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The Most Luminous Stars

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The intrinsically brightest stars are also the most massive. Is there a limit to stellar masses and luminosities?

Not long ago, most astronomers supposed that stars with much more than 60 times the mass of the sun were exceedingly rare or even nonexistent. Such objects, which we call "very massive" stars, would be more luminous than the sun by factors of a million or more, and were thought to be unstable. But today many very massive stars are known in our Galaxy and in several nearby galaxies. A few especially impressive objects may have masses of the order of 1000 $M_\odot$ (where $M_\odot$ is the mass of the sun, 2×10^{33} g) and luminosities of 10^7 $L_\odot$ or more ($L_\odot$, the sun's luminosity or radiated power, is nearly 4×10^{26} W). Very roughly, one star in a billion may be above 60 $M_\odot$.

Theoretical developments have kept apace with the new observational perspectives. We now know that a massive star's evolution is modified by internal mixing as well as by mass loss. Quite unlike the standard doctrine of only a decade ago, the star may remain "quasi-homogeneous" in chemical composition during most of its lifetime; and dramatic instabilities occur at particular stages of evolution. These processes are consequences of turbulent fluid physics in the presence of radiation.

In this article we review some of the recent observational and theoretical discoveries about very massive stars. We discuss the broader perspective now available from observations of stars in other galaxies and also a few individual stars of special interest (*1*). Such important topics as stellar winds and mass loss, which are now crucial in stellar astronomy (*2*), cannot be explained in detail here. We only briefly mention the Wolf-Rayet stars, which have very likely evolved from massive stars and which figure prominently in current research (*3*). We must also neglect the chemical enrichment of the interstellar gas and theories of massive supernovae. Even so, there is much to relate about massive stars and their evolution.

Summary. Stars with individual luminosities more than a million times that of the sun are now being studied in a variety of contexts. Observational and theoretical ideas about the most luminous stars have changed greatly in the past few years. They can be observed spectroscopically even in nearby galaxies. They are not very stable; some have had violent outbursts in which large amounts of mass were lost. Because of their instabilities, these stars do not evolve to become red supergiants as less luminous stars do. Theoretical scenarios for the evolution of these most massive stars depend on the effects of turbulence and mixing combined with high radiation densities.

Historical Development

It has been known since the 1920's that radiation accounts for most of the pressure in a sufficiently massive star and that this reduces the star's stability (*4*). A self-gravitating ideal gas sphere supported entirely by radiation pressure would have zero net binding energy; so a very massive star is stable only because some of its pressure is due to ordinary gas rather than to radiation. A relatively small amount of energy can cause large-amplitude pulsations in a weakly bound object. Moreover, the CNO cycle of nuclear reactions, which liberates energy in massive stars, is very temperature-sensitive, and this helps motivate a pulsating heat engine. Stars above a critical mass—the Ledoux-Schwarzschild-Härm limit, estimated in 1959 to be about 60 $M_\odot$—are therefore vibrationally unstable (*5*). Before 1970 it was supposed that such a star's pulsation amplitude must grow until its outer layers were ejected, quickly reducing the mass or even destroying the star. Theory seemed to preclude the existence of observable very massive stars.

But a few known objects nevertheless appeared to be very massive. The total mass of one famous double star system had long been known to exceed 110 $M_\odot$ and very likely 150 $M_\odot$ (*6*). By 1960 Feast *et al.* (*7*) had observed the brightest stars in the Large and Small Magellanic Clouds, which are small satellite galaxies to our own Milky Way Galaxy. Luminosities of massive stars within our Galaxy tend to be uncertain, because their distances are usually uncertain and also because interstellar dust obscures most of our galactic disk at visual and ultraviolet wavelengths. The Magellanic Clouds, on the other hand, have well-determined distances [55 and 70 kpc, where 1 kpc (kiloparsec) is about 3260 light-years] and are not heavily obscured. Feast *et al.* found that many stars in the Clouds are luminous enough to require masses close to 100 $M_\odot$. By about 1970, Eta Carinae (η Car) was thought to be a very massive star; at the same time Walborn (*8*) introduced a new spectral classification system for the hottest stars and assigned a new type, O3, to several stars in our Galaxy, implying very high temperatures and luminosities.

Also around 1970, theorists found that the Ledoux-Schwarzschild-Härm limit may be closer to 100 $M_\odot$ than to 60 $M_\odot$ and that the vibrational instability can be self-limiting (*9*). The pulsation amplitude

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is limited by nonlinear effects, that is, by dissipation in shock waves. Some continuous, noncatastrophic mass loss may result from the pulsation (this is still quantitatively uncertain) but, at least, very massive stars are theoretically permitted to exist. During the past decade, further observations of the brightest stars in our Galaxy and in other nearby galaxies have revealed many very massive stars where few were previously believed to exist.

A very massive star is near the edge of catastrophe not only because of interior effects but also because of a direct consequence of radiation pressure in the star's outer layers. There the ratio between opposing forces of radiation pressure and of gravity depends simply on the star's luminosity/mass ratio, L/M, multiplied by an opacity coefficient. If L/M exceeds a critical value, generally called the Eddington limit, then emergent radiation will progressively blow the outer layers away. For very hot stars, where opacity is mainly due to scattering by free electrons, the Eddington limit is

$$(L/M)_{\max} = 4 \times 10^4 \, L_\odot/M_\odot$$

and additional causes of opacity tend to reduce this value. For moderately large stellar masses, 10 to 40 $M_\odot$, the mass-luminosity relation is such that L/M is roughly proportional to M^2. If extrapolated, this relation would violate the Eddington limit for $M \gtrsim 60 \, M_\odot$. Very massive stars must evidently be affected in their structures by radiation pressure, in such a way as to keep their L/M ratios safely below the Eddington limit—so that the mass-luminosity relation is modified above 40 $M_\odot$. For extremely large masses, the mass-luminosity relation may even be determined by the Eddington limit; L/M then becomes almost constant. Along with internal vibrational instability, surface radiation pressure may help to provoke continuous mass ejection (*2*).

The Hertzsprung-Russell Diagram

The physical characteristics of the very luminous stars (also called supergiants) with different surface temperatures are summarized in Table 1. The most luminous, most massive stars have surface temperatures above 30,000 K and therefore radiate mostly at ultraviolet wavelengths. At the visual wavelengths traditionally used in ground-based astronomy, the intrinsically brightest stars are somewhat cooler, less massive supergiants with temperatures around 10,000 K, like Cygnus OB2 #12 (see Fig. 1). These moderate-temperature supergiants will be the visually brightest ones in other galaxies; they are the most conspicuous stars in photographs of other nearby spiral galaxies.

Figure 1 is the Hertzsprung-Russell (H-R) diagram—that is, a plot of luminosity versus surface temperature with temperature increasing toward the left—for the most luminous known stars ($L \geq 5 \times 10^5 \, L_\odot$) in our Galaxy (*10*), the Magellanic Clouds (*11*), the nearby small spiral galaxy M33 (*12*), and the nearby small irregular galaxies NGC 6822 and IC 1613 (*13*). (Because of its large size and high tilt angle there are no extensive surveys for the brightest stars in the giant spiral galaxy M31, the Andromeda nebula.)

The most significant feature of this H-R diagram is an observed upper envelope to the luminosities of normal stars. This luminosity boundary declines with decreasing temperature for the hotter stars, but becomes essentially constant for the cooler supergiant stars. The most luminous, most massive stars occupy the left part of Fig. 1, while the upper right is empty.

Our empirical knowledge of the brightest stars in our own Galaxy is largely restricted to the "solar neighborhood," a region 6 kpc in diameter centered on the sun which is only a few percent of the galactic disk. Stars at greater distances in the galactic disk are badly obscured at visual and ultraviolet wavelengths by interstellar dust. The galactic stars in Fig. 1 are members of star clusters and stellar associations, whose distances are reasonably known, and they are representative of the stellar population in the spiral arms of the Milky Way.

A more complete sample of luminous stars is available for the Large and Small Magellanic Clouds. The H-R diagram for the Large Cloud looks very much like that for the most luminous stars in the solar neighborhood, revealing very similar distributions of stellar temperatures and luminosities in the two galaxies (*14*). In the Small Magellanic Cloud the luminosities of the brightest hot stars are less than those of their counterparts in our Galaxy and the Large Cloud (*11*); this may be a size-of-sample effect, although it is also possible that star formation produces a different statistical distribution of initial stellar masses in the Small Cloud (*11*). In two other small nearby galaxies, NGC 6822 and IC 1613, there appear to be few hot stars with masses above 80 $M_\odot$ (*13*). Among the several galaxies that we have mentioned, the primary difference appears to be that smaller galaxies have fewer of the most luminous, hot stars. Otherwise, the H-R diagram for each galaxy resembles Fig. 1. It is significant that the upper luminosity envelope for the cool supergiants is the same in all of these galaxies.

"Main sequence" stars, which still have hydrogen at their centers, should be near the left (hot) side of Fig. 1; and as core hydrogen is exhausted, evolution should carry massive stars to the right across the diagram along nearly horizontal tracks as they expand and become cooler at roughly constant luminosity. Stars with masses less than 60 $M_\odot$, in the lower part of Fig. 1, apparently can evolve all the way across the diagram. Why, then, are the most luminous stars restricted to the left side of the H-R diagram? What prevents a very massive star from evolving into a yellow or red supergiant whose surface is cooler than 15,000 K but whose luminosity exceeds $10^6 \, L_\odot$? We will return to the theoretical implications of this question later; the answer is not simple.

Individual Very Massive Stars

We now describe a few remarkable objects whose characteristics and behavior provide important clues to the natures of very massive stars. We begin with a remarkable association of stars in the Milky Way constellation Carina, located in a prominent spiral arm of our Galaxy and close enough for us to study in detail. The Carina nebula, NGC 3372, is a region of star formation about 2.8 kpc (9000 light-years) away. Associated with this nebula are the famous variable star η Car and many other luminous stars, including several O3 stars. The O3 type denotes the hottest classified stars that have not yet evolved far from the main sequence (*8*). Their surface temperatures may be close to 50,000 K (*15*). Of the ten O3 stars known in 1982, six are associated with the Carina nebula (*16*). These, plus η Car, may all be within a region less than 15 pc across—an amazing concentration of very luminous stars. The brightest of the Carina O3 stars, HD 93129A, probably has a luminosity close to $5 \times 10^6 \, L_\odot$ (*15*, *17*), about the same as that of η Car and indicative of an initial mass around 200 $M_\odot$. These are the two most luminous known stars in the solar neighborhood.

Eta Carinae has been famous since the middle of the 19th century. Except for statements that it was visible to the naked eye and probably variable, little is known about its history prior to 1830. (It can be observed only from southern latitudes, where there were few astronomers at that time.) Then, between 1836 and 1858, η Car was seen to undergo a spectacular and prolonged outburst (*18*). In 1843 it was briefly the second brightest star in the sky. Later, between 1858 and 1870, its apparent visual brightness faded by a factor of several hundred. For a long time afterward it remained constant in visual brightness, except for one or two brief episodes; but since 1940 it has been gradually brightening.

Eta Carinae is now surrounded by a small nebula of gas and dust, called the "homunculus" because of its appearance (see cover). The homunculus is expanding at several hundred kilometers per second and was obviously ejected during the explosion (*19*). The mass of the ejected material is most likely 0.1 to 1 $M_{\odot}$, additional outlying nebulosities suggest that other explosions occurred before 1800, and there is evidence for continued outflow from the star. The apparent fading between 1858 and 1870 was due to the formation of dust grains in the expanding ejected gas. These dust grains now absorb most of the star's visual and ultraviolet luminosity and are thereby heated enough to reradiate the luminosity at infrared wavelengths. Infrared radiation from the homunculus now provides us with a measurement of the total luminosity, about 5×10^6 $L_{\odot}$ (*20*).

This same luminosity can nearly account for the maximum visual brightness seen in the 1840's and also seems reasonable for the ultraviolet luminosity before the explosion. From these and other considerations involving its spectrum, η Car is thought to have an effective surface temperature around 30,000 K (*21*).

Even though η Car and HD 93129A were formed in the same region and have similar luminosities, η Car appears to be cooler and less stable. Why? The most likely explanation is that their evolutionary states are different. Either η Car is so young that it has not yet reached the main sequence in the H-R diagram, or it is an evolved very massive star near the end of its lifetime. The latter alternative was favored by Burbidge (*22*) more than 20 years ago, but only lately have relevant and incisive observations been made. Ground-based spectra taken by A. D. Thackeray and by N. R. Walborn, and ultraviolet data taken by K. Davidson and T. R. Gull with the International Ultraviolet Explorer (IUE) satellite, have shown that the ejected gas is nitrogen-rich but carbon- and oxygen-poor (*23*). This is a natural outcome of the CNO cycle of nuclear reactions (*24*). The implication is that η Car has had enough time to mix the nuclear products from its core to its surface, from which the observed ejecta came. The star is therefore evolved. Moreover, the fact that mixing has occurred lends dramatic support to some theoretical ideas by Maeder, discussed later.

Table 1. Summary of the physical properties (*47*) of the luminous stars of different temperatures.

Property	Hot	Intermediate	Cool
Spectral types (*48*)	O, B, A	F, G, K	M
Surface temperature (K)	50,000 to 10,000	10,000 to 4,000	< 4,000
Luminosity range ($L/L_{\odot}$)	10^4 to $> 5 \times 10^6$?	10^4 to 8×10^5	10^4 to 5×10^5
Mass range ($M/M_{\odot}$)	20 to 300?	20 to 50	20 to 50
Size range ($R/R_{\odot}$)	10 to 100	30 to 1,000	300 to 2,000

The precise reason why η Car is unstable—the cause of the observed outburst—is not yet understood. We later mention some possible single-star explanations and why they are relevant to Fig. 1. Alternatively, η Car may be a double star, with one component dynamically interfering with the surface of the other; this idea probably requires that at least one member of the hypothetical pair has evolved and is attempting to expand.

In any case, during recent centuries η Car has probably lost mass unsteadily but at an average rate between 0.001 and 0.1 $M_{\odot}$ per year (*14, 25*). The star may therefore lose most of its mass in less than 10^5 years. A very massive star's total lifetime, however, is much longer than this—of the order of 3×10^6 years. Eta Carinae has evidently reached a critical stage in its evolution.

Another well-known, unstable luminous star in our galaxy is P Cygni (P Cyg). This star temporarily brightened during the 17th century but has not fluctuated much since. Its total luminosity is now around 10^6 $L_{\odot}$ and its surface temperature is 20,000 K or somewhat cooler. It is now losing mass at a rate variously estimated to be 3×10^{-5} $M_{\odot}$ per year (*26*) or 3×10^{-4} $M_{\odot}$ per year (*27*). P Cygni may be qualitatively like η Car but cooler, less luminous, and less massive.

Several very luminous blue variable stars in other galaxies are similar to η Car and P Cyg. These include S Doradus in the Large Magellanic Cloud and the Hubble-Sandage variables in the nearby spiral galaxies M31 and M33 (*28*). One of these, Var A in M33, has a record of variability reminiscent of η Car as well as infrared radiation suggestive of dusty circumstellar gas. Ultraviolet spectra of five Hubble-Sandage variables were recently obtained with the IUE (*29*). Their ultraviolet fluxes, together with ground-based data, imply luminosities and temperatures intermediate between those of P Cyg and η Car. All of these are near or even above the empirical upper luminosity envelope for normal stars in Fig. 1.

Conspicuous in the upper left of the H-R diagram is Radcliffe 136a (R136a), a possible supermassive star. R136a, also called HD 38268, is the central object of the giant nebula 30 Doradus in the Large Magellanic Cloud (Fig. 2). Several years ago Schmidt-Kaler and Feitzinger (*30*)

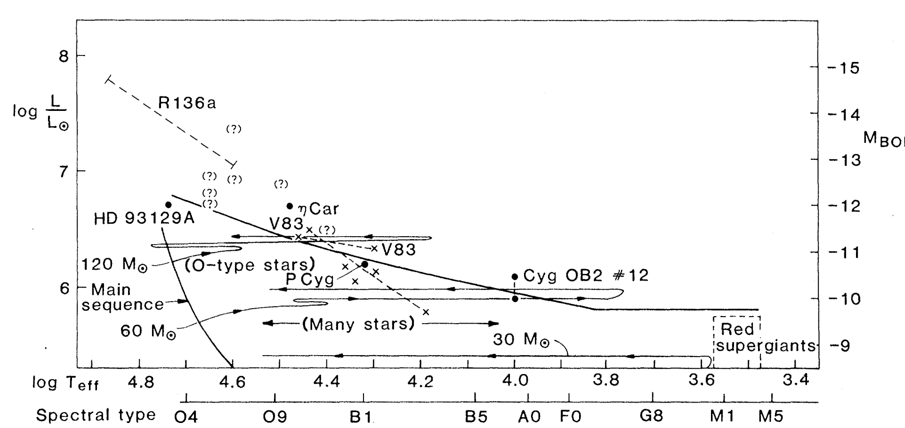

Fig. 1. The H-R diagram. Luminosity versus temperature is shown for the most luminous stars ($L > 5 \times 10^5$ $L_{\odot}$); M_{BOL} is bolometric magnitude. The position of the hydrogen-burning main sequence and the empirical upper luminosity boundary for normal stars are shown by solid lines. The locations of the O-type stars and the red supergiants are marked, as well as those of individual stars discussed in the text; the Hubble-Sandage variables are shown by x and the suspected supermassive Wolf-Rayet stars in M33 by (?). The evolutionary tracks for stars of 30, 60, and 120 $M_{\odot}$ are from Maeder (*39, 41*).

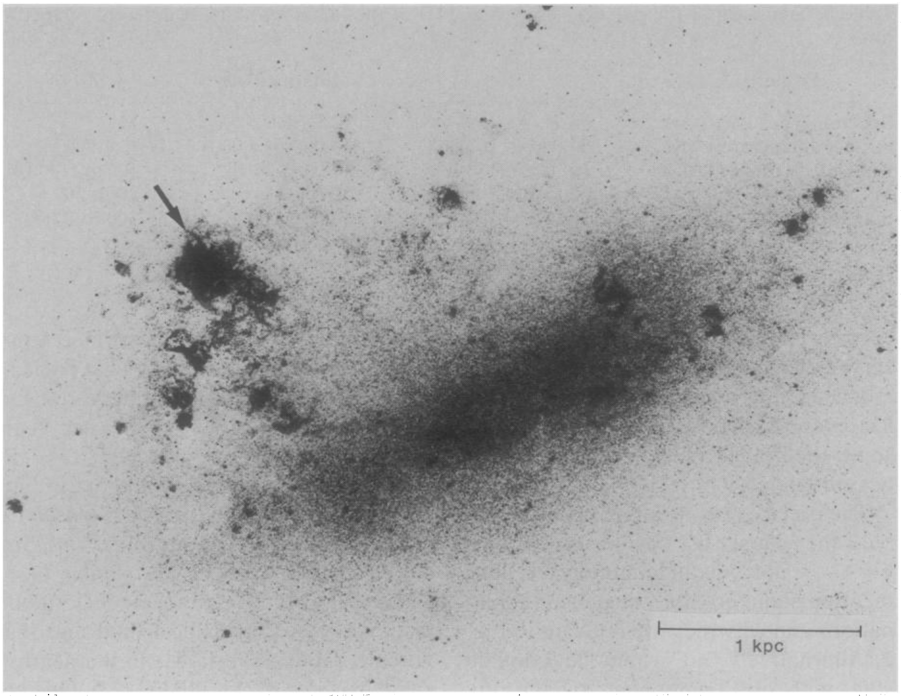

Fig. 2. The Large Magellanic Cloud showing the 30 Doradus or Tarantula nebula. [Photograph of the Large Magellanic Cloud reproduced by courtesy of AURA, Inc., Cerro Tololo Inter-American Observatory]

proposed that R136a accounts for most of the ultraviolet radiation that ionizes the nebula; this would entail a huge luminosity. After obtaining ultraviolet data with the IUE satellite, Cassinelli *et al.* (*31*) in 1981 concluded (along with Schmidt-Kaler and Feitzinger) that R136a is a single star, with a surface temperature above 60,000 K, whose luminosity exceeds that of η Car or HD 93129A by a factor of 10 or 20. The suggested mass was close to 3000 $M_{\odot}$. According to Savage *et al.* (*32*), newer data on the ultraviolet continuum are consistent with a somewhat lower mass of about 2000 $M_{\odot}$.

R136a is clearly a significant and extreme object, but there are two crucial uncertainties regarding its parameters. First, is it really a single object? This is uncertain because it is so far away. Second, what is its surface temperature? Most of the luminosity is at unobservably short wavelengths ($\lambda < 1000$ Å) and therefore must be extrapolated from the IUE and ground-based data (1000 Å $< \lambda <$ 3 μm). The derived luminosity is roughly proportional to the cube of the assumed temperature.

Regarding the first question, direct photographs and visual observations show that R136a is smaller than 0.1 pc. Speckle interferometry (a new specialized technique for obtaining good angular resolution despite blurring by the earth's atmosphere) and the Space Telescope are capable of placing a limit of 0.005 pc on the size of R136a (*33*). But even 0.005 pc is large by some standards—it is 1000 times the earth-sun distance—and does not prove that R136a is a single star. A plausible cluster of many (more than ten) stars cannot be fit into 0.005 pc, but a double, triple, or quadruple system of stars is easily possible within that size. (The period for a 0.005 pc orbit would be of the order of a thousand years.) Long before the current brouhaha, Walborn (*34*) suggested that R136a is analogous to the very compact set of luminous stars in NGC 3603, the most massive nebula that has been optically observed in our Galaxy.

The appropriate temperature for R136a is also uncertain. Schmidt-Kaler and Feitzinger (*30*) derived high temperatures by assuming that R136a photoionizes the entire 30 Doradus nebula. Cassinelli *et al.* (*31, 32*) argued from the general appearance of the ultraviolet spectrum that a temperature of 60,000 K or more seemed likely, and noted that this also sufficed for the ionization. However, various astronomers have noted that 30 Doradus is an extremely large nebula and contains many hot stars, which are not well studied and which may account for most of the ionization (*35*). The temperature of R136a should therefore be estimated more directly, from its spectral features. The shape of the observed continuum resembles a 40,000 K blackbody (*32*) and we take this to be a lower limit to the actual relevant temperature. Spectral lines at visual and near-infrared wavelengths resemble those in an O3-type spectrum, but not perfectly, and are not easy to analyze (*36*). The best temperature indicator may be the near absence of certain ultraviolet Si IV lines (*32*), implying that silicon is more than triply ionized. However, sophisticated atmosphere models—at least as good as those by Kudritzki (*15*) but specifically adapted to R136a—will be needed to quantify this. At present, it is quite conceivable that the relevant temperature is as low as 45,000 K. This would imply a luminosity around 1.5×10^7 $L_{\odot}$, only three times as great as that of η Car. One star with a mass less than 1000 $M_{\odot}$ can achieve this.

Intuitively, and with little proof, we suspect that R136a will turn out to be either a single star with a mass between 500 and 1200 $M_{\odot}$, or else two or three stars in the range 200 to 1000 $M_{\odot}$. Such a "conservative" view is appealing because it does not leave a large gap between R136a and other known objects. Even so, R136a is a wonderfully extreme object and the recent observations constitute a significant and fascinating advance in our knowledge of the most massive stars.

Several objects with Wolf-Rayet–like spectra (*3*) have been identified in the large nebulae in M33 (*37*). Some of them may resemble R136a (*38*). Their proposed locations in the H-R diagram, denoted by question marks in Fig. 1, are less extreme than that of R136a. Unfortunately, since M33 is much farther away (700 kpc) than the Large Cloud, we cannot tell whether any of them are single stars.

In summary, Table 2 is a list of the physical parameters for several of the objects we have mentioned.

Theoretical Considerations

Several aspects of theory are influenced by the observational discoveries that we have described. In this article we can discuss only a few important theoretical ideas, but first we should outline some background. Nuclear reactions in a massive star, during most of its lifetime, occur within a central core which is continually stirred by convection. The hydrogen in this core is gradually changed into helium. Outside the core, according to the simplest view held a few years ago, material should remain mostly hydrogen because convective mixing does not generally occur there. During the past 15 years it has been recognized that massive stars tend to lose mass continuously (*2*). The outflowing "stellar winds" can be studied through infrared-, visual-, and ultraviolet-wavelength spectroscopy and even through radio and x-ray observations. Calculations of stellar evolution must therefore include mass loss, while theorists also attempt to explain why the stellar winds occur. (Radiation pressure plays a leading role but is not the only important process.) Some objects known as Wolf-Rayet stars appear to be relevant (*3*). A Wolf-Rayet star typically has a strong stellar wind and a hot surface which is hydrogen-poor but helium-rich and (relative to most stars) either carbon- or nitrogen-rich (spectral types WC and WN). If a moderately massive or very massive star can lose enough exterior mass while evolving a hydrogen-poor core, the star is eventually peeled down to its inner, processed material; it is then a Wolf-Rayet star. Hence, the stellar evolution and mass loss theorists have been greatly motivated by studies of Wolf-Rayet stars (*2, 3*).

While keeping this background situation in mind, we think that very massive stars provide remarkable insights which are not obvious from studies of ordinary stellar winds or of Wolf-Rayet stars. Consider the upper envelope to luminosities in the H-R diagram (Fig. 1). What prevents a very massive star from crossing this boundary while evolving rightward (expanding and cooling) across the upper left-hand part of Fig. 1? In 1979 we drew attention to this question and proposed an intuitive answer, which naturally involved mass loss (*14*). Evolutionary calculations by de Loore, Chiosi, Stothers, Maeder, and others (*39*) show that continuous high mass loss rates do indeed prevent very massive stars from evolving far to the right or to cooler temperatures in the H-R diagram, but the average observed mass loss rates are inadequate to make normal loss the full explanation. Our 1979 hypothesis was somewhat different because we emphasized unsteady mass loss. Note that η Car, P Cyg, and at least some of the Hubble-Sandage variables, all lying near the critical boundary in Fig. 1, are thought to suffer spectacular episodes of mass ejection. These examples inspired our scenario, wherein some particular instability causes a drastic increase in mass loss just as the evolving star reaches the critical line in the H-R diagram. (Incidentally, the line drawn in Fig. 1 is an empirical envelope to the sample of "normal" stars. We expect the true boundary line for instability to lie slightly above this; perhaps η Car marks its location.) A star may even "bounce" recurrently on the critical line. When the star has evolved to this limit, perhaps the sudden instability causes an η Car–like outburst which ejects a fraction of a percent of the star's mass. This moves the star slightly away from the critical line and temporarily relieves the instability, but then, in a few centuries or decades, the star evolves back to the limit and suffers another explosion; and so on, perhaps until the star is reduced to a Wolf-Rayet star (unless it becomes a supernova first).

Table 2. Physical characteristics of some very luminous stars.

Characteristic	η Car	P Cyg	R136a	Var 83 in M33 (Hubble-Sandage variable)
Mass ($M/M_\odot$)	~ 200	~ 80 to 100	≤ 2,000	~ 100 to 150
Luminosity ($L/L_\odot$)	5×10^6	$\leq 1.5 \times 10^6$	$\leq 6 \times 10^7$	2×10^6
Temperature (K)	30,000	≤ 21,000	45,000 to 75,000	20,000 to 30,000
Mass loss rate ($M_\odot$ per year)	10^{-1} to 10^{-3}	10^{-4} to 10^{-5}	$\sim 5 \times 10^{-4}$	$\sim 3 \times 10^{-5}$

What causes the instability? There are several alternatives. An internal effect—possibly reminiscent of the classical vibrational instability—may be responsible [see a recent discussion by Stothers and Chin (*40*)]. But more likely, surface radiation pressure is involved. The temperature suspected for the surface of η Car, 30,000 K, is just low enough to allow the mostly ionized gas to contain a perceptible concentration of neutral hydrogen and low-ionization heavy ions (*21*). These raise the opacity noticeably above the value that applies at higher temperatures, which is due to scattering by free electrons. Lower temperature therefore means higher opacity, which means that the Eddington limit $(L/M)_{max}$ is decreased. For a given stellar L/M ratio, the star's surface then becomes less stable than it would be at higher temperatures. Thus, unless η Car has a mass well above 200 $M_\odot$, its surface temperature cannot evolve much below 30,000 K without some drastic change in its atmosphere. This is not really an explanation of the instability—a model atmosphere may be able to meet the opacity-related difficulty by expanding to lower densities—but the temperature dependence of the opacity seems to hint that the left-hand, sloping part of the luminosity envelope in the H-R diagram is at a critical location for the opacity-dependent Eddington limit.

Another promising cause for the hypothetical instability has been discussed by de Jager (*1*, pp. 11–14) and by Maeder (*41*). This intriguing but complicated mechanism involves turbulence. Supergiant stars with surface temperatures below 10,000 K or so are convective in some outer layers. This entails a pressure due to turbulent motions. Near the star's surface, dissipation of convective kinetic energy gives rise to a gradient of turbulent pressure. A pressure gradient, however, is in effect a volume force, which can oppose gravity. According to de Jager, the turbulent pressure gradient fully counteracts gravity if the star's luminosity is sufficiently high. (This may be analogous to the Eddington limit, with turbulent pressure instead of radiation pressure.) The expected luminosity limit is said to be at about the same location as the cooler, flat part of the empirical line in Fig. 1. Maeder remarks that this result is insensitive to chemical composition, which means that the luminosity limit for cool stars should be about the same in all star-formation regions and in all galaxies—which is what the observations suggest (*10–14*). It is not clear, though, whether the turbulent pressure mechanism is applicable to stars much hotter than 10,000 K. Stothers and Chin (*40*) discussed a few other processes that may contribute to the hypothetical instability.

Some of the most ambitious evolutionary calculations for massive stars have been done by Maeder (*41, 42*). A novel part of his work concerns mixing within very massive stars. Until recently, it was supposed that the chemical composition at the surface of a massive star (excluding Wolf-Rayet stars) is largely unaffected by the nuclear reactions in the core. Proposed mixing mechanisms (convective overshooting, meridional circulation due to rotation) did not seem to be very effective. Recently, though, Maeder found that turbulent diffusion incited by differential rotation can be important. Differential rotation is expected to occur inside a typical massive star. But the rotation-speed gradient (the shear) cannot be extremely large, for if it were, strong turbulence would develop and would redistribute the angular momentum. Hence, there is a tendency for differential rotation to adjust itself so that turbulence is only marginally induced (*43*). The Reynolds number is thus automatically of the order of 100. Turbulent mixing occurs and behaves like diffusion of material; the effective diffusion coefficient is roughly equal to the viscosity multiplied by the Reynolds number. In most stars this product is too small to have much effect. Maeder pointed out, however, that radiative viscosity, like radiation pressure, becomes large in massive stars, so that the turbulent diffusion coefficient is large—large enough for the mixing time scale in a very massive star to be less than the star's lifetime (*42*). This enables the star to remain quasi-homogeneous in its chemical composition even though nuclear processing occurs in the convective core. Maeder's turbulent mixing theory has apparently been confirmed by the discovery, mentioned earlier in this article, that nitrogen-rich material exists at the surface of η Car (*23, 41*).

In Maeder's models, which include mixing as well as mass loss, very massive stars become hot Wolf-Rayet stars after losing mass during their η Car–like encounters with the critical luminosity envelope in the H-R diagram. Mixing is important in this scenario. An interesting consequence concerns supernova events. A star that starts out moderately massive is probably a cool red supergiant when it explodes as a supernova, but a star which is initially very massive becomes a supernova while it is a hot Wolf-Rayet object.

It is not easy for very massive stars to form. One difficulty is that a massive protostar may be self-limiting in its "cocoon" stage. The densest part of a protostellar cloud should contract fastest, to form a sort of condensation nucleus. This is essentially a star, which grows as the outer parts of the surrounding cloud—the cocoon—continue to fall inward. As Larson and Starrfield and later Kahn noted (*44*), this growth should stop when the central object develops sufficient luminosity for radiation pressure to reverse the infall of dusty gas, because dust in the gas makes the effective opacity very large. At the same time, ultraviolet radiation may ionize and heat the same gas, making it less susceptible to gravitational infall. These limiting effects may occur when the star has acquired mass of the order of 60 $M_{\odot}$, and they become progressively more likely with increasing mass. However, according to Wolfire and Cassinelli (*45*), larger stellar masses are possible if the dust is more easily destroyed than Kahn assumed. The situation is not clear. We also do not know what special conditions occurred in the Carina nebula to create such a large and unusual concentration of very massive stars. This question is obviously relevant to theories of the "initial mass function," that is, of the statistical distribution of stellar masses throughout our Galaxy and in other galaxies.

Finally, we mention an unconventional idea by Bath (*46*) in which many of the very luminous objects we observe are really accretion disks around moderately massive stars in binary systems. One star in a very close binary system may lose mass, which is then accreted onto the other star; this accretion flow forms a luminous disk because of angular momentum and turbulent viscosity. The Eddington limit is modified in this context, so that a given luminosity requires smaller individual stellar masses. One objection to this type of model is that the part of Fig. 1 containing O3 stars, η Car, and the Hubble-Sandage variables can be explained without invoking accretion disks. It is difficult to assess the probability that there are enough massive, compact binary star systems in the necessary stage of their evolution. Bath's suggestion is perhaps most appealing for the most extreme objects. In the case of R136a, one naturally wonders whether the central object might be a massive black hole, with an accretion disk, rather like a miniature version of an active galactic nucleus. Savage *et al.* (*32*), on the other hand, remark that theoretically one does not expect an accretion disk to produce the observed O3-like spectrum.

The past decade has produced surprising revelations about the evolution of the most massive stars, and we expect that the study of very massive stars will figure prominently in the research programs of future very large telescopes and space telescopes. The angular resolution expected with the Space Telescope will be ten times better than with current ground-based telescopes. A good high-resolution Space Telescope image of the homunculus of η Car should be spectacular. The high spatial and spectral resolution planned for the telescopes of the future will be crucial for observations of individual stars in other galaxies.

References and Notes

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49. We are grateful to N. R. Walborn, P. Conti, and R. Kennicutt for many discussions about massive stars. In our work on this topic, we have been guest observers in the NASA-supported IUE program, as well as visiting astronomers at Kitt Peak National Observatory and Cerro Tololo Inter-American Observatory, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation. R.M.H.'s work is partially supported by an NSF grant.

Amphiphilic Secondary Structure: Design of Peptide Hormones

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Summary. Peptide synthesis can be used for elucidating the roles of secondary structures in the specificity of hormones, antigens, and toxins. Intermediate sized peptides with these activities assume amphiphilic secondary structures in the presence of membranes. When models are designed to optimize the amphiphilicity of the secondary structure, stronger interactions can be observed with the synthetic peptides than with the naturally occurring analogs.

The rational design and construction of biologically active peptides and polypeptides is now an attainable goal through the applications of the tools of modern chemistry (*1*). Foremost among these tools is the technique of solid phase peptide synthesis (*2*). No longer is it necessary for a chemist interested in preparing a peptide 20 or 30 amino acids in length to spend a substantial portion of his career in its construction. Rather, through the judicious application of modern purification and analytical techniques such as high-performance liquid chromatography (HPLC), it is now possible for a graduate student in the course of his thesis studies to prepare as many as five to ten peptides of this size and to characterize their physical and biological properties. Because of these technological advances, it is feasible not only to propose structural hypotheses for the construction of biologically active peptides and polypeptides but also to test thoroughly the experimental aspects of these proposals.

Although we have increased our understanding of tertiary structure in recent years, we have not yet reached the point at which the folding of a peptide with a given amino acid sequence into a tertiary structure can be predicted with confidence. In contrast, a solid foundation has been laid for the prediction of amino acid sequences that form certain types of secondary structures. The recognition of the importance of these secondary structures has led us to a new approach to the design of biologically active peptides such as hormones.

A host of biologically important peptides composed of 10 to 50 amino acids are devoid of well-defined tertiary structure. As a rule, they lack disulfide bonds, they are linear (*3*), and their conformation depends entirely on their environment; they can assume completely different secondary structures in water, in a detergent micelle, or in trifluoroethanol or other organic solvents. Many of these peptides play very specific roles as hormones, cofactors, signals for membrane translocation, and the like. The high activity and the specificity of their action imply a well-defined structure traditionally associated with ligand-enzyme and ligand-receptor interactions, although their behavior in aqueous solution gave no evidence for any predominant structure that could be associated with their biological activity. Probing for the "active site" of many of these molecules by selective chemical modification gave different results from those seen in similar experiments with enzymes; it appeared that all parts of the molecule were essential for high activity, although in some cases a number of amino acids could be modified without a major change in activity. The requirement that most of the

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