

Are Most Stars

Many a single point of light in your telescope is two or more stars orbiting closely about the center of mass. Much information is available from these double-star systems, which are closer to natural experiments than any other astronomical phenomenon.

by Louis Winkler

Members of Double-Star Systems?

A DOUBLE-STAR SYSTEM consists of two separate stars that orbit about the center of mass of the system much as a planet orbits the sun. For the most part, these double-star systems appear as single points of light, even with the aid of a telescope. Nevertheless, there is evidence that a large fraction of all the single points we see are really double-star systems.

Unfortunately, it is not possible to count all the double-star systems that are located in any given spherical neighborhood about our sun. One reason is that some of the stars are too close together and have their orbital planes nearly perpendicular to the lines of sight. Another reason is that other double-star systems have members that are too faint.

Much astronomical information is derivable from double-star systems, which probably come closer to being natural experiments in astronomy than any other type of celestial system. The evolution of a member of a double-star system may be quite different from that of a single star.

How to detect them

A star is a very large mass of gases held together by its own gravitational

force, which radiates nearly like a black body by virtue of the opacity of its outer layers. Each double-star system in our galaxy is composed of two stars orbiting about their center of mass according to the theory of motion of two bodies. Even though many other stars that are members of the galaxy exist near double-star systems, their gravitational attraction does not perturb the motions of the components greatly. The gravitational attractions of the neighboring stars are negligible compared to the attraction between the binary stars. For widely spaced systems the gravitational attraction of the neighboring stars is isotropic and tends to result in a zero net force. A triple-star system is often composed of two stars fairly close to each other and a third more distant member, all of which orbit about their common center of mass. The concept of a multiple-star system involves four or more stars which revolve about one another in some fashion.

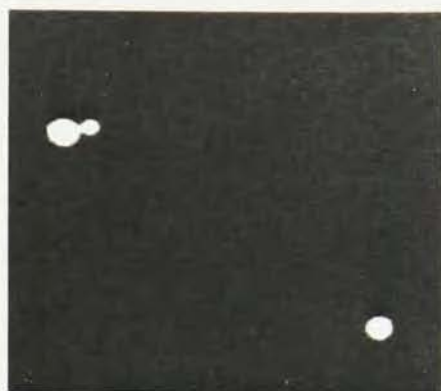
In 1650, shortly after Galileo Galilei constructed the first optical telescope, John Baptist Riccioli casually noted that Mizar (Epsilon Ursae Majoris) in the handle of the Big Dipper was resolved into two stars with the aid

of a telescope. It was not until 1803 that William Herschel announced that the components of Castor (Alpha Geminorum) were orbiting about one another. This was the discovery of the first visual double-star system, or visual binary, where the components can be observed to revolve about their center of mass. Many observations made later show that in reality Mizar is a quadruple-star system consisting of a double star orbiting about another double star. Eventually Castor was shown to be a sextuple system.

Since an extremely large number of stars can be observed with a telescope, many stars will appear to have nearly the same coördinates in the sky. Some will be binary systems and oth-

The author is an assistant professor of astronomy at the Pennsylvania State University. He conducts research in the fields of double stars, statistical analyses and stochastic processes in observational astronomy. He received his BS at Rutgers, MS at Adelphi and PhD at Pennsylvania.





1908



1915



1920

KRUEGER 60 with mutual revolution of the components during 12-year period. Bright star in lower right-hand corner is used as a reference. —FIG. 1

ers will be widely separated stars that lie almost in the same line of sight. The latter are called "optical doubles" and are of little interest to double-star astronomers.

One can detect double stars other than by noting their mutual revolution with a telescope. Many double-star systems have their orbital planes oriented in space so that an observer on earth can witness the stars alternately crossing in front of each other. These are eclipsing binaries in which one star eclipses the other star, reduces the amount of light and decreases the total intensity of the system. Existence of the first eclipsing binary was suggested by John Goodricke in 1783. He surmised that the light variations on Algol (Beta Persei or Demon Star) were caused by one star crossing in front of another.

Still other double-star systems make their presence known by periodic oscillation of the absorption lines in their spectra. Absorption lines are formed by absorption and re-emission of continuous radiation from the interior by atoms in the outer layers of the star. The periodic oscillation is caused by the Doppler shift due to the components of orbital motion along the line of sight. Such a system is a spectroscopic binary, first discovered in 1889 by Edward C. Pickering. He found that Mizar exhibited periodic shifts in its spectral lines and hence was the first known visual and spectroscopic binary. One of the interesting devel-

opments in astronomical thought is found in the annals of spectroscopic binary research. The first known example of absorption lines produced by interstellar atomic matter was found in the spectrum of Delta Orionis. Absorption lines produced in the atmosphere of the star showed periodic oscillations while the absorption lines produced by the intervening cosmic gas remained stationary.

In figure 1 are three photographs of the visual binary Krueger 60 taken over a period of 12 years. Figure 2 is a sketch of the variation of the apparent intensity of an eclipsing system. Figure 3 is a sketch of the variable Doppler shift due to orbital motion that might be found in a spectroscopic system. In the last two figures various positions of the components are depicted during a period of revolution. (A glossary of technical terms appears on page 48.)

A binary star system can be detected by any or all of these three means. If the components of a system are not widely separated, their diffraction patterns, as produced by the objective of a telescope, will overlap and the duplicity will not be determined easily. One can see that the discovery of a visual binary is not particularly dependent on the orientation of the orbital plane in space. Only with the most eccentric orbits can the orientation of the plane greatly foreshorten the maximum separation of the components.

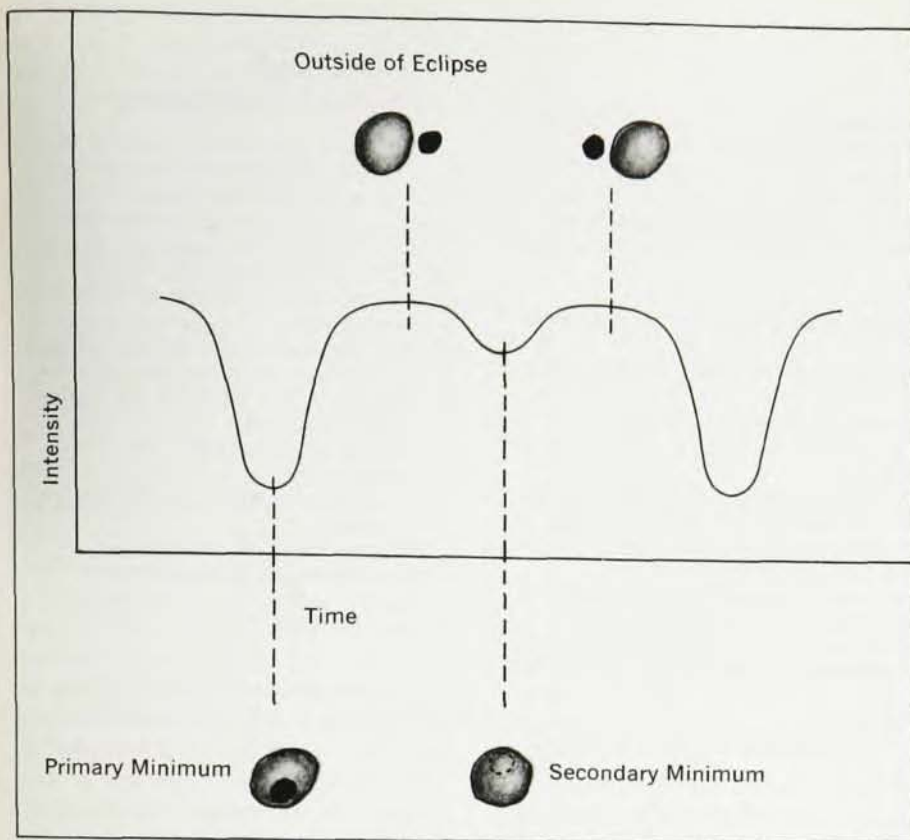
If the orbital plane of a double star

almost contains the line of sight, it tends to be discovered as either a spectroscopic or eclipsing binary. The smaller the orbit of a spectroscopic binary, the more likely it is to be discovered. This situation exists because according to two-body theory the peak Doppler shift is inversely proportional to the square root of the semimajor axis of the relative orbit. Since eclipsing binaries undergo partial eclipses, those systems with widely different surface temperatures tend to be discovered. Thus, a number of selection effects exist in the detection of binaries. Such systems are classified by the way in which they are detected rather than by any parameter or parameters that would segregate them physically. Although more meaningful classes can be specified, the existing heuristic subdivisions persist because of many decades in which they have had precedence.

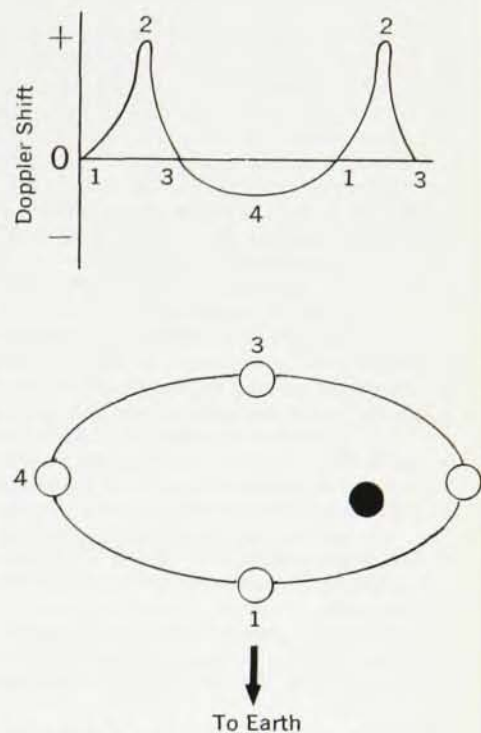
Frequency of occurrence

From the description of the means of detection you can see that not all double, triple or multiple systems in a given spherical neighborhood of the sun can be discovered. An important class that can not be detected is one in which the components are not widely separated and whose orbital plane is nearly perpendicular to the line of sight. Thus, one can not make any direct count of the number of double-star systems.

Another important class of double-



TOTAL INTENSITY as a function of time for an eclipsing binary with a large hot component and a small cool component. Large component exhibits nonuniform illumination over disk called limb darkening. —FIG. 2



DOPPLER SHIFT due to orbital motion as a function of time for a spectroscopic binary with an elliptical orbit. —FIG. 3

triple- or multiple-star systems that can not be detected by the above method is one in which a member of the system is not very bright. A dim component often tends to have a small mass and to be of relatively small dimensions. A companion that is not massive will not produce orbital motion in the massive component. No motion of the more massive member will be seen relative to the more distant background stars and no Doppler shift due to orbital motion will be found in the spectrum of the more massive member. Since many of the common stars have luminosities that vary as the second power or more of the mass of a star, many of the less massive stars have very small luminosities. Less massive stars usually will not be seen as visual binaries nor will their spectra be detectable in the overpowering light of the more massive star. Thus, a very small star tends not to be discovered as a member of an eclipsing binary system. A small body would not block much of the radiation during transit of the

brighter star or exhibit much apparent light loss while the brighter member eclipsed it.

Many astronomers feel that a large fraction of the stars (at least in the neighborhood of the sun) are members of double- or multiple-star systems. The data involve some well known and nearby systems. Alpha Centauri, our closest neighbor to the sun, is in reality a spectroscopic-visual binary with a third member. Sirius, which appears to be the brightest star in the sky is attended by an extremely dense and small star called a "white dwarf." Algol is an eclipsing-spectroscopic binary having two additional attendants.

Perhaps the most conclusive data¹ concerning the high proportion of stellar membership in double or multiple systems are the existing statistics in a 10-parsec radius of the sun. Of the 55 stars within 5 parsecs of the sun at least 36 belong to double or triple systems. Of the 222 stars within 10 parsecs of the sun at least 109 belong to double, triple or quadruple systems.

The existence of double-star systems is not unique to our galaxy. Although no visual or spectroscopic binaries can be detected in external galaxies, some eclipsing binaries can be detected.

Planet-like objects

The principal difference between a planet and a star is that the star is generating energy by thermonuclear processes whereas the planet is radiating away the energy it acquired at the time it was formed plus the energy absorbed from its star. Both a star and a planet are nearly in thermodynamic equilibrium. The smallest known stars are smaller than some planets of our solar system. For example, 40 Eridani B is approximately 14 000 miles in diameter. Although it is suspected that many other stars besides the sun have planet-like attendants, evidence² for only one has been found to date. The object that most closely resembles a planet is the companion of Barnard's star, which exhibits the greatest observed angular motion in the sky per

Glossary of Important Terms

- apastron**—Applied to the orbit of one star about another in a binary system, it is the point in the orbit of the star which is farthest from the other star.
- apsides**—The points in an elliptical orbit of a secondary body about a primary body where the radius vector between the bodies is a maximum or a minimum. The line joining these two points is called the line of apsides.
- AU**—Abbreviation for astronomical unit equal to the mean distance of the earth from the sun or 9.3×10^7 statute miles.
- epoch**—A date selected as a point of reference.
- intrinsic variable star**—Many stars of this type vary periodically in size, surface temperature and brightness.
- limb**—An astronomical term referring to the edge of the disk which is the projection of a spherical body.
- line of nodes**—The intersection of the orbital plane and plane defining i .
- parallax**—Is a measure of the distance to a star and is the maximum angle that the AU subtends at the distance of the object.
- parsec**—The distance at which a star would have a parallax of one second of arc approximately equal to 3.258 light years or 1.915×10^{13} statute miles.
- periastron**—Applied to the orbit of one star about another in a binary system, it is the point in the orbit of the star which is closest to the other star.
- primary minimum**—In eclipsing binaries this is the minimum intensity level of the system and results when the hotter star is obscured by the cooler star.
- secondary minimum**—This is a relative minimum intensity level and results in eclipsing binaries when the cooler star is obscured by the hotter star in the system.
- supergiant**—Refers to the intrinsically brightest stars.
- white dwarf**—An unusual star that is not in thermodynamic equilibrium and represents the last stage of evolution in a star.

Orbital and Physical Parameters

- A = the semimajor axis of the ellipse of the orbit of one component about the other.
- e = the eccentricity of the ellipse.
- P = the period of revolution of one component about the other.
- T = the epoch that the stars are at periastron.
- i = the inclination of the orbital plane to a plane perpendicular to the line of sight of an earth-based observer.
- ω = the longitude of the periastron.
- Ω = the longitude of the line of nodes.
- M = the mass of a component.
- R = the radius of a component.

unit time (10 seconds of arc per year) and is the second closest system to the sun. The companion of Barnard's star has a mass only about 60% more than Jupiter's mass.

It is interesting that the mass of Jupiter is near the lower limit for maintaining thermonuclear reactions. If the mass of Jupiter were slightly above this lower limit, Jupiter would have been an intrinsically faint star. Consequently, the earth as well as seven other planets would be members within a double-star system. If the solar system, with Jupiter as a feeble star, were placed at the distance of Alpha Centauri, which is 4.3 light years, Jupiter and the sun would appear as a visual binary with a maximum separation of about 5.2 AU. Then the concept of day and night as we know it on earth would have been very different.

Physical parameters

Because of the physical interaction between components a double-star system will in general provide more information than two isolated stars. The particular information derivable depends on the way or ways in which the system can be detected. The data of figures 1–3 vary as orbital and other physical parameters change.

Specific procedures^{3,4} used to reduce observed data on double-star systems are numerous and quite detailed. At the same time only the more elementary forms of mathematics are used. Often we make ingenious geometrical and algebraic interpretations of the data.

The orbital and physical parameters of the system are defined in the box on this page. Although the components physically revolve about their center of mass, it is desirable mathematically to discuss the orbit of one component about another. This method is commonly used. For example, an observer on earth often states that the sun is rising or setting. i , ω and Ω are shown in figure 4.

When detailed reduction procedures are applied to double-star data, the following information can be found:

Visual binaries: A (angular units), e , P , T , i , ω , Ω , M_1 , M_2 . A (angular units) is the angle that the distance A would subtend at the earth if A were perpendicular to the line of sight. To convert A (angular units) into A one must know the parallax of the system.

Spectroscopic binaries: $A_1 \sin i$, e , P , T , ω . Here A_1 represents the semimajor axis of the orbit of the brighter

component about the center of mass of the system. This assumes that one spectrum is visible. If one star is much brighter, the spectrum of the fainter will be masked by the spectrum of the brighter. If two spectra are observed, one can also obtain $A_2 \sin i$, $M_1 \sin^3 i$, $M_2 \sin^3 i$. A_2 is the semimajor axis of the orbit of the dimmer component about the center of mass of the system, and M_1 and M_2 are the masses of the brighter and dimmer components respectively.

Eclipsing binaries: i , R_s/A , R_g/A , P , T' . Here R_s and R_g represent the radii of the smaller and the larger components respectively, and T' represents the epoch of primary minimum in the system.

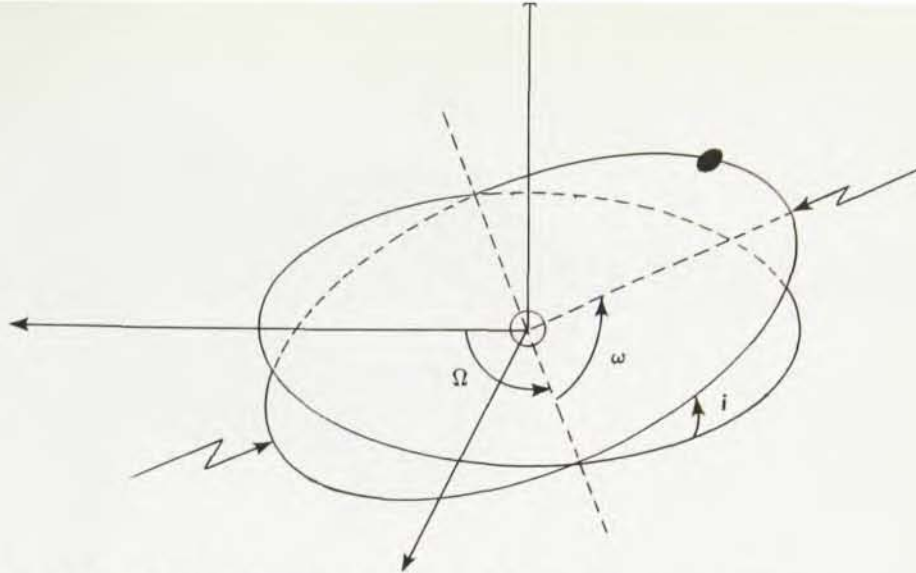
Theory of the interior of stars indicates that the temperature decreases with increasing distance from the center. Radiations along the line of sight to the center originate from hotter gases than do radiations from a line of sight near the limb. This variation in brightness is called limb darkening. It can be seen in figure 2 that the shape of a light curve of an eclipsing binary during eclipse is affected by the degree of limb darkening. Star components are sometimes so close that one stellar surface reradiates the energy from the other star. Of course, this is not entirely a monochromatic reradiation since the stellar surface is gaseous. Again, it is not difficult to see that the shape of a light curve of an eclipsing binary is affected during

and outside of eclipse by the reflection effect. By using arguments similar to the ones mentioned above, it is also possible to obtain information regarding the shapes of the components.

For all double-star systems, Kepler's generalized third law applies, so that $P^2 = A^3/(M_1 + M_2)$. With this relation and information derivable from a visual binary whose parallax is known, the separate masses of the stars can be computed since $M_1 + M_2$ and M_1/M_2 are known. If a system is eclipsing and spectroscopic with two spectra, or is visual and spectroscopic with two spectra, the individual masses can also be obtained since $M_1 \sin^3 i$, $M_2 \sin^3 i$, and i are known. Since this is essentially the only means for obtaining accurate mass information on stars from earth observations, information on masses is available only for double-star systems. The true frequency distribution of the masses of single stars may be quite different.

If a system is eclipsing and A is available from visual or spectroscopic data, the size of the individual components can be found since R_s/A and R_g/A are known. This turns out to be the most accurate way in which stellar sizes are found. Unfortunately, the true frequency distribution of sizes of single stars can not be compared with the true frequency distribution of double stars primarily because of selection effects previously mentioned for double stars. Some selection effect exists even in single stars since the faintest single stars are not likely to be detected.

The semimajor axis of the orbit of a double-star system passes through the apsides of the orbit, namely periastron and apastron positions. Thus the semimajor axis is also called the line of apsides. If the components of a system are spinning rapidly enough or are elongated tidally they will cause the line of apsides to rotate in the plane of the orbit if the orbit of the system is not circular. Consequently this will produce a periodic shift in the time of occurrence of secondary minimum relative to primary minimum in an eclipsing binary. The theory of celestial mechanics shows that this apsidal motion is related to the density gradient of the stellar interior. This turns out to be the only technique for obtaining information on stellar interiors



SOME ORBITAL PARAMETERS of a typical double-star system. —FIG. 4

other than by theory alone. An example of a system that exhibits apsidal motion is Gamma Cygni with a 46-year rotation period of the line of apsides.

Let me emphasize that the above discussion does not include, by any means, all the information derivable from double-star systems. Many other physical parameters can be established from special circumstances that can be found in the systems. The parameters discussed above are only the fundamental and common ones. Although the size of some of the nearest single largest stars can be determined with the aid of an interferometer, the accuracy of this measurement is far less than it is for the sizes as determined from eclipsing binaries. The masses of some nearby white dwarfs can be found from relativistic red shifts of their spectral lines, but the accuracy is far less than for the masses determined for double-star systems.

The range of the values of the physical parameters is found to be immense. Periods of systems, for example, range from a few hours to many thousands of years. As far as the most fundamental parameters are concerned (size, mass and surface temperature) there is a continuous distribution of values between extremes.

Before it was recognized that some single stars were intrinsically variable, these stars were analyzed as double-star systems. Their light curves and velocity curves were reduced according to procedures established for

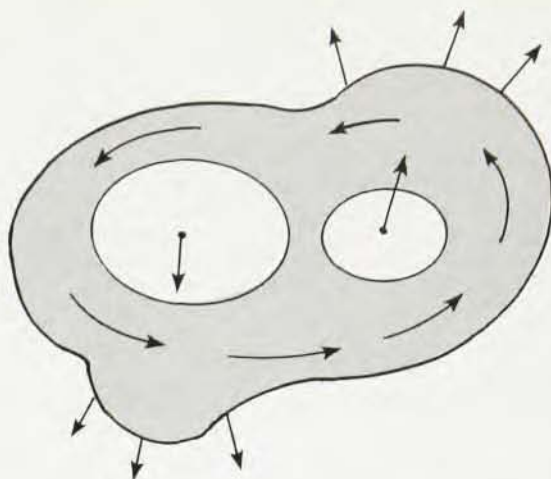
eclipsing-spectroscopic double-star theory. Peculiar distributions of system parameters resulted. Only when astronomers were led to the situation where one star appeared to be orbiting *inside* another were they fully aware of a gross misconception. One star can not orbit inside another because of disrupting drag effects. Moreover the interior star would not remain in thermodynamic equilibrium since the added exterior insulation provided by the larger star would prevent it from radiating away the energy generated in its core fast enough.

An observational science

To this day astronomy remains essentially an observational science. Except for meteorite analysis, artificial satellites, space vehicles and radar in the solar system, no celestial experiments can be performed. The varying physical state of the double-star system offers perhaps the nearest situation to an experiment. Although the number of physical states in any given system may not be large enough to satisfy an experimentalist, this is offset by the fact that an exceedingly large array of double-star systems exists in the universe.

One of the very interesting classes of systems is the W Ursae Majoris^{5,6} type. These are eclipsing-spectroscopic systems having two spectra with a period often less than one day. The short period arises from the extremely small value of A . Stars of this type are often so close that they are touching; they tidally distort one

W URSAE MAJORIS
double-star
system.—FIG. 5



another so that they are ellipsoidal. Often gaseous streams are found around one or both components. The trajectories of the circulating atmospheres are quite complex, in general, because the gaseous particles are accelerated simultaneously by magnetohydrodynamical and gravitational forces. The nature of these gas streams was first recognized by Otto Struve. A schematic of a W Ursae Majoris system is shown in figure 5.

Theory and observation of double-star systems indicate that one or both components may evolve^{7,8} in such a way as to fill up its critical equipotential surface.⁹ This surface, as specified by George Hill's restricted three-body theory, would intersect a plane containing the line between the centers of mass of the components in a figure eight. When a star fills up beyond its equipotential surface, material from that star appears to be transferred to the other star. It is not clear just how the transfer takes place but there is some reason to believe that it may occur through the innermost Lagrangian point. Hence the evolution of one star can affect the other. In this way some double-star members could evolve differently.

Another type of double-star system that comes close to a natural experiment is the eclipsing-supergiant type. This variety consists of a very hot star that is somewhat larger than the sun and a supergiant that is very large and very cool. An example is Zeta Aurigae having a period of 973 days. As the small component passes in back of the large component the light of the small star passes through increasingly thicker layers of the atmosphere of the large star. Since some absorption

spectral lines are formed by the hot star shining through the cool star, the elements present in the large star and their location can be established. This information is of considerable interest to the astrophysicist.

The existence of double-star systems indicates that Newton's laws of motion and law of gravitation hold in interstellar and intergalactic space. If Newton's laws are assumed, Kepler's laws of planetary motion as applied to exact two-body theory can be derived.

Astronomers can not describe the origin of double-star systems. It is suspected that the origin is similar for all types of systems because there is a fairly continuous distribution of all orbital and physical parameters. One theory of the origin is random capture. This idea is appealing because a typical galaxy may have 10^{11} stars. However, capture is not likely because the separations between stars are so great. Another theory that is natural to conceive is bifurcation. From spectral-line-broadening analysis it can be deduced that many stars rotate. Some rotate near the limit where the reaction to centripetal acceleration at the equator offsets the gravitational attraction. In this way material can be dissociated from the spinning star. But the theory does not explain how this material can recombine into another separate unit in thermodynamic equilibrium. Whatever the origin of double-star systems, this idea probably can be used to describe the origin of triple or multiple systems by repeated application.

In the future

Theory of stellar interiors indicates that the life span of a star is a number

of billions of years. The time during which an astronomer sees a particular star in his lifetime is only an infinitesimal fraction of the star's lifespan. The astronomer must completely theorize the evolution of a star. He may reduce the theoretical aspect somewhat by assuming that out of the large array of stars, certain ones represent earlier or later stages of others. This, of course, could bring about misleading ideas.

Figure 5, for example, is the result of many thousands of hours of observations, which extended over many years or even decades. Various observations must be correlated until a physical model is developed which is consistent with the observations. The closest systems exhibit the most rapid superficial changes and of course these systems exhibit two nearly coincident diffraction disks due to the telescope objective. Unfortunately with a telescope one cannot directly see the superficial changes that occur. As artificial-satellite and space-vehicle technology is advanced, extremely large telescopes can be located on board. These telescopes will not be limited by problems caused by absorption and the inhomogeneities in the earth's atmosphere. Indeed, eventually, with interstellar flight, naked-eye observations will enable one to observe in a relatively short period of time what the astronomer now deduces indirectly over a period of many years.

References

1. P. van de Kamp, p. 223 in *Encyclopedia of Physics*, Vol. 1 (ed. by S. Flugge), Springer-Verlag, Berlin (1958).
2. P. van de Kamp, *Astron. J.* **68**, 515 (1963).
3. R. Aitken, *The Binary Stars*, McGraw-Hill, New York (1935).
4. L. Binnendijk, *Properties of Double Stars*, University of Pennsylvania Press, Philadelphia (1960).
5. O. Struve, *Stellar Evolution*, Princeton University Press, Princeton (1950).
6. Z. Kopal, *Close Binary Systems*, Chapman and Hall, London (1959).
7. J. A. Crawford, *Astrophys. J.* **121**, 71 (1955).
8. F. B. Wood, *Astrophys. J.* **112**, 196 (1950).
9. J. M. A. Danby, *Fundamentals of Celestial Mechanics*, Macmillan, New York (1962).