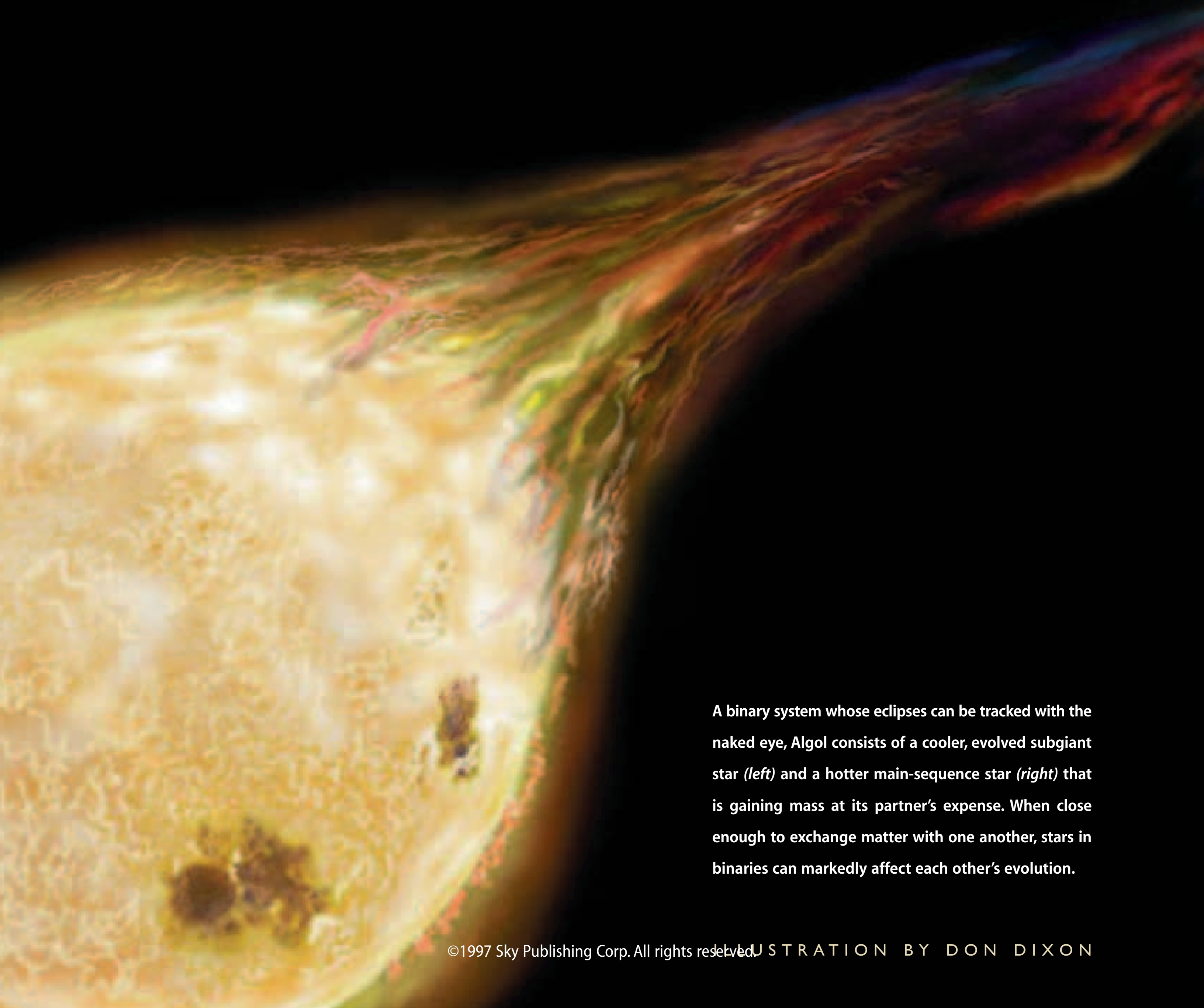
THE LIVES OF

FROM BIRTH TO DEATH AND BEYOND

SECOND OF TWO PARTS

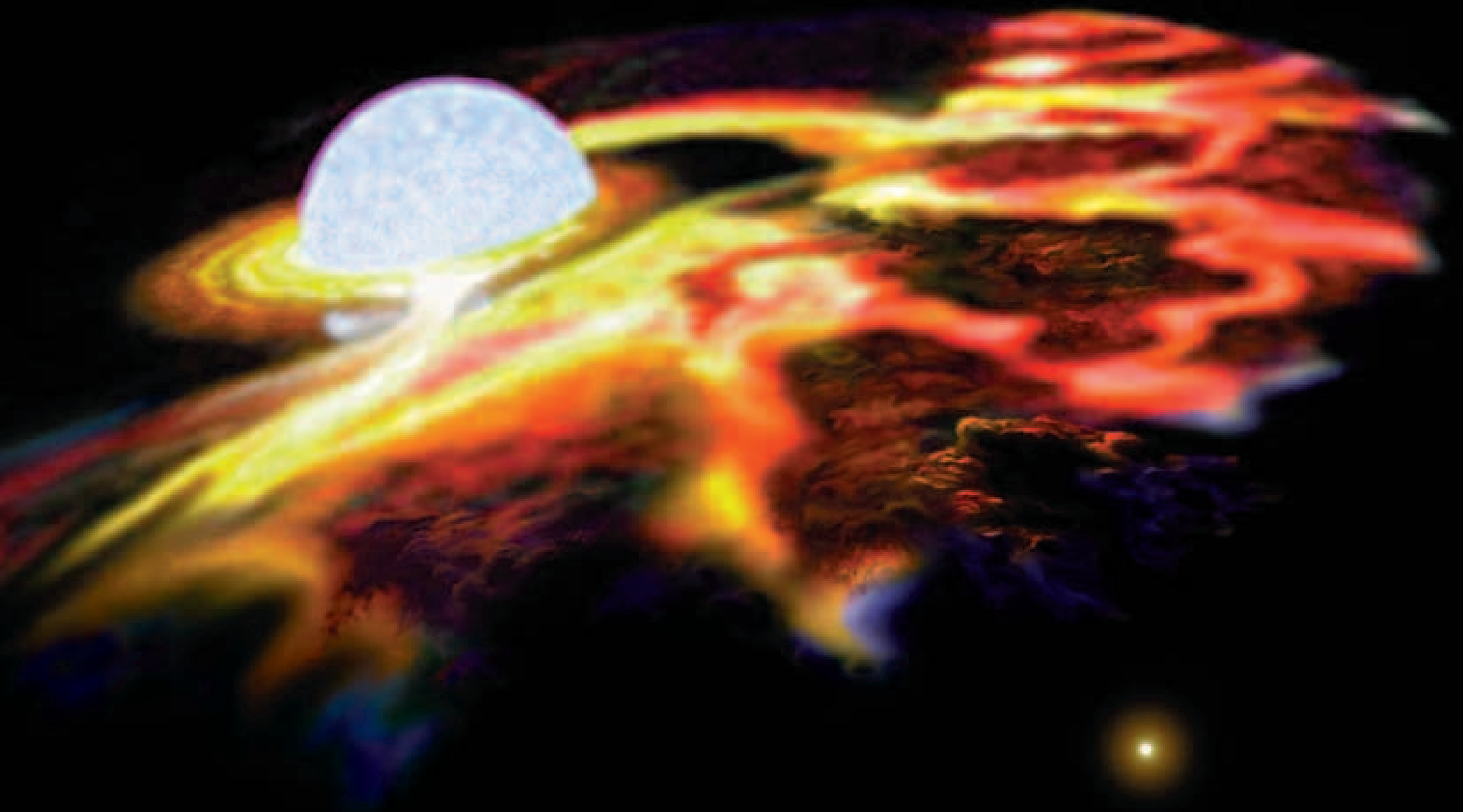
BY ICKO IBEN JR. AND ALEXANDER V. TUTUKOV



A binary system whose eclipses can be tracked with the naked eye, Algol consists of a cooler, evolved subgiant star *(left)* and a hotter main-sequence star *(right)* that is gaining mass at its partner's expense. When close enough to exchange matter with one another, stars in binaries can markedly affect each other's evolution.

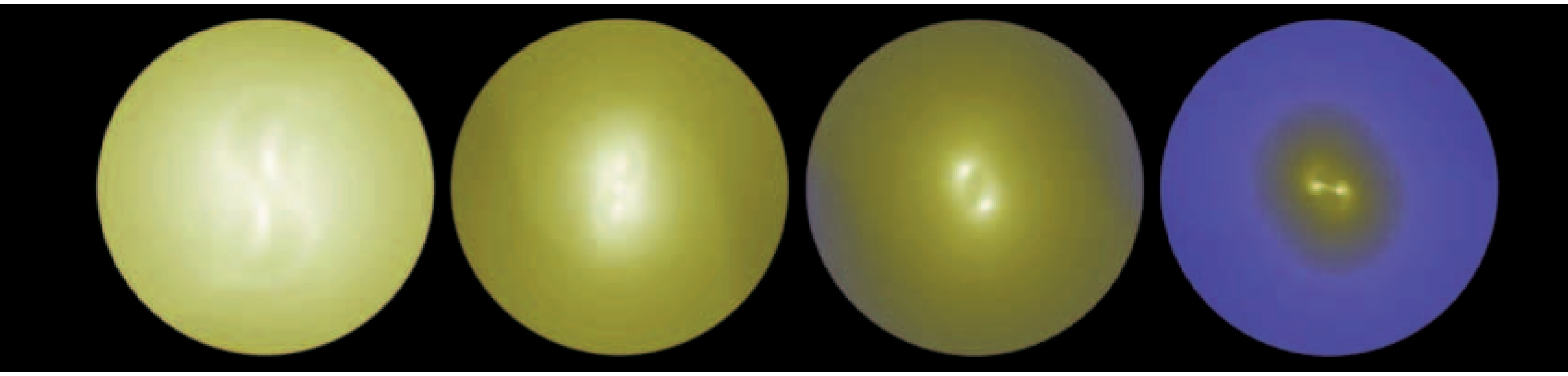
ILLUSTRATION BY DON DIXON

BINARY STARS



In the stellar life story we told last month, we pretended that stars form in isolation. However, observations show that most stars are found in binary systems whose individual members are bound to each other by gravity. Being in a binary can dramatically alter the way in which a star lives and dies — that is, if a star in the binary system is close enough to exchange material with its companion. Mass exchange gives rise to a panoply of exotic phenomena, including X-ray binaries, nova-producing cataclysmic variables, and supernovae. In each of these cases, one member of the binary system has evolved into a "dead" remnant, only to be reborn by the gift of material from its nearby companion.

ALAN P. BOSS

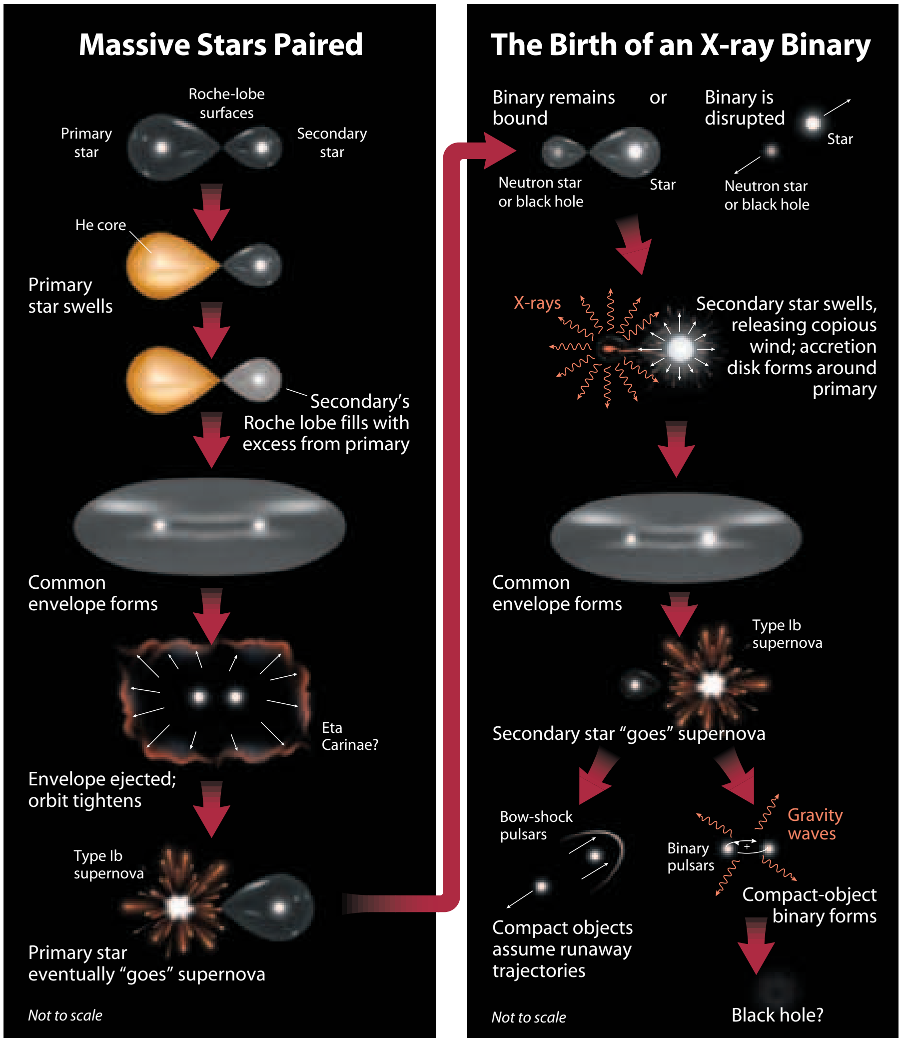


The birth of a binary. Whiter colors depict higher densities in this computer model of a rotating gas cloud that fragments into two protostars.

Scrambling Cosmic Eggs

As with solitary stars, initial mass largely dictates the evolution of stars in binary systems. For starters, the star with more mass at the outset (henceforth called the *primary*) evolves as if it were alone. After passing through its relatively stable hydrogen-fusion phase on the main sequence, the primary forms a helium core and expands until it fills its *Roche lobe* — its teardrop-shaped "sphere" of gravitational influence (see page 47). At this point, mass spills toward the smaller star (henceforth called the *secondary*). In a system with a relatively massive primary, material is transferred faster than it can be "digested" by the secondary. As a result, it eventually overflows the latter's Roche lobe as well. A *common envelope* forms, containing both stars in its interior.

The stars then act like a cosmic eggbeater, pumping their orbital energy into the envelope. As a result, the envelope matter is ejected while the binary star's orbit shrinks. Eta Carinae and SS 433 may be examples of binary stars in the process of ejecting their respective common envelopes.



SKY & TELESCOPE / GREGG DINDERMAN

After its envelope has been dispersed, a high-mass binary consists of a compact helium star and one that remains on the hydrogen-burning main sequence. The former, more evolved star "burns" helium (that is, fuses it into carbon) within its core. And if its mass is larger than about 30 Suns, it sheds so much matter that it becomes a Wolf-Rayet star. Ultimately, it loses the inexorable fight against gravity and collapses when nuclear reactions wane; the result is a supernova explosion. The supernova produces a neutron star if the primary initially held 40 solar masses or less; otherwise, a black hole results.

If the mass ejected by a binary's first supernova is less than that which remains in the two stars, those stars stay gravitationally bound to one another — though the binary will then have a very eccentric orbit and travel rapidly through space. This scenario may explain the origin of most stellar runaways, many of which show evidence for unseen low-mass companions that can be explained in this manner. On the other hand, if enough mass is lost during its first supernova explosion, a close, massive binary will be disrupted and its members will follow divergent, high-velocity trajectories.

X-raying the Sky

When a massive binary system does manage to survive its first supernova explosion, it may undergo a rather spectacular transformation even before the secondary explodes in turn. In binary systems that have survived a first supernova, the still-evolving star typically has a mass of more

A handful of binary pulsars has been found in our galaxy, and over the next several billion years some of them may merge, forming black holes and giving off enormous amounts of energy.

than 11 Suns. This means that after it forms its own helium core, the surviving star expands until it almost fills its Roche lobe. It then expels a copious stellar wind that forms a hot accretion disk. The disk surrounds the neutron star or black hole that was created when the first star went supernova.

Because gas is so strongly heated when it falls into the steep gravity well of a neutron star or black hole, the accretion disk transforms the system into a powerful source of X-ray emission (*S&T:* May 1996, page 38). About one hundred such sources are known in our galaxy. They are called *high-mass X-ray binaries* (HMXBs) and each lives for a period of 10,000 to 100,000 years. Cygnus X-1 (with a black-hole accretor) and Centaurus X-3 (with a neutron star) are two famous examples.

A high-mass X-ray binary with a neutron star eventually retraces the steps of its predecessors, since there is also a maximum rate at which the neutron star can "feed" from the accretion disk. (It remains less clear what happens when a black hole is involved.) When the mass-exchange rate becomes much higher than the neutron star can handle, gas builds up around the neutron star and the system once again forms a common envelope. X-ray emission ends at this point. After a mere 10,000 years, the envelope becomes visible as an expanding hydrogen-rich nebula around a second Wolf-Rayet star. This second helium star ends its life as a supernova as well.

Usually this second explosion expels so much mass that the binary is disrupted into two freely moving compact objects, the majority of which will be neutron stars. This may explain the high velocities (typically several hundred kilometers per second) evinced by most *pulsars:* spinning neutron stars that, like lighthouses, emit radiation from localized "hot spots" on or near their surfaces.

On rare occasions, however, the neutron stars or black holes created by the two supernovae remain in a close, eccentric orbit around one another. The first empirical evidence for this sort of system was the radio signals from the now-famous radio source known as PSR 1913+16. Discovered by Russell A. Hulse and Joseph H. Taylor (Princeton University) in 1974, this binary pulsar's rapidly decaying orbit has demonstrated the existence of gravitational radiation — a key prediction of Einstein's general theory of relativity.

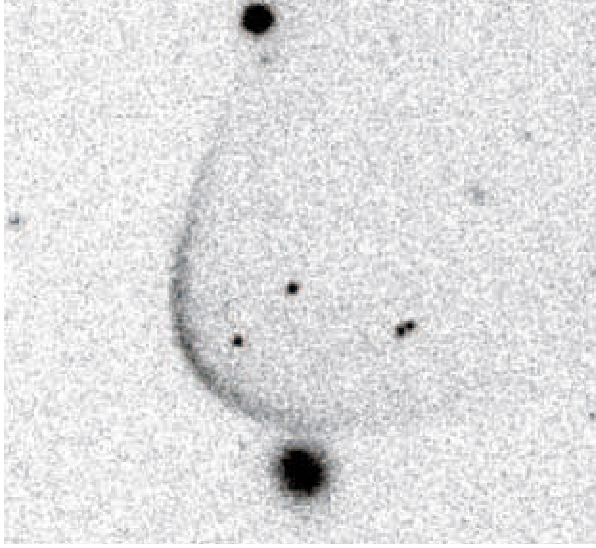
A handful of other binary pulsars has been found in our galaxy, and over the next several billion years some of them may merge, forming black holes and giving off enormous amounts of energy as they do so. In fact, such a scenario has been invoked as a possible explanation for still-mysterious *gamma-ray bursts,* which may be even more energetic than supernova explosions (*S&T:* September 1996, page 32).

A Slower Road to Degeneracy

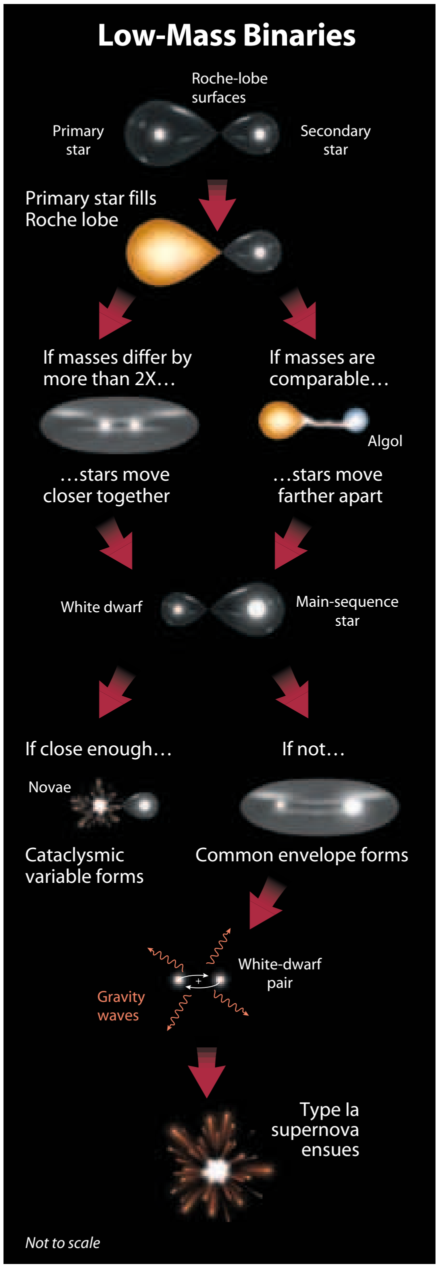
In general, when a close binary's components are initially less massive than 11 Suns, neither component evolves into a neutron star or a black hole. Rather, the stars typically are destined to become *white dwarfs* — degenerate spheres of tightly packed electrons within which atomic nuclei wander freely. However, the way this happens depends sensitively on the relative masses of the two stars.

If the component's initial masses differ by more than a factor of two — and if the primary fills its Roche lobe *after* it has developed a helium core but *before* that core has become degenerate — a common envelope forms and the binary's orbit shrinks until one of two things happens. The primary may become a detached compact helium star, or the remains of the primary may merge with the secondary to form a single star. If a merger is avoided, the helium star generally becomes a carbon-oxygen white dwarf (one whose atomic nuclei are predominantly those of carbon and oxygen), or a white dwarf rich in carbon and neon.

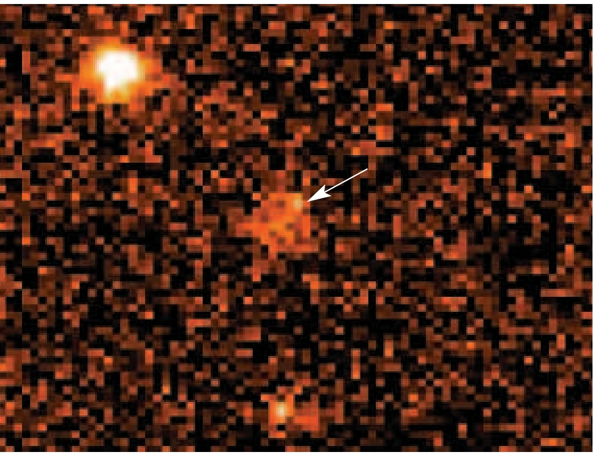
On the other hand, if the binary's component masses are initially comparable — and if the primary fills its Roche lobe while it has a helium core — the


ANDREW FRUCHTER / NASA

This red-light image shows a glowing arc of hydrogen gas being lit up by a speeding pulsar (itself unseen) — an intriguing yet predictable consequence of binary-star evolution.



SKY & TELESCOPE / GREGG DINDERMAN


K. SAHU / STScI / NASA

Gamma rays momentarily flashed from this part of the sky last February 28th; a possibly related variable "star" (arrowed) was caught hours later, next to what may be its host galaxy billions of light-years away. Such gamma-ray bursts may be the final outcome of merging neutron-star binaries.

To explain the ultimate in stellar explosions, we must consider the apparently innocuous binaries that contain carbon-oxygen white dwarfs — crystalline spheres of degenerate electrons on whose surfaces runaway nuclear explosions take place.

primary gradually transfers matter to its companion until it has essentially lost its entire hydrogen-rich envelope. Because angular momentum is conserved and the mass of the secondary becomes larger than that of the primary, the orbital separation increases during the mass-transfer phase. The famous eclipsing binary star Algol (Beta Persei) is presently undergoing this type of evolution.

A Nova Is Born

The evolution of a binary star with one white-dwarf component becomes particularly interesting if the other star's mass is less than our Sun's and if the pair started out less than 10 solar radii apart. In this case, the binary can become "semidetached" because the main-sequence star's magnetic field can become coupled to its particulate "solar" wind.

It seems counterintuitive that something as tenuous as the solar wind can dictate the orbital evolution of a binary star. Yet it can. In a close binary, tidal forces keep the same side of the main-sequence star facing its companion. This prevents the magnetized solar wind from reducing the spin rate. However, the solar wind continues to carry away angular momentum. Since the only other available supply of angular momentum is the binary's orbit, the stars become closer and their Roche lobes shrink.

If the binary components were initially separated by 10 solar radii or thereabouts, the shrinking orbit brings the main-sequence star into contact with its Roche lobe. This enables the star to transfer matter to its white-dwarf companion. Binary stars known as *cataclysmic variables* are undergoing this kind of evolution.

In a cataclysmic variable, a layer of hydrogen-rich matter accumulates on top of the white dwarf. As this second skin thickens, gravity compresses it until much of it becomes degenerate. In degenerate matter, pressure is a function primarily of density, not temperature. This deprives the material of a "safety valve" with which to accommodate its still-rising temperature. As a result, when hydrogen begins to fuse in the layer, nuclear energy is released at an exponentially increasing rate. In a matter of hours, even electron degeneracy can no longer fight the sudden increase in temperature, and the accreted shell is blown off into interstellar space. The burning dies out and accumulation begins again, eventually leading to another explosion.

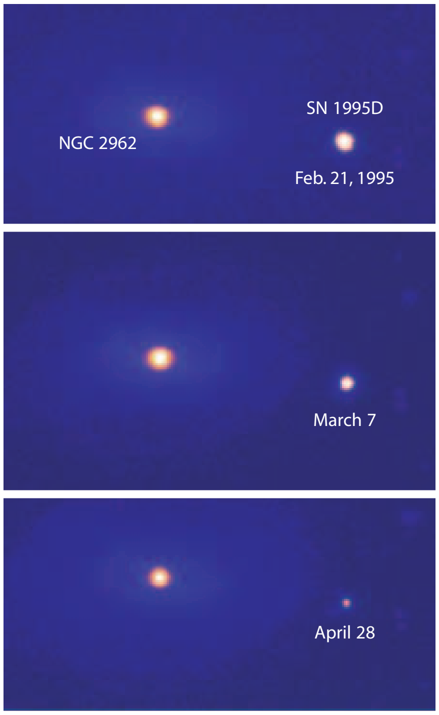
This scenario explains classical *novae,* outbursts that occur in cataclysmic variables. Hydrogen accumulation by a low-mass binary's white dwarf is periodically interrupted by nuclear explosions whenever a critical amount of matter builds up. Most of the accreted matter is ejected during outbursts, so cataclysmic variables usually do not evolve into supernovae.

Making Stellar Timepieces

What happens if the compact object at the receiving end of this kind of mass transfer is a neutron star rather than a white dwarf? As you may have already guessed, the system becomes what astronomers call a *low-mass X-ray binary* (LMXB). As in HMXBs, an intense stream of X-rays is emitted when the neutron star accretes matter. How are such systems born? Their progenitors are heavily lopsided binaries with a 13- to 15-solar-mass primary and a 0.3- to 2.0-solar-mass secondary.

Intriguingly, when the donor in an LMXB fills (or nearly fills) its Roche lobe, it absorbs as much as 10 percent of the X-rays given off by the accretor. These X-rays may amount to thousands of times more energy than the donor produces in its interior. The result? The donor forms a corona from which a powerful wind blows, carrying copious amounts of matter out of the binary system.

In spite of this loss, the neutron star accretes so much matter (and with it, angular momentum) that it can end up spinning hundreds or thousands of times per second. It is precisely this kind of scenario that seems to explain the presence of *millisecond pulsars.* First observed by Shrinivas R. Kulkarni (now at Caltech) in 1982, the radio blips from these rapidly spinning neutron stars are generally considered to be the most reliable "clock" found in na-



ADAM RIESS

These electronic images, acquired with the 1.2-meter Fred L. Whipple Telescope on Arizona's Mount Hopkins, depict the fading light of a Type Ia supernova in NGC 2962, a galaxy 115 million light-years away in the constellation Hydra.

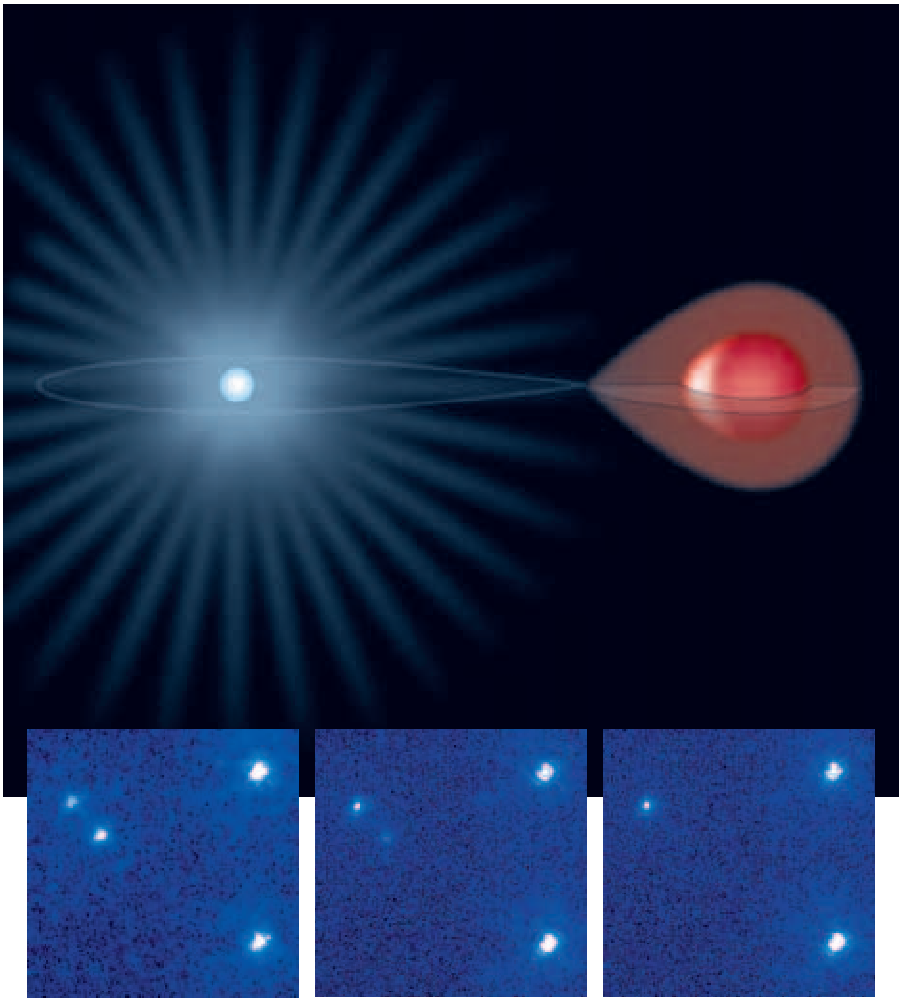
ture (*S&T:* April 1995, page 19).

Despite their renewed lease on life, millisecond pulsars show little gratitude to the companion stars that spun them up. Their fierce particle winds completely evaporate any main-sequence donor; we see this taking place in the so-called Black Widow Pulsar in Sagitta (*S&T:* July 1995, page 13). The hydrogen-rich envelope of a giant donor fares no better. But its degenerate helium core is compact enough to resist evaporation. The result is a millisecond pulsar that is orbited by a helium white dwarf. Solitary millisecond pulsars and those in binaries have been seen both in our galaxy's disk and in globular star clusters, where close binaries are frequently formed by stellar collisions.

When White Dwarfs Meet

To explain the ultimate in stellar explosions, we must consider once again the apparently innocuous binaries wherein the primary star becomes a carbon-oxygen white dwarf. If its initial mass is larger than our Sun's, the secondary star will expand after forming a helium core, filling its Roche lobe. The white dwarf can accrete matter only so fast, but its partner pours it on at a much higher rate. A second shared envelope results and is eventually ejected, leaving a pair of white dwarfs.

If the white-dwarf pair is formed at a separation larger than 3 solar radii, very little of interest occurs. But the situation changes dramatically if the newly formed white-dwarf pair is closer together than

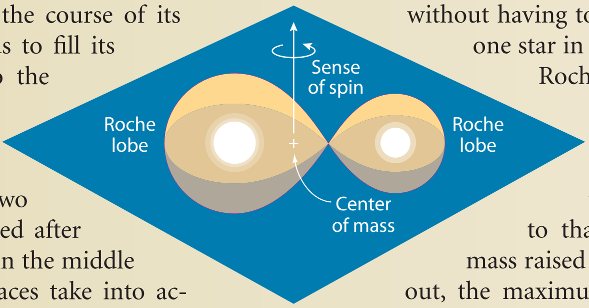


The Black Widow Pulsar (left) once gained matter and angular momentum from its now-tiny stellar companion, which is evaporating under the pulsar's stellar wind. The Hubble Space Telescope frames below show the companion's "hot spot" rotate in and out of view as it orbits the unseen pulsar. *Sky & Telescope* illustration by Steven Simpson; Hubble frames courtesy A. Fruchter.

HOW CLOSE IS CLOSE?

Binary stars form with separations that range from light-seconds (roughly the distance from the Earth to the Moon) to light-years (the typical separation between *unrelated* stars in much of the Milky Way). Which binary systems should then be considered close-knit? Astronomers consider a binary star "close" if, in the course of its evolution, either component expands to fill its Roche lobe and transfers matter to the other component.

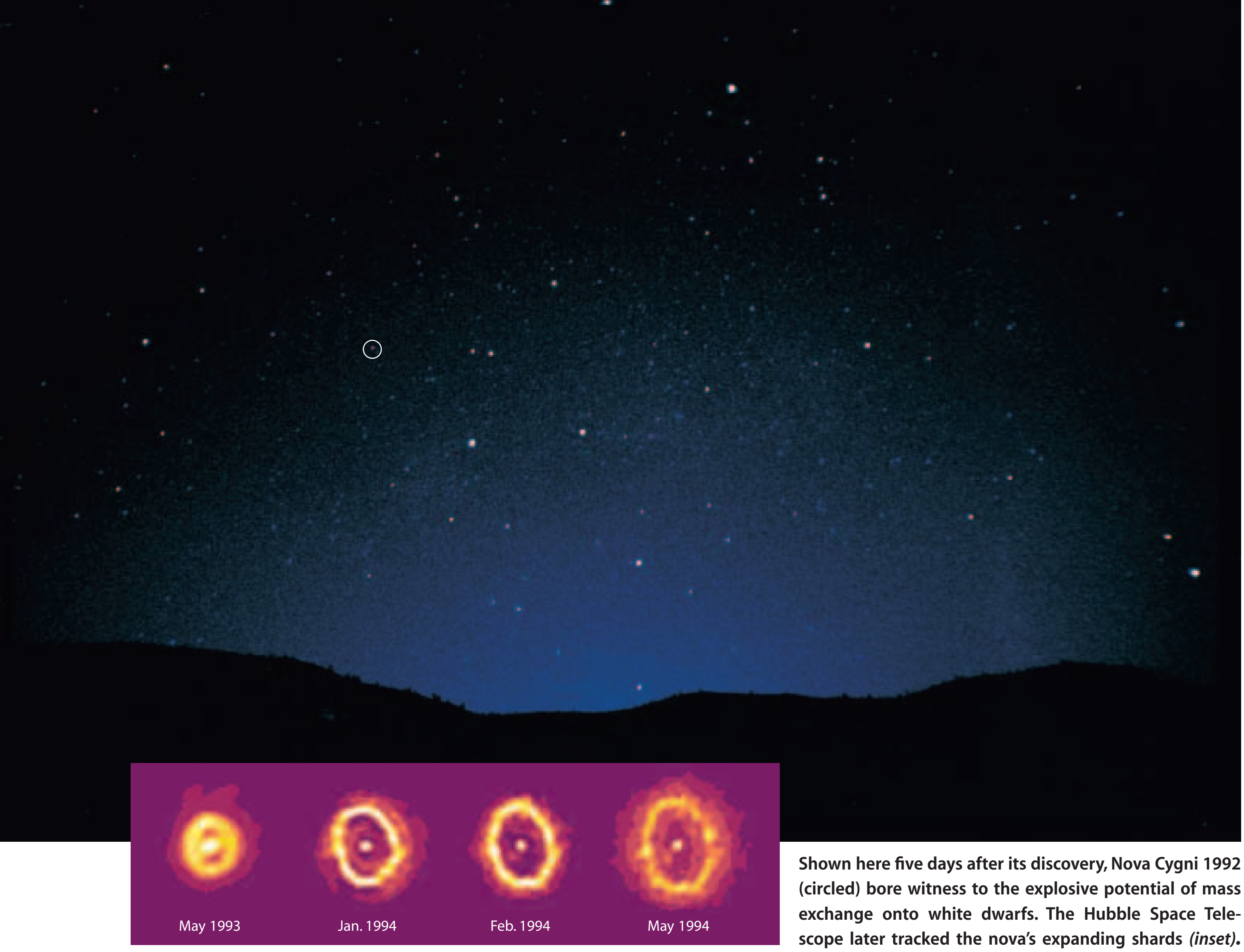
What is a star's Roche lobe? Roche lobes form a unique gravitational "surface" surrounding any two objects that orbit one another. Named after Édouard Roche, who analyzed them in the middle of the last century, Roche-lobe surfaces take into account the combined effects of gravity and orbital motion. The orbit of two stars around their shared center of mass introduces a centripetal force; this affects how we perceive the motions of nearby material when we imagine the binary system as a stationary entity.



Viewed in cross section (as shown below), the Roche-lobe surface of a close binary consists of two star-embracing teardrops joined in a figure eight. Like the 1,000-meter elevation line in a topographical map of the Alps, this figure-eight represents a surface of constant energy — material can move around it without having to "climb" or "descend." As a result, if one star in a close binary system swells to fill its Roche lobe, material can spill over and surround the companion star.

The radius of a given star's Roche lobe is proportional to the system's orbital separation, and to that star's share of the system's total mass raised to the four-tenths power. As it turns out, the maximum diameter of a single star is less than 1,000 times that of today's Sun, and only members of binaries with orbital separations less than 1,250 solar diameters (5.8 Earth orbits) can fill their Roche lobes and hence interact by mass exchange. Studies show that about half of all stars are born in binaries that meet this condition.

ADAPTED FROM *THE PHYSICAL UNIVERSE* BY FRANK SHU



Shown here five days after its discovery, Nova Cygni 1992 (circled) bore witness to the explosive potential of mass exchange onto white dwarfs. The Hubble Space Telescope later tracked the nova's expanding shards *(inset)*.

ALAN B. GORSKI / *INSET:* W. HACK AND F. PARESCE, STSCI

that. At such close quarters, gravity waves are generated effectively, and the components ultimately merge.

What happens next depends on the white dwarfs' chemical compositions and on their masses. If a helium white-dwarf pair totals less than a half Sun, the result is simply a single helium white dwarf. Otherwise, the merger produces a single star that burns helium in its core, then evolves into a CO white dwarf topped with a layer of helium.

However, if one of the merging white dwarfs is made of carbon and oxygen while the other contains helium, the merger produces a bright supergiant star with an extended helium envelope. Such stars have been observed and are called *R Coronae Borealis* stars. An intense stellar wind transforms such a star into a CO white dwarf with a surrounding helium-rich planetary nebula.

Finally, true fireworks ensue if two carbon-oxygen dwarfs together add up to more than 1.4 Suns — the so-called Chandrasekhar limit. When this critical limit is exceeded, an unavoidable thermonuclear explosion transforms the carbon and oxygen nuclei into iron-peak elements. This explains the explosions that astronomers call *Type Ia supernovae.* Such supernovae distinguish themselves from other types by occurring even in elliptical galaxies, where the most massive stars that remain on the main sequence all lie below the Chandrasekhar limit and hence cannot "go supernova" on their own. Type Ia supernovae are a major source of iron in the universe. They also serve as "standard candles" that cosmologists use to measure the universe's size and expansion rate.

A World View Validated

In his remarkable 1929 book, *The Internal Constitution of the Stars*, Sir Arthur Eddington wrote about the nascent science of stellar evolution: "The partial results already obtained encourage us to think that we are not far from the right track." Although much of today's essential physics was then unknown, the passage of time has supported Eddington's optimistic assessment. It is not unreasonable to believe that we have now deduced the correct evolutionary path for most stars, be they isolated or in close binary systems.

At the same time, the study of stars and other cosmic objects has strongly demonstrated the universal validity of the physical laws that have been deduced in terrestrial laboratories. As Eddington surmised: "We have seen how closely the manifestations of the greatest bodies in the universe are linked to those of the smallest."

ICKO IBEN JR. *is Distinguished Professor of Astronomy and Physics at the University of Illinois.* ALEXANDER V. TUTUKOV *heads the Department of Stellar Evolution at the Institute for Astronomy in Moscow, Russia. They have coauthored numerous scientific publications as well as this article's precursor, which appeared in the December 1997 issue of* Sky & Telescope.