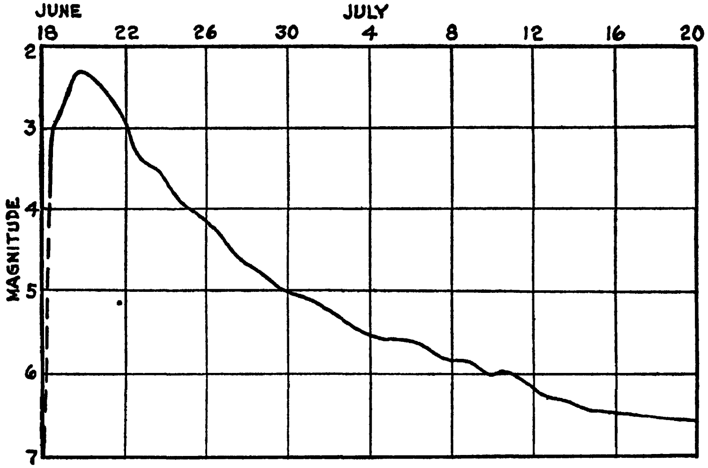

FIG. 9. Light curve of Nova Lacertae 1936.

Where do these curious visitors come from and what was their previous estate? To deal intelligently with the analysis of cause and effect the continuity of the phenomena must first be traced,—a large part of the business of science. The postulate that continuity does exist, is the fundamental philosophical basis of scientific method. *Natura non fecit saltum.*[1] Is the outburst of a new star a spectacular exception to this old Latin rule?

When an unexpected and mysterious flash of light occurs, the sequence of scientific inquiry is: (*a*) what is the nature of the light, i.e. its intensity and quality? (*b*) in what form was the energy before it became visible light?; (*c*) what caused the release or transformation of this light? In the present description of our knowledge of new stars it may be better to take the phenomena in their chronological order, and thus first to consider question (*b*).

A routine observation, upon the appearance of a new star, is to measure, usually by means of a photograph, its exact position in the sky. A search of old photographs is then made to ascertain whether or not any object had previously existed in this location. In this way it has been found that novae regularly develop from telescopic stars formerly so faint and undistinguished that no attention had even been paid to them. There is good reason to believe that the humble origin of a nova is an obscure star, actually about as bright as our sun. Statistically, therefore, our sun is a suitable object to produce a nova. Should this occur, the inhabitants of our poor earth would shortly find themselves in a most unfortunate pre-

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[1] Nature makes no leap (or discontinuity)

dicament. Not only would the sun expand and burn us with incandescent gases, it would probably vaporize the solid earth beneath our feet. This may happen, but then again it may not. Mr. David Seabury would probably not recommend the possibility as a subject for successful worry.

These pre-nova dwarfs are little fellows somewhat over 12 magnitudes fainter than the transcendent luminaries into which they are to develop. The increase in brightness,—by the astonishing factor of 80,000 times—takes them in an incredibly short time from obscurity to a commanding position in the galaxy. Thus of the thousands of millions of stars in the galaxy, novae are for a short interval among the most brilliant. The average absolute magnitude is placed by astronomers at –7.0.[2] Among well known stars only a few exceptional ones such as Canopus (α Carinae), Deneb (α Cygni), or Rigel (β Orionis) can compete with them at all. Now as seen from the earth, a new star may or may not become conspicuous, depending on its distance. If at a great distance it will appear no brighter than thousands of intrinsically fainter stars placed nearer to us, just as a powerful search-light miles away will look less bright than an ordinary electric light across the room.

If we could proceed a considerable distance outside our galaxy and then look back, all the objects in it would be sensibly at the same distance, and the brightness of various stars would appear in true

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[2] The absolute magnitude of the sun is + 4.8.

proportion. The intrinsically brighter stars would all *look* brighter than the others and would thus be readily distinguishable; a newcomer in the select company would therefore be more readily detected than from inside the galaxy, where, to paraphrase an old saying, we may fail to see the trees for the bushes. Now space-rocket transportation to extra-galactic points is not yet operating on schedule, and if it were it wouldn't do us much good, because at any conceivable speed of passage all human passengers would grow old and die long before they crossed the frontier. We can, however, obtain a most interesting test of the above deduction concerning the visibility of novae by examining other galaxies than our own. This has been carefully done with results wholly consistent with expectation. Because of its relative nearness, the great spiral in Andromeda is the most suitable object, and has been observed in the greatest detail. Eighty or ninety novae have been found in this island universe, and Hubble estimates that if it could be kept under constant adequate observation, as many as 30 per year might be recorded. This is probably of the same order as the number appearing in our own system.

The outflow of light and heat from a star may be compared with a stream of water from a reservoir. The behavior of an ordinary star corresponds to the steady flow of water through a pipe of a certain size; of a periodic variable to a pulsating flow caused by a regular rise and fall of the level of the water in the reservoir or to some automatic geyser-like action of the outlet system; in a nova, the dam breaks. The hope that the cataclysm will betray itself in the analyzed light is not disappointed when a nova is examined by the spectroscope. The photographed spectrum reveals a wild cosmic melodrama of upheaval and catastrophe, whose main plot is furnished by incandescent gases rushing furiously outward from the central star. Stated in more scientific terms, the suddenly increased flow of light is accompanied by an outward surge of matter.

It is characteristic of the nova spectrum that the bright lines are widened symmetrically about their normal places while the dark lines are displaced toward the violet. Like the famous red-shifts in the spectra of distant spiral nebulae, the only available explanation is motion,—toward the observer for the violet shift, away for the red. Halm was the first to suggest a specific explanation of the curious relationship of bright and dark lines. The bright lines are displaced in both directions, i.e. widened, because light comes from a shell of gas expanding about the star, the front portion approaching us, the rear receding. The dark lines, on the other hand, can originate only in that part of the shell between us and the disk of the star which furnishes the background light. Matter can *shine* in any location but obviously it can absorb part of a ray of light only if the ray passes through it. Thus the particular beam of light from the star directed toward the earth passes only through that part of the shell directly in line. Under the hypothesis of expansion this part of the shell is approaching the earth and the dark lines it produces are shifted toward the violet.

Displacements of spectral lines, and in a few instances direct photographs, indicate that violent outward motion of matter is a characteristic nova phenomenon. The outer strata seem somehow, possibly through light pressure, to have gone out of control of the gravitation of the main body of the star. The gist of the matter was put very concisely in a famous cablegram from the late Dr. J. Hartmann of La Plata to the editor of the Astronomische Nachrichten: "Nova Problem gelöst. Stern bläht sich auf, zerplatzt." ("Nova problem solved. Star swells up, bursts!") Many observational details are still very difficult to interpret, but this theory holds sway as the best working hypothesis available, and most astronomers believe it to be correct, at least in general outline.

Details of the spectra of novae, bewildering in their complexity and rapid change, are matters for the specialist. A single fact may be mentioned here because it constitutes one of the extraordinary cross-connections which are frequent in astrophysics. The analyzed light of novae shows regularly, at a certain stage, the queer green oxygen line, $\lambda 5577$, which for many years was known only in the light of the terrestrial aurora borealis or northern lights.

Assuming that the characteristic phenomenon of a new star is a sudden expulsion of the outer portions of a previously well behaved star, we should like very much to know why such a thing occurs. Theories naturally fall into two classes, postulating either a collision of some kind, or explosion from an internal cause. Most recent writers favor the second alternative. Random collision of two stars fails on the ground of improbability. Stars are so small compared to the space in which they move that collisions would be considerably less frequent than the appearance of new stars. A plunge of a star into a nebula has been considered, as well as a collision with a smaller body such as a planet, but neither seems satisfactory. The circumstances of individual collisions should vary enormously; why should the results be so much alike?

It seems more probable that well beneath the star's surface some critical physical condition arises which suddenly releases a large amount of energy, probably sub-atomic. The violent expansion jams the upper layers together into an incompressible mass which moves rapidly outward. As soon as the driving force subsides the atoms quickly evaporate and again become gaseous, retaining by inertia their high outward velocities. Several after-explosions may occur providing additional shells, some of which may continue to move outward for many years. The shells may be irregular, or in some instances jets of gases might be a better description.

Such is the astronomer's present picture of one of nature's most catastrophic events. The picture lacks precision, and parts of it are quite uncertain; but the closest students of novae agree that the general outline cannot be wholly wrong.

SUPER-NOVAE

Among the new stars found in spiral nebulae, a few far surpass the others in brightness and seem to belong to a special class. These "super-novae" recently studied particularly by Drs. Baade and Zwicky, have as their distinguishing characteristic extreme brilliance. The average difference in intrinsic brightness between common and super-novae is of the order of seven magnitudes corresponding to an intensity ratio of 600. While our ordinary nova is about as bright as one of the brighter stars in a galaxy, a super-nova is nearly as bright as the whole galaxy put together! If super-novae are individual stars, they are the brightest single objects known in the whole universe. Their light cures are similar to those of ordinary novae, and the spectra, although observed as yet only on a small scale, appear to have the same general characteristics. These objects are of relatively infrequent occurrence; Baade and Zwicky estimate that, while a galaxy produces 30 or more common novae per year, it accomplishes a super-nova only once in several centuries. One was seen in the Andromeda nebula in 1885. Recently, in January, 1936, a relatively bright one was discovered in the small

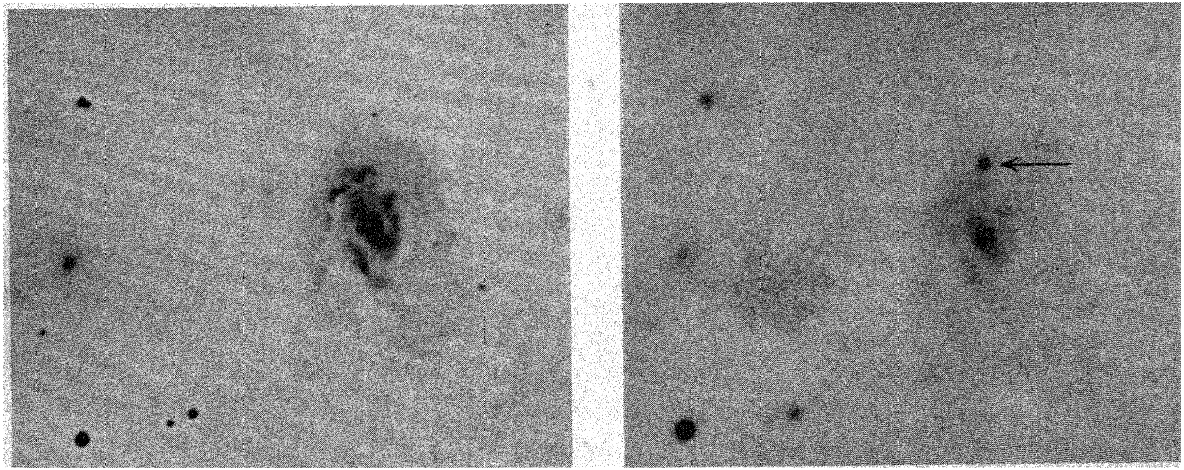

PLATE II. Photograph of the super-nova in the spiral nebula N.G.C. 4273, taken by van Maanen **with the 100-inch telescope on February 16, 1936. The photograph on the left, on which the nova is absent, was taken by Hubble on May 10, 1931. The blurred appearance of the nova photograph was caused by bad "seeing," an atmospheric condition beyond the control of the observer.**

spiral known as N.G.C. 4273 (see Plate II) and altogether about 15 have been recorded to date.[3] In our own galaxy, no recent nova can be assigned to the "super" estate, but a possible member was Tycho Brahe's great nova in 1572. This object was brighter than Venus and easily visible in the daytime. Unless this unusual brilliance were coupled with great distance, however, the star would not rank as a super-nova. On this point we have no knowledge. Zwicky's idea that cosmic rays may originate in super-novae awaits confirmation.

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[3] A super-nova of apparent magnitude 8.5 was found in August, 1937, in the dim, but fairly large, spiral nebula N.G.C. Index Catalogue 4182. The absolute magnitude at maximum, estimated from the probable distance of the spiral in which it appeared, was –16.3, making it the brightest of all super-novae for which we have data, and probably the brightest single object ever observed. If the estimated distance is correct, it was five thousand times as bright as an ordinary nova, several hundred million times as bright as the sun!

CHAPTER VII

MOTIONS

To the naked eye, or even through a powerful telscope, the stars appear to be relatively fixed, as if fastened in a rigid but invisible matrix. As a matter of fact, nearly all the stars move at speeds of many miles, not per minute, but *per second,*—hundreds of times as fast as the fastest train and dozens of times as fast as a cannon ball. Yet hurtling through space with these tremendous speeds, they get nowhere; the universe is too big. Here again, as in other properties of the stars, we encounter the bewildering contrast between the apparent and the real.

To ancient observers the stars seemed immobile, and were called "fixed" to distinguish them from planets or wandering objects. For centuries neither the motions of individual stars nor the heroic migrations of great groups of stars evoked the notice of terrestrial observers. Finally, early in the eighteenth century, Halley recognized that a few bright stars must have moved since Ptolemy's time. Later, by a process akin to "setting stakes," numbers of stars were caught in the act of changing their positions, and thus began the study of stellar motions.

Since Halley's discovery, more than two centuries ago, a vast amount of astronomical energy has been devoted to measuring stellar motions, and although the observations are exacting and laborious, the data now accumulated are very extensive. We know with fair accuracy the actual motion in space, relative to the solar system, of a few thousand stars, and have partial information concerning a few thousand more. These data, however, refer largely to stars in the immediate vicinity of the sun. Although the range of observation has been gradually increasing, astronomical equipment is not yet powerful enough to give us much information about motions in the more distant portions of our galaxy. It has therefore been extremely difficult to gain a clear comprehension of stellar motions as a unified general system. Similarly an observer on a down town street corner might record accurately the passage of numerous street cars, and still remain in ignorance of the general features of the trolley system of the city. Important statistical relationships, however, have been brought to light by many investigators among whom may be mentioned Herschel, Kapteyn, Campbell, Schwarzschild, Eddington, and Seares, but their results appear to be but parts of the whole picture and to fall far short of a complete solution of the problem.

The magnificent celestial pin-wheels known as spiral nebulae, believed to be island galaxies, are obviously rotating; the development of such objects without rotation of some kind would be incredible. If therefore our own galaxy is similar to the spirals, as is now generally believed, it also probably is rotating; and unless it rotates like a solid body (which is very unlikely) there should be internal evidence of this motion. During the past few years, investigations by Oort, Linblad, Strömberg, Wilson, Plaskett, and others have shown that numerous observations of stellar motions do in fact harmonize with a galactic rotation in which objects move more rapidly the nearer they are to the center, just as planets near the sun move with greater orbital speeds than those farther away. Numerous stars appear, however, to be at least partially independent of the general rotation, and the interpretation of the motions of these objects, among which certain types of variables occupy a conspicuous position, requires special hypotheses of far reaching significance,. to be discussed in the next chapter.

Imagine a line (often called the line of sight) drawn from the observer to a distant star. If the star's motion in space happens to be along this line, the distance of the star from us will change, but its apparent position in the sky will remain unaltered. Chart photographs, taken at intervals, would give no indication of any motion at all. True the brightness should be increasing if the star is approaching, and decreasing if it is receding, but the changes are so slight that a time lapse of many human lifetimes would be required to detect them, for in spite of the enormous speeds at which the stars move, say ten miles a second, the space traversed in a decade represents but a minute fraction of the distance to the earth. This "line-of-sight" or "radial" motion, measured only by means of the spectroscope, is of great importance in the study of variable stars. It is of course not the only kind of motion which a star may have. There is no reason, for example, why a star's motion might not be exactly at right angles to the line of sight, thus causing a sideways displacement but no change in the distance from us. This type of motion, called "tangential" motion, alters slightly a star's apparent position in the sky and may thus be detected from two or more chart photographs taken at different times, preferably several years apart. Most stars have at the same time both types of motion. This means merely that the line representing the actual space motion is neither exactly in the line of sight nor exactly at right angles to it, but, as might be expected, usually makes an oblique angle with it. Such oblique-angle motion may be considered as if divided or "resolved" into a radial and a tangential-motion component.

Tangential motion manifests itself by the angular change in a star's position as seen from the earth. This quantity is called "proper" motion[1] and is usually given in seconds of arc per year. The linear speed in miles per second (of time), corresponding to a certain proper motion, can be computed only if the star's distance is known. Unfortunately the

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[1] The word *proper* in this connection refers to a star's own motion relative to other stars as distinguished from an apparent motion such as aberration or precession due to a change in the circles of reference or to some other effect of the *earth's* motion.

distances of very few variables can be determined accurately by direct methods. Another limitation of proper motion data lies in the fact that many of the observed displacements are scarcely larger than errors of measurement, and in these instances no reliance can be placed on results for individual stars. Statistical conclusions of value may be obtained, however, provided the methods of combining the data are such as to eliminate or reduce the effects of errors of measurement.

Sample data for the brighter stars of various periods are exhibited in Table IX. The annual proper motions are minute, but few exceeding the small angle 0″.1 (only two, viz. RR Lyrae and *o* Ceti, in Table IX), a fact suggesting at once that the variables

TABLE IX

PROPER MOTIONS OF VARIABLE STARS

Star	Period Days	Mag. at Max.	Spectrum	Proper Motion Per Year
RR Ceti	0.55	9.2	F8	0″.069
RR Lyrae	0.57	7.2	A6	.223
RT Aurigae	3.73	5.4	F8	.024
T Vulpeculae	4.44	5.4	F8	.000
δ Cephei	5.37	3.7	G2	.011
η Aquilae	7.18	3.7	G4	.013
ζ Geminorum	10.15	3.7	G0	.010
l Carinae	35.52	3.6	G7	.021
R Leonis	315	5.0	M8e	.042
o Ceti	331	2.0	M6e	.229
R Geminorum	370	6.5	Se	.008
R Aquarii	387	5.8	M7e + Pcc.	.029
R Hydrae	404	3.5	M8c	.065
R Andromedae	407	5.6	Se	.026
χ Cygni	413	4.2	M6pe	.093
R Cassiopeiae	426	4.8	M7e	.071
T Cassiopeiae	447	6.7	M8e	0.040

as a class are relatively distant and therefore of high intrinsic brightness. This tentative conclusion, which indicates that variables are giant stars rather than dwarfs, is confirmed by fuller investigation.

The cepheids, represented in Table IX by the variables RT Aurigae to l Carinae, have on the average smaller motions than other types of variables. This implies that they are more distant than the others, and therefore intrinsically brighter, or that they move more slowly. Other data show that they are both brighter and slower than other variables and indeed than most non-variable stars.

Thus some of the things we most wish to know about variables may be learned by measuring their very small departures from exact fixity in the sky. An even more powerful method of studying stellar motions is that furnished by the spectroscope. We therefore turn now to a consideration of motions of approach and recession. It is especially fortunate that the spectroscope is able to measure these motions because they do not enter into the proper motions, and would otherwise be unobservable. Moreover, since the spectroscopic measurements yield with considerable accuracy the actual linear motions in miles per second,[2] some of the uncertainties inherent in the use of proper motions are avoided.

The determination of stellar radial velocities rests

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[2] Because of the high speeds of the stars, the number of miles per *hour* would usually be too large for convenient use; hence the smaller unit of time is adopted. Astronomers reckon the speeds in kilometers per second. A kilometer is about five-eighths of a mile, or more precisely, 1 kilometer = 0.6214 mile.

upon the famous Doppler-Fizeau principle, which states that all the lines in the spectrum of an approaching source of light have their wave-lengths shortened by an amount which bears the same ratio to the normal wave-length that the velocity of the source (relative to the observer) bears to the velocity of light; and the lines of a receding source have their wave-lengths lengthened by like amounts. Algebraically:

$$\Delta\lambda/\lambda = V/C$$

where λ = normal wave-length.
$\Delta\lambda$ = change in wave-length.
V = velocity of source.
C = velocity of light.

The velocity of light is 300,000 kilometers (186,000 miles) per second, while 30 km./sec. would be a typical stellar velocity. According to the equation given above, the corresponding shift in wave-length would be 30/300,000 or 1/10,000 of the wave-length itself. The lines usually employed in velocity determinations are in the violet with wave-lengths of, say, 0.0004 millimeter.[3] The change in wave-length caused by the star's motion is therefore about 0.00000004 millimeter. To measure so minute a quantity in a feeble beam of star-light would seem a difficult undertaking. It is possible only because the spectrograph, in effect, multiplies the changes in

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[3] A millimeter is about one twenty-fifth of an inch, or more precisely, 1 millimeter = 0.03937 inch.

wave-length by a very large factor. Even in a small single-prism spectrograph, such as is regularly used in stellar observations, the factor is about 250,000. In a spectrum having a dispersion of 40 angstrom units[4] per millimeter (a typical value for a small stellar spectrograph) a wave-length difference of 0.000004 millimeter is stretched out to cover a whole millimeter. A spectrogram can be measured to about 0.001 mm, if placed on a carriage moved by an accurate screw and viewed through a low-power microscope provided with a cross-wire at right angles to the spectrum; and this distance along the spectrum corresponds to 0.04 angstrom units or about 3 kilometers per second.[5]

The spectroscopic method of measuring velocities has been applied to all the brighter variables with varied and sometimes surprising results which "illustrate once again," to borrow the words of Sir James Jeans, "that it is usually the totally unexpected that happens in science,—the unaided human mind can seldom penetrate far into the darkness which lies beyond the small circle of light formed by direct observational knowledge."

Cepheid variables exhibit the extraordinary habit of (apparently) lurching toward us when they are bright, away when faint, these spasmodic displacements being superposed on a steady march through

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[4] 1 angstrom unit = 0.0000001 millimeter.

[5] For a more complete account of the Doppler-Fizeau principle and its applications, the reader is referred to Dr. Campbell's book "Stellar Motions" published in 1913 by Yale University Press.

space. It was once thought that the variable is swinging about an unseen companion star in a small orbit, but this is no longer the accepted interpretation; *pulsation,* first suggested by Dr. Harlow Shapley, now holds the field as the best working hypothesis. If the star were expanding and contracting rhythmically, like an inflated toy balloon into which an additional puff of air is introduced and withdrawn at regular intervals, the hemisphere visible to the observer would alternately approach and recede, and might thus produce the observed motions.

RR Lyrae, and presumably other variables of its class, perform in the same way.

Turning now to long-period variables we find, as might be expected, that *o* Ceti, the patriarch of all long-period stars, has been observed more extensively than any other. According to a compilation by Joy,[6] reproduced in Table X, the velocity had been measured at fourteen maxima up to and including that of January, 1925. The general agreement of the results is excellent, the range among the determinations entitled to the higher weights being small. The average result corresponds to a recession (indicated by the plus sign) at the rate of 64.5 kilometers or 40.0 miles per second.

A small oscillation in velocity probably takes place during each light cycle. At least that has been found at Mount Wilson to be true of one or two variables but the data are very meager. At maximum light the

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[6] *Mt. Wilson Contr.,* No. 311; *Astrophysical Journal, 43,* 281, 1926.

TABLE X

Radial Velocity of *o* Ceti at Maximum Light

Maximum	*Mag.*	*Velocity km./sec.*	*No. Plates*	*No. Prisms*	*Observer*
Nov. 1897	3.7	+62.0	3	3	Lick, Campbell
Oct. 1898	2.9	62.8	2	3	Lick, Campbell
June 1902	3.5	66.	1	1	Lick, Stebbins
Dec. 1906	3.9	65.4	2	3	Ottawa, Plaskett
Dec. 1906	3.9	66.1	3	3	Bonn, Küstner
Dec. 1906	3.9	64.2	4	3	Yerkes, Frost
Dec. 1906	3.9	71.	2	1	Yerkes, Frost
Jan. 1915	3.9	70.	3	1	Yerkes, Frost
Jan. 1915	3.9	54.	2	1	Ottawa, Harper
Jan. 1915	3.9	63.7	1	1	Detroit, Merrill
Dec. 1915	3.5	63.4	5	4	Cape, Lunt
Dec. 1915	3.5	66.	1	1	Yerkes, Frost
Nov. 1916	3.8	63.3	3	1	Mt. Wilson, Joy
Sept. 1917	3.6	64.1	5	1	Mt. Wilson, Joy
Sept. 1917	3.6	66.	2	1	Yerkes, Frost
Sept. 1918	3.6	68.	2	1	Yerkes, Frost
Sept. 1918	3.6	70.	1	1	Ottawa, Harper
Sept. 1918	3.6	59.1	1	1	Mt. Wilson, Joy
Aug. 1919	3.3	65.8	1	1	Mt. Wilson, Joy
Aug. 1919	3.3	69.	1	1	Yerkes, Frost
June 1920	3.1	64.8	2	1	Mt. Wilson, Joy
March 1923	2.8	66.2	3	1	Mt. Wilson, Joy
Feb. 1924	4.7	62.0	4	1	Mt. Wilson, Joy
Jan. 1925	3.8	66.4	3	1	Mt. Wilson, Joy
Jan. 1925	3.8	+61.3	1	3	Mt. Wilson, Joy
Weighted mean		+64.5			

oscillatory motion is of recession, instead of approach as in cepheid variables.

The velocities in Table X were determined from the measured displacements of the dark or "absorption" lines in the star's spectrum. These lines arise in the gaseous strata immediately above the star's incandescent boundary or photosphere, and their mean displacements probably correspond closely to the velocity of the star as a whole. In an earlier chapter attention has been called to the presence in the spectra of nearly all long-period variables of conspicuous bright lines of hydrogen, iron, silicon, and magnesium. Since these lines come from glowing gases which belong to the star, we should expect their displacements to indicate the same stellar velocities as the dark lines. But here we find a puzzling discrepancy, for the measured velocities are not quite the same; the gases which produce the bright lines appear to be leaving the star in the direction of the earth. This anomaly has been observed in too many stars to be regarded as accidental. A possible interpretation is that the more brightly glowing gases are rising from the whole surface of the star, but a wholly satisfactory explanation has not yet been worked out. A curious fact is that the longer the period of the variable, the greater is the discrepancy between velocities yielded by bright and dark lines.

SPACE MOTIONS OF VARIABLES

The minor internal motions (pulsations, or a rising atmosphere) just discussed, although they cause certain observational difficulties, do not prevent our determining the general motion of the variables as they travel through space.[7] Imagine watching a small

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[7] Space affords us no fixed marks to which stellar velocities may be referred; hence the motions we discuss are *relative*. As actually measured they are relative to the observer on earth, but since the earth is moving about 30 km./sec. in its (nearly) circular orbit about the sun, the relative stellar velocities change from month to month. It is therefore simpler to make allowance for the earth's orbital motion, and to

flashlight carried on a dark night in the hand of a pedestrian. It would have a jerky to and fro motion from the swinging of his arm, but nevertheless with a little care one could soon tell well enough how fast the man was walking.

The velocities of some 300 variables have now been determined,—a number sufficiently large to guarantee the significance of the outstanding results. Most striking is the conclusion, scarcely to have been anticipated, that RR Lyrae stars and long-period variables move rapidly, cepheids slowly. A simple selection of material will serve to indicate the facts concerning high velocities. In Table XI are listed all known periodic variables with radial velocities in excess of 100 kilometers (62 miles) per second. Of the 21 objects, 12 are long-period variables, 9 are RR Lyrae stars, while not a single cepheid appears. Thus the two groups of variables which appear to have the least resemblance, exhibit the common property of high speeds. On the other hand the remarkable difference between the motions of RR Lyrae stars and of cepheids must indicate some profound divergence in the origin or history of these somewhat similar types.

Another totally unexpected result is that among

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tabulate the stellar motions as they would be if measured from the sun. This is always done in published results such as those in Tables X and XI. The sun itself has a high speed but this is sensibly constant in direction and amount and causes little inconvenience. For special purposes, stellar velocities may be referred to axes through the center of our galaxy.

TABLE XI

PERIODIC VARIABLES WITH RADIAL VELOCITIES EXCEEDING 100 KILOMETERS (62 MILES) PER SECOND. A PLUS SIGN INDICATES RECESSION, A MINUS SIGN, APPROACH. VELOCITIES ARE GIVEN IN KILOMETERS PER SECOND.

STAR	DESIGNATION	TYPE	PERIOD	VELOCITY
			days	km/sec
RR Ceti	012700	F0	0.55	− 102
R Arietis	021024	M3e	186.	+ 114
TU Persei	030152	A5	0.61	− 350
R Pictoris	044349	M0e	165.	+ 208
U Leporis	045227	A4	0.58	+ 114
X Monocerotis	065208	M4e	155.	+ 157
S Carinae	100661	K9e	149.	+ 298
SU Draconis	113267	A3	0.66	− 174
RV Ursae Majoris	132954	F9	0.47	− 180
S Librae	151520	M2e	192.	+ 295
V Coronae	154539	Nbe	357.	− 115
VX Herculis	162618	A3	0.46	− 390
R Draconis	163266	M5e	246.	− 138
RW Draconis	163358	A5	0.44	− 109
T Herculis	180531	M3e	165.	− 125
W Lyrae	181136	M5e	197.	− 174
RZ Lyrae	183932	A2	0.51	− 221
XZ Cygni	193056	A3	0.47	− 196
RT Cygni	194048	M3e	190.	− 115
Z Cygni	195849	M5e	263.	− 165
RR Aquarii	210903	M3e	180.	− 182

the long-period variables the extremely high velocities are largely confined to stars having periods between 150 and 250 days. This is particularly difficult to understand because these objects (spectral type about M3e) appear to be physically intermediate between variables with longer periods and stars of types M0 to M3, which are either constant in brightness, or, like α Orionis, vary irregularly through a small range. Variables of class S appear not to have extremely high velocities; nor, in general, do those of class N, although one star, V Coronae, appears in Table XI. Curiously enough several R-type stars, either constant in light or with small variations, have very high speeds. All these remarkable kinematical properties of certain groups of stars should give pause to those attempting to set up physical theories of stellar evolution.

One more queer fact about stellar motions remains to be described. It is this, that objects with high speeds do not move wholly at random but exhibit a preference for a particular direction. Their preferred line of motion points toward the southern hemisphere, and this fact combined with the circumstance that the sun is moving nearly in the opposite direction (apparently a mere coincidence), causes most of the variables in the northern sky[8] to be approaching us while most of those in the southern sky are receding. The preferential motions of high-speed variables offer an excellent example of the so-called "asymmetry" of stellar velocities. We may compare the situation with a bird-eye's view of pedestrians on the streets of a city: most of them are seen to be walking at a moderate rate, approximately equal numbers moving in all directions; but a few are running and these, attracted perhaps by a fire on the south side, are all going south. The probable explanation of these facts in terms of tremendous galactic orbits must be left for Chapter VIII.

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[8] For a more exact statement, substitute for *northern sky* and *southern sky, less than 90°* and *more than 90°* from the point R.A. = 278°, Dec. = + 35°.

CHAPTER VIII

VARIABLE STARS AND THE STELLAR SYSTEM

THE stars are separated from each other by the appalling chasms of interstellar space, and, except in special cases, their interactions appear to be as slight as those of a few marbles rolling about the floor of a skating rink. Great cosmic forces controlling their characteristics and behavior are not easily recognizable. The observational picture of a star is largely that of an independent unit pursuing its way with little interference from its neighbors or the galactic federation. Groups of stars, it is true, often exhibit similar motions or have other characteristics in common but the causal influences are not in evidence. Any close connections which may once have existed between various stars have been obscured by time immemorial and now lie hidden under the cloak of apparent independence. This is all too true of variable stars. These objects, many of which have essentially identical properties, exhibit no obvious common origin; many have large random space motions; and the cause of the light variation of each individual appears to be intrinsic.

It is highly improbable, however, that each star is a closed kingdom of its own, created and formed in isolation, having no kinship whatsoever with other bodies. Our galaxy is certainly homogeneous in its fundamental properties, and we firmly believe that the stars do form a system, some members of which, at least, must in the past have had very intimate relationships. The historical development of the various components of this system is usually called stellar evolution, but the word should not be taken in the biological sense, for we are concerned with the life history of individual objects, not with the gradual variation of a species through successive generations. One generation of stars is all that is available to scientific study, and one is enough to keep us busy for some time.

The story of our knowledge of stellar evolution is a sad one of small successes and large blunders. Following Laplace, astronomers believed that stars condensed from nebulae; that they were originally very hot and that their lives were spent in cooling off. Next we were told that the youngest stars were tenuous, low-temperature objects (red giant stars); that for a time they become hotter by condensation until a certain physical condition is reached after which (as dwarf stars) they cool by radiation. At present most astronomers admit almost total ignorance concerning stellar life histories. Students of stellar evolution have passed through the stage of the freshman who knows not, but knows not that he knows not, into the more hopeful condition of the sophomore who knows not, but knows that he knows not. Perhaps in a few hundred years junior and senior standing may be achieved.

In discussing the relationships between variable stars and other astronomical objects, therefore, we cannot at present have the co-ordinating assistance of a general theory of stellar evolution. Instead we must endeavor to find, in the numerous well established facts concerning variables, guidance in forming such a theory.

Because we cannot see back into the astronomical past even with the eye of the mind, we must judge from the observed characteristics of variable stars whether they are distinguished from non-variables by their physical constitution, or whether on the other hand their variability is a more or less accidental circumstance—something that might happen to any star.

To gain a general insight into those properties of the stellar ensemble which are most important from an observational standpoint, nothing is more helpful than the famous "Russell diagram" which shows the relationship between a star's intrinsic brightness and its color. This diagram is well known to astronomers, and will amply repay careful study by anyone interested in the system of the stars. In Fig. 10 the horizontal scale indicates either color or one of the closely related quantities, effective surface-temperature or spectral type; the vertical scale represents brightness expressed either in terms of the

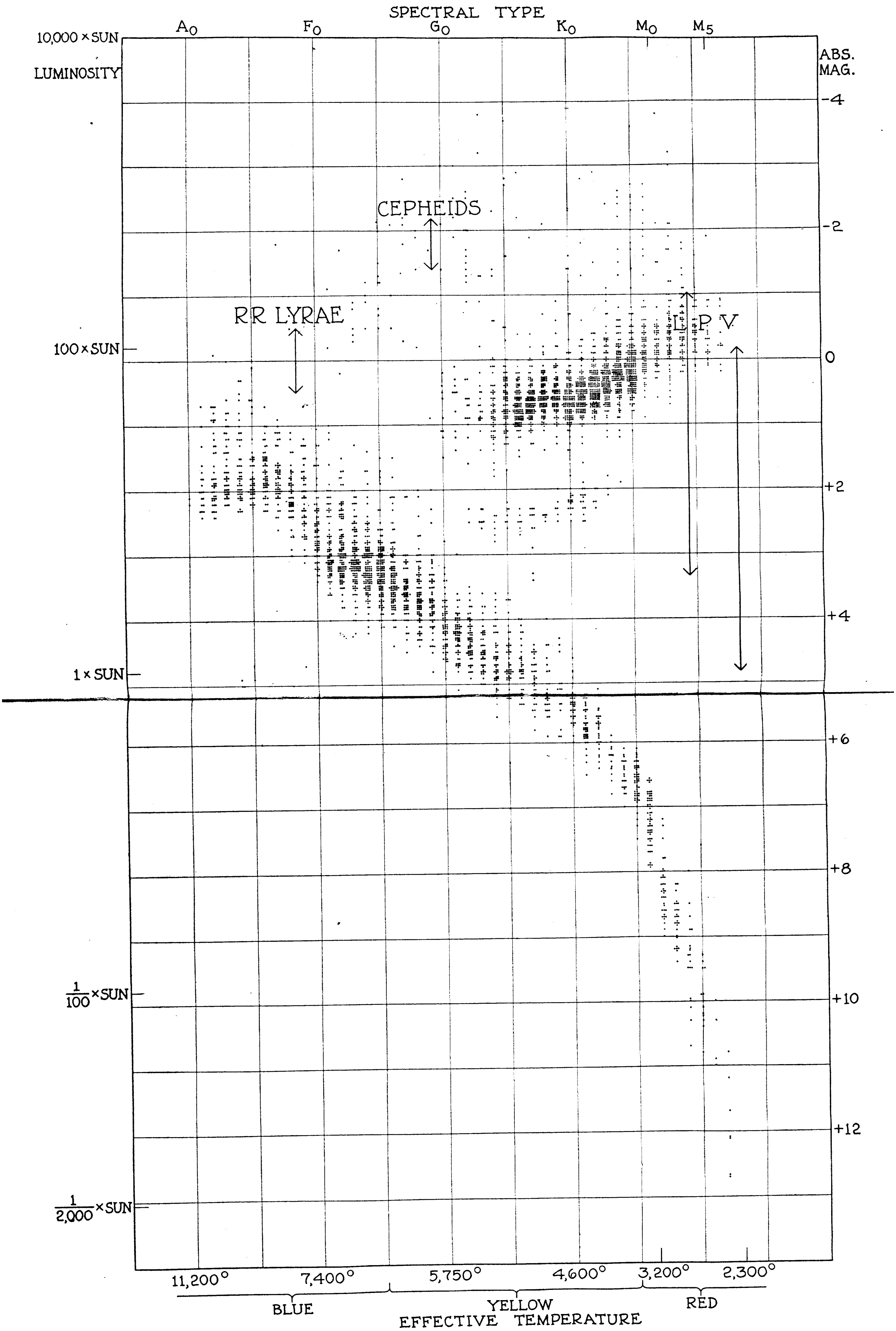

FIG. 10. "Russell diagram" showing luminosities and effective temperatures of the stars. The light ranges of three types of variables are indicated by arrows. Adapted from *Contributions from the Mount Wilson Observatory*, No. 511.

sun's brightness or of "absolute" magnitude.[1] Any point on the diagram represents a particular combination of color and brightness. Notice that the plotted points representing actual stars are not strewn at random but fall in two well defined groups. The "dwarf" branch comprising the lower (fainter) group of stars, slopes rapidly down to the right indicating that brightness declines with temperature.[2] This relationship is similar to that exhibited by a number of metal spheres at various high temperatures: the coolest and reddest would also be the faintest. The "giant" stars—above and to the right—behave very differently. Here the cooler stars are on the average brighter than the hotter ones, although the progression is not very rapid. The explanation of this rather strange fact is found in the *sizes* of the stars. The cooler stars are larger and the increased surface area more than compensates for the diminished surface brightness which accompanies the lower temperature.

It is significant that the phenomenon of variability is limited to the giant stars. All well known variables are giants or even, in the case of cepheids, supergiants. The positions of the three types of variables,

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[1] The so-called "absolute" magnitude differs from the ordinary or "apparent" magnitude in that it is free from any effect of distance, and thus indicates the star's intrinsic light-giving power. The apparent magnitude of a star seen from a distance of 10 parsecs or 32.6 light years is numerically equal to its absolute magnitude.

[2] The very hot O and B type stars have been omitted from the diagram. They would form an extension of the dwarf group upward toward the left. The complete branch formed in this way has been called the "main sequence."

with their mean light ranges, are indicated on the diagram. Although giant stars are somewhat more massive than dwarfs, they are distinguished especially by large volume and low density. Expand a dwarf sufficiently and it imitates a giant. Thus condensation of stellar mass seems incompatible with variability. Even among the giants the tendency toward variability is greatest for the most distended objects. Low density is therefore apparently a sine qua non of stellar variability. Low density, however, merely predisposes a star to variability; many tenuous stars exist in equilibrium. In short *variability is a disease of bloated stars.* As might be expected, its incidence appears to increase with the degree of distension.

It will therefore be interesting to construct a diagram similar to Fig. 10 in which density replaces brightness. It happens to be convenient to use the special co-ordinates indicated on the diagram, Fig. 11, but for a qualitative study it is sufficient to know that temperature increases from left to right, density from below to above. This reverses the Russell diagram and puts the dwarfs above, while the coolest, most tenuous stars occupy the lower left-hand corner. Along the giant branch the tendency to variability increases toward the region of the long-period variables near the lower left-hand corner. Moreover, a special low density family of stars paralleling the giant group contains the cepheid variables along with certain non-variable stars of great luminosity, known after Miss Maury's notation, as "c" stars.

This may be a suitable point for a very brief discussion of theories of variable stars. At the outset it must be admitted that astronomers know much less about *why* stars vary than *how* they vary. The fact that we know so little about stellar evolution makes it all the more worth while to go as far as we can toward forming a picture of what actually takes place in a variable, even if, for the time being, we remain in ignorance of what started the process or by what underlying mechanism it is enabled to keep going.

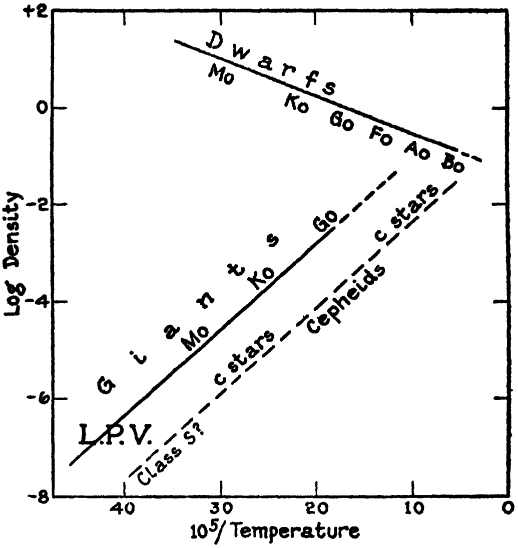

FIG. 11. Mean densities and effective temperatures of the stars. Reciprocal temperature is plotted against logarithm of the density. (*Popular Astronomy*)

The egregious weakness of many of the older theories is the assumption that the variables may be solid or liquid bodies rather than globes of gas at low densities. This departure from fact lessens the consideration we need give to certain hypotheses. One or two suggestions made years ago deserve mention, however, for their historical interest.

"Maupertius," says Sir William Herschel, "accounts for the periodical appearance of changeable stars, by supposing that they be of a flat form, like Saturn's ring, which becomes invisible when the edge is presented to us." Another, less naive, suggestion is credited by Herschel to Keill, whom he quotes as follows: "It is probable that the greatest part of this star (o Ceti) is covered with spots and dark bodies, some part thereof remaining lucid; and while it turns about its axis, does sometimes show its bright part, sometimes it turns its dark side to us." As a purely formal explanation this is not bad, because with an arbitrary arrangement of bright and dark areas, almost any light curve may be reproduced; but in actual stars—tenuous globes of fiery gas—the continued existence of a definite pattern such as would be necessary to account for the observed behavior of many variables seems highly improbable. A modern version of the rotation theory appears in the suggestion by Sir James Jeans that changes in brightness depend on the rotation of a pear-shaped body. Neither this explanation (which may apply to special bodies such as β Lyrae) nor any other in which the orientation of the star's axis plays a leading role appears acceptable for the standard types of variables. Astronomers incline to the view that a variable has approximate spherical symmetry, which means that it will at all times look the same from all directions, and thus that the observed phenomena will not depend on the location of the observer.

While the rotation of a star as a whole seems inadequate to explain stellar variability, the circulation of the gases beneath the surface may possibly be of fundamental importance. The discussion by Bjerknes of possible internal currents in the sun in their relation to sun-spots and other solar phenomena is well known; in a very interesting paper, Svein Rosseland has suggested that similar ideas may have an important application to variable stars.

> "The spots are presumably secondary phenomena which are generated and controlled by the large scale internal circulating currents in the sun. The close study of these circulating currents is, I believe, the fundamental problem of stellar variability."

According to Rosseland his ideas "lead to a view intermediate between the pulsation and rotation theories."

The idea of a general analogy between the fluctuations of variables and the eleven-year cycle in the frequency of sun-spots is, of course, quite old. If the analogy is significant, the activity of the outer layers is important rather than the dimming of the surface by the dark spots, for the shape of the curves makes it clear that the times of greatest stellar brilliance correspond not to the minimum of solar spottedness but to the maximum. Doubtless because of the vast differences between the phenomena of sun-spots and those of typical long-period variables, the whole comparison must be of a pretty general nature, and because it has never produced any very valuable results has gradually fallen into the background.

MODERN THEORIES

The famous "pulsation" hypothesis has served as the central idea for much discussion of short-period variables. A gaseous sphere such as a star has two sets of opposed forces active within it. One set arising from the rapid heat motions of the atoms (gas pressure) and from the pressure of radiation tends to cause expansion. This tendency is counteracted by the gravitational pull exerted on every particle, and in a well behaved star a definite equilibrium size is steadily maintained. Suppose such a star were somehow compressed to, say, four fifths of its natural size and then released. The internal pressure would cause it to surge outward, the outer layers acquiring a considerable velocity. When the previous (normal) size was reached, the pressure would be equalled by gravitation, but the moving gases could not stop abruptly. Instead they would go on past the mark, being brought to a gradual stop by the increasing preponderance of gravitation drawing them inward.

Now the sphere would be too large and would at once begin to contract. Again the strata would be in motion when the position of equilibrium was reached, and the sphere once more would become too small and the whole process would automatically start over again. This in outline is the best picture astronomers have been able to form of the mechanism of cepheid variation. If it be at all correct, the period of variation is not something imposed on the star by the orbit of a companion or by any outside agency, but is the star's own natural period of vibration. The observed periods are not inconsistent with those derived by calculation for gaseous spheres having the probable dimensions and physical characteristics of cepheids. The star is brightest not when it is largest, but when it is expanding most rapidly, and is faintest when contracting. This is shown by spectroscopic observations of velocity made throughout the light cycle.

The success of the pulsation theory in the cepheid problem makes it pertinent to inquire what would be the period of a volume pulsation of the tenuous long-period variables. Intuition suggests that the period would be long, and this is confirmed by mathematical calculation. Eddington has seen fit to turn the problem about, and to compute, on his theory of the internal constitution of the stars, the diameter of a variable having a period of 300 days and a mass ten times that of the sun. He finds approximate agreement with values determined in other ways and concludes that "the dimensions are accordingly consistent with the hypothesis that the period of about 300 days is that of the natural pulsation of the star." The light curves and the spectra of long-period variables differ so radically from those of cepheids that the burden of proof would seem to be upon those who would explain both types of variables by the same mechanism. Nevertheless it is not impossible that behind the scenes (i.e. underneath the star's surface) the same fundamental cause actuates both types.

Whatever the fundamental cause may be, we must attempt to study the physical effects which act directly to change the observed brightness of variables. Those most deserving of consideration appear to be:

1. Change in surface temperature.
2. Change in size.
3. Change in band absorption.
4. Veiling, or the formation of high clouds.

1. *Change in surface temperature.* Generally speaking, this is probably the most important effect of all. In cepheids a typical range of temperature would be from 5300° C. at maximum to 4600° at minimum; in long-period variables from 2300° to 1800°.

2. *Change in size.* The direct effect on the total brightness is probably not very large, and may be of relatively minor importance.

3. *Change in band absorption.* In long-period variables of class M the strong absorption bands of

titanium oxide block out much of the visible light, and as their intensity becomes greater toward minimum they may accentuate the fluctuations in light.

4. *Veiling.* In long-period variables with large ranges in light, particularly in S-type stars, effects 1, 2, and 3 seem inadequate to produce the observed changes; and the formation of a cloud-like veil of liquid particles condensed at the fainter phases from gases of the upper atmosphere has been suggested. Objections to this hypothesis do not now seem as serious as they did a few years ago, but it cannot be claimed that all doubt has been removed.

Let us now return to a few final considerations bearing on the relationship of variable stars, especially long-period variables, to the stellar system.

The temperature sequence of giant stars (see Figures 10 and 11) seems to terminate abruptly with long-period variables whose temperatures, at maximum, are between 2000° and 2300° C. Do still cooler stars exist, undetected, among those which have not as yet been subject to detailed spectroscopic scrutiny? The excellent infra-red sensitive plates developed within the past few years are now being applied in attempts to answer this question, and important new data may soon be available. Previous searches have failed to disclose any objects (with the possible exception of a 14th magnitude star near the Trifid nebula) with lower temperatures than those of stars already known. Present data therefore seem to indicate that some physical cause sets a fairly definite lower limit to the surface temperature of tenuous stars, and that the approach to this limit is marked by the instability of long-period variables.[8] If we accept this conclusion, the interpretation of long-period variables on the Lockyer-Russell theory of stellar evolution would be as follows. Stars are formed by condensation of exceedingly tenuous dark matter perhaps in the form of finely divided dust particles. While the embryo star is taking shape, its outer portions, being cooler, remain murky after the nucleus has become incandescent. As the temperature of the nucleus and the intensity of its radiation increase, a stage will be reached at which the outlying dust clouds will be vaporized and their chemical compounds partly dissociated. The star then will shine forth much more brilliantly than before. It may soon cool again somewhat by radiating too rapidly for equilibrium, with a consequent decrease in the intensity of emitted light. The decrease in brightness may be greatly accentuated by the re-formation of titanium oxide or other molecules that strongly absorb visual light; and a light surface veil of liquid or solid particles may possibly reappear. Such a process may occur many times in a cyclical fashion until the star is hot enough (and the outer portions drawn in close enough) to hold the materials of its outer envelope in a nearly transparent state. Until this comes

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[8] Cooler stars, if they exist, may resemble long-period variables at minimum, with absolute magnitudes not exceeding, say, $+4$.

to pass the object will be a red variable star. According to this notion a new long-period variable should occasionally appear in the sky if the process of star making is still going on. Objects with plenty of carbon and little oxygen will be of class N, the others mostly of class M, but a few of exceptionally low density (possibly with an extra supply of zirconium) will be of class S.

Motions of Variable Stars

The galactic system is a flattened disk like a very thin watch, probably rotating about an axis near its center, at least so most astronomers now believe. It must be admitted that the actual observational evidence for rotation is none too convincing, but this may be because most of those stars whose motions we can measure with present telescopes—the sun's neighbors in space—have pretty much the same motion as the sun itself. You cannot determine the speed of an elevator by looking at your fellow passengers. If we could learn the speeds of stars half-way across the galaxy, we would know the truth concerning hypotheses suggested but not conclusively proven by present data. An extensive investigation by Joy of the Mount Wilson Observatory of the velocities of faint cepheid variables is nearing completion. We have seen in a previous chapter that cepheid variables are intrinsically bright objects. To appear faint, they must therefore be at great distances from us. Joy's observations will thus yield velocities of objects in a region of space in which very few motions had previously been determined. In this way cepheid variables are being used to extend our knowledge farther out into the galaxy than the limits reached by observing ordinary stars. Moreover, the random hither and thither velocities of individual cepheids are small: it should therefore be relatively easy to use these objects to determine systematic galactic motions. Joy's complete results are awaited with interest. A preliminary announcement indicates substantial confirmation of the galactic rotation previously found for the region nearer to the sun.

Picture now a group of stars about the sun moving at a speed of 280 kilometers (or 175 miles) per second in a great circular orbit about the center of the galaxy. Even at this high velocity several hundred million years will be required before a single rotation is completed. Segments of the orbit passed over in any human length of time will be so short that they cannot possibly exhibit any curvature, and we cannot therefore observe any star change its direction of motion. In short all stars will be observed to move through space in straight lines. (We are here excluding from consideration the relatively tiny orbits of double stars for which of course curvature can actually be observed.) The majestic galactic orbits are inferred not from watching individual stars but by noticing that objects in various parts of space have relative motions consistent with a general rotation.

Next suppose the sun to encounter a group of stars not taking part in the rotation, i.e. standing still in space. We would think they had very high motions just as an aviator passing through a flock of stationary captive balloons would, if he were as self-centered as we are in cosmic matters, consider them to rush past him at a rate which would of course be nothing but the reflex of his own speed through the air. Now stars cannot very well be tethered out in space like the captive balloons, but they can move about the center of the galaxy in elongated orbits with less forward motion than that of the sun's family. This is just what the "high velocity" long-period variables and RR Lyrae stars are supposed to be doing. A schematic diagram of the situation is shown in Figure 12. A represents the galactic orbit of the sun S; B typical orbits of high velocity stars. Bearing in mind that observations give us the *relative* motion of sun and star, we see that the velocities toward and away from the center of the galaxy will enter for nearly their full values, and that in either direction the outward velocities should on the average equal the inward ones. In the tangential direction, however, the sun's faster forward motion makes itself felt and causes the group of variables as a whole to appear to be drifting backward. Variables ahead of the sun will in general be approaching, and those behind the sun, receding. These deductions correspond to the facts described in Chapter VII. The assumed orbits therefore explain the high random speeds of long-period variables and RR Lyrae stars, as well as their systematic group motion in a line approximately at right angles to the direction of the galactic center.

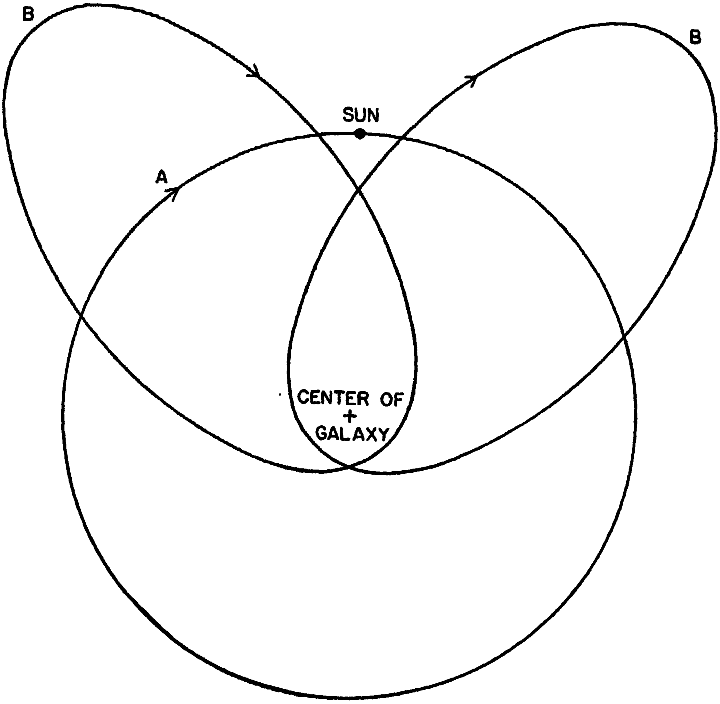

FIG. 12. Circular galactic orbit of the sun, and elliptical orbits of high-velocity variables.

As seen from the earth, cepheid variables have the strong concentration near the Milky Way characteristic of stars of unusually high luminosity. Long period variables and RR Lyrae stars, on the other hand, exhibit little preference for the galactic plane.

This distribution may arise because their elliptical galactic orbits are not confined to the galactic plane so closely as are the circular orbits of other stars.

Just why certain variable stars should have elliptic galactic orbits while those of ordinary stars are circular is hard to say. In fact one of the least tractable of the great problems of modern astrophysics is the explanation of the remarkable connections between the motions of the stars and their physical properties.

Accepting the usual postulate that the galactic system had its origin in an immense amorphous nebula of primordial gas, Strömberg of the Mount Wilson Observatory, has published some interesting speculations on the formation of circular and elongated orbits. His idea is that a rotary motion, induced perhaps by the fairly close approach of another system, becomes strongly marked in the more viscous central portions, while the tenuous parts far from the center are given but a slight tendency to rotate in the same angular direction. Stars with circular orbits are thus those formed in the denser central part, while those with elliptical orbits originated in the outer parts of the nebula, or may even have been captured from inter-galactic regions.

CONCLUSION

Variable stars are doubtless trying hard to tell us important facts concerning stellar evolution. We hear them shouting and can recognize many words and an occasional phrase, but cannot fit many of these together into intelligible sentences. In the future we must try to be more skillful in interpreting their cries; or, in search of clues, we may listen more attentively to their fainter utterances; or finally, by more pointed questions, we may extract from them new and more helpful information.

At present the numerous problems of variable stars appear to be divided into two groups: on the one hand those of individual stars, and on the other those concerning relationship to the stellar system. Eventually problems of both groups will probably be seen as different aspects of one underlying interpretation. Increasing knowledge and insight will tend to draw together and unify diverse phases of present research. It is impossible to predict how or when the next great advance will come, but important ideas may be just around the corner. The present difficulties are so interesting that we might almost regret to see them solved except for the confident expectation that the solution will lead to problems still more fascinating.

INDEX OF INDIVIDUAL VARIABLE STARS

See Table II, p. 24; III, 29; VII, 61; IX, 102; XI, 110

GENERAL INDEX