20 July 1984, Volume 225, Number 4659 **SCIENCE**

Binary Stars

Bohdan Paczyński

Summary. Most stars in the solar neighborhood are either double or multiple systems. They provide a unique opportunity to measure stellar masses and radii and to study many interesting and important phenomena. The best candidates for black holes are compact massive components of two x-ray binaries: Cygnus X-1 and LMC X-3. The binary radio pulsar PSR 1913 + 16 provides the best available evidence for gravitational radiation. Accretion disks and jets observed in close binaries offer a very good testing ground for models of active galactic nuclei and quasars.

The star closest to us, our sun, is single. This singularity is an exception rather than the rule. Most stars form either double or multiple systems held together by their gravitational interaction. For example, among solar type stars the observed ratios of single:double:triple:quadruple systems is 45:46:8:1 (*1*). This seems to be a typical situation in the galactic disk, close to the plane of symmetry of our Milky Way, whereas in the galactic halo a majority of stars are single (*1*). The reason for this difference is not known.

Multiple systems usually have hierarchical structure: at a much larger distance from a close pair of stars, there might be another star or another close pair. It is easy to understand why all the components of a multiple system cannot have comparable mutual separations—such systems are known to be unstable unless the number of components is very large. Rich and very rich systems do exist, and they are known as clusters of stars and galaxies.

Various binaries may differ enormously in their extent. There are many pairs of stars touching each other. These are the contact systems of the W Ursae Majoris or SV Centauri type (*2*). A whole contact binary is only slightly larger than the sun, some 3×10^{11} cm in diameter. At the other extreme there is the nearby triple system, α Centauri ABC. The component α Centauri C, also known as Proxima Centauri, is a distant companion to a binary, α Centauri AB. The separation between components A and B is 3×10^{14} cm, whereas component C is about 10^{17} cm away from A and B.

Various binaries populate fairly uniformly a whole range of separations from about 3×10^{11} to 3×10^{17} cm, which corresponds to orbital periods of 1 to 10^9 days (that is, up to about 3 million years). Roughly 10 percent of all stars are binaries with orbital periods between 1 and 10 days, another 10 percent have orbital periods between 10 and 100 days, and so on (*1*). There is a rapid cutoff in the number of systems with separations larger than about 3×10^{17} cm, most likely due to gravitational perturbations caused by other stars belonging to our galaxy and randomly passing by (*3*). The average distance between separate stars or stellar systems in the solar neighborhood is about 4×10^{18} cm.

Ordinary Stars in Binary Systems

Binary and multiple stars are so common that an understanding of their origin and evolution is important for an understanding of the origin and evolution of stars in general. Binaries, like single stars, spend most of their "lives" burning hydrogen in their deep interiors. That phase of evolution a star spends on the main sequence. This is a relatively narrow band on the Hertzsprung-Russell or color-magnitude diagram, where the majority of known stars are located. The band runs diagonally across this diagram from faint and cool (that is, red) stars all the way to luminous and blue (that is, hot) stars. This confinement of a vast majority of known stars to an almost one-dimensional domain on a two-dimensional diagram implies that stellar properties are largely determined by one parameter. It is firmly established now that this parameter is the stellar mass. Low-mass stars are faint and cool, whereas massive ones are luminous and hot. The empirical relations between stellar masses, luminosities, and radii were obtained through studies of binaries. For the main sequence these relations may be well approximated as

$$R/R_\odot \approx (M/M_\odot)^{0.8}, \; L/L_\odot \approx (M/M)_\odot)^{3.5}$$

where $M_\odot = 1.99 \times 10^{33}$ g, $R_\odot = 6.96 \times 10^{10}$ cm, and $L_\odot = 3.86 \times 10^{33}$ erg sec^{-1} are the solar mass, radius, and luminosity, respectively. These empirical relations are well understood and reproduced theoretically with numerical models of stars calculated with modern computers.

Many other parameters can be measured more conveniently or more accurately in binaries than in single stars. The following example may illustrate how this is done.

ζ Phoenicis, also known as HD 6882 or HR 338, is a bright binary with an orbital period of 1.67 days. Its light intensity (*4*) as well as the radial velocities of the two components (*5*) vary with this period. The variations are shown in Fig. 1. The light curve (Fig. 1A) displays two eclipses: the primary at phase 0 (or 1), when the cool component partly eclipses

The author is professor of astrophysical sciences at Princeton University, Princeton, New Jersey 08544. He is on leave from the N. Copernicus Astronomical Center, Polish Academy of Sciences, Warsaw, and is a long-term member of the Institute for Advanced Study, Princeton.

the hotter one and the secondary at phase 0.5 (or 1.5), when the hot component is in front and the cool component is hidden behind it. A detailed analysis of the light changes during the eclipses allows accurate determination of relative stellar radii, expressed in units of their mutual separation. A schematic presentation of the binary is given in Fig. 2. The extent of stellar motion and the size of the binary orbit follow from an analysis of the radial velocity curves (Fig. 1B). Using Kepler's law, one may determine the stellar masses as well. The results for ζ Phoenicis are as follows (*4*):

$$M_1/M_\odot = 3.85,\ R_1/R_\odot = 2.84,\ L_1/L_\odot = 320$$

$$M_2/M_\odot = 2.50,\ R_2/R_\odot = 1.85,\ L_2/L_\odot = 32$$

There are several dozen systems for which a similar analysis has been done with high accuracy, that is with errors less than 10 percent and sometimes significantly less (*6*).

A binary like ζ Phoenicis is very useful because all the parameters are known very accurately and the two stars have significantly different masses. This allows one to estimate the age and chemical composition of this system by comparing stellar models with the observations.

A main sequence star generates energy by burning hydrogen in the core. The energy diffuses from the core to the surface, and finally it is radiated away. Gradually, hydrogen is processed through a sequence of thermonuclear reactions into helium. As a result of this process, stellar luminosity and radius increase with time (*7*). The best quantitative comparison between models and real stars is possible for binaries like ζ Phoenicis. Calculations of models for a star of a given mass and a given chemical composition provide the variations of stellar radius and luminosity as a function of time. Chemical composition may be conveniently described with just two parameters: helium content Y and heavy element content Z. All the remaining matter is hydrogen. It is natural to assume that both components of a binary system were formed simultaneously from condensations of interstellar gas, and that the initial chemical composition was the same for the two stars. As we know the masses of the two stars from observations, there are only three parameters that we may vary in the models: age (t), Z, and Y. We want to reproduce four observed quantities: the present radii and luminosities of the two stars (R_1, R_2, L_1, L_2). Therefore, we may even check the models for self-consistency (*4*). This type of analysis gives for ζ Phoenicis

$$t = 8 \times 10^7 \text{ years},\ Y = 0.28,\ Z = 0.015$$

Similar modeling has been done for about half a dozen systems and has provided the best quantitative checks of the modern theory of stellar evolution, and perhaps the most accurate determination of the helium content in stars. The helium abundance obtained in this way is in good agreement with determinations from models of hot stellar atmospheres and from observations of the interstellar medium. It is now believed that helium was produced mainly during the first 3 minutes after the Big Bang; hence, a determination of helium abundance is of considerable cosmological importance.

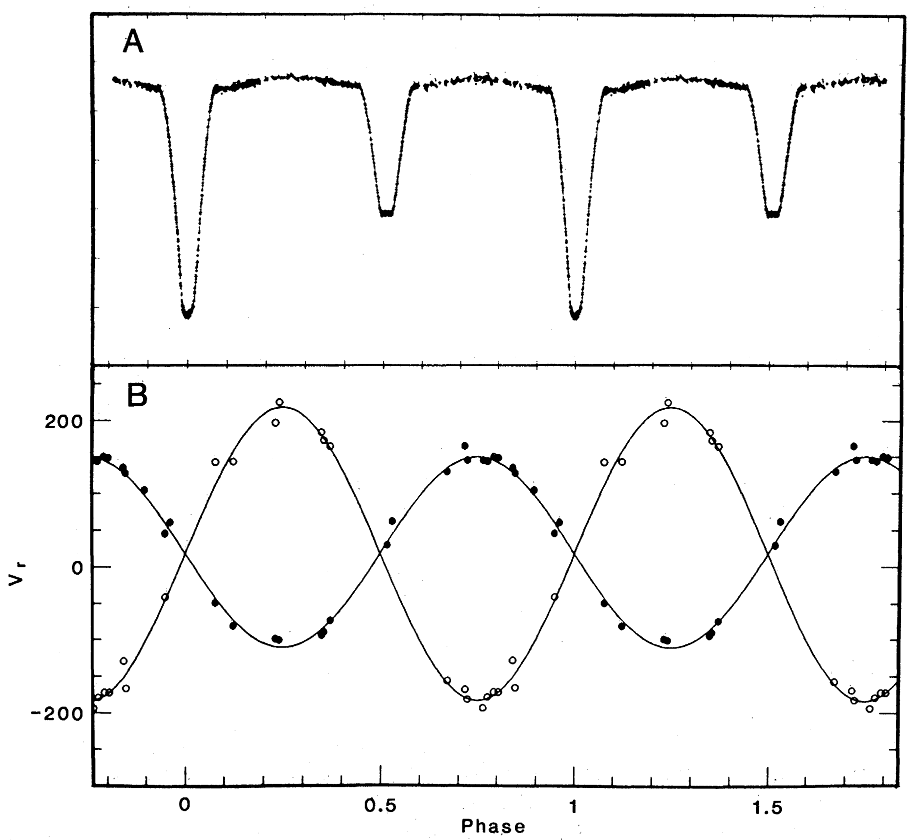


Fig. 1. Light variations (A) and radial velocity variations (B) for a bright binary, ζ Phoenicis. All the variations have the 1.67-day binary period. At phase 0 (or 1) the hotter of the two stars is eclipsed by the cooler companion (primary eclipse). At phase 0.5 (or 1.5) the cooler star is eclipsed by the hotter one (secondary eclipse). The radial velocities, expressed in kilometers per second, are displayed for the hot primary with filled circles and for the cool secondary with open circles. Radial velocity is positive when the source is receding from the observer.

White Dwarfs, Neutron Stars, and Black Holes

Not only main-sequence stars but also more exotic objects may have their masses measured if they are members of binary systems. The three white dwarfs for which masses are well known are Sirius B (0.94 $M_\odot$), Procyon B (0.65 $M_\odot$), and σ^2 Eridani B (0.43 $M_\odot$). All are members of multiple systems (*6*). Their radii are also reasonably well determined and are consistent with the mass-radius relation for cool, degenerate stars (*8*). According to this relation, no white dwarf can exist with a mass exceeding the Chandrasekhar limit of 1.4 $M_\odot$. Indeed, none is known. For many decades white dwarfs were the most compact stars known to astronomers.

Even more compact objects, neutron stars, were discovered as single radio pulsars (*9*). But it was only after the discovery of x-ray pulsars, which are neutron stars in close binaries, that their masses could be measured (*10, 11*). Most available estimates have rather large errors, but all are in the range of 1 to 2 $M_\odot$, as expected theoretically. The best available estimates for the neutron star masses are provided by a binary radio pulsar, PSR 1913 + 16. Both components have almost identical masses of 1.4 $M_\odot$ with an accuracy of a few percent (*12*). Unfortunately, existing observations do not allow reliable determinations of neutron star radii. Some attempts were made for x-ray bursters, a subclass of binary neutron stars undergoing thermonuclear flashes in freshly accreted matter (*11*). The masses and radii of x-ray bursters agree reasonably well with the prediction of models, but the available estimates are not very accurate. It is not yet possible to use them to select the correct equation of state at supernuclear densities (*13*).

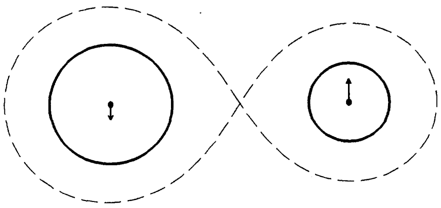
No matter what equation of state is adopted at supernuclear densities, there can be no cool stars above 3 $M_\odot$, provided that the theory of general relativity is correct in the strong field limit (*13*). Anything more massive must ultimately collapse and form the most compact object so far imagined, a black hole. Discovery of a black hole would be one of the most spectacular achievements of modern astronomy. There are two general areas where the search is going on: active galactic nuclei and quasars (*14*) and massive x-ray binaries (*10*). So far there is no proof that a black hole has been found, but there are two very good candidates, the compact components of two binary systems: Cygnus X-1 in our galaxy (*10*) and LMC X-3 in the nearby galaxy, Large Magellanic Cloud (*15*). Observations indicate that in both binaries one component is a fairly normal, massive, hot and luminous star, probably close to the main sequence, whereas the second component is a very strong x-ray source. Each component has a mass of about 10 $M_\odot$.

It is generally believed that there are only two types of stars that can be strong emitters of x-rays, and both are very compact. These are neutron stars and black holes powered by the accretion of matter flowing from the nearby companion. A majority of strong x-ray sources have masses between 1 and 2 $M_\odot$ and display strong short-period variations in their x-ray power. These are the x-ray pulsars, believed to be rotating neutron stars with strong magnetic field channeling the accretion flow toward the magnetic poles, where the two bright spots are formed. Rotation periodically displays the spots and hides them behind the star, hence the so-called pulsations. It is believed that a black hole must be axially symmetric, and accretion onto a black hole cannot give rise to strictly periodic rapid oscillations. Indeed, neither of the two black hole candidates is a pulsar. Unfortunately, present theoretical models of x-ray emission cannot predict with any accuracy the x-ray spectrum to be expected from an accreting black hole, and the evidence for the existence of black holes in Cygnus X-1 and LMC X-3 is still rather circumstantial. In fact, it is difficult to formulate a realistic criterion that would convince everybody of the presence of black holes in these two systems. One of the problems is that black holes are the most extreme objects predicted by general relativity. Their convincing discovery would be a very important step in demonstrating that general relativity is the correct theory of gravitation in strong-field conditions. However, there is no independent observational evidence that this theory is really valid when the gravitational field becomes very strong. So far, almost all tests of this theory were restricted to the weak field and the so-called post-Newtonian approximation. With one important exception.

The post-Newtonian approximation for gravitation and motion allows for terms of the order $(v/c)^2$, where v is the characteristic velocity of objects in the system under consideration and c is the speed of light. Higher order terms are too small to produce detectable effects under most astronomical conditions. The only exception is gravitational radiation, which is supposed to carry away energy at a rate proportional to $(v/c)^5$. This is a post-post-Newtonian effect, and it is usually too small to notice, as there are so many other competing astrophysical processes. However, there is one ideal case of a binary radio pulsar, PSR 1913 + 16, which has an eccentric orbit with a period of 7 hours and 45 minutes. The pulsar itself is an excellent clock, rotating once every 59 msec. Timing the radio pulses arriving at the radio telescope in Arecibo, Puerto Rico, can be done with an accuracy of a few tens of microseconds. As a result, this became the binary system with the best known orbital parameters. It seems that the companion is also a neutron star, and the two objects may be treated as two point masses while one is analyzing the dynamics of their orbit. Gravitational radiation should remove energy from the binary and should reduce the binary period P at the dimensionless rate $dP/dt = -2.403 \pm 0.005 \times 10^{-12}$. The best recent observations give the empirical value of $dP/dt = -2.30 \pm 0.22 \times 10^{-12}$ (*12*). It is likely that in a few years the observational errors will be reduced by an order of magnitude. If the observed rate agrees with that predicted by general relativity to an accuracy of 1 percent, then it will be very difficult to imagine that the period change is an unrelated phenomenon and that the agreement is just a coincidence. The present agreement at the level of 10 percent is highly suggestive evidence for gravitational radiation. For agreement at the 1 percent level that is likely to be accepted as a proof, there would be increasing confidence in general relativity and indirect support for the inferred existence of black holes in Cygnus X-1 and LMC X-3.

Accretion Disks

Some relatively nearby binaries exhibit phenomena similar to those displayed on a much larger scale by very distant active galactic nuclei and by quasars. The characteristic linear scale of galactic nuclei is larger by many orders of magnitude than the scale of close binaries. Therefore, the characteristic time scale for any variations is orders of magnitude longer in galactic nuclei than in binaries. This makes binaries much easier to study and to understand within the limited lifetime of the astronomers. Among many possible phenomena and structures that may be similar in these two different types of objects, there are two that are most interesting: accretion disks and jets.



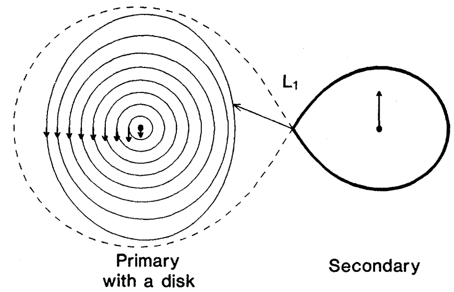


Fig. 2 (left). The two components of the binary system ζ Phoenicis are shown as circles. Their relative dimensions and the separation were deduced from the light curve shown in Fig. 1A. Their velocities, indicated with arrows, were measured spectroscopically (see Fig. 1). The infinity-shaped figure drawn with a dashed line represents the Roche surface around the two stars. Fig. 3 (right). A schematic picture of a cataclysmic binary. The primary is a very compact star: a white dwarf, a neutron star, or a black hole. The secondary is a solar type (that is, main-sequence) star. It slightly overflows its Roche lobe. Tidal forces due to the primary pull matter through the vicinity of the inner Lagrangian point, L_1, toward the primary. Coriolis forces deflect the stream of gas and let it collide with the outer rim of a gaseous accretion disk rotating around the primary. Arrows indicate the orbital velocities of the two stars and the rotational velocity of the disk.

There is a large class of very compact binaries, called cataclysmic because of their violent activity (*16, 17*), ranging from minor flares to fair-sized dwarf nova eruptions to powerful explosions of novae. It is also possible that type I supernovae are the end products of the evolution of some cataclysmic binaries. Supernovae are the most powerful stellar explosions known, energetic enough to destroy a whole star. A standard geometrical model of a cataclysmic binary is shown in Fig. 3. Their typical orbital periods are a few hours. The shortest of all known binary periods is 17.5 minutes. This record belongs to a cataclysmic star, AM Canum Venaticorum (*18*).

The more massive component of a cataclysmic system is a compact star of about 1 $M_{\odot}$. The less massive secondary is usually a main-sequence star. It overflows its Roche lobe slightly and loses matter through the vicinity of inner Lagrangian point (L_1) because of tidal forces induced by the primary. The outflowing gas is deflected by the Coriolis forces and collides with an outer rim of gaseous disk rotating around the primary. A disk is like a thin star. It is rotationally supported against the gravitational pull of the centrally located primary. Ordinary stars are supported against their own gravity with a pressure gradient.

Most of the energy radiated by a cataclysmic binary is generated by viscous dissipation in a differentially rotating disk. The inner parts of the disk rotate faster than the outer parts. This gives rise to a shear flow. Viscosity generates a lot of heat throughout the disk, and it also transfers angular momentum outward. From the outer rim of the disk angular momentum is transferred back to the binary orbital motion through the tidal forces induced by the secondary. Outward transport of angular momentum forces disk matter to spiral toward the primary. The ultimate source of energy is gravitational. Disk luminosity may be calculated as a product of the rate of mass accretion and the gravitational binding energy at the surface of the primary. The smaller the stellar radius, the larger the binding energy and the more efficient the accretion disk "engine." This is why it is most efficient to have a compact star at the center.

The most popular model for the central parts of an active galactic nucleus or a quasar is an accretion disk around a supermassive black hole (*14*). This makes it fairly similar to the popular model of a cataclysmic binary. There is one major problem with both models. It is not known what physical processes give rise to disk accretion (*19*). Ordinary "molecular" viscosity is too small by many orders of magnitude. Magnetic fields and turbulent motions are likely to be important, but it is not known how to calculate their effect on disk evolution. In practice, one is forced to compensate for one's lack of knowledge by introducing some free parameters in the model.

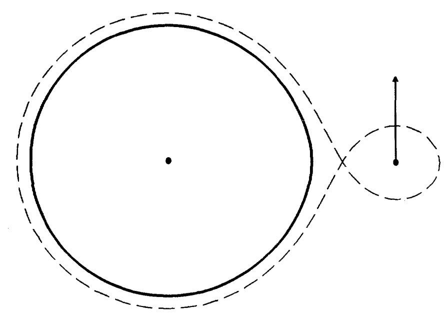


Fig. 4. A schematic picture of a binary system with a mass ratio 20:1. The big star, the more massive primary, almost fills its Roche lobe, the dashed line. A low-mass secondary is much smaller than its Roche lobe.

Studies of cataclysmic binaries are easier than studies of active galactic nuclei. Binaries are smaller, and therefore all variations have shorter time scales. For example, a few decades of observations contributed to the development of a phenomenological model of disk instabilities in dwarf novae. Recently, many groups more or less independently developed a disk model that reproduces the observed instability and relates it to the partial ionization of hydrogen and helium in the outer parts of an accretion disk (*20*). Rapid progress in the development of those models and the availability of a large number of easily observable dwarf novae leave little doubt that the understanding of processes involved in disk accretion will increase rapidly in the near future. Application of models to the more difficult stellar and extragalactic objects will become possible. Certainly, the most important development would be a realistic model of a quasar. But there are less dramatic opportunities, too. For example, there are reasons to believe that many stars that are forming now, and have not yet reached their location on the main sequence, have extended disks around them. Some disks may be predecessors of planetary systems (*21*). Some, like FU Orionis stars, may have unstable accretion disks, just like dwarf novae (*22*). However, those disks are a few hundred times larger than those found in dwarf novae. Therefore, eruptions of FU Orionis stars may last more than 10 years, while the eruption of a dwarf nova lasts only a week.

Jets

Radio jets, some expanding with highly relativistic velocity, are known to be ejected from some active galactic nuclei and quasars (*14*). These are among the most spectacular phenomena in the universe. They are studied on scales as small as 1 parsec (3×10^{18} cm), and as large as 1 megaparsec (3×10^{24} cm). Jets are found very close to the "central engine," most likely streaming along the rotation axis of an accretion disk that spins around a supermassive black hole. Enormous energies are transmitted with jets to the distant "radio lobes" where jets collide with tenuous intergalactic matter. In spite of considerable effort the formation of jets and their dynamics are poorly understood. Similar phenomena are observed on a much smaller scale in two binaries in our own galaxy. These are Scorpio X-1 (*23*) and SS 433 (*24*).

Scorpio X-1 is the brightest x-ray source in the night sky. It is a binary with an orbital period of 0.787 days and a prominent disk accreting onto a neutron star or a black hole. Scorpio X-1 is also a triple radio source, pretty much like a typical radio galaxy, but on a scale millions of times smaller. The central radio source coincides with optical and radio images of Scorpio X-1. On the two sides there are two additional radio sources, presumably formed in a collision between the jets and interstellar matter. It is most puzzling that recent observations failed to detect any motion of the outer radio sources (*23*). In fact, a surprisingly small upper limit of 32 km sec^{-1} has been put on their velocity. There is no hope to achieve a comparable accuracy of measurement for any extragalactic radio source in the foreseeable future.

The binary system SS 433 has an orbital period of 13 days and an accretion disk that precesses with a period of 164 days. The most spectacular phenomenon is a pair of gaseous jets outflowing along the rotation axis of the disk in opposite directions, each with a velocity of 80,000 km sec^{-1}, that is, just over a quarter of the speed of light. The twin jets precess with a period of 164 days, just like the disk, and over thousands of years they have produced a huge bubble in the interstellar medium.

The two binaries with jets are very different from each other, and their jets are very different also. There is no good model for them, and this gives little credibility to models of much more powerful jets generated by active galactic nuclei and quasars. It is clear that a lot of work must be done before these phenomena will be understood. Scorpio X-1 and SS 433 offer a very convenient testing ground for theories of jets. We may hope that by understanding them we may come to understand their powerful extragalactic relatives.

Evolution of Close Binaries

Binaries with orbital periods in excess of about 10 years have their components so far apart that they evolve as two single stars. Neither star can affect the internal structure or the evolution of the companion. The evolution of single stars is reasonably well understood (*7*). While on the main sequence, they burn hydrogen into helium. When hydrogen is exhausted in the core, the core contracts and heats up. After some time helium ignites and burns into carbon. The sequence of nuclear reactions in the cores of massive stars can lead all the way to iron. In low mass stars this chain is terminated with carbon or oxygen. While this nuclear evolution proceeds in the deep interior, the outer part of the star, its envelope, gradually expands. The star becomes first a red giant and later a supergiant, almost as big as our planetary system. The evolution may be terminated in two ways. A star initially less massive than about 8 $M_{\odot}$ loses its envelope upon becoming a red supergiant. The loss is gradual and supplies fresh matter into the interstellar medium. A hot stellar core is left. It slowly cools and finally becomes a white dwarf. More massive stars die more violently. Their cores are too massive to support themselves against gravity when they run out of nuclear fuel. They collapse and become neutron stars. The collapse of a very massive star is likely to produce a black hole. Tremendous energy released in the process is believed to give rise to a supernova explosion and the violent ejection of the outer layers of the star.

How is this scheme changed if a star has a nearby companion? To be effective the companion must be at a distance not larger than the largest extent of the primary. The primary is the star that is initially the more massive of the two (the companion is called the secondary). As a result of its nuclear evolution, the primary expands, fills its Roche lobe, and starts transferring matter to the secondary (*25, 26*). Observations and model calculations show that well over 50 percent of the primary's mass is transferred, and the secondary becomes the more massive of the two stars. There is an enormous variety of possible evolutionary patterns, depending on the initial masses of the two stars and their initial separation (*2*). It seems that the qualitative features of binary evolution and mass transfer between the components are reasonably well understood but there are only a few binaries for which a detailed successful model has been calculated (*27*). There is a major uncertainty about the mass loss rates of binaries undergoing vigorous mass transfer. Also, it is not known how much angular momentum may be carried away from a binary. This problem is as difficult as the problem of mass outflow from single stars. It appears from observations that the high rate of loss of matter by luminous stars is important for their evolution. Unfortunately, there is no generally accepted theory for the phenomenon (*21*). The rate at which angular momentum may be lost is even more difficult to estimate, not only theoretically but also observationally.

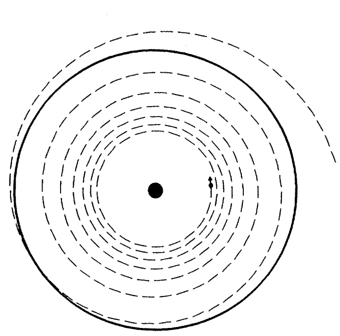


Fig. 5. A schematic picture of the evolution of a binary system with a very large initial mass ratio. The low-mass secondary spirals through the expanding common envelope toward the dense core of the primary.

It is very likely that the concept of a Roche lobe, which turned out to be so fruitful for understanding the evolution of many binary systems, may not be useful when the mass ratio is very different from unity. As an example, a schematic picture of a binary with a mass ratio 20:1 is shown in Fig. 4. The moment of inertia due to orbital motion is smaller than the primary's moment of inertia due to internal structure. The concept of Roche lobes is useful as long as we may assume that the two components rotate synchronously with their binary motion. The synchronism is easy to maintain if the internal stellar moments of inertia are small as compared to the orbital moment of inertia. This is certainly so when the two stars have comparable masses. It is no longer true when their mass ratio is 20:1. While the massive primary gradually expands, its moment of inertia increases. The tides due to the secondary component try to enforce the synchronous rotation of the primary. A large part of the orbital angular momentum is used to spin up the expanding primary. This transfer of angular momentum forces the binary orbit to shrink. The secondary star spirals toward the primary, sinks in the extended envelope, and later spirals down toward the primary's core as shown in Fig. 5. Because of its angular momentum, the secondary cannot just fall straight down onto the core. While moving through the extended envelope, it experiences a strong drag. This drag transfers angular momentum from the secondary to the envelope, allows the secondary to spiral in, and dissipates a lot of energy.

We may expect two different outcomes from this type of evolution. In the first case the energy released during the spiral-in phase is so large that it cannot be radiated fast enough from the stellar surface. The common envelope first expands, and later it is driven away. The binary is left with much reduced mass and separation, and with a much smaller orbital angular momentum and period. The bulk of initial mass and angular momentum has been carried away with the expelled envelope. In the second case the energy released during the spiral-in phase is not sufficient to disrupt the envelope. The process continues until the secondary merges with the primary's core. The binary fuses, and a single star is left. It is very difficult to model this type of evolution, as the problem is really three-dimensional and time-dependent. However, it is to be expected that the first scenario may be valid when the secondary mass is not too small, whereas the second scenario is more likely when the secondary mass is really tiny. Ultimately, theory and observations should make more quantitative statements possible.

Binary evolution through a common envelope stage should be about as frequent as binary evolution for which Roche lobes and the mass transfer concept are useful. However, the common envelope scenario is much more difficult to deal with. It has been invented rather late, and it has not yet received sufficient study (*28*). Nevertheless, it is generally accepted that common envelope evolution is needed to explain the formation of cataclysmic binaries. Even though not a single case of a common envelope binary has been observed so far, there are binaries that have recently emerged from their common envelopes. These are the short-period systems discovered in the centers of some planetary nebulae (*29*). The nebulae are the original common envelopes ejected some 10,000 years ago. It is very likely that future progress in this area will be semiobservational and semitheoretical, with theory organizing a rich "zoo" of observed objects into a plausible evolutionary pattern.

References and Notes

1. H. A. Abt, *Annu. Rev. Astron. Astrophys.* **21**, 343 (1983).
2. V. Trimble, *Nature (London)* **303**, 137 (1983).
3. J. M. Retterer and I. R. King, *Astrophys. J.* **254**, 214 (1982).
4. J. V. Clausen, K. Gyldenkerne, B. Gronbech, *Astron. Astrophys.* **46**, 205 (1976).
5. D. M. Popper, *Astrophys. J.* **162**, 925 (1970).
6. ——, *Annu. Rev. Astron. Astrophys.* **18**, 115 (1980).
7. I. Iben, Jr., *ibid.* **12**, 215 (1974).
8. S. Chandrasekhar, *An Introduction to the Study of Stellar Structure* (Univ. of Chicago Press, Chicago, 1939); J. Liebert, *Annu. Rev. Astron. Astrophys.* **18**, 363 (1980).
9. R. N. Manchester and J. H. Taylor, *Pulsars*, (Freeman, San Francisco, 1977); W. Sieber and R. Wielebinski, Eds., International Astronomical Union Symposium No. 95, *Pulsars* (Reidel, Dordrecht, Netherlands, 1980).
10. J. N. Bahcall, *Annu. Rev. Astron. Astrophys.* **16**, 241 (1978).
11. P. C. Joss and S. A. Rappaport, *ibid.*, in press.
12. J. H. Taylor and J. M. Weisberg, *Astrophys. J.* **253**, 908 (1982).
13. S. L. Shapiro and S. A. Teukolsky, *Black Holes, White Dwarfs, and Neutron Stars* (Wiley, New York, 1983).
14. M. J. Rees, *Q. J. R. Astron. Soc.* **18**, 429 (1977); J. B. Hutchings, *Publ. Astron. Soc. Pac.* **95**, 799 (1983).
15. A. P. Cowley, D. Crampton, J. B. Hutchings, R. Remillard, J. Penfold, *Astrophys. J.* **272**, 118 (1983).
16. E. L. Robinson, *Annu. Rev. Astron. Astrophys.* **14**, 119 (1976).
17. J. S. Gallagher and S. Starrfield, *ibid.* **16**, 171 (1978).
18. J. Smak, *Acta Astron.* **17**, 255 (1967); J. Patterson, R. E. Nather, E. L. Robinson, F. Handler, *Astrophys. J.* **232**, 819 (1979).
19. J. E. Pringle, *Annu. Rev. Astron. Astrophys.* **19**, 137 (1981).
20. R. Hoshi, *Prog. Theor. Phys.* **61**, 1307 (1979); F. Meyer and E. Meyer-Hofmeister, *Astron. Astrophys.* **104**, L10 (1981); J. Smak, *Acta Astron.* **32**, 199 (1982); J. K. Cannizzo, P. Ghosh, J. C. Wheeler, *Astrophys. J.* **260**, L83 (1982); for a review, see J. Smak, *Publ. Astron. Soc. Pac.*, in press.
21. D. Sugimoto, D. Q. Lamb, N. D. Schramm, Eds., International Astronomical Union Symposium No. 93, *Fundamental Problems in the Theory of Stellar Evolution* (Reidel, Dordrecht, Netherlands, 1980).
22. B. Paczyński, paper presented at the First European Conference on Astronomy, Leicester, England, 1975 [reported by V. Trimble, *Q. J. R. Astron. Soc.* **17**, 31 (1976)].
23. E. W. Gottlieb, E. L. Wright, W. Liller, *Astrophys. J.* **195**, L33 (1975); E. B. Fomalont, B. J. Geldzahler, R. M. Hjellming, C. M. Wade, *ibid.* **275**, 802 (1983).
24. B. Margon, H. C. Ford, S. A. Grandi, R. P. Stone, *ibid.* **233**, L63 (1979); J. I. Katz, S. F. Anderson, B. Margon, S. A. Grandi, *ibid.* **260**, 780 (1982); K. Davidson and R. McCray, *ibid.* **241**, 1082 (1980).
25. H.-C. Thomas, *Annu. Rev. Astron. Astrophys.* **15**, 127 (1977).
26. F. H. Shu and S. H. Lubow, *ibid.* **19**, 277 (1981).
27. S. Refsdal, M. L. Roth, A. Weigert, *Astron. Astrophys.* **36**, 113 (1974).
28. J. P. Ostriker, personal communication; B. Paczyński, in International Astronomical Union Symposium No. 73 (Reidel, Dordrecht, Netherlands, 1976), p. 75; H. Ritter, *Mon. Not. R. Astron. Soc.* **175**, 279 (1976); R. E. Taam, P. Bodenheimer, J. P. Ostriker, *Astrophys. J.* **222**, 269 (1978); F. Meyer and E. Meyer-Hofmeister, *Astron. Astrophys.* **78**, 167 (1979); M. Livio, J. Saltzman, G. Shaviv, *Mon. Not. R. Astron. Soc.* **188**, 1 (1980); M. Livio, *Astron. Astrophys.* **105**, 37 (1982).
29. H. E. Bond, in *Cataclysmic Variables and Low-Mass X-Ray Binaries*, J. Patterson and D. Q. Lamb, Ed. (Reidel, Dordrecht, Netherlands, in press).

30. This work was supported by NSF grant AST-8317116.

Dynamic Structure of Membranes by Deuterium NMR

Rebecca L. Smith and Eric Oldfield

Summary. Progress in our understanding of the dynamic structure of membrane lipids and proteins has recently been made possible by the advent of high-field "solid-state" nuclear magnetic resonance spectroscopic studies of specifically deuterium-labeled systems. Major features of lipid and protein dynamics have been deduced.

Cell membranes are composed predominantly of lipids, proteins, and sterol molecules and are responsible for a wide variety of biochemical processes, including respiration, vision, photosynthesis, cell-cell recognition, and nerve impulse transmission. Not surprisingly, then, considerable efforts have been spent over the years in trying to characterize both the molecular structures of and intermolecular interactions between the individual membrane components in an attempt to relate the structure of membranes to their function. One of the most successful models of membrane structure which has emerged is the 1972 fluid mosaic model of Singer and Nicolson (*1*). This envisions membrane proteins as being dispersed in a fluid, liquid crystalline lipid bilayer, and is undoubtedly correct for many membrane systems. It is, however, by its nature a macroscopic rather than microscopic model of membrane structure, and there is now considerable interest in obtaining more detailed information on the actual structural details of, for example, protein-lipid interactions, or on the static and dynamic structure of membrane proteins (*2, 3*).

In this article we discuss recent advances in our understanding of lipid and protein dynamics in membranes, including some details of lipid-protein and lipid-sterol interactions and of cell surface dynamics, which have been made available primarily by observations of deuterium nuclear magnetic resonance (NMR) spectra of specifically ^{2}H-labeled species incorporated into both model and intact functional biological membranes. Such detailed experiments were not technically feasible at the time of the Singer-Nicolson hypothesis (*1*), when only relatively crude information on membrane structure could be obtained by the ^{2}H NMR method (*4, 5*). Recent advances in instrumentation—specifically the availability of high-field superconducting magnets for added sensitivity and improved pulse techniques for improved spectral line shape rendition (*6*)—now permit data acquisition at rates three or four orders of magnitude higher than in the early studies. This has opened up new vistas in membrane research, in particular, as discussed below, in the ability to monitor dynamic events in membrane proteins themselves.

Information from Spectra

Currently, most NMR studies of membrane structure employ the ^{2}H NMR method with high-field ($\sim$ 3.5 to 11.7 tesla) superconducting magnets and Fourier transform pulse methods (*6*) to investigate the line shapes, quadrupole splittings, and spin-lattice relaxation times of specifically ^{2}H-labeled species (lipids, sterols, or amino acids in proteins) introduced into the system of in-

Rebecca L. Smith is a research assistant and Eric Oldfield is a professor of chemistry at the University of Illinois at Urbana-Champaign, Urbana 61801.