Dancing with Stars

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Binary Stellar Evolution

1. Multiple Stars

Cecelia Payne-Gaposhkin was a pioneer of modern astronomy. She devoted much of her research to the study of multiple star systems and coined a comic adage to describe one of the basic tenets of that work: “Three out of every two stars are in a binary system.” By this she meant to illustrate that roughly half the stars in the sky have companion stars in orbit. If you were to look closely at half the stars you would find that there are two stars where a more casual examination would have revealed only one point of light. Many people know that the nearest star to the Sun is Alpha Centauri. Less well known is that Alpha Centauri has a companion in wide orbit, known as Proxima Centauri. A closer examination shows that Alpha Centauri itself is not a single star but has a closely orbiting companion as well. Of the “two” stars closest to the Sun, three are in the same mutually orbiting stellar system.

Stars occur in many combinations. Single stars and pairs are most common, but some systems contain four and five stars in mutual orbit. In this chapter, we will concentrate on the systems with a pair of stars, double stars, or, somewhat more technically, binary stars (but we try to refer to the phenomenon of duplicity, not the mangled–jargon born “binarity” that creeps into the literature). Binary stars come in two basic classes: wide and close. Wide binaries are stars in large, long-period orbits. Such systems probably formed by the accidental gravitational capture of two stars born separately. These stars will evolve independently, as two separate single stars. That they are a gravitational pair will not concern us much here. Of greater interest, because of the effect on the evolution of the stars, are the close binaries. These systems probably formed by the fragmentation of an initial single protostellar clump. Triple and quadruple systems probably formed in the same way. These close pairs are of particular significance because the presence of a nearby companion profoundly alters the course of stellar evolution.

2. Stellar Orbits

The force of gravity and the principles of conservation of linear and angular momentum govern the orbits of a pair of stars. Recall from Chapter 1 that linear momentum is the product of mass multiplied by velocity, whereas angular momentum, or spin, is the product of the mass, the velocity, and the size of the object under consideration.

Orbits of stars are very nearly ellipses. This is not exactly true if one considers the small effects of the complete theory of gravity as described by Einstein's general theory of relativity, but the assumption that orbits are ellipses is adequate for all our purposes now. We will mostly consider orbits that are the simplest special case of ellipses, namely circles. Two stars orbit one another on elliptical paths around a common *center of mass*. This center of mass can drift through space, but for simplicity we will pretend that there is no net motion of the two stars. Although the two stars share the same sense of the orbit, for instance clockwise, at any given moment, the individual stars move in opposite directions in their mutual orbital dance. They must do so to conserve the linear momentum, to keep the net momentum constant and equal to zero. If they moved in the same direction, the momentum would be first directed in one direction and later in another in violation of the principle of conservation of momentum. Nature does not allow such behavior. The sizes of the orbits are different if the masses of the two stars are different. Again to balance momentum, the smaller-mass star must move faster in the opposite direction to offset the momentum of the larger-mass star. The *period*, or the time for the stars to complete an orbit, must be the same for both. When the first star has traveled all around the second, the second cannot have traveled only part way around the first. If the smaller star moves faster but takes the same amount of time to complete an orbit as the more massive star, then the smaller star must cover more distance. The orbit of the smaller star must be larger.

Similar laws govern the orbits of the planets around the Sun. The planets move in relatively large orbits about the center of mass that lies between the planets and the Sun. At the same time, the Sun is not completely stationary but moves in a tiny orbit about the center of mass. The size of the Sun's orbit is about the same as the physical size of the Sun itself. The Sun moves at about 30 miles per hour, a small but measurable speed. The presence of large planets around nearby stars was recently established with techniques to measure such speeds. The Sun's orbit is fairly complex in detail. Although the Sun mostly responds to Jupiter, the Sun is trying to orbit around the center of mass of nine planets at once.

Using the data on planetary motion carefully garnered by his mentor, the Danish astronomer Tycho Brahe, Johannes Kepler deduced empirically that planets move on ellipses (his first law) and that the period of the orbit is simply related to the size of the orbit (his third law). The angular momentum of the orbital motion depends on the mass and velocity of the two stars, just as the linear momentum does. The angular momentum also depends on the size of the orbits. For this reason, the angular momentum helps to determine exactly how big the orbits will be for two stars of given mass and velocity. Kepler's second law of orbital motion comes about because the angular momentum of each star about the center of mass is constant.

With the help of Newton's law of gravity, we now interpret Kepler's third law as saying that the square of the period, P, of an orbit is proportional to the cube of the size, a, of the orbit divided by the total mass, $Mtot$, of the two orbiting stars. This law and the understanding of it are crucial in astronomy. The relation between period, orbital size, and mass provides the only reasonably direct way to measure the masses of stars. For two stars in a binary system, astronomers can measure the period fairly easily and the separation between the two stars with some difficulty. These two pieces of information and Kepler's third law as codified by Newton determine the total mass of the system. Astronomers must obtain other information to suggest how much of the mass is in each star. One of the reasons why the study of double-star systems is so important is that double-stars provide direct information on the masses of stars.

3. Roche Lobes: The Cult Symbol

Before reading this section you must assume the posture and repeat the oath of secrecy. Curl your right arm over your head and place the fingers of your right hand on your left shoulder. Then curl your left arm so that the fingers of your left hand also touch your left shoulder. Now whisper loudly, “I solemnly swear not to reveal what I am about to learn to anyone upon penalty of being ridiculed by my peers.” As we proceed with this chapter you will find that the significance of the posture is that your brains were about to undergo mass transfer onto your shoulder.

For two stars in a binary system, each reaches out to gravitationally dominate some region beyond its own surface, as shown in Figure 3.1. The more massive star, the star on the left in Figure 3.1, has a larger sphere of influence. If one carefully maps the regions of influence of each star, accounting for the complexities of the fact that each star is moving in orbit, you find that the boundary of the two regions, seen in cross section, resembles a figure eight turned on its side. The two halves of the figure are called *Roche lobes* after the German scientist who first worked out their mathematical form. The physical importance of these gravitational lobes is so great that no lecture on binary stars can continue without a sketch of the famous figure. For this reason one of our colleagues refers to this sketch as the “cult symbol” of the priesthood of the binary-star specialists.

The neck of the figure where the two lobes join is called the first or *inner Lagrangian point,* after the French mathematician Lagrange who also studied these systems. This point represents the position in space where the pull of gravity from the two stars just balances. A slight tip in either direction will send a bit of matter falling toward one star or the other. Beyond the surface of the Roche lobes, matter would belong to neither star but would be comfortable to orbit both of them. On a line extending out through the stars are the second and third Lagrangian points. Beyond these points, centrifugal forces overwhelm the combined pull of gravity of the two stars and tend to throw matter out of the system completely. At right angles to the line between the stars, one finds the fourth and fifth Lagrangian points. These are of little interest to us in the present context, but these Lagrangian points are potentially important in the subject of space colonization, as past members of the L5 Society will know (the fifth Lagrangian point was their cult symbol). The fourth and fifth points are locations at which a third body is locked in a stable position in the gravity of the two main objects. The idea is that this would be a good place to locate an artificial space colony between Earth and the Moon.

4. The First Stage of Binary Evolution: The Algol Paradox

One of the first lessons learned in the study of binary star systems is that the presence of a companion alters the course of evolution. Recall one of the most important aspects of the evolution of single stars. More massive stars have more fuel to burn, but they burn the fuel at a profligate rate. As a result, massive stars live a much shorter time than smaller-mass stars that hoard their meager allotment of hydrogen fuel. Given this most important lesson, how are we to understand the demon star Algol?

The star Algol presents a blue-white appearance to the eye. Algol also appears to be brighter and then dimmer every few days. When it is dimmer, it appears to be a little redder. In some early cultures a red, winking light in the sky did not bode well. Thus Algol acquired the name the demon star, “Algol” being the Arabic word for demon. We now understand that Algol is a binary system. The red appearance comes because one of the stars is an evolved red giant. The winking derives from the fact that we happen to be looking almost edge-on to the orbits of the stars and hence witness the eclipses as each star in turn moves in front of the other. The slight reddening occurs because one of the stars is a red giant, and we see more of its light and less from that of the blue-white companion when the red giant is in front. We can go a step farther. Because one star has already evolved and has become a red giant, and the other star is still on the main sequence, we know which is the more massive. The red giant has evolved first so the red giant must be the more massive.

Wrong! From the measured period, some astronomical tricks, and Kepler's ever-handy third law, we can work out the masses and find that the red giant has a mass of about 0.5 solar mass, whereas the main sequence star has 2–3 solar masses. This is the *Algol paradox.* How can the evolved star be the less massive one?

To resolve the paradox, we hold firm to the idea that the red giant must originally have been the more massive in order for it to have evolved first. Our basic lessons are impeccable there. The key to resolving the paradox is that, unlike most single stars, close binary stars do not retain the mass with which they were born. When two stars are close together, as in the Algol system, one star can transfer mass to the other. The star that was the most massive became a red giant and then transferred mass to the other star until the mass ratio reversed completely: the originally more massive star became the less massive, and the originally less massive became the more massive.

5. Mass Transfer

To see how this process of mass transfer occurs, we must return to the meaning of the cult symbol, the Roche lobes. Even in a binary system, evolution begins on its normal course. Two stars in a close binary system are presumably born out of the same fragment of interstellar gas, and hence born at the same time. These are fraternal, not identical, twins, however. The chances of the stars being of identical mass are virtually nil. One star will be appreciably more massive than the other. The more massive star uses up its supply of hydrogen in the center and begins to evolve first. The core shrinks, the envelope expands, and the star begins to become a red giant. The more massive star has a greater gravitational domain and hence the larger Roche lobe. The size of the lobe is still finite, however – roughly the same size as the distance between the stars, as you can see from Figure 3.1. As long as the stars are closer together than the eventual size the red giant would normally attain, the presence of the companion star interrupts the normal evolution. This interruption of the evolution is the basic criterion for whether a given binary system is categorized as a close binary system.

The story must change when the more massive star expands to the point where that star fills its Roche lobe. The internal forces of core contraction continue to cause the envelope to expand. As the outer parts of the star pass beyond the Roche lobe, however, they are beyond the gravitational influence of the star from which they came. When that happens, the matter that has moved out beyond the star's Roche lobe no longer belongs to that star. Some of the mass will take up a swirling orbit around both stars, but a great deal will find itself forced through the neck at the inner Lagrangian point joining the Roche lobes of the two stars. Matter that passes through the inner Lagrangian point now finds itself within the gravitational region of influence of the second star. The more massive star transfers matter through the inner Lagrangian point to the other star.

This mass-transfer process is unstable and results in rapid changes in the stars. To see this, recall the nature of the Roche lobes. The more massive star has the larger lobe. The star evolves, fills its lobe, and begins to lose mass. As the star loses mass, the star has a smaller region of influence, so its Roche lobe shrinks, as illustrated in Figure 3.2. Matter otherwise safely attached to the star finds itself cast adrift because the Roche lobe is smaller. That causes the loss of even more mass, resulting in an even smaller Roche lobe. A positive feedback operates in the sense that the more mass the star loses, the more it is forced to lose. The more massive star only approaches the condition of mass loss on the relatively slow time dictated by the contracting of the core. After the mass loss starts, however, it continues at a rapid pace independent of any internal changes in the structure of the star.

This rapid phase continues until the stars have equal mass – the bigger one having lost mass, and the smaller one having gained it. Up to this point, the stars have been spiraling closer together as the star transferred mass. This is due, in large part, to the conservation of angular momentum. Mass is being added to the less massive star that moves with a higher velocity. Higher mass at a higher velocity would mean excess angular momentum. The stars correct this problem by moving together since a smaller-size orbit has less angular momentum. That the stars get closer together during the rapid phase of mass transfer only enhances the rate of transfer because the Roche lobes of both stars, particularly of the star losing mass, get smaller as the stars move together (Figure 3.1).

Although it does slow down, the mass transfer does not halt after the stars attain the condition of equal mass. Now conservation of angular momentum works to make the stars spiral apart. As the star continues to lose mass, it is now the smaller-mass, higher-velocity star. Angular momentum would decrease if the star did not move to a larger-size orbit as mass moved from the more quickly moving star to the slower. The tendency for the stars to move apart once the mass-losing star becomes the less massive means that, as the star loses mass, its Roche lobe gets bigger, not smaller. In order for the mass transfer to continue, the star must expand to fill its new larger Roche lobe. This expansion occurs, but only on the longer time of the internal changes of the structure as the core contracts. The mass transfer no longer involves a positive feedback, and it is thus slower; but mass transfer will continue until the star ceases its attempt to become a red giant. The Algol system is presumably in this slow mass transfer phase.

6. Large Separation

When the two stars are of relatively large separation, but still close enough to qualify as a “close” binary, mass transfer does not begin until the more massive star has become nearly a full-fledged red giant. In this case, the mass-losing star will have a large envelope and a tiny core. The mass transfer continues until virtually the whole envelope vanishes and only the core remains.

If the original star was not too massive (less than about 8 solar masses), the core left behind will be dense and supported by the quantum pressure. It will just cool to become a white dwarf. The result will be a tiny white dwarf orbiting around a more massive main sequence star. The main sequence star will have grown in mass because it is the repository of much of the envelope matter that originally shrouded the white dwarf.

A more massive star (one originally more than about 8 solar masses) can leave a larger core behind. Such a core will be supported by thermal pressure. It can continue to evolve without the envelope by contracting and heating until new nuclear fuels ignite in its center. The likely outcome for such a core will be to develop an inner iron core that is susceptible to the inevitable collapse. The situation is then similar to that for single stars. The collapse could create an explosion that would leave a neutron star behind. Alternatively, the collapse could be complete, resulting in the formation of a black hole. The result is that we could reasonably envisage the creation of binary systems with a normal star orbiting any of the types of compact stellar remnants we have discussed: white dwarfs, neutron stars, or black holes. We will discuss these cases in Chapters 5, 8 and 10.

7. Small Separation

If the two stars are too close together, the stars evolve in a very different way. Stars swell a bit in size as they consume their hydrogen on the main sequence. This is because the helium that builds up in the center occupies less volume than the hydrogen did. When the helium contracts, the gravitational energy transfers to the outer parts of the star, causing those parts to gain energy, expand, and cool slightly. The process is very similar to that which causes a star to become a red giant, but on a much smaller scale. If the stars are very close together, even this gentle swelling on the main sequence can cause the more massive star to fill its Roche lobe.

The twist comes after the rapid phase of transfer halts, when the two stars have equal masses. Ordinarily, the mass-losing star is a red giant and is evolving internally so rapidly that the mass-receiving star, which is still on the main sequence, is a totally passive partner. In the present case, however, we end up with both stars still on the main sequence. The mass-losing star is evolving slowly, continuing to push mass onto its companion. The evolution of the companion speeds up as it gains mass. Normally, the speed-up is insignificant, but for the case of close stars, the second star also swells to fill its Roche lobe. Each star then tries to transfer mass to the other simultaneously. The situation gets quite messy.

One thing that surely happens with both stars shoving mass beyond their Roche lobes is that material escapes to the region where it surrounds both stars. This matter will orbit in a disk that is in the same plane as the orbit of the two stars and that surrounds both stars. Matter flows outward into this disk, so such configurations have been dubbed *excretion disks* to distinguish this flow from *accretion disks* where material settles inward. Accretion disks will be the topic of Chapter 4. The system probably ejects some material completely into the surrounding space.

Computer calculations show another interesting possibility. With both stars trying to move mass onto the other, only one can win. The calculations show that the star that had the smaller mass may win this contest, or lose it, depending on your point of view, in the sense that it transfers all its mass to the larger one. The big star consumes the little one! The net outcome is not some exotic binary, but a single star, perhaps surrounded by an excretion disk, the sole evidence of the cannibalism.

8. Evolution of the Second Star

In the standard picture where the star of initially smaller mass remains patiently on the main sequence until the other star completes its evolution, the second star eventually gets its turn. The second star will consume the hydrogen in its center, including perhaps some of that added by the other star. Then the second star will begin to swell as its core contracts, and it, too, will eventually fill its Roche lobe.

At this point, the second star will begin to lose mass to the first. The second star does not particularly care what form its companion is in; it will just proceed to push mass over onto it. From an astronomer's point of view, the results can be quite exciting because the star receiving the mass is a white dwarf, a neutron star, or a black hole – a compact star with a large gravitational field. The effect can be quite spectacular. Astronomers have observed many systems where a star is transferring mass to a compact star. Some of these binary systems with compact stars may have evolved in the rather clean way described in the previous paragraph, with the second star simply swelling to fill its Roche lobe. In other cases, we will see that the actual evolution is probably more complex.

9. Common-Envelope Phase

The principle factor that can spoil the simple picture of one star filling its Roche lobe and transferring matter to the other star that passively accepts the mass is that the second star is unlikely to be a completely passive partner. The mass-gaining star can resist the process, as happened for two main sequence stars very close together. The issue is, if neither star wants the mass, where does it go?

This issue arises more critically for stars that are more compact. For a star of a given mass, whether it is a main sequence star, a white dwarf, or a neutron star, the strength of the gravitational pull depends only on the distance from the center of the star. The gravity does get stronger, the closer one gets to the center of the star. For this reason, the gravity at the surface of a white dwarf is much greater than the gravity at the surface of a normal star of the same mass, and the gravity at the surface of a neutron star of the same mass is greater even yet. The implication is that, if matter falls from a mass-transferring star at a given rate onto a normal star, the impact of the matter with the stellar surface will liberate energy and create luminosity at a certain rate. If the same star transfers mass to a white dwarf at the same rate, the energy liberated when the matter strikes the white dwarf surface will be much greater, thus generating much more heat and a much larger luminosity. The case of a neutron star will be even more extreme. Although a black hole does not have a surface, matter can still respond to the effects of the strong gravity very near the black hole. The result can again be the generation of a large luminosity.

The luminosity generated by the matter that falls in can serve to resist that very infall. The luminosity flooding outward can exert a pressure. In the extreme case, and this case arises in common circumstances for neutron stars, the luminosity can exceed the Eddington limit (described in Chapter 2). This means that the infalling matter is creating a luminosity so great that the resulting pressure is sufficient to prevent the infall! Even in less extreme circumstances, the energy of infall can inhibit the infall. Faced with this resistance, some of the matter will not collect on the mass-gaining star but will go in orbit around both stars.

When this process gets extreme, the matter lost from one star goes predominantly into orbit around both stars, interacts with itself, and bloats to become an approximately spherical (in the imagination of theorists, anyway) bag of gas in which the core of the mass-losing star and the mass-gaining star orbit. The resulting configuration is known as a *common envelope* because the envelope of matter surrounds both stars.

This situation can profoundly affect the orbits of the stars. Now they are not orbiting in the vacuum of space but in a bag of gas. The gas resists their motion, the stars feel friction and drag, and their motion heats the gas. The drag will tend to slow the forward velocity. In the ever-present grip of gravity, the result will be that the stars spiral toward one another and end up orbiting even faster. This will create more friction, heat, and drag and cause the orbits to shrink even faster. The energy and angular momentum lost from the star goes into the common envelope at an ever-increasing rate.

The details of this process are not well understood, but the principle of conservation of energy gives insight into the general nature of the subsequent events. The gravitational energy from the decaying orbits eventually becomes equal to the gravitational energy that binds the common envelope to the two stars. At this point, the energy injected into the envelope by the motion of the stars will be sufficient to blow the envelope away. This process is not an explosion but something more like the ejection of a red-giant envelope to make a planetary nebula. The common envelope will be ejected, and the two stars – whatever configuration they may be in, the core of the mass-losing star and the mass-gaining star – will again orbit in the vacuum of space, but now they will be very close together. Astronomers think this process produces pairs of white dwarfs, neutron stars, and perhaps black holes, in addition to various combinations of these stars and normal stars. We will explore these combinations in Chapters 5, 8, and 10.

10. Gravitational Radiation

Suppose two stars have survived as compact stars, white dwarfs, neutron stars, or black holes that have weathered mass transfer from first the originally more massive star, then the originally less massive star and any intermediate common envelope phase. Now they are orbiting quietly in space. Is this the end of the story? The answer is no!

An important prediction of the general theory of relativity is that gravitational waves spread like ripples through curved space. If a wiggle occurs in the curvature of space, waves will propagate outward carrying off energy and momentum. Imagine an elastic rubber sheet on which you grab a pinch and shake it up and down or the act of poking your finger in the surface of a still pond. Ripples will move outward across the sheet or pond. Ripples in space-time will propagate in the elastic curved space described by general relativity.

Two stars moving in orbit cause a rhythmic change in the curvature of the space around themselves as they circle. The effect is as if you were to twirl a small paddle on the surface of a pond. Ripples spread out across the pond, and gravitational waves spread out through space away from the orbiting stars. The waves carry energy and angular momentum away from the stellar orbits and cause the stars to spiral closer together in the grip of gravity. Eventually, they must collide in some way. In some very special, but important, cases, this loss of energy can determine the life and death of stars. We will discuss these issues further in Chapter 6.