4 April 1980, Volume 208, Number 4439

SCIENCE

Strong Stellar Winds

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Stellar winds are a ubiquitous phenomenon among stars (*1*, *2*). The sun loses roughly 10^{-14} solar mass ($M_\odot$) per year in a solar wind that varies strongly with the solar cycle and its associated magnetic surface activity (*3*). Many stars that have exhausted the hydrogen nuclear fuel in their cores become red giants with relatively cool surfaces and huge distended envelopes, losing a significant fraction of their mass in a stellar wind of relatively low velocity. Some of the most powerful stellar winds are found in the very hottest (O type) stars. The spectral classification O type is given to the optically observed stars that have the highest surface temperatures ($T > 30,000$ K) and the greatest masses ($20 < M < 100\ M_\odot$) in the main-sequence phase of their lifetimes (during core-hydrogen burning). Certain kinds of less massive stars in advanced states of evolution, such as Wolf-Rayet stars, horizontal branch stars, the central stars of planetary nebulae, and white dwarf stars, also have such very high temperatures and, with the exception of the last group, substantial stellar winds.

Summary. The hottest and most luminous stars lose a substantial fraction of their mass in strong stellar winds. These winds not only affect the evolution of the star, they also carve huge expanding cavities in the surrounding interstellar medium, possibly affecting star formation. The winds are probably driven by radiation pressure, but uncertainties persist in their theoretical description. Strong x-ray sources associated with a few of these hot stars may be used to probe the stellar winds. The nature of the weak x-ray sources recently observed to be associated with many of these stars is uncertain. It is suggested that roughly 10 percent of the luminous hot stars may have as companions neutron stars or black holes orbiting within the stellar winds.

The O stars, which are the youngest and most massive stars in the Milky Way, have stellar winds with mass loss rates ranging from about 10^{-8} to about $10^{-5}\ M_\odot$ per year. Such large mass loss rates have major implications for the evolution of the stars and for the dynamics of their interstellar environment. The quest to understand the driving mechanisms and consequences of these strong stellar winds has become one of the most active and exciting areas of modern astrophysics.

The O-type stars are rare: our galaxy contains only about 10^4 such stars in its total population of some 10^{11} stars, yet they are so luminous that they contribute a substantial fraction of the galactic light. Their lifetimes ($\lesssim 10^7$ years) are short compared to those ($> 10^{10}$ years) of most stars; their death rate is comparable to (say 20 percent of) the galactic supernova rate. Therefore, despite their small number, they may make a significant contribution to element synthesis in the galaxy.

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Observations

The first evidence for stellar winds in O-type stars was obtained in 1967, on an unmanned rocket flight making ultraviolet (UV) spectroscopic observations of the stars in the belt of Orion (*4*). The Si^{3+} and C^{3+} resonance doublets at 1394, 1403 and 1548, 1551 angstroms, respectively, show profiles with emission to the red of line center and absorption to the blue. Such profiles are designated as P Cygni type after the prototype star, P Cygni, where these types of profiles are observed in the visible region. The interpretation of this kind of line profile in terms of a stellar wind is illustrated in Fig. 1. Assume, for simplicity, that the stellar photosphere emits a smooth continuum of photons. These photons must propagate through a stellar wind containing ions capable of scattering photons whose frequency in their rest frame corresponds to some resonant transition. The frequencies of the scattered photons, as seen by an observer at the right, may be either blue-shifted or red-shifted with respect to the laboratory frequency as a result of the velocities (indicated by arrows in Fig. 1) of the scattering ions. Figure 1 shows that a photon such as 1 must be on the blue side of the laboratory resonant frequency in order to be Doppler-shifted to the resonant frequency of the atom in the stellar wind. Removal of such photons from the beam to the observer creates a blue-shifted absorption feature. Similarly, a photon such as 2, which is scattered into the beam to the observer, will appear as excess emission on the red side of the resonant frequency. The P Cygni–type profiles observed in the Orion's belt stars unequivocally indicate mass loss, because the observed velocities, 1500 to 1900 kilometers per second, are appreciably larger than the stellar escape velocities of 600 to 700 kilometers per second.

Line profiles of the P Cygni type are observed in the visible region in a few hot stars, but their detailed interpretation is difficult because such lines are invariably subordinate lines, corresponding to transitions between excited

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atomic levels whose populations are uncertain. Such spectral lines are usually formed by a combination of emission and scattering rather than by scattering alone. In many cases, only an emission component is observed (for instance, in the red Hα line of hydrogen). A cleaner theoretical interpretation is possible for UV resonance lines, corresponding to scattering by ions in their ground state. The P Cygni profiles due to UV resonance lines are much stronger than those found in the visible because most ions in stellar winds are in their ground state. The line profile for ζ Puppis (*5*) shown in Fig. 2 is due to the doublet 1032, 1037 Å of the ion O^{5+} (O VI), which is far less abundant than hydrogen.

Owing to the successful operation of UV spectrometers on the orbiting telescopes Copernicus (OAO-3) and the International Ultraviolet Explorer (IUE), the UV spectra of many O-type stars can now be observed and the properties of their stellar winds can be inferred. The blue-shifted extremes of the strong UV resonance lines indicate the terminal velocities of the stellar winds. Although it is not easy to infer stellar mass loss rates from these resonance lines, this task can be accomplished in principle by comparing lines from different elements (*6*). For spherical symmetry, the mass loss rate may be written

$$\dot{m} = 4\pi r^2 \rho(r) v(r)$$

where the density ρ and the velocity v are functions of distance r from the stellar surface. The P Cygni profiles give some direct information on the velocity law $v(r)$, but the analysis of $\rho(r)$ and the evaluation of r itself require stellar atmosphere models. In particular, knowledge of the ionization state of the wind is crucial, since one is observing ions that make up only a tiny fraction of the gas, which is mostly hydrogen and helium. For stars that have relatively dense winds, Hα is found in emission in the optical region. (Unfortunately, the resonance Lyman lines of hydrogen are absorbed by the interstellar medium and cannot be observed.) Mass loss rates for these stars can be inferred with a suitable model of the wind and a solution of the line transfer problem in a moving envelope (*7*).

At radio and infrared (IR) wavelengths, continuum absorption is so strong that the apparent surface of a star is actually in the stellar wind, and the radius of this surface depends on the density of the wind. With an estimate of the relevant temperature, one can find the apparent size at a given wavelength from the observed radiation flux, and from that infer the density of the wind. With IR observations, one infers the density of the wind close to the star, where the expansion velocity is uncertain. However, with radio observations, one measures the wind far from the star, where the velocity has reached a terminal value that can be measured from UV resonance lines. Therefore radio observations should provide the most reliable estimate of the mass loss rate.

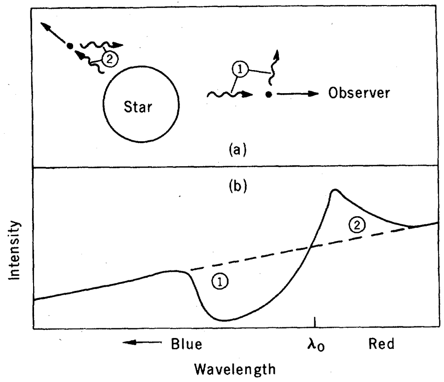

Fig. 1. (a) Formation of P Cygni-type profile by resonant scattering in a stellar wind. Arrows denote velocity vectors of ions in the wind; wavy arrows denote photons. (b) Resulting P Cygni line profile, showing red-shifted emission and blue-shifted absorption due to resonance at λ_0. The dashed curve represents the stellar continuum before resonant scattering.

For the few stars for which measurements are available, the mass loss rates deduced from IR and radio observations agree to within a factor of 2 with those inferred from Hα emission line strengths and UV spectroscopic observations; this agreement is about as good as can be expected, given the limitations in the data and the methods. For example, the star ζ Puppis has a mass loss rate of 7×10^{-6} $M_\odot$ per year as determined by these four methods (*1*). We can expect rapid advances in our ability to determine the properties of stellar winds as instrumental capabilities in radio, IR, optical, and UV astronomy improve.

Present observations yield the following properties (*1, 8–10*). Without exception, O-type stars manifest stellar winds with mass loss rates ranging from 10^{-8} to about 10^{-5} $M_\odot$ per year; the stellar luminosity ranges from $10^{4.5}$ to $10^{6.5}$ solar luminosities ($L_\odot$). The terminal velocities of these winds range from about 1200 to about 4000 km/sec, and are typically a few times the escape velocity from the stellar surface.

Strong stellar winds are also observed in some slightly cooler stars if they are exceptionally luminous. These stars, called B supergiants, appear to be the result of stellar evolution of O stars. We will designate stars that are luminous and hot enough to manifest stellar winds as OB stars. It appears that the strong stellar wind phenomenon abruptly vanishes for stars less luminous than about $10^{4.5}$ $L_\odot$ or temperatures less than about 12,000 K (*10*) (except for the aforementioned winds of red giant stars).

It would be convenient if the mass loss rates observed for OB stars were correlated with some other observable property, such as the luminosity. We do know that only these very luminous stars have presently detectable winds, but the actual rates seem to differ significantly among OB stars with similar properties. Stars with Hα emission have mass loss rates of order 0.5×10^{-5} to 1×10^{-5} $M_\odot$ per year. Stars without such emission have lower rates: for example, 10^{-7} $M_\odot$ per year for 9 Sagittarii, a hot O star with about the same temperature and luminosity as ζ Puppis (*9*).

There is a related class of hot, luminous stars in which the optical spectrum is dominated by emission lines. These stars are called Wolf-Rayet (WR) stars after their discoverers, who found them by eye observations at a spectroscope attached to a telescope of the Paris Observatory (*11*). We now understand that the spectral appearance of these stars results from an optically thick wind, or envelope. The stellar photosphere is not seen in most cases. The WR stars have mass loss rates even larger than those of O-type stars; values of 10^{-5} to 10^{-4} $M_\odot$ per year have been quoted from modeling of the wind and from measures of the IR and radio continuum flux (*1*). The general absence of hydrogen and the predominance of helium suggest that these stars are highly evolved objects, whose outer layers have been stripped away. The substantially higher mass loss rates of WR stars, compared to OB stars, may be due to this difference in chemical composition, but it is not well understood.

In a few cases, P Cygni lines and emission lines in OB and WR stars have been observed to vary with time (*12*). The fluctuations can be interpreted as variations in density, velocity, or ionization state in the wind. The time scales of the variability are on the order of hours or, in some cases, months. The former timescale is similar to that needed for material to flow outward from the surface through the entire envelope. The observed variability is near the present limit of detectability, and it is not known whether the phenomenon is common to all OB and WR stars or only to the few in which it has been observed. Better observations are badly needed.

Physical Basis of Winds

What are the physical mechanisms responsible for driving stellar winds? The solar wind has its origin in the solar corona, whose temperature, $\approx 10^6$ K, is so great that thermal gas pressure is sufficient to support an extended atmosphere and to drive the wind. The mechanism responsible for heating the solar corona is not understood in detail, but it is believed to involve the dissipation of mechanical energy associated with convection and magnetic activity at the solar surface (*3*). The mechanical power of the solar wind is a small fraction (roughly 10^{-7}) of the solar luminosity. There is now evidence from orbiting x-ray and UV telescopes that solar-type coronas and winds are typical of cool stars like the sun (*13*).

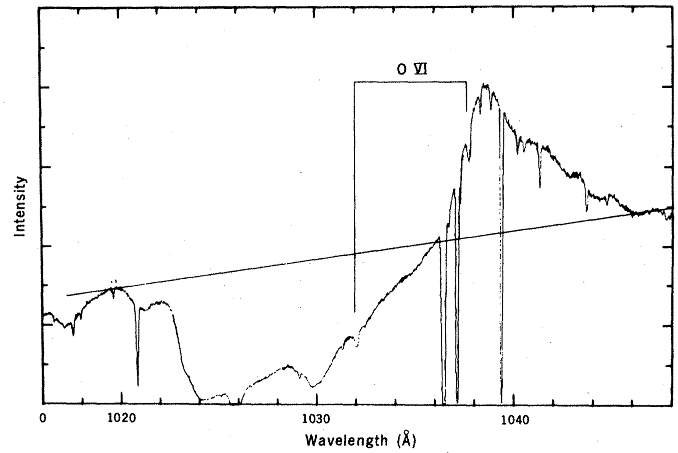

Fig. 2. Ultraviolet spectrum of the star ζ Puppis in the vicinity of the resonance doublet 1032, 1037 Å of O^{5+} (O VI). The straight line denotes the estimated flux level of the stellar continuum. The broad spectral feature consisting of absorption extending from 1022 to 1036 Å and emission from 1036 to 1045 Å is a P Cygni profile due to O^{5+} in the stellar wind. The doublet of narrow absorption lines marked O VI is due to O^{5+} in interstellar gas far from the star. Several other sharp interstellar absorption lines are evident. [From (*5*), courtesy of the *Astrophysical Journal*]

The strong stellar winds of the O-type stars are evidently an entirely different phenomenon. First, the mass loss rates and mechanical power of these winds exceed those of the solar wind by huge factors—say 10^6 to 10^9. Even allowing for the difference in stellar luminosities, the fractional power of O-type winds, ranging from 10^{-4} to 10^{-3}, greatly exceeds that of the solar wind. The strong stellar winds cannot be driven by thermal pressure; spectroscopic observations indicate that they have temperatures $\lesssim 10^5$ K—far too cool to support an expanding corona.

It now seems clear that the dominant driving mechanism is radiation pressure—the transfer of momentum by resonant scattering from the stellar radiation to ions of trace elements in the wind (*14*). Most of the resonance lines are found in the extreme ultraviolet spectral range, at wavelengths $\lambda < 912$ Å, and are impossible to observe directly in the OB stars because of interstellar opacity. The few observed resonance lines that do occur in the spectral range $\lambda > 912$ Å account for only a small fraction of the driving force. The abrupt appearance of strong stellar winds with increasing stellar temperature is principally a consequence of the fact that effective momentum transfer to the gas requires stellar radiation with $\lambda < 912$ Å, dominant only in OB stars.

For completeness, we should mention that the winds of red giant stars are thought to be driven by yet a third mechanism: radiation pressure acting on refractory grains that form in the cool stellar atmospheres (*2*).

The empirical fact that the winds of the hottest stars have a momentum flux comparable to that of the stellar radiation is good evidence that radiation pressure is driving the winds. It can be understood in a simple way by assuming that the spectral density of resonance lines due to trace elements in the wind is sufficient for most stellar photons with $\lambda < 912$ Å to have at least one resonant scattering in the wind. (Multiple scatterings do not significantly increase the momentum transfer.) Theoretical investigations of the composition and atomic properties of the wind (*14*) indicate that this assumption is a satisfactory one.

Most astronomers agree that radiation pressure must be the main determinant of the structure of the winds, but the details remain uncertain and controversial. The problem of theoretically describing the transfer of radiation in the wind is especially difficult because of the multiplicity of ions and overlapping resonance lines. The challenge to theorists is compounded by the need to couple such a radiative transfer theory with a gas-dynamical theory for the wind, in which the driving force depends in a complicated, nonlinear way on the velocity gradient and the radiation field. Even though substantial progress has been made, it is not surprising that the theoretical models of the winds do not yet provide a detailed description of their observed properties, such as velocity profiles and ionization balance.

Observations of highly ionized elements such as N^{4+} and O^{5+}, whose presence in the wind cannot be explained by processes occurring at temperatures comparable to that of the stellar photosphere (say 3×10^4 to 4×10^4 K), lead to the suspicion that the theoretical models lack some important ingredient. One possibility is that instabilities in the stellar atmosphere or wind convert mechanical energy into high temperatures through shocks, as in the solar corona (*15*). A mechanism for instability in the atmospheres of OB stars has not been found, but that is no proof of stability. The observations of time variations in spectral line profiles strongly suggest unstable flows in the winds.

Very recently, the Einstein X-ray Observatory, which was launched into earth orbit in November 1978, has found that most of the O-type stars are weak x-ray sources, with x-ray luminosities on the order of 10^{-5} times the bolometric luminosity of the star (*16, 17*). For example, Fig. 3, a and b, are photographs of a region in the southern constellation Carina that contains several O stars, a WR star, and the famous "slow supernova," η Carinae. Figure 3a is the region as seen in x-rays from 1 to 3 kiloelectron volts, showing x-ray sources coincident with η Carinae, the WR star HD 93162, the O stars HD 93249, HD 93403, and HD 93250, and Trumpler 14, which is a cluster of three O stars. Diffuse x-ray emission throughout the region is also evident. Figure 3b is the same region taken in near-ultraviolet light (3300 to 3900 Å), with x-ray brightness contours superimposed. Such observations, when thoroughly analyzed, may provide vital clues to the nature of the winds. That strong stellar winds might contain a source of x-rays of such intensity had been predicted (*18*) in order to account for the highly ionized trace elements. But the source of these x-rays remains a mystery, to which we will return below.

Effects on Stellar Evolution

A substantial fraction of stellar mass can be carried away by a stellar wind if the mass loss rate is high enough. This seems to be the case for stars with masses greater than about 40 $M_\odot$. In contrast, the winds in less massive stars, and in the sun, are insufficient to have any significant effect on stellar evolution. Let us briefly review the precepts of stellar evolution and then discuss what observable effects have been found as a result of stellar winds.

All stars, including the sun, spend about 90 percent of their total lifetime in the so-called main-sequence phase, during which thermonuclear reactions in the central core "burn" hydrogen to helium. After the core hydrogen is exhausted, the star undergoes a sequence of drastic structural reorganizations: first hydrogen is burned in a shell surrounding the helium-rich core; then helium itself is ignited to form carbon in the core. During these phases, which last for only about 10 percent of the main-sequence lifetime, the luminosity of a relatively massive star remains constant but the radius increases dramatically as the surface temperature drops. (In stars like the sun, the luminosity during the hydrogen shell-burning phase increases as the radius increases and the surface temperature drops.) The latter phases of massive star evolution correspond to the red supergiant stage (so-called because of the relatively low surface temperature and large radius).

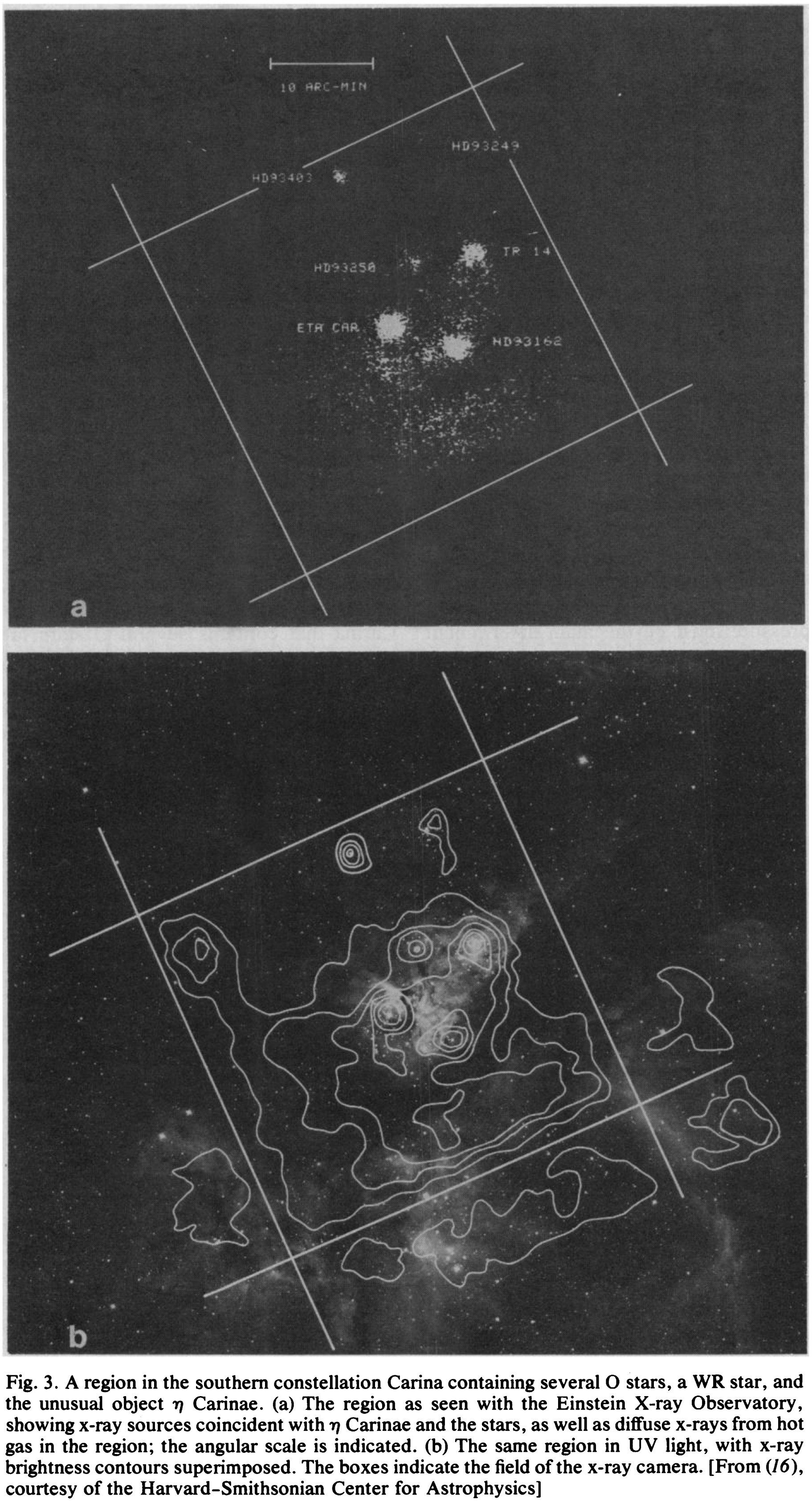

Fig. 3. A region in the southern constellation Carina containing several O stars, a WR star, and the unusual object η Carinae. (a) The region as seen with the Einstein X-ray Observatory, showing x-ray sources coincident with η Carinae and the stars, as well as diffuse x-rays from hot gas in the region; the angular scale is indicated. (b) The same region in UV light, with x-ray brightness contours superimposed. The boxes indicate the field of the x-ray camera. [From (*16*), courtesy of the Harvard-Smithsonian Center for Astrophysics]

The primary observables of stellar astronomy are the brightness of a star, its luminosity, and its spectral type, related to its surface temperature. A fundamental theorem of stellar astrophysics is that the luminosity and temperature evolution of a star are uniquely determined by its initial mass and composition. To study stellar evolution theoretically, models are calculated from three underlying physical principles: hydrostatic equilibrium, in which gravity is balanced by internal pressure, convective and radiative energy transport, and thermonuclear reaction theory. The advent of high-speed computers has revolutionized such calculations. The starting point for a stellar model, at which hydrogen is first ignited in the core, is called the zero age main sequence (ZAMS). As the star consumes hydrogen in its core, and subsequently burns hydrogen in a shell and helium in the core, the internal composition and structure alter, changing the position of the star in a diagram of luminosity versus effective temperature, T_{eff} (a Hertzsprung-Russell diagram).

Figure 4 shows such a diagram for the most massive stars. (The sun, with log T_{eff} = 3.77, would be located far below this figure.) Theoretical evolutionary tracks (*19*) during the main-sequence phase are shown for stars with 80, 40, and 20 $M_{\odot}$, respectively, both with no mass loss and with mass loss rates similar to those observed. The main effects of such mass loss are to cause a star to evolve to a lower surface temperature and lower luminosity than it would have reached without mass loss. The main-sequence lifetime is lengthened somewhat, and the mass at the end of this phase is typically about two-thirds of the initial mass. The evolutionary tracks are highly sensitive to the actual mass loss rates. Adopting values a factor of 2 higher would result in tracks that become even less luminous and turn back toward the ZAMS. The accuracy of the data does not exclude this possibility.

Actual luminosities and temperatures for a set of relatively well-studied O-type stars are also shown in Fig. 4 (*20*). The O stars with rates larger than $10^{-6}\,M_\odot$ per year are indicated by separate symbols, but it should be kept in mind that all individual stars shown in Fig. 4 have stellar winds (*10*). With few exceptions, the stars with the highest mass loss rates are initially more massive than 40 to 50 $M_\odot$, and have evolved to the right of the ZAMS in Fig. 4. The implication of a gradual and substantial increase in mass loss rate for the most massive stars while they are still burning hydrogen in the core is not understood, and this mystery is fundamental to the entire problem of strong stellar winds.

The crosshatched area in Fig. 4 indicates the nominal upper limit to the luminosity of stars of all other spectral types in our galaxy and in a reasonably well-studied nearby galaxy, the Large Magellanic Cloud (*21, 22*). Five stars do exist above this limit at type B, including P Cygni itself, but at least two of them appear to be highly unstable; all have probably evolved from even more massive stars than those on this diagram (*22*). We have not plotted individual stars other than O types in Fig. 4, but such data can be extracted from (*21*). Mass loss rates established for a few of the brightest B- and A-type supergiants (*23*) range up to $4 \times 10^{-6}\,M_\odot$ per year for the hottest stars. From the appearance of P Cygni profiles in the UV spectra, the presence of winds in stars over this entire diagram has been established (*10*), but the mass loss rates are not yet known.

In evolution without mass loss, the bright blue supergiants in the upper left region of Fig. 4 should evolve horizontally in the diagram, with constant or slightly increasing luminosity. Although blue supergiants with estimated masses of order 100 $M_\odot$ are present in our galaxy and in the Large Magellanic Cloud, evolved red supergiants of comparable mass are absent (*22*). The most luminous red supergiants, with log $L/L_\odot = 5.8$, have masses of roughly 50 $M_\odot$. We infer that the most massive O stars must lose roughly half their mass, decreasing in luminosity as they evolve to the red supergiant region (if, indeed, they ever reach this phase); this result is consistent with the mass loss rates observed in the strong stellar winds of these stars.

So far, we have considered only the evolution of single stars, whereas it is known that about 50 percent of all stars are in binary systems with two components of similar mass (*24, 25*). If the stars are close enough to each other, then evolution of the initially more massive star, which evolves more rapidly, is greatly influenced by the gravitational potential of its companion. When the atmosphere of the first star begins to swell, mass is transferred to the second star or ejected from the system, or both. The evolution of such binary systems is beyond the scope of this article, but reviews can be found in the literature (*26, 27*). One particular aspect of this kind of evolution for massive stars, the production of strong x-ray sources, is discussed below.

We have indicated that the strong stellar winds observed in the most luminous and massive O-type stars can carry away a substantial fraction of their mass. Aside from the documented absence of red supergiants, is there any other evidence for such evolution? Unfortunately, it is impossible to measure the masses of stars directly unless they are in binary systems, and even then it can be done only under especially favorable circumstances. In many systems with observed strong stellar winds we do find relatively undermassive components, consistent with this picture (*28, 29*). However, one always worries about the complications of the binary system interaction, apart from the stellar wind, and such data, while suggestive of mass loss, are not conclusive.

In a previous section we pointed out the existence of other luminous stars, the WR stars, which also have strong stellar winds. At present, we do not understand these stars very well. Surface abundance anomalies observed in their spectra suggest that they may have lost a substantial fraction of their hydrogen-rich envelope in systems that are binaries (*30, 31*). The WR stars, whose unusually high luminosity-to-mass ratios indicate that they are burning helium in their cores, may be products of the evolution of the most massive stars; perhaps such stars never become red supergiants. The further evolution of binary systems containing WR stars (*32*) may lead to the strong binary x-ray sources.

Effects on the Interstellar Environment

The strong stellar winds of the OB stars have a dramatic effect on the interstellar environment (*33*). Over the lifetime of such a star, the wind can impart some 10^{49} to 10^{50} ergs in mechanical en-

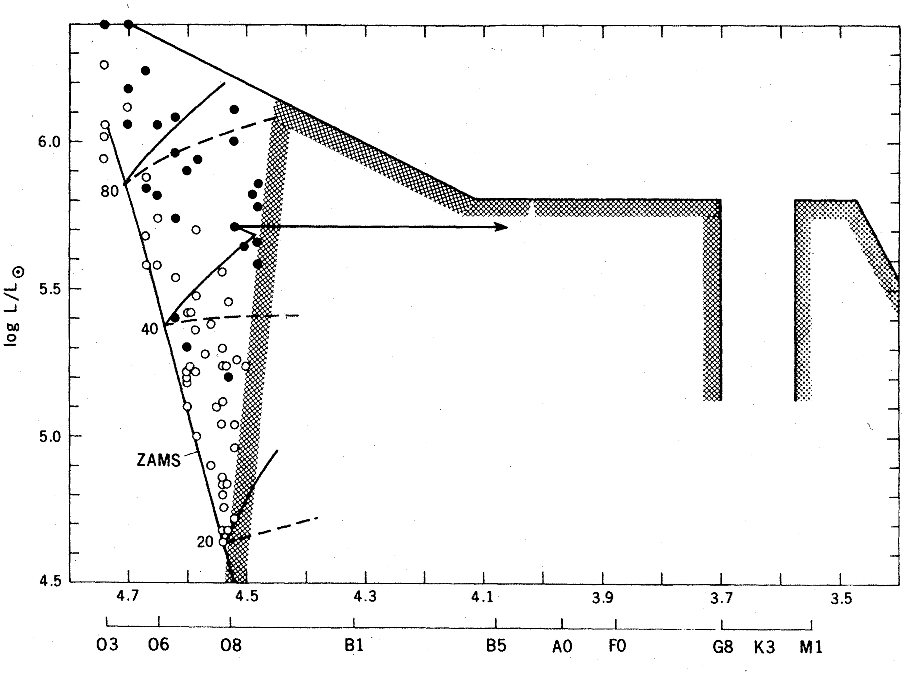

Fig. 4. Schematic luminosity-temperature diagram for massive stars, adapted from (*19–22*); the upper scale on the abscissa shows log $T_{\rm eff}$. Solid lines represent evolutionary tracks during core hydrogen burning for 80, 40, and 20 solar masses, assuming no mass loss; dashed lines represent corresponding tracks for the same masses, assuming average mass loss rates of order 6×10^{-6}, 3×10^{-6}, and $6 \times 10^{-7}\,M_\odot$ per year, respectively. (○) O stars with winds of mass loss rate $< 10^{-6}\,M_\odot$ per year; (●) O stars with larger rates, such that significant fractional mass will be removed during the main-sequence lifetime. The crosshatched boundary shows the upper limit to the luminosity of stars in our galaxy (and the Large Magellanic Cloud) for all other spectral types and temperatures. The horizontal arrow on the 40 $M_\odot$ track indicates the expected evolution from the blue supergiant region (OB stars) to the red supergiant region following the main-sequence phase; analogous behavior is expected for all masses shown on this diagram. Massive red supergiants do not exist because substantial matter is lost during the blue supergiant phase.

ergy to interstellar space, a value comparable to the mechanical energy released in a supernova explosion. The wind acts to create an expanding cavity of hot ($T \approx 10^6$ K) low-density gas, surrounded by a relatively dense shell of swept-up interstellar gas. The resulting "interstellar bubble," whose diameter may grow to 10 to 100 light-years over the 10^6- to 10^7-year lifetime of the star, is very similar in structure to the expanding shell of interstellar gas created by a supernova explosion, except for the presence of a central star in the bubble. Shell-like structures due to stellar winds should be more common than supernova shells because they remain luminous hundreds of times longer, more than compensating for the fact that the supernova rate exceeds by a modest factor the birth rate of the OB stars that cause the bubbles.

A beautiful optical example of a probable interstellar bubble is the Rosette Nebula, shown in Fig. 5. At its center is a small cluster of hot stars, which illuminate the surrounding interstellar gas with ultraviolet radiation, causing fluorescent emission of visible light (primarily Hα) by the nebula. Figure 5 clearly shows a cavity at the center of the nebula, presumably due to the action of the winds of the central stars on the interstellar gas. Many examples of shell-like structures in optical emission nebulae have been found in our own galaxy and in neighboring galaxies, and suggestions that such structures result from the action of stellar winds have appeared in the literature from time to time (*34*). However, until recently the situation has been confused, and many authors have identified the Rosette Nebula and similar shell-like emission nebulae as supernova shells.

Many hot stars are moving with relatively high velocities, say 10 to 100 km/sec, with respect to the ambient interstellar gas. In this case, the resulting bubble is deformed into a paraboloid-like shape, and the star is not centrally located. A spectacular example of such a deformed bubble was identified recently in the Orion Nebula (*35*).

The importance of the interaction of stellar winds with the interstellar environment gained recognition when quantitative evidence of the phenomenon was provided by the UV spectrometers on the Copernicus and IUE spacecraft. In addition to confirming that hot stars have stellar winds of sufficient force to have important dynamical effects, the UV spectra of these stars contain narrow absorption lines due to intervening interstellar gas. A few of these interstellar lines are evident in Fig. 2. Some of these lines provide additional evidence for expanding shells of gas driven by stellar winds; for example, the Copernicus spacecraft was able to observe rich absorption band spectra due to molecular hydrogen toward several stars. Analysis of these spectra showed that a significant fraction of the molecules were rotationally excited, indicating strong UV pumping, and that the spectral lines were blue-shifted relative to the stellar spectrum, indicating motion away from the stars and toward us (*36*). These spectral features can be understood if the molecules exist in a thin shell of interstellar

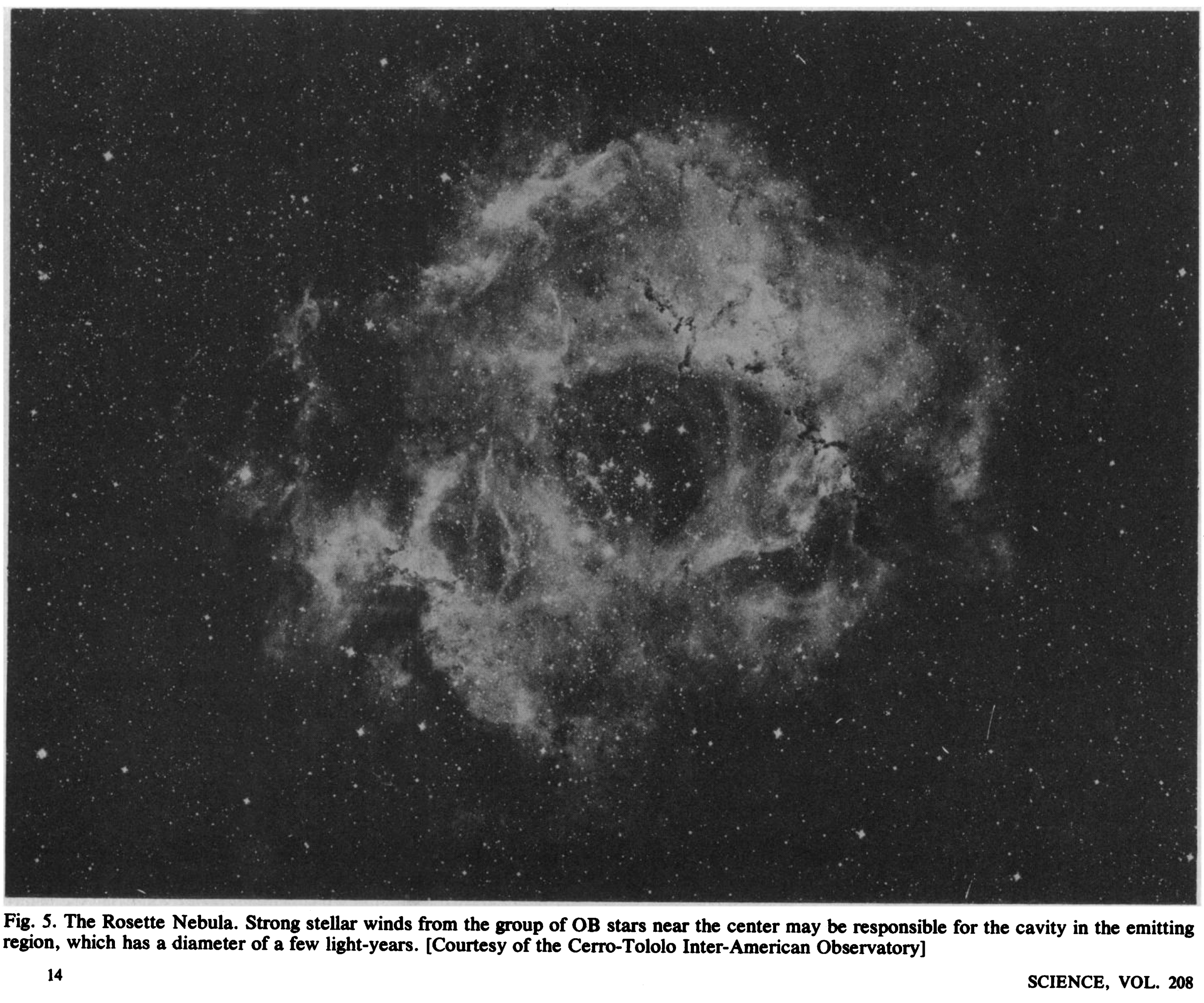

Fig. 5. The Rosette Nebula. Strong stellar winds from the group of OB stars near the center may be responsible for the cavity in the emitting region, which has a diameter of a few light-years. [Courtesy of the Cerro-Tololo Inter-American Observatory]

gas at unusually high pressure, expanding away from the star with the kind of velocity and radius expected for an interstellar bubble (37).

Another, more controversial kind of evidence for interstellar bubbles was provided by observations of broad interstellar absorption lines at 1032 and 1037 Å due to highly ionized oxygen (O^{5+}), indicating interstellar gas at a temperature of a few times 10^5 K (38). It was a surprise to find that these absorption lines were so common in the spectra of hot stars, since such temperatures were considered unlikely in the interstellar gas. One possible explanation for the O^{5+} absorption lines is that they originate in the conductive interface between the hot interior of the interstellar bubble and the expanding shell of cooler gas surrounding the observed star; the theory for the bubbles (33) predicts column densities of O^{5+} comparable to the observed values. However, the UV observations indicate that the O^{5+} is generally distributed in the interstellar medium and is not especially correlated with the hot stars, implying that the bubbles surrounding the observed stars are responsible for only a small fraction, say 10 to 20 percent, of the observed O^{5+} (39). The rest must reside in other conductive interfaces between hot and cold gas, perhaps resulting from ancient supernovae (40).

The implications of the dynamical effects of stellar winds on their interstellar environments have not been fully explored. For example, when an O star finally dies, presumably in a supernova explosion, the resulting blast wave must propagate through the cavity created by the wind until it strikes the preexisting shell. How many of the known supernova remnants have had their dynamical evolution modified by this effect, and what is implied about the interpretation of the observations?

Planetary nebulae are another important class of astronomical objects whose structures may be modified significantly by stellar winds. These objects, which are shells of gas typically 0.1 light-year in diameter, contain hot, relatively low-mass stars at advanced stages of evolution, which are now known to have substantial stellar winds (41). The shells are the result of mass ejection by the central star, now in an advanced stage of evolution. How are the structure and evolution of these shells affected by the winds?

Perhaps the most important environmental effect of stellar winds is their action on the dense, optically opaque interstellar clouds, where stars are presumed to be born. Recent advances in IR and radio astronomy have made it possible to observe OB stars embedded within these clouds. The winds from these stars must create expanding cavities within the clouds, perhaps disrupting the clouds, terminating star formation, and exposing the stars to a distant observer. The observable consequences of strong stellar winds within dense molecular clouds and the implications for star formation have yet to be explored.

Perhaps x-ray astronomy will help to elucidate these effects. The cavity created by the action of a strong stellar wind on its environment is expected to contain gas hot enough to emit x-rays. The diffuse x-rays shown in Fig. 3a may result from the action of the strong winds of the many nearby OB stars on the dense gas cloud in that region. The mysterious object η Carinae, which may have the strongest stellar wind in our galaxy, could contribute significantly to the diffuse x-ray emission as it acts to disrupt the gas cloud around it.

X-ray Sources in Stellar Winds

We have already mentioned that most OB stars are weak x-ray sources, with an x-ray to stellar luminosity ratio $L_x/L_* \approx 10^{-5}$. In addition, some 10 of the 10^4 OB stars in our galaxy are known to be strong x-ray sources, with $L_x/L_* \approx 10^{-2}$ to 1 (42). (The actual number may be a few times greater, since only a fraction of the strong x-ray sources have identified optical counterparts.) These sources are known to be in binary systems, in which a collapsed star in a very close orbit emits x-rays as a result of accreting gas captured from the O star. These binary x-ray systems include the famous source Cygnus X-1, which appears to be a black hole, as well as several pulsating x-ray sources believed to be neutron stars. Besides having great intrinsic interest, these x-ray sources have much to tell us about the nature of the stellar winds in which they are embedded.

The binary x-ray sources are probes of the stellar winds. As they orbit the OB star, with periods of typically a few days, the x-rays from the compact object must pass through a substantial amount of gas in the wind, whose column density observed from the earth varies with the orbital period. The column density in a strong stellar wind should be sufficient to cause observable absorption of soft x-rays, whose spectra and temporal characteristics can be ascribed unequivocally to the wind (43, 44). This phenomenon has been observed (45), but not yet in sufficient detail to take advantage of its potential for probing the structure of the wind.

Another way that strong binary x-ray sources can be used to probe the winds is by observing their indirect effect on the UV resonance lines formed in the wind (44). Some of these x-ray sources are luminous enough to modify the ionization balance in a substantial volume of the wind around the x-ray source—for example, by changing the predominant ionization stage of carbon from C^{3+} to C^{4+}. The result is that the shapes of the P Cygni lines due to ions affected by the x-ray source vary periodically with the orbit. This effect has also been seen recently with the IUE satellite (46).

Strong embedded x-ray sources offer a potentially powerful tool for interpreting the structures and mechanisms of stellar winds, but their exploitation is complicated by the fact that such strong x-ray sources are likely to modify the wind substantially. For example, when the x-ray source changes the ionization balance of trace elements in the wind, it also changes the radiation force acting on the ions to drive the wind, thus breaking the (presumed) spherical symmetry of the wind. By using combined observations of x-ray absorption and UV spectra of many ions, one could hope to disentangle the various effects. In that case, the modification of the wind by the x-ray source will provide a direct probe of the radiative acceleration mechanism.

Another fascinating area is related to the origin of the strong binary x-ray sources, which comprise at least 10^{-3} of all the OB stars in our galaxy. What accounts for their number? The x-ray sources are neutron stars or black holes, stars at the end points of their evolution, whose formation is thought likely to involve a supernova explosion. Is it reasonable to expect a significant fraction of all OB stars to contain such compact companions? Roughly 50 percent of all known OB stars are found in binary systems (25), with two stars of roughly comparable masses in a close orbit. Given that the lifetimes of the two massive stars are not identical, one might therefore expect a significant fraction (20 to 30 percent) of all systems born as binary O-star systems to be in a stage in which the originally more massive (and thereby shorter-lived) component has evolved to become a compact neutron star or a black hole. When this happens, the originally more massive star has most likely become the less massive one, as a result of mass transfer and mass loss. In that case, the binary system is not likely to be disrupted even if a supernova explosion occurs (32). By this reasoning, we might expect some 10 percent of all OB stars to contain such a compact companion.

What does this imply about the strong and weak x-ray sources associated with OB stars? That is, assuming that a substantial number of OB stars have a compact companion, what fraction of these should be observable as strong or weak x-ray sources? The answer to this question may involve the mechanism for mass transfer from the O star to the compact object.

There are two obvious mechanisms for mass transfer in such systems. One is capture of the stellar wind (47); the other is an overflow of the stellar atmosphere from the gravitational potential well of the star to the compact object. The resulting accretion feeds the x-ray source. To account for the luminosity of a strong x-ray source, capture of only a small fraction, say 10^{-3}, of the stellar wind is required. However, a careful analysis of orbital velocities and eclipse durations of the known systems indicates that most strong x-ray sources are so close to their companion star that gas may flow directly from the stellar atmosphere to the x-ray source, even without a stellar wind (48). Furthermore, the gravitational capture cross section of a compact object in a high-velocity stellar wind is so small that it is difficult to explain the capture of even the required 10^{-3} of the wind in many of these systems (28, 49).

On the other hand, if the strong x-ray sources result from overflow of the companion stellar atmosphere onto the compact object, a new dilemma is raised. According to current calculations, when such overflow occurs it is difficult to avoid having too much gas flowing toward the compact object, making the x-ray source invisible. (A thickness of only a few grams of gas per square centimeter is sufficient to absorb x-rays and convert their luminosity to UV or visible radiation.) Furthermore, when matter is transferred from the more massive to the less massive component of a binary system, the orbit shrinks, increasing the flow and leading to a runaway mass transfer which will surely bury the x-ray source in a common envelope. The time scale for such runaway to develop is difficult to estimate, but it is unlikely to be greater than 10^5 years (50).

The puzzle is this: If the runaway takes less than 10^5 years to develop in a system whose total lifetime is a few times 10^6 years, then for every system that is found at the stage of mass transfer where it shows up as a luminous x-ray binary, there must be more than 30 times as many progenitor systems that have not yet reached this stage. But we have already mentioned that the fraction of OB stars that presently have luminous x-ray companions is roughly 3×10^{-3}; this implies that a substantial fraction, say 10 percent, of all the OB stars in our galaxy must have compact neutron star or black hole companions in order to account for the known frequency of luminous binary x-ray sources with OB companions.

The argument above is not airtight, and one can imagine loopholes permitting a lower fraction, say 1 percent. One is that the instability of the overflow may be somehow suppressed, permitting this phase of mass transfer to last longer. Mass loss in a strong stellar wind (possibly enhanced by the x-ray emission) may provide just such a mechanism; in contrast to mass transfer, mass loss by the more massive star tends to increase the orbit separation, thereby suppressing the overflow (51). Therefore, the stellar winds may play a role in prolonging the duration of luminous x-ray binaries, even if they are not directly responsible for the mass transfer.

Another loophole arises from the possibility that the x-ray luminous phase repeats many times, separated by quiescent intervals when mass transfer is minimal. That such repetition indeed occurs is strongly indicated by observations of luminous binary x-ray systems in which the x-ray source is pulsing regularly, with periods ranging from minutes to hours. Invariably, the pulse rate in these sources is increasing, with characteristic time scales ranging from decades to a few thousand years. The pulsations and the increasing pulse rate are plausibly interpreted as resulting from accretion onto a rotating, magnetized neutron star (52). The short spin-up time scales imply that the x-ray luminous phase is a short-lived phenomenon which, if it occurred only once in the lifetime of a progenitor system, would require more quiescent systems than all the known OB stars in our galaxy. Therefore, we must infer that the x-ray luminous phase repeats many times, and that the rotating neutron star spins down during each quiescent interval. The number of quiescent systems should exceed the number of x-ray luminous systems by a factor roughly equal to the ratio of the characteristic spin-up time scale (say 10^3 years) to the spin-down time scale. We presume that similar episodic mass transfer also occurs in binary systems containing a black hole companion. Then, if the fraction of OB stars containing neutron star or black hole companions does not exceed 10 percent, the characteristic spin-down time scale must be less than about 3×10^4 years. However, a physical mechanism that would cause such a rapid spin-down rate has not yet been identified.

What physical mechanism could cause such episodic mass transfer? One possibility is enhanced mass loss from the system caused by x-ray illumination of gas flows. For each atomic mass that falls to the compact object, some 100 millielectron volts of gravitational energy is released as x-rays. It takes only a few kiloelectron volts of heating per atom to disperse gas from the system. Therefore, supposing plausibly that a few percent of the x-ray luminosity emitted by a compact object is intercepted by gas flowing in the system, we might expect 10^3 times as much gas to be expelled from the system by x-ray heating as is captured by the x-ray source. The enhanced mass loss rate resulting from such x-ray heating may substantially exceed the normal mass loss rate due to the stellar wind, causing the stars to separate and terminating the phase of rapid mass transfer, until the continued evolution of the massive star renews the cycle.

A compact object orbiting an OB star is likely to be observable even during the quiescent phase, because it should still capture some small fraction, say 10^{-5} to 10^{-6}, of the stellar wind. This is enough to account for a weak x-ray source with $L_x \approx 10^{-5}$ of that associated with an OB star. As with the strong x-ray sources, these sources may show x-ray variability due to orbital motion. What fraction of the weak x-ray sources, such as those in Fig. 3, are binary systems with the compact object in a relatively quiescent phase? We doubt that it is 100 percent because we think that more evidence of the binary nature of these systems would have been seen already in periodic Doppler shifts in the optical spectra. However, we would not be surprised if the fraction were 10 percent. The origin of the weak x-ray sources in the other 90 percent remains a mystery.

The Future

We have learned that OB stars have stellar winds of sufficient strength to modify their evolution and to have dramatic dynamical effects on their interstellar environment. Radiation pressure appears to play an important role in driving the winds, but the theoretical descriptions are not yet adequate to describe the details of their ionization and dynamics. Weak and strong x-ray sources observed to be associated with

OB stars offer new possibilities for probing the winds, at the same time raising new questions about the evolution of binary star systems containing compact objects. What news will the future bring?

Advances in space astronomy promise to make the next decade a most fruitful one for stellar wind studies. Even now, observations with the IUE satellite are greatly increasing the number of OB stars whose winds have been measured spectroscopically. Within the past few months the Einstein X-ray Observatory has revealed that most if not all OB stars are x-ray sources; more extensive observations of OB stars with this telescope, including searches for time variability, promise to reveal much about the nature of the winds and their embedded x-ray sources. Later in the 1980's, orbiting IR telescopes of greatly increased sensitivity will permit observations of the dynamical effects of stellar winds within the dense interstellar clouds where stars are born. Our ability to observe stellar winds in the UV and in x-rays will be greatly improved and extended to neighboring galaxies by the Space Telescope and by the proposed Advanced X-ray Astronomy Facility.

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53. This work was supported by grants from the National Science Foundation.

Potato Protoplasts in Crop Improvement

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Potatoes, including sweet potatoes, yams, cocoa yams, and cassava, represent an important class of world food crops in which commercial propagation is asexual rather than through true seeds. Vegetative reproduction preserves essential varietal characteristics from one generation to the next, whereas, when seeds from these plants are used, progeny are only reasonable facsimiles of the parent. Despite their economic significance, these species have not been the beneficiary of the "green revolution" breeding technology, so successful for such crops as wheat, maize, and rice. In some examples, outright neglect is a contributing factor, but with the establishment of international crop development centers, improvement of these species is now receiving increased attention (*1*).

For potatoes, a concerted improvement program has been active for the past 75 years in both Europe and North America. Despite these efforts, no single potato cultivar has emerged with, for example, multiple resistances to most major diseases, quick adaptability to new geographic settings, and the embodiment of all horticultural traits, including yield potential, viewed as essential. In the United States, four cultivars constitute 72 percent of the total potato acreage (*2*); the most significant cultivar emerged in 1871 as a selection by the renowned botanist Luther Burbank (*3*). In Europe, "antique" varieties such as 'King Edward' and 'Bintje' continue

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0036-8075/80/0404-0017$02.00/0