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Invited Review Paper

The Luminous Blue Variables: Astrophysical Geysers

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ABSTRACT. Some of the most luminous stars have sporadic, violent mass-loss events whose causes are not understood. These evolved hot stars are called luminous blue variables (LBVs), and their instability may shape the appearance of the upper HR diagram. LBV eruptions are interestingly reminiscent of *geysers* or even volcanos. They have received considerable observational attention since 1980, but theoretical work to explain the instability has been scarce. In a typical LBV eruption, the star's photosphere expands and the apparent temperature decreases to near 8000 K. During these *normal* eruptions the bolometric luminosity remains constant, as typified by S Doradus, AG Carinae, and R 127. A few LBVs, specifically Eta Carinae, P Cygni, V12 in NGC 2403, and SN 1961V, have *giant* eruptions in which the total luminosity actually increases by more than one or two magnitudes. The star may expel as much as a solar mass or more with a total luminous output rivaling a supernova. The classical LBVs have luminosities greater than $M_{\rm Bol} \simeq -9.6$ mag, suggesting initial mass greater than 50 $M_{\odot}$. These stars have very likely not been red supergiants as there are no evolved cool stars of comparable luminosity. Their instability may prevent their evolution to the red supergiant region. There is also a group of less luminous LBVs ($M_{\rm Bol} \simeq -8$ to -9 mag) with low temperatures, smaller amplitudes, and lower mass-loss rates. These stars have probably been red supergiants and have shed a lot of mass prior to their current unstable state. Although the physical cause of the LBV instability is not yet understood, the most likely mechanisms involve radiation pressure (the opacity-modified Eddington limit) or dynamical instabilities in the outer layers as the star evolves off the main sequence. In this review, we summarize the physical characteristics and behavior of LBVs and discuss their brief but critical role in massive star evolution, and possible mechanisms for their remarkable instability.

1. INTRODUCTION AND HISTORICAL PERSPECTIVE

Trail sign in Yellowstone National Park:

> STEAMBOAT GEYSER
>
> Infrequent Major Eruptions
> (World's Tallest)
> 300–400 ft.
> (Last Major Eruption: June 4, 1990)
>
> Frequent Minor Eruptions
> 10–70 ft.

We have often used the word *eruption* to describe the irregular behavior of certain extremely luminous stars, because in many ways these highly unstable stars remind us of geysers. (By geyser we mean the underlying physical process, not a linear jet.) Two famous historical examples, Eta Carinae and P Cygni, help to illustrate why.

Between the years 1600 and 1800, astronomers occasionally noticed η Car as either a second- or fourth-magnitude star; apparently it was fluctuating between those two limits. It began to vary more rapidly after 1820. In the late 1830s Eta suddenly became one of the brightest stars in the sky and remained so for nearly 20 years—varying between magnitudes +1 and −1. John Herschel called it "fitfully variable" and described its "sudden flashes and relapses." Eventually it faded to eighth magnitude as the eruption ceased and circumstellar dust formed. The total luminous output of the eruption rivaled that of a supernova, but the star survived and we now see it surrounded by ejecta. During the 20th century, η Car has begun to brighten again, but with only small-amplitude oscillations so far. Some of the outlying debris lead us to suspect that this sequence of events has occurred before. Anyone who has watched a geyser or read about volcanos will recognize the pattern: moderate activity, then violent burbling, then the fitful eruption itself, followed by a period of relative quiescence (see reviews by Davidson 1987a, 1989).

In the 17th century P Cyg did something similar. Apparently unnoticed earlier, P Cyg suddenly "appeared" in 1600 and reached third magnitude. It then faded below naked-eye visibility until another eruption in 1655 when it became nearly as bright. It has remained relatively stable near fifth magnitude since then, with a slow, gradual increase in brightness since 1700 (de Groot 1988; de Groot and Lamers 1992). In this century, astronomers have known P Cyg better for its famous emission-line profiles than for its variability.

Astronomers of the mid-twentieth century were familiar with the names P Cygni and η Car and also S Doradus in the Large Magellanic Cloud, but they did not realize that these different stars may represent a similar unstable evolutionary state for the most massive stars. It is only recently that we have begun to learn enough about them to understand their important role in massive star evolution, and a good theoretical understanding of their remarkable instability is still missing. In the Appendix to this paper, we review early ideas about these stars.

Beginning in the 1970s, studies of massive stars from several different perspectives—UV measurements of mass loss, infrared observations of circumstellar material, models of interior evolution, plus observations of very luminous stars in nearby galaxies—showed that the stars which inhabit the upper HR diagram were all losing mass, that their high mass loss influenced their evolution, and that the most massive star populations in different galaxies had many characteristics in common. At this time we were just beginning to recognize the similarities among stars that were known variously in the literature as S Dor variables, P Cyg stars, and the Hubble–Sandage variables in M31 and M33 (Humphreys 1975, 1978a; Humphreys and Davidson 1979; Sharov 1975; Wolf et al. 1980, 1981). Subsequently, in 1984 Peter Conti coined the term "Luminous Blue Variables" (LBVs) to describe this group of stars with geyser-like behavior.

The large *visual* light variations in the LBVs are typically more than one or two magnitudes but the total or *bolometric* luminosity of each star remains essentially constant during normal eruptions. These eruptions or outbursts may last years or even decades and be highly irregular with long periods of relative quiescence (visual minimum), while in other LBVs the outbursts, lasting several years, may be much more frequent and nearly semiregular as in S Dor and in recent years AG Car. At the extreme end of LBV behavior are the more violent giant *eruptions* in which the star increases by more than two or three magnitudes in visual light and may expel more than one solar mass in a single eruption. During a giant eruption the star may actually increase in bolometric luminosity. Eta Car and P Cyg in our galaxy are the famous historic examples of this type of LBV behavior.

LBVs exhibit a highly irregular variability in which the individual eruptions may be similar or very different. In this way LBVs are like geysers with irregular eruptions of varying degree. Moreover some aspects of the underlying physical processes may also be analogous to geysers (see Sec. 5). Thus the sign from Yellowstone Park is very applicable to LBVs; all one has to do is replace the geyser's name with one's favorite LBV and give the date of its last eruption. However, the behavior of the LBVs and the physics of their outbursts or eruptions is not as well understood as geysers.

These very luminous, unstable stars may also provide important clues to understanding the observed upper luminosity boundary in the HR diagram, an envelope of declining luminosity with decreasing temperature for the hot stars (>10000 K) which merges with a temperature-independent upper luminosity limit for the cooler supergiants (Humphreys and Davidson 1979, 1984).

Two symposia in the late 1980s dealt directly with the problems and questions of instabilities in LBVs and related objects. *Instabilities in Luminous Early Type Stars* (ed. Lamers and de Loore 1987) and *Physics of Luminous Blue Variables* (ed. Davidson, Moffat, and Lamers 1989). Nevertheless, theoretical work has lagged behind the observations and most of the fundamental questions are still unsolved. Is the instability driven by an interior or an atmospheric phenomenon; what is the role of rotation; do binaries play a role; and what is the cause of the bipolar symmetry seen in some LBVs?

In this review article we describe the characteristics of the LBVs with some particularly interesting examples (Secs. 2 and 3), their location on the HR diagram and important role in the final stages of massive star evolution (Sec. 4), and the possible origin of their instability and the bipolar symmetry (Sec. 5). In the final section we return to a historical perspective. A review of the origins of this subject is given in the Appendix.

2. WHAT IS AN LBV?

In order to be useful, a class of objects such as "LBVs" must be physically coherent. As originally understood in early discussions of this topic, an LBV is an unstable massive star that exhibits a *particular type of instability*, a phenomenon that may determine the appearance of the upper HR diagram. There are many stars that are luminous, blue, and slightly variable but are not LBVs, and sometimes an LBV is temporarily not blue or is not conspicuously varying! More than one class of LBVs may exist (see Sec. 4). Here we attempt to define the class by a list of characteristics, adapted and updated from a review by Humphreys (1989).

2.1 Luminosity

The LBVs are stars of high intrinsic luminosity. The "classical" examples, including most of the well-studied LBVs, have absolute bolometric magnitudes brighter than -9.5, corresponding to luminosities of the order of $10^6\ L_\odot$. These are at or near the top of the empirical HR diagram, too luminous to become red supergiants (Humphreys and Davidson 1979, 1984). There may also be a class of somewhat less luminous LBVs with $M_{\rm bol}\approx -8$ or -9, discussed in Sec. 4 below.

The most luminous LBVs are close to the famous "Eddington limit," an upper limit to the luminosity/mass ratio

(L/M) for a nearly static stellar atmosphere. In a hot star's photosphere, the ratio of (outward radiation force/inward gravity force) is

$$\Upsilon = \frac{\kappa L}{4\pi c G M},$$

where κ is the opacity per unit mass, averaged over wavelength in an appropriate way. Since Υ cannot exceed unity, this implies an upper limit to L/M. In the "classical" Eddington limit, applicable to hot stars with ionized photospheres, κ is taken to be the value due to scattering by free electrons, which is conveniently independent of wavelength, gas density, and temperature; this is the minimum likely opacity, giving the maximum likely L/M ratio. LBVs are generally close to the Eddington limit, within a factor of 2 and probably closer, so radiation pressure obviously reduces their stability.

2.2 Photometric Variability

Photometric variations in LBVs are observed with a wide range of amplitudes and time scales. The variations we discuss here refer to the visual wavelengths and primarily represent fluctuations in apparent temperature rather than in luminosity.

(a) *Giant eruptions* of $\geqslant 2$ mag in M_v refer to sudden ejections of unusually large amounts of mass and a probable increase in bolometric luminosity. The most famous example is of course η Car's dramatic outburst from 1837 to 1860 when it became the second brightest star in the sky. Eta Car briefly increased its total luminosity by two magnitudes while M_v brightened by 3–5 mag (van Genderen and Thé 1985; Davidson 1989), and probably violated the classical Eddington limit by a substantial factor. The time scales for these giant eruptions are of course very uncertain, but because we see so few, hundreds to thousands of years are reasonable estimates of the frequencies of these events.

Other examples of giant eruptions are P Cyg's behavior around 1600 (see review by de Groot 1988), when it brightened from invisibility to about third magnitude, and V 12 in NGC 2403 (Tammann and Sandage 1968). Another probable example is SN 1961V in NGC 1058 (Goodrich et al. 1989). After such major outbursts, these stars may fade rapidly and remain relatively quiescent for a long period. Davidson has described these violent outbursts in two review papers (1987a, 1989). The light curves of these four LBVs are shown in Fig. 1.

(b) *Eruptions* of 1–2 mag are often observed on time scales of 10–40 yr. From the minimum or quiescent phase, the star may brighten by up to two magnitudes in the visual, often within a few months. Both the minima and the maxima may last several years, although smaller variations may be superposed. At visual maximum, the star's atmosphere is greatly expanded. The luminosity or bolometric magnitude remains practically unchanged during an ordinary LBV eruption; the visual brightening is due to a change in the bolometric correction as the star cools (in other words, the luminosity shifts from UV to visual wavelengths; see Appenzeller and Wolf 1982 and Wolf et al. 1981 concerning R 71; Stahl and Wolf 1986 for R 127 and Leitherer et al. 1985 for S Dor). S Dor and R 127 in the LMC, AG Car in our galaxy, plus some of the LBVs in M31 and M33 (Hubble and Sandage 1953) are good examples of this type of variability which may even look semiregular at times. Figure 2 shows recent light curves for S Dor, AG Car, and R 127, and Fig. 3 the historic light curves for some of the H-S variables.

(c) Smaller *oscillations* of about half a magnitude are often observed on time scales of months to a few years, on top of the longer-term normal eruptions.

(d) *Microvariations* of $\leqslant 0.1$ mag have been described by van Genderen et al. (1985, 1990) for R 71, AG Car, and HR Car, but these variations have also been reported in normal supergiants; see papers by van Genderen et al. (1989, 1992b).

2.3 Spectra

Their spectra typically show prominent emission lines of H, He I, Fe II, and [Fe II], often with P Cygni profiles when observed at sufficiently high resolution. The spectra are variable, corresponding to the photometric variations. At visual minimum or quiescence an LBV has the spectrum of a hot supergiant with H and He I emission. In many LBVs the Fe II and [Fe II] emission is strongest at minimum. But some LBVs at minimum also resemble the Of/WN9 stars (Walborn 1977; Bohannan and Walborn 1989). R 127 was one of the original Of/WN9 stars and AG Car and HDE 269582 are now considered members of this class at minimum light. At visual maximum, the optically thick expanded atmosphere or "pseudo-photosphere" (Leitherer et al. 1985) resembles a much cooler supergiant of spectral type A or F; the Fe II emission is weaker, and at high resolution, P Cygni profiles are still observed in hydrogen and other lines. At maximum light the LBVs have remarkably similar spectra implying very similar physical conditions in their expanded atmospheres [see Fig. 4 Wolf et al. (1981) for R 71; Fig. 1 Wolf and Stahl (1982) for AG Car and S Dor; Fig. 2 Wolf (1989b) for R 127 and S Dor, also Fig. 8 of this paper].

2.4 Characteristic Temperatures

The spectral and photometric variations obviously represent changes in apparent temperature. At visual minimum an LBV is hot, with temperatures from 12,000 to 30,000 K. In this "quiescent state" the hottest LBVs tend to be the most luminous ones. At visual maximum, in the "eruptive state," LBVs have cooler temperatures around ~7000–8000 K regardless of luminosity. As noted earlier, the corresponding changes in bolometric correction account for most of the visual-wavelength photometric variation.

The photospheric layers may be quite diffuse during an eruption, with outflow velocities comparable to the local speed of sound (perhaps faster, in a giant eruption). The visible layers can be called "an extended envelope" or a "pseudo-photosphere" in an opaque stellar wind; either way, the observed minimum temperature can be understood in terms of decreasing opacity below 9000 K (see Davidson

1987b; the same explanation also applies to a nova or supernova explosion[1]).

In a situation as diffuse as an LBV eruption, the traditional "effective temperature" parameter, formally a relation between luminosity L and radius R, is inappropriate. The main reason is that R is not uniquely defined and may not even be very meaningful. Some authors discussing LBV and Wolf–Rayet envelopes refer to the temperature at a radius where the optical depth is said to be 2/3, but this is unsatisfactory, because that choice may be both artificial and ambiguous when the model is not plane parallel. Part of the difficulty is that opacity in the pseudo-photosphere is mainly scattering. Even if we ignore wavelength dependence, in this situation the effective optical depth can be defined in various ways.[2] Moreover, scattering makes the relation between temperature in a given layer and emergent energy distribution much less direct. The primary motivation for using $T_{\rm eff}$ is that it provides a clear, simple relation between observables and stellar radius for normal stars, so that observations and theoretical evolution tracks can be plotted together in the HR diagram, for instance. When the relation becomes less clear, as for LBV eruptions, then the concept of effective temperature loses most of its scientific appeal.

It would be useful to adopt some clear, standardized form of "characteristic" or "apparent" temperature, defined in terms of the emergent spectrum itself. For instance, one might simply refer to the average photon energy; this can be calculated accurately in a model, and usually it can be estimated fairly well from observations. Without inventing a formal definition yet, in the rest of this paper we shall use the term "apparent temperature" or $T_{\rm app}$ as a loose description of the emergent energy distribution.

2.5 Mass-Loss Rates

The active or shell ejection (pseudo-photosphere) phase of an LBV coincides with high mass-loss rates, which are typically 10^{-5}–10^{-4} $M_\odot$ yr^{-1} for most LBVs. According to the consensus view, these rates are 10–100× those of normal supergiants of comparable luminosity. In quiescence the mass-loss rates may be more like those of normal supergiants of the same temperatures and luminosities (Lamers 1989); although Leitherer et al. (1994) say that there was no change in the mass-loss rate for AG Car. The observed mass-loss rates as well as most of our information on temperatures, gravities, and compositions have resulted from extensive moderate- and high-resolution ground-based and UV studies of these stars in our galaxy and the LMC by many different groups. The mass-loss rates are derived in an indirect way from the observations and are highly model dependent usually with the assumption of spherical symmetry in the outflow. For a review of mass loss from hot stars, see Conti and Underhill (1988).

A procedural caveat regarding complexity in models is worth noting here. Increasingly sophisticated models of stellar atmospheres and winds have been used to estimate temperatures, mass-loss rates, gravities, etc. However, the reliability of results does not necessarily improve just because more effects have been included in a computer code. As one obvious instance, even the most complex spherical model may be less valid than a simplified axisymmetric analysis, if the object is bipolar. Other geometrical effects are difficult to incorporate in models (see Moffat and Robert 1994 for an example). In general, for a complex model to be worthwhile when deriving stellar parameters, *the number of successfully reproduced independent observables should exceed the number of adjusted input parameters*. Moreover, a single failure to account for a *major* observable is sufficient cause to distrust a model. These precepts may seem almost too obvious to cite, but they have been neglected surprisingly often.

2.6 Ejecta and Circumstellar Material

Most LBVs show some evidence for an excess of infrared radiation and circumstellar ejecta. A small excess in the near IR (1–3 μm), due to free-free and free-bound emission, is common (Humphreys et al. 1984; Leitherer et al. 1985). Many of these stars also have longer-wavelength radiation due to circumstellar dust (McGregor et al. 1988). In the case of η Car the dust is thick enough to obscure the star (Westphal and Neugebauer 1969). Figure 4 shows examples of different LBV energy distributions.

Some ejecta are clearly visible, as in the "homunculus" of η Car (Fig. 5), although this case is perhaps exceptional. More common is the presence of a ring nebula or circumstellar shell. Some examples are AG Car (Thackeray 1977; Stahl 1987), He 3-519 (Stahl 1987), R 127 (Stahl 1987; Clampin et al. 1993), and HR Car (Hutsemekers and Von Drom 1991). These circumstellar shells and ejecta are produced by the high mass loss and ejection of shells from the LBVs. Some Of/WN (He 3-519) and some Wolf–Rayet stars (HD 96548, for example) also show these ring nebulae. Figure 6 shows the ring nebulae around AG Car and He 3-519.

Quantitative analyses of the ejecta, as in η Car, and the atmospheres and circumstellar envelopes of these stars and related objects show that they are nitrogen and helium rich (Davidson et al. 1982, 1986; Allen et al. 1985; Dufour and Mitra 1987; Pacheco et al. 1992 and reviews by Walborn 1988, 1989). This is presumably CNO-processed material brought to the surface by mixing and mass loss.

2.7 Total Mass Ejected

To determine the total mass lost during the LBV stage we need to know both its duration and a time-averaged mass-loss rate. The duration can be estimated by comparing their numbers with WR stars, but we need to be cautious because the number of known LBVs is incomplete. Because the quiescent phase can be decades long we may have missed sev-

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[1] Idealized, semianalytic calculations are still valuable in the modern era of specialized computer codes, because they can illustrate general effects without extraneous complications. An example is the apparent temperature of an extended envelope as a function of mass-loss rate and velocity, as described by Davidson (1987b). Leitherer et al. (1989a,b) asserted that the same paper contains an incorrect theory for the behavior of the underlying star, but in fact no such theory is presented there. The apparent temperature in this situation depends on luminosity, mass-loss rate, velocity, and velocity gradient, all of which can vary.

[2] Two examples: One could use either $\tau_{\rm eff}=(3\tau_{\rm tot}\tau_{\rm abs})^{1/2}$ or else $\tau_{\rm eff}=\int k_{\rm eff}\,dr$ with $k_{\rm eff}=(3k_{\rm tot}k_{\rm abs})^{1/2}$; these can be quite different.

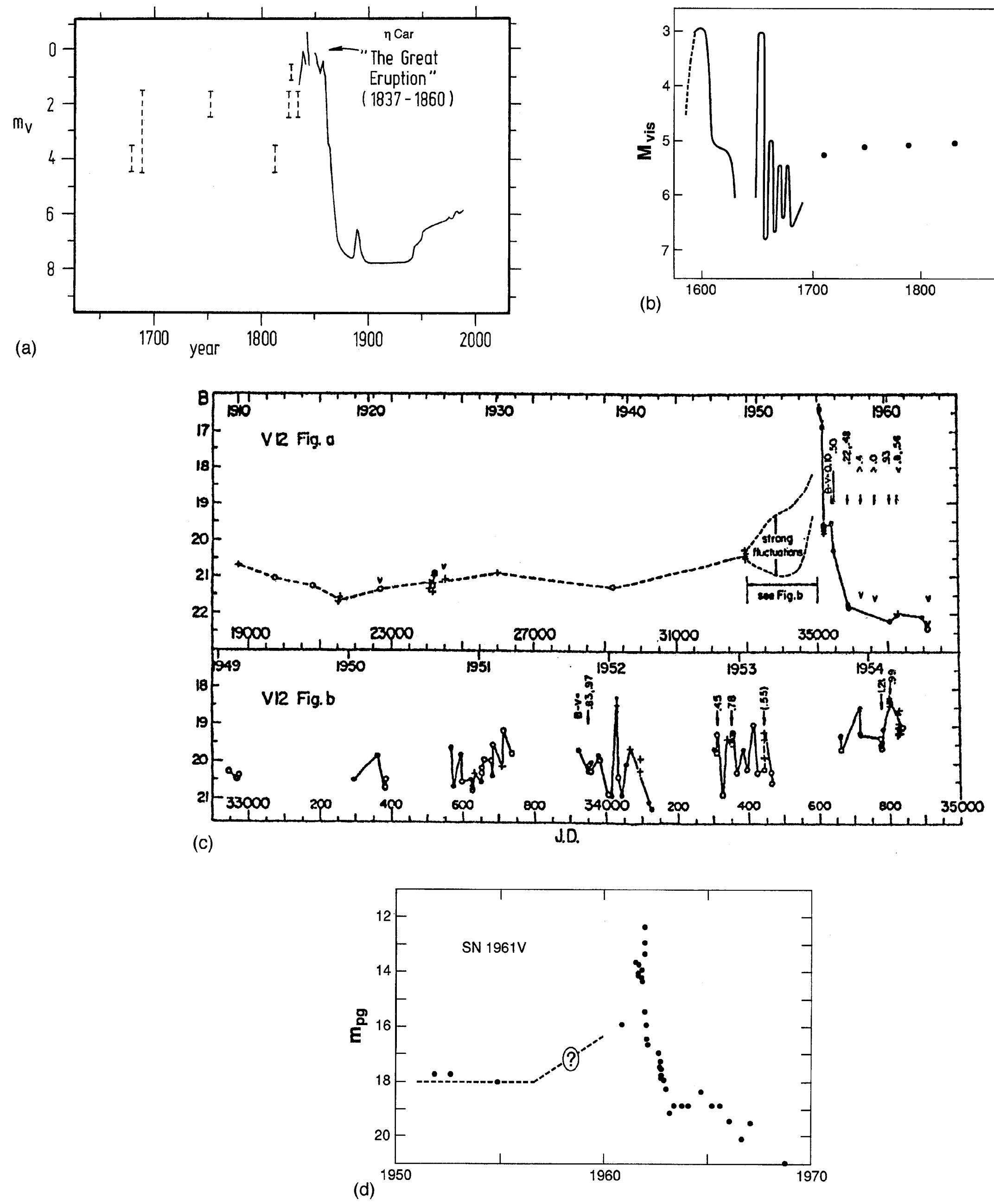

FIG. 1—Light curves of the "extreme" LBVs, (a) η Car from Davidson (1987), (b) P Cyg (adapted from de Groot 1988 and Lamers and de Groot 1992 with their permission), (c) V 12 in NGC 2403 from Tammann and Sandage (1968) with their permission, and (d) SN 1961V (based on the summary in Doggett and Branch 1985).

eral. For example, two new LBVs have recently been reported in the LMC: R 110 (Stahl et al. 1990) and R 143 (Parker et al. 1993). Thus in the LMC there are now six confirmed LBVs (see Table 1) and 115 WR stars. Then N(LBV)/N(WR) is 0.05. With a total lifetime of $\approx 5\times10^5$ yr (Maeder and Meynet 1987) for WR stars, the LBV lifetime is about 25 000 yr. This number may be an underestimate.

Typical mass-loss rates are 10^{-5} to 10^{-7} $M_\odot$ yr^{-1} during quiescence or minimum light and 10^{-4}–10^{-5} $M_\odot$ yr^{-1} during maximum light in eruption phase though higher values sometimes occur. Lamers (1989) suggested a time-averaged normal mass-loss rate of $\approx 10^{-5} M_\odot$ assuming an LBV spends half the time in each phase. But there is increasing evidence that many LBVs pass through a much more violent eruption phase like P Cyg or η Car at least once, during which the mass-loss rate is much higher. For example, η Car probably lost 2–3 $M_\odot$ during its famous 1840s outburst and its current mass-loss rate is estimated at about 10^{-3} $M_\odot$ yr^{-1} (Sec. 3 below).

P Cyg during the seventeenth century is another example

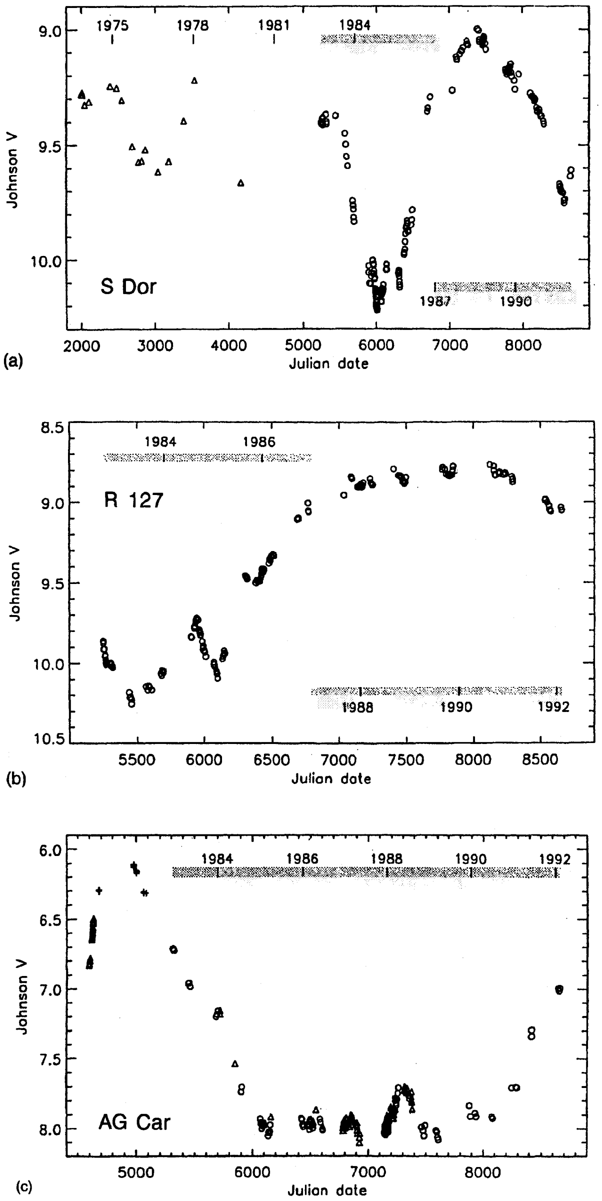

FIG. 2—Recent light curves for (a) S Dor, (b) R 127, and (c) AG Car reproduced from de Koter (1993) with permission.

of a star that had a more violent eruption. Of course we have no measurement of its mass loss at that time, but its extended Hα and N II emission measured by Leitherer and Zickgraf (1987) corresponds to continuous mass loss of $4\times10^{-4} M_\odot\,\mathrm{yr}^{-1}$. Other stars such as AG Car and R 127 have circumstellar gaseous shells or rings and estimates of their kinematic ages and masses lead to average mass-loss rates $>2\times10^{-4}\ M_\odot\,\mathrm{yr}^{-1}$ (Stahl 1987). Thus the average mass-loss rate over the duration of the LBV stage may be somewhat larger than what we observe during the normal eruptions.

The total mass lost during the lifetime of an LBV is, of course, uncertain because we do not know the frequency of the more violent eruptions; however, the above numbers suggest that $\approx2\times10^{-4}\ M_\odot\,\mathrm{yr}^{-1}$ is a reasonable estimate for classical LBVs like AG Car and R 127, assuming they all pass through one or more violent eruptions. With an estimated duration of $\geqslant$25,000 yr, the total mass lost during the LBV stage is $\geqslant 5\ M_\odot$. This is close to the mass (5–10 $M_\odot$) that a 50–100 $M_\odot$ star must shed after core H-burning to become a Wolf-Rayet star [based on the models of Maeder and Meynet (1987)]. The total mass shed as an LBV may be mass dependent, so that a very massive star like η Car may lose more total mass.

2.8 So What Is an LBV?

An LBV is an evolved, *very luminous, unstable* hot supergiant which suffers *irregular eruptions* like S Dor and AG Car or more rarely the *giant eruptions* as in η Car and P Cyg. Although the exact cause of their instability is not known, it results in a greatly enhanced average mass outflow which leads to the formation of an expanded atmosphere or pseudo-photosphere at visual maximum. At this stage the slowly expanding (100–200 km s^{-1}) envelope is cool (7000–9000 K) and dense ($N\sim10^{11}$ cm^{-3}), and the star resembles a very luminous A-type supergiant. At minimum light, or the quiescent state, the LBV is at its "normal" high temperature (usually >15,000 K) and the mass-loss rate may be lower. During these variations the bolometric luminosity remains essentially constant. The visual light variations are caused by the apparent shift in the star's energy distribution driven by the instability.

There are many luminous, hot emission-line stars that are not known to be significantly variable. Shore has described the diverse characteristics of some of these stars in what he calls his "Zoo sample" in the LMC (Shore and Sanduleak 1984; Shore 1989, 1993). Because long quiescent periods are possible, some of these stars may eventually be found to be LBVs. Although we expect more LBVs to be identified, only observations over a long period of time will show whether they are LBVs or other types of luminous emission-line stars. The Of/WN9 stars may represent the quiescent state for many LBVs, although not all LBVs show the Of/WN9 spectral characteristics at their minima; for example, AF And and AE And do not (Humphreys et al. 1994).

Among these luminous emission-line stars are the B[e] supergiants. Zickgraf et al. (1985, 1986) have identified several members of this group and have noted how they differ from LBVs. The B[e] stars are not variable; their emission-line spectra are hybrid with narrow Fe II and [Fe II] lines but broad absorption components in H, He I, and UV resonance lines with terminal velocities typical of B supergiant winds. (However, Shore et al. 1990; Shore 1992 has reported UV variability in S 22, a B[e] star in the LMC.) These hybrid characteristics are explained by a two-component model with a normal B supergiant wind from the poles and a denser, slower-moving wind from an equatorial disk. We do not know enough about the B[e] stars to propose a direct connection with the LBVs. The B[e] stars may be fast rotators or binary systems.

In a series of papers, van Genderen and his collaborators (1989, 1992a,b) have identified several luminous O-, B-, and

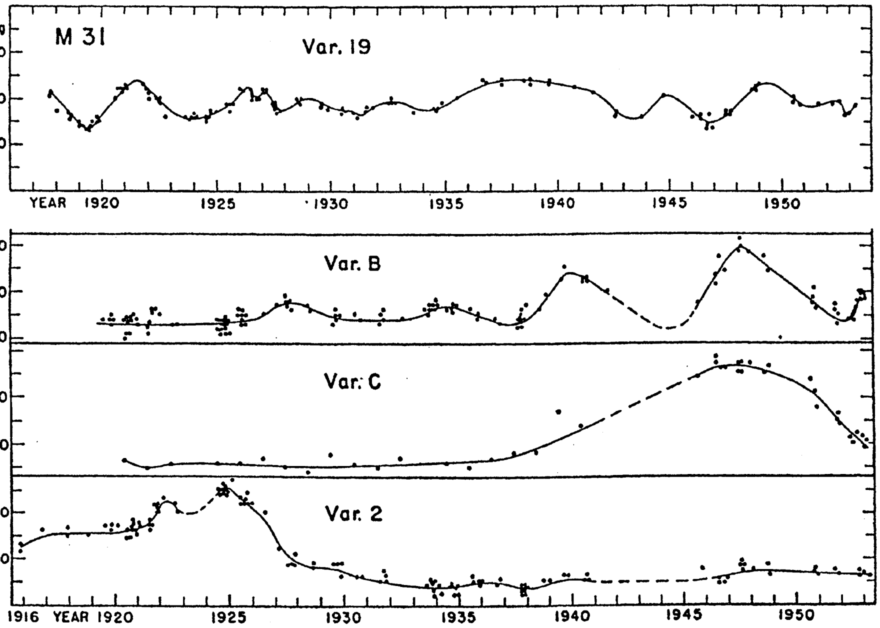

FIG. 3—The historic light curves for four of the luminous blue variables in M31 (V 19=AF And) and M33 (Var B, C, 2) reproduced from Hubble and Sandage (1953) with the latter's permission.

A-type stars that they call "α Cyg variables" which show small variations in visual light less than 0.5 mag and most often of the order of $\leqslant 0.1$ mag. While these small oscillations and microvariations are undoubtedly an indicator of an unstable atmosphere, quite common among many luminous stars, they fall far short of the more dramatic eruptions that characterize the LBVs. There is a very large difference in scale. While some of these supergiants may eventually evolve into an LBV stage, this type of variability should not be confused with the much more extreme LBV phenomenon.

Most of our information about LBVs is derived from studies of only a few well-known examples, especially P Cyg, S Dor, η Car, and more recently R 127 and AG Car. The known LBVs in nearby galaxies are listed in Table 1. Many stars have some characteristics in common with the LBVs but have not been *observed* to have an actual eruption, at least of the S Dor variety. These stars we tentatively call "candidate LBVs." They include a variety of objects ranging from several Of/WN9 stars to candidates from ratio surveys. Several examples are listed in Table 2 with comments and references.[3]

In addition, Allen et al. (1990) and Krabbe et al. (1991) have described a cluster of He I emission stars in the galactic center whose properties—H I emission, high mass loss $\sim 10^{-4}$ $M_\odot$ yr^{-1}, and temperatures ($\sim$35,000 K)—are like LBVs and the closely related Of/WN9 stars. Interestingly, all 17 identified cluster stars must be of this type! Thus LBVs could be very important contributors to the energies of starburst galaxies. Najarro et al. (1994) have obtained a near-infrared spectrum of the brightest member of this group and find that its characteristics resemble the Of/WN9 stars. Surprisingly, its luminosity, 2–3$\times 10^5$ $L_\odot$ is not very high.

In this section we have summarized the characteristics of the luminous blue variables, specifically their dramatic eruptions, high mass loss, and photometric and spectral variability. Although the members of this rather small class of stars share these properties, they can also be remarkably different. In the next section we describe some of these remarkable stars in more detail.

3. A FEW SPECIAL STARS

Each of the LBVs described in this section was selected for a specific reason—the extreme behavior of η Car and P Cyg, the ring nebula of AG Car, and the relatively low luminosity of R 71. Each of these stars is telling us something significant about the LBV phenomenon and its origin.

3.1 P Cygni

Historically, P Cyg is the first known LBV. P Cyg first appeared as a third magnitude star in 1600. No star had been cataloged at its location prior to that time. It stayed bright for several years and then faded fainter than the naked eye limit. It had a second outburst in 1655, nearly as bright as the first, and then faded again (see Fig. 1 for the light curve). In two recent papers, de Groot and Lamers have reproduced its his-

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[3] LBVs and related stars are listed, with useful cross-references to alternative names, in the index to *Physics of Luminous Blue Variables*, IAU Colloquium 113 (ed. Davidson, Moffat, and Lamers 1989).

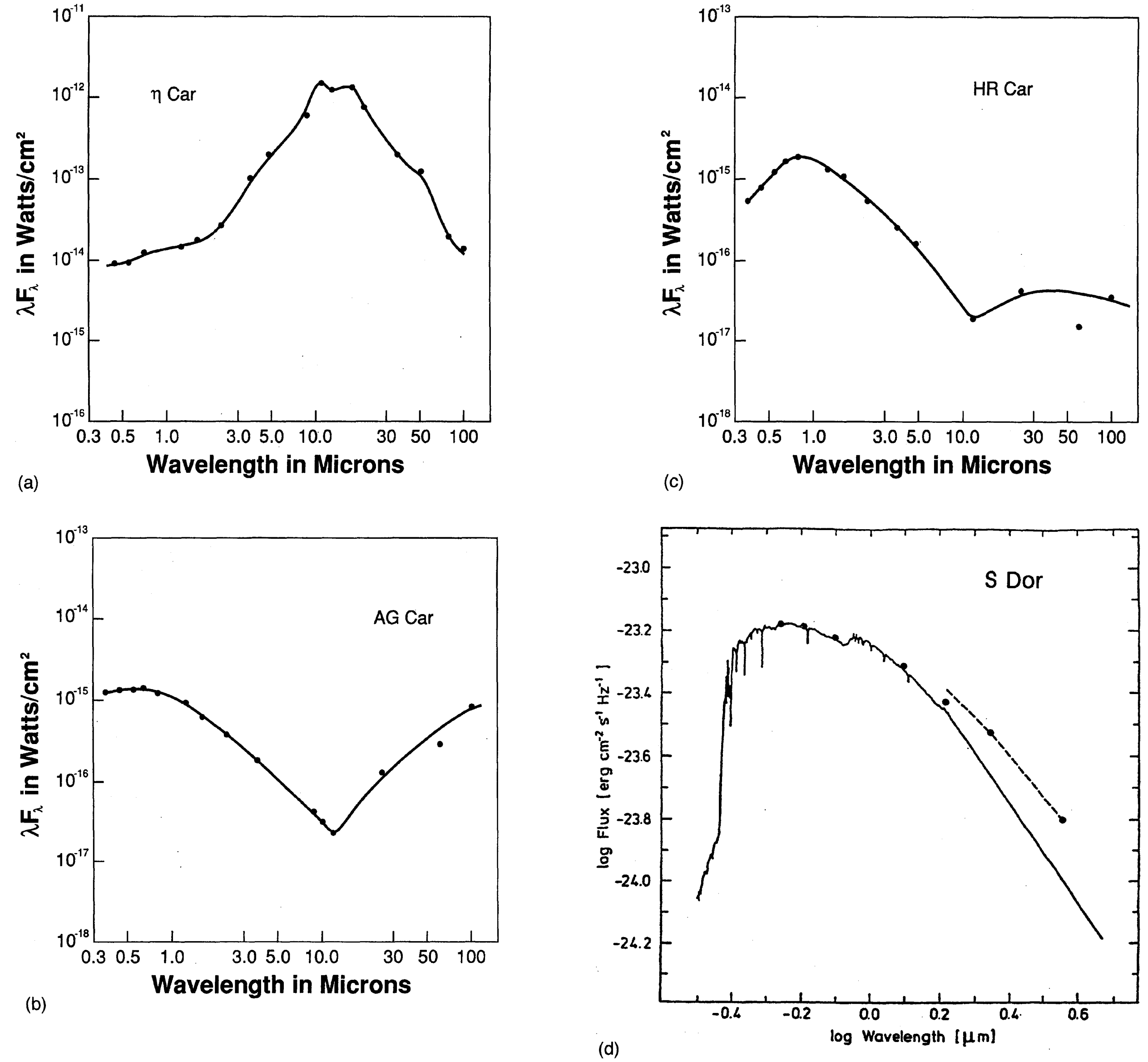

FIG. 4—Examples of energy distributions for different LBVs, (a) η Car, an obscured hot stellar continuum plus circumstellar dust in its ejecta, (b) AG Car, and (c) HR Car showing a reddened stellar continuum plus free-free emission and cool dust [based on data summarized in McGregor et al. (1988)], and (d) S Dor showing a Kurucz model atmosphere fit to the observations with the excess free-free emission in the near infrared from Leitherer et al. (1985) with permission.

torical light curve from 1700 to the present with some very interesting results (de Groot and Lamers 1992; Lamers and de Groot 1992). They find that P Cyg has been gradually brightening since 1700 and argue that this is due to the actual redward evolution of the star, probably from the contraction of the core and expansion of the envelope on a Kelvin–Helmholtz time scale. However, we note that an LBV is likely to be far from thermal equilibrium just after a giant eruption, and its subsequent readjustment must be taken into account.

Lamers and de Groot (1992) also present evidence for an actual increase in the luminosity of P Cyg during the outburst. For example, if like other LBVs at maximum, P Cyg had an optically thick wind, its apparent temperature would have been ~8000 K. Its observed red color must then be due to some circumstellar reddening. If this was the case, they contend it was bolometrically brighter, very likely by 1–2 magnitudes ($M_{\rm Bol}\simeq -11$ to -12 mag) than it is now ($M_{\rm Bol}\simeq -9.9$ mag). This is a very interesting possibility because η Car was also more luminous than usual, by two magnitudes or so, at the maximum of its giant outburst.

A low intensity spherically symmetric emission nebula, presumably from the 17th century eruptions, surrounds the star. Recent coronagraphic imaging by Clampin et al. (1994) shows that the N II nebular emission is resolved into blobs.

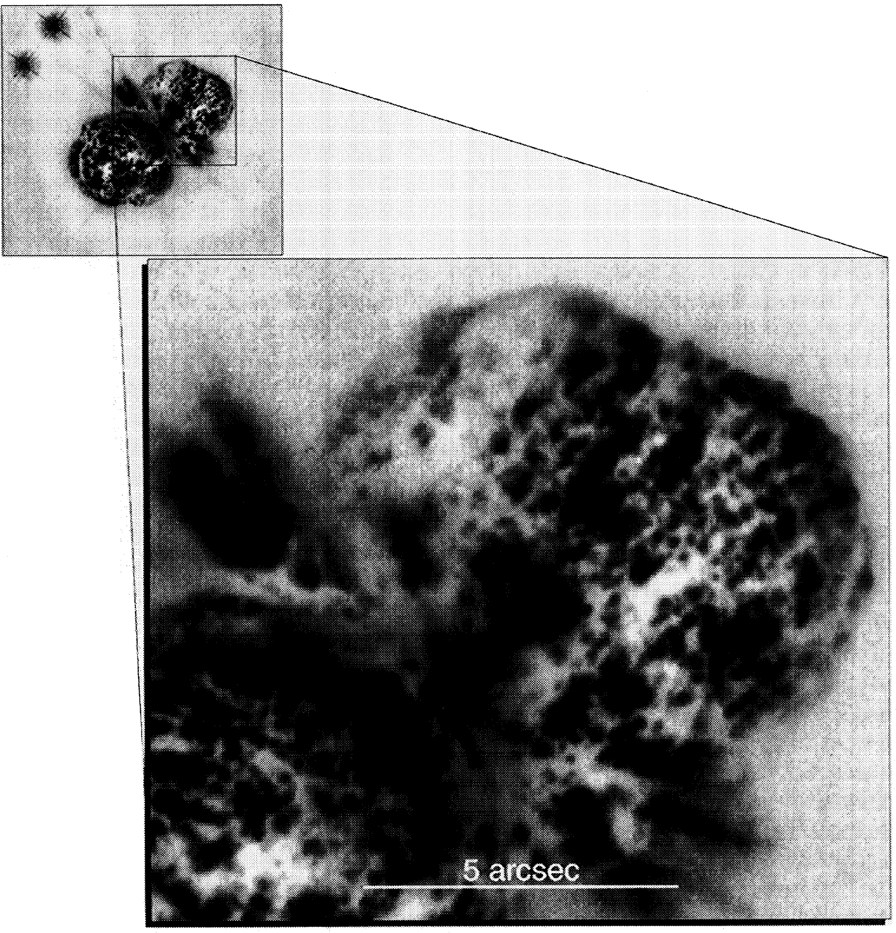

FIG. 5—The homunculus of η Car, ejecta from the giant eruption that was observed about 150 years ago. In order to show a very wide range in surface brightness, this image was made by applying R. White's "adaptive histogram equalization" algorithm to *HST*/PC2 data obtained by D. Ebbets' group in 1994 (cf. earlier images, Ebbets et al. 1992, 1993). This image represents violet continuum light. The diameter across the two bipolar lobes appears to be roughly 0.2 pc. The lower left (southeast) lobe is expanding obliquely toward us at speeds of the order of 600 km s^{-1}. Between the two lobes is a fragmented equatorial structure so the whole arrangement is shaped "like an insect wearing a tutu." Faint radial streaks project far outward from the equatorial debris, possibly due to ablation from equatorial condensations or even from a small disk. The enlargement shows the detail in the equatorial region and the upper, northwest lobe.

3.2 Eta Carinae

The 19th-century giant eruption of η Car was arguably the most remarkable stellar outburst that has ever been well documented. After volcano-like preliminaries, the star exceeded its classical Eddington limit by a significant factor for several years, far longer than any dynamical time involved. During its eruption between 1830 and 1860, η Car actually increased it total luminosity, very briefly reaching $M_{\mathrm{Bol}} \simeq -14$ mag. Roughly 10^{49} ergs of luminous energy was radiated during that time, about the same as in a supernova explosion. The mechanical energy of the eruption was of the same order of magnitude while at least a solar mass of material was ejected; but the star survived and may do the same thing again, centuries or millennia hence. Meanwhile, η Car is the most luminous of the well-observed LBVs, the brightest extrasolar 20 μm IR source in the sky, and the brightest thermal stellar wind radio source in the sky. This general background has been described in previous reviews, particularly Davidson (1987a, 1989) and van Genderen and Thé (1985) and also by Viotti et al. (1990). (Concerning the ratio source, see White et al. 1994). Here we review a few of the many pertinent recent observations.

At normal ground-based spatial resolution, η Car shows (1) a "core" less than 0.01 pc ($<1''$) across, (2) ejecta from the giant eruption, now about 0.2 pc ($16''$) across, the famous "homunculus" (see Fig. 5), (3) some fairly bright condensations just outside the homunculus or projected on it, and (4) fainter outlying condensations that may be older. The chemical composition is CNO processed (Davidson et al. 1986). The most interesting development in recent years has been a clear recognition of the structure's bipolar morphology, described below. First, we discuss the present condition of the "core," especially the star itself.

Ground-based and *IUE* spectroscopy of the core unfortunately includes luminous gas that is hundreds of AU (0.001–0.01 pc) from the star, plus the star itself with its dense, nonspherical wind. No wonder, then, that the combined spectrum is a bewildering jungle of emission lines with a wide

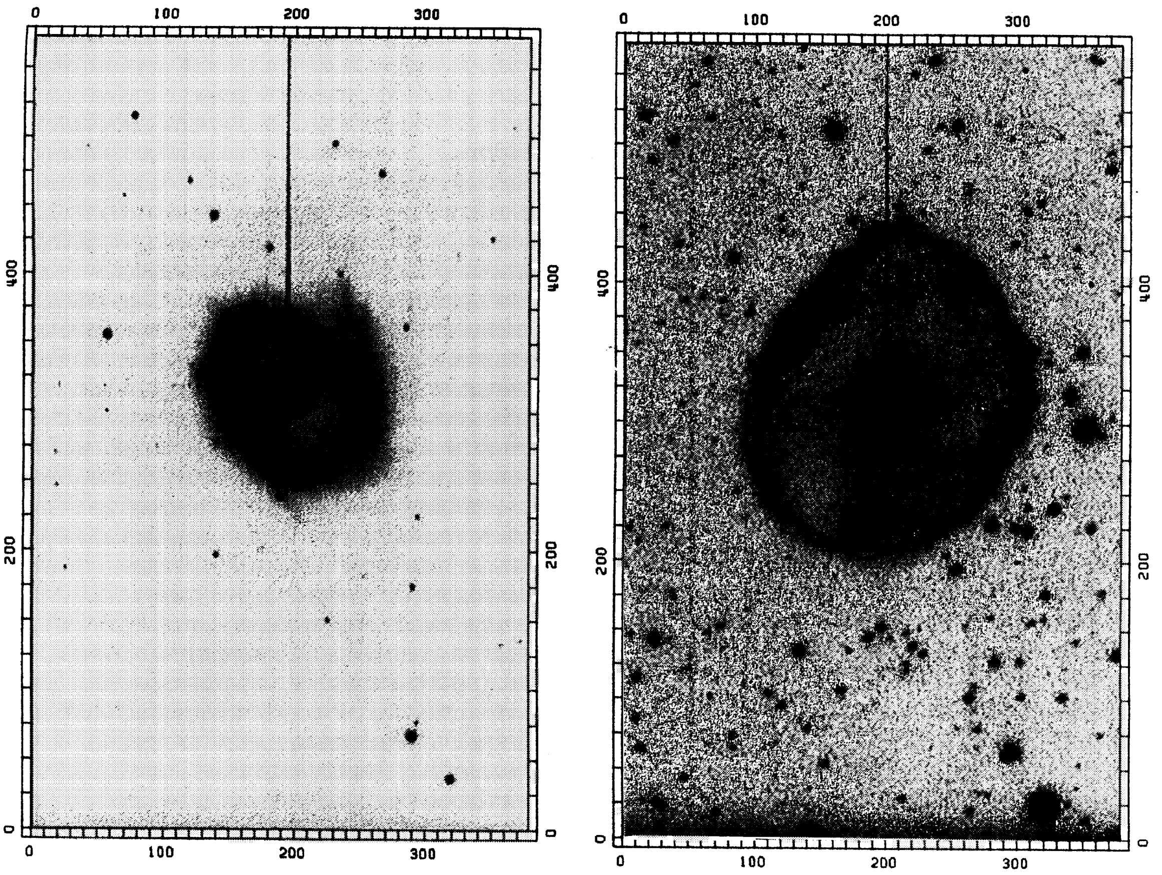

FIG. 6—The circumstellar ring nebulae around AG Car (left) and He 3-519 (right) from Stahl (1987) with permission.

range of ionization states, plus a few absorption features, all superimposed on a hot continuum. The stellar wind velocity is several hundred km s^{-1} but may have faster components. Modern ground-based spectroscopic studies include those by Zanella et al. (1984), Allen et al. (1985), McGregor et al. (1988), Hillier and Allen (1992), Hamann et al. (1994); see also older refs. cited therein. The ultraviolet spectrum, observed at high spectral resolution with *IUE*, has been described in detail by Viotti et al. (1989), who emphasize that *"the expanding envelope is far from being spherically symmetric."*

This situation was further complicated in the mid-1980s when speckle interferometry showed at least four compact components in the core of η Car (Weigelt and Ebersberger 1986; Hofmann and Weigelt 1988). Component "A" (the star itself) is brighter than the others, which are a few hundred AU (<0.005 pc) away from it. Initially it was unclear whether the fainter components were companion stars or ejected blobs (Davidson and Humphreys 1986); but in any case, all ground-based and *IUE* spectral data include all of the components together, along with various amounts of diffuse ejecta.

The *Hubble Space Telescope's* Faint Object Spectrograph (FOS) has been used to effect a rudimentary separation of the spectrum of Component A from the combined spectrum of Weigelt's Components B+C+D+etc., in the wavelength range 2500–5500 Å (Davidson et al. 1994). Component A does indeed have a stellar spectrum with strong permitted emission lines of hydrogen and Fe II, and no forbidden lines. A preliminary estimate of the mass-loss rate is about 10^{-3} $M_{\odot}\ \mathrm{yr}^{-1}$, consistent with a radio estimate by White et al. (1994). These are the first proper measurements of the current mass-loss rate of η Car, and they are in accord with some earlier estimates (see, e.g., Davidson et al. 1986 and other references therein). Although circumstellar extinction

TABLE 1
Confirmed LBVs in Nearby Galaxies

Milky Way:	η Car, P Cyg, AG Car, HR Car, HD 160529
LMC:	S Dor, R 71, R 127, HDE 269582 (=MWC 112), R 110, R 143
SMC:	R 40
M31:	AE And, AF And, Var A-1, Var 15
M33:	Var B, Var C, Var 2, Var 83
NGC 2403:	V 12, V 22, V 35, V 37, V 38
M81:	I 1, I 2, I 3
M101:	V 1, V 2, V 10
NGC 1058:	SN 1961V

TABLE 2
Candidate LBVs

Star	Galaxy	Comment	Reference
He 3-519	Milky Way	Of/WN9 star with ring	Davidson et al. (1993) Smith et al. (1994)
He 3-591 (=WRA 751)	Milky Way		Hu et al. (1990) de Winter et al. (1992)
G 79.29+0.46	Milky Way	radio source with ring	Higgs et al. (1994)
G 25.5+02	Milky Way	shell or ring	Subrahmanyan et al. (1993)
R 84	LMC	Of/WN9, small variations	Stahl et al. (1984)
R 99	LMC	Of/WN9, small variations	Stahl et al. (1984)
S 61	LMC	Of/WN9, ring	Stahl (1987), Wolf et al. (1981)
S 119	LMC	Of/WN9, ring or shell	Nota et al. (1994)
Romano's star	M33	variability	Romano (1978)

is difficult to assess, the continuum of Component A in the FOS data is consistent with earlier estimates of an apparent temperature in the range 23,000–40,000 K (Davidson 1971; Allen et al. 1985; Davidson et al. 1986; Tovmasyan et al. 1992).

Since the other components, B+C+D, have a complicated forbidden line spectrum, evidently they are ejected blobs rather than companion stars. In order to explain their apparent brightness relative to the star, we must suppose that circumstellar extinction is less for them than for the star. Images made with the *HST* by Weigelt et al. (1994) and Ebbets et al. (1992, 1993) reinforce these ideas: B+C+D appear more diffuse toward shorter wavelengths. There is also evidence that B, C, and D are moving outward.

A spectral peculiarity worth noting is the very conspicuous Fe II λλ2506–2508 emission, which originates in B+C+D (see Fig. 7). This feature is prominent in only a few known stellar spectra, and has been discussed by Jordan (1988), Viotti et al. (1989), and Johansson and Hamann (1993). According to Johansson and Hamann, it is most likely photoexcited by Lyman-alpha emission in this case. Further analysis may give useful information about the radiation field in the core region.

The FOS data on B+C+D may also be related to some interesting spectral changes described by Zanella et al. (1984), Ruiz et al. (1984), Bandiera et al. (1989), and Bidelman et al. (1993). We now think that the fluctuating high-excitation forbidden lines and narrow hydrogen and helium emission components are produced in B+C+D (and, perhaps, in more diffuse material surrounding these components), where the Fe II λ2507 feature mentioned above may also originate. The relevant gas is very likely "equatorial" (see below). The "apparent" spectrum of the core region probably varies more than its total *intrinsic* spectrum does, because B+C+D have less intervening extinction than the star as noted above. Nevertheless, the fluctuations provide valuable evidence for changes either in the star itself or in the circumstellar dust; this is definitely not understood yet and more work is needed.

The *bipolar structure* in the homunculus is important because it indicates that η Car, the star itself, has a well-defined axis. Hindsight shows bipolar morphology in the best images of the homunculus made many years ago (see Figs. 5 and 12 in van Genderen and Thé 1985, and the covers of *Sky and Telescope*, July 1972, and *Science*, 20 January 1984; cf. later images by Burgurella and Paresce 1991 and Fig. 5, this paper). The first unmistakable signs, "horns" like those seen in other bipolar flows, appeared in IR images of the warm dust (Hackwell et al. 1986). Bipolarity in η Car was discussed by Warren-Smith et al. (1979), Hyland et al. (1979), Mitchell et al. (1983), Meaburn et al. (1987), and Allen (1989); altogether these papers describe two bipolar lobes plus something like a very large equatorial disk. Both lobes and the equatorial material are dusty reflection nebulae at visual wavelengths. Using radial velocity data, Meaburn et al. explained that the southeast bipolar lobe is moving obliquely toward us at several hundred km s^{-1}, while the northwest lobe moves in the opposite direction away from us. Allen suggested that the lobes are clumpy and hollow. (Velocity profiles shown by Hillier and Allen 1992 are consistent with a two-lobed geometry, even though their discussion appears to imply otherwise.)

High-spatial-resolution images made with the *Hubble Space Telescope* now show that the homunculus is indeed one of the most dramatic known bipolar structures. In most respects the *HST* images are strikingly consistent with the main features of the Meaburn et al. and Allen models cited above.

The first *HST* image to appear was published by Hester et al. (1991). Unfortunately it used a narrow filter which passed a complicated, velocity- and position-dependent mixture of direct H-alpha emission, reflected H-alpha emission, and [N II]. Partly because the bright central region was saturated in their data and thus could not be examined, the authors' interpretation was inconsistent with the models cited above and is not supported by later results.

Images made in continuum light show more clearly the distribution of dust in the homunculus (i.e., scattered light). Such images made with *HST* have been discussed by Ebbets et al. (1992, 1993, see also Davidson 1993); a recent one is

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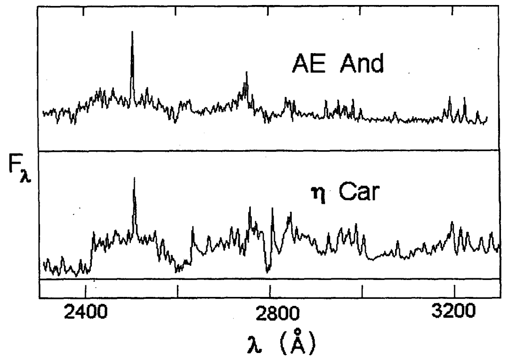

FIG. 7—The very strong 2507 Å [Fe II] emission feature in η Car and AE And. It is probably produced by fluorescence from Lyman α.

shown in Fig. 5. Two hollow-looking bipolar lobes are present as noted above. Other material appears "equatorial," including several radially elongated features composed of large clumps and radial streaks (the outermost streaks are prominent in the Hester et al. 1991 image). One such feature has often been called a "jet" to the northeast of the core, but another almost equally "jetlike" feature is superimposed on the northwest lobe (cf. Fig. 12 in van Genderen and The 1985) and is roughly aligned with Weigelt's components B, C, D. This feature appears to be on the side of the equatorial flow that is closest to us. The equatorial streaks may represent ablation from a much smaller, dense circumstellar disk.

All these bipolar characteristics were vividly illustrated in an excellent "early public release" *HST*/WFPC2 image obtained by Trauger et al. That image was made with an emission-line filter, however, which, complicates the interpretation as noted above. The bipolar morphology of the homunculus is surely crucial for models of the central object and other LBVs; presumably either a close binary or a rotating single star is present but we cannot tell which. (Van Genderen et al. et al. 1994) have presented weak evidence for a 52-day periodicity.] We return to this question in Sec. 5 below.

3.3 V 12 and SN 1961V

In addition to the famous examples of P Cyg and η Car, V 12 in NGC 2403 and SN 1961V in NGC 1058 also exhibited giant eruptions in which their total luminosities increased. V 12 in NGC 2403 reached $B=16.3$ ($V\simeq16.1$) at its extreme maximum in 1954 (Tammann and Sandage 1968). If V 12 was also about 8000 K at its maximum, then its $M_{\rm Bol}$ was -11.6 mag, at a distance modulus for NGC 2403 of 27.5 mag and with interstellar extinction $A_v\approx0.2$ mag. If the extinction is any higher, and it might be because V 12 is in the inner part of the galaxy, then its $M_{\rm Bol}$ would have been even more luminous. Was this a giant eruption like that of η Car? Yes, because a normal LBV eruption is typically two magnitudes which for V 12 would have been a rise from its normal blue magnitude of 20.5 to about 18.5 mag or $M_{\rm Bol}\simeq-9.6$ mag.

Eta Car, P Cyg, and V 12 in NGC 2403 apparently all increased their bolometric energy output in violent outbursts exceeding the "normal" LBV eruptions. But SN 1961V, Zwicky's Type V supernova, takes the prize for the brightest absolute visual and bolometric magnitudes. During its bizarre outburst, this object achieved luminosities rivalling the fainter supernovae and may have survived the experience like η Car (see Fesen 1985; Doggett and Branch 1985; Goodrich et al. 1989). Its remarkable light curve is shown as part of Fig. 1. SN 1961V appears to have progressed in steps to increasingly more energetic outbursts. These stages are summarized in Table 3. The star first showed an increase in its blue brightness by about two magnitudes (Step 2) which is typical of a normal LBV-type eruption (like S Dor). Note, however, that its bolometric luminosity, presumed to remain constant during these eruptions, indicates that SN 1961V was already more luminous than η Car and may imply an initial mass greater than 200 $M_\odot$. (η Car is usually assumed to have been initially a 100–150 $M_\odot$ star.) It then increased another two magnitudes, entering a stage presumably similar to η Car at its maximum. But SN 1961V then increased another 1.5 magnitudes to what we can only describe as a super-eta Car stage with $M_{\rm Bol}\simeq-17$ mag (!), assuming the closest published distance for NGC 1058 (5.3 Mpc; Bottinelli et al. 1985). Thus SN 1961V increased 3.5 mag over its normal luminosity.

At maximum light, the spectrum of SN 1961V showed "narrow" emission lines of H, He, Fe II with an expansion velocity $\sim$2000 km s^{-1}. With these spectral characteristics SN 1961V was definitely not an ordinary supernova and closely resembles η Car (see Goodrich et al. 1989). SN 1961V then quickly faded past its pre-outburst stage; it had a plateau at $\sim$19 mag for 4 yr and then faded fainter than 22 mag. It probably formed a circumstellar dust shell similar to η Car.

Thus four stars substantially increased their total bolometric luminosity during an LBV outburst. The increase in bolometric magnitude ranges from possibly one magnitude for P Cyg to about two magnitudes for η Car, V 12, and SN 1961V, although, during the latter's brief super-eta Car outburst, the increase above its normal magnitude was 3.5 magnitudes. However, during their giant eruptions, SN 1961V and η Car radiated comparable amounts of total energy, $\approx10^{49}$ ergs.

3.4 S. Doradus

S Dor in the LMC is the classical or prototypical LBV and is sometimes used as an example of normal LBV eruptions as opposed to the more violent or energetic events described above (see review by Wolf 1989a). S Dor has been known to be variable since its discovery in 1897. Because it is so bright at maximum light ($m_v\simeq8.8$ mag) S Dor has been very well studied at high dispersion and with the *IUE*; consequently, it has provided us with some of the most detailed work on an LBV at maximum light. S Dor apparently stays at visual maximum for very extended periods (see Fig. 5 in Sharov 1975), longer than in quiescence, while other LBVs

TABLE 3
The Super-Outburst of SN 1961V (with $r{\sim}5.3$ Mpc and $A_B{\sim}0.6$ mag)

		m_{pg}	M_{pg}	$M_{\rm Bol}$	Comment
Step 1	preoutburst star (1937–1960)	~18	−11.2	···	assume this is a hot supergiant when an LBV in quiescence
Step 2	S Dor-type eruption, discovery: Nov. 21, 1960	15.8	···	−13.6	assume $T{\sim}8000$ K and BC≃0.0 mag
Step 3	η Car-like outburst, July 1961	14.0	···	−15.4	"
Step 4	Super η Car, Dec. 1961	12.5	···	−17.0	"
Step 5	Rapid decline Sept. 1968	>22	···	···	probable dust shell

spend equal or more time at minimum. It has now been at its current maximum phase since 1971, more than 20 yr with a brief dip in 1984–1985 (see Fig. 2).

3.5 AG Carinae

AG Car was recognized as an LBV with S Dor-type eruptions by Wolf and Stahl (1982; see also Caputo and Viotti 1970) during its last outburst. Its spectrum at maximum light is also strikingly similar to S Dor at maximum, and Stahl (1986) has noted its resemblance to the Of/WN9 stars at minimum light. Viotti et al. (1993) describe its recent minimum (1984–1990) as the hottest so far recorded.

AG Car was formerly assumed to be part of the complex of young massive stars at 2.0–2.5 kpc in the Carina spiral arm. However, its radial velocity and corresponding kinematic distance (6.4–6.9 kpc; Humphreys et al. 1990) plus the variation of interstellar extinction in its direction (Hoekzema et al. 1992) suggest that AG Car is much farther away, between 5 and 7 kpc. With this larger distance its luminosity is -10.5 to -11.2 mag ($M_{\rm Bol}$), more consistent with its spectroscopic characteristics and photometric behavior.

AG Car's most distinguishing characteristic is its prominent ring nebula (see Fig. 6). High-resolution coronagraphic imaging by Paresce and Nota (1989) revealed a double-helix-shaped jet seen by reflected light from the star; however, a very recent new visual image with the WFPC2 camera on *HST* (Nota et al. 1994) shows that the "jet" is resolved into individual clumps or reflection clouds. The double helix was apparently an illusion that went away with higher resolution imaging. However, ground-based coronagraphic imaging by Nota et al. (1992) confirms the presence of highly axisymmetric features in AG Car's nebulosity; the expanding shell is not spherically symmetric. Schulte-Ladbeck et al. (1994), using spectropolarimetry, report large and variable polarization and find evidence for an axis of symmetry in the stellar wind as well. They suggest that AG Car's circumstellar axisymmetric geometry already exists within a few stellar radii of the star. Leitherer et al. (1994) reach the same conclusion with observations from *HST* and attribute the variable polarization to a variable outflow with a density enhancement in the equatorial plane.

3.6 R 127 in the LMC

R 127 is remarkable because it was one of the Of/WN9 stars originally recognized by Walborn (1977). The discovery by Walborn (1982b) and by Stahl et al. (1983) that R 127 was having an S Dor-like eruption clearly demonstrated the important connection between LBVs and the Of/WN stars. R 127, an LBV, is an Of/WN9 star during its quiescent phase. At maximum light it very closely resembles S Dor. Figure 8 shows spectra of both LBVs during their recent eruptions.

Coronagraphic imaging by Clampin et al. (1993) confirms the presence of a circumstellar shell (Stahl 1987) and shows that it is highly asymmetric, similar in size and structure to the shell surrounding AG Car. Their observations support the equatorial circumstellar disk model proposed by Schulte-Ladbeck et al. (1993) based on spectropolarimetry measurements of R 127. Schulte-Ladbeck et al. also report high and variable polarimetry, much like what they observe for AG Car.

3.7 A Lower-Luminosity LBV

R 71 in the LMC is included here as the best studied of the lower luminosity LBVs. The star has been well observed in both the maximum and minimum state (Wolf et al. 1981). Most LBVs are noticed and observed at maximum light, so we have less information about their quiescent state. The light and temperature variations for R 71 show a much smaller range than do the more luminous stars like AG Car and R 127. The amplitude of its last eruption was little more than a magnitude and its temperature variation was only from ~8000 to 13,600 K at quiescence, in contrast to the much larger temperature variations shown by the more luminous or "classical" LBVs (see Fig. 10).

3.8 AE Andromedae

AE And was the visually brightest star in M31 when W. Luyten discovered it in 1928 (≃14.6 mag) and would have had $M_v \simeq -10.3$ mag ($\simeq M_{\rm Bol}$). From analysis of the [N II] emission lines in its current red spectrum, Humphreys et al. (1989) reported that the total mass of the [N II] emitting gas in its photoionized shell is $>6\times10^{-3}\,M_\odot$. This is probably the material ejected during its maximum in 1927 which lasted 20 yr, implying a mass-loss rate $>3\times10^{-4}\ M_\odot\ \mathrm{yr}^{-1}$ during the ejection event.

Today, AE And has an emission-line spectrum that closely resembles η Car (Humphreys 1975). Its UV spectrum from recent *HST* observations (Humphreys et al. 1994) shows an unusually strong emission line of Fe II at 2507 Å. The only other star that shows this line so strong with respect to the continuum is η Car (see Fig. 7). It is probably produced by fluorescence from Lyman alpha (Johannson and Hamann 1993).

3.9 He 3-519

He 3-519, a candidate LBV, is an example of a possible transition object and is a case study of some ambiguities that can arise in this subject.

He 3-519 is reminiscent of AG Car with its Of/WN-like visual spectrum (Bohannan and Walborn 1989) and large expanding shell nebula (Stahl 1987). It is also in the Carina arm at a distance of ~8 kpc. The expansion age of the shell is estimated at >20,000 yr neglecting deceleration (Stahl 1987; Davidson et al. 1993; Smith et al. 1994) comparable to the suspected duration of the LBV stage. The age plus the lack of observed eruptions suggests that He 3-519 may now be in a post-LBV state; although it was very likely an LBV when the shell was ejected.

Davidson et al. (1993) combined UV and visual spectra and photometry to estimate the star's luminosity. The visual-wavelength He emission lines (He I and He II) suggest a characteristic temperature $T_{\mathrm{app}}\approx35{,}000$ K. With this high temperature, both the UV continuum and the *UBV* photometry indicated a reddening close to $E(B-V)=1.5$ mag, and led to an absolute bolometric magnitude $\approx-11.0\pm0.6$, comparable to AG Car. However, Smith et al. (1994) then found a strikingly different result, $M_{\mathrm{Bol}}\approx-9.4$, comparable to the lower luminosity LBV-like stars. The disagreement is due primarily to the correction for interstellar extinction. Based on the Hα/Hβ emission-line ratio from the nebula, Smith et al. estimate $E(B-V)\sim1.14$ instead of 1.5 mag, which leads to a factor-of-10 difference in the UV flux corrections and a large difference in the total luminosity. However, this smaller reddening implies an intrinsic $B-V=+0.1$, too red for such a star. Circumstellar dust might cause the star to be reddened, but the weak infrared emission indicates only a small amount of dust (Davidson et al. 1993).

Smith et al. (1994) used a star-plus-wind model intended for WR stars to derive a somewhat lower temperature of 27,000 K. The two temperature estimates do not really disagree very badly, because they refer to different definitions of temperature. The Smith et al. value is the classical effective temperature defined by radius and luminosity; the hotter Davidson et al. value, although it was unfortunately called T_{eff}, was really T_{app}, based on the emergent energy distribution (see Sec. 2 above). As noted in Sec. 2 above, T_{eff} and T_{app} can be quite different.

The results for He 3-519 are also a good example for our cautionary remarks concerning the use of "black box" computer codes. The Smith et al. model had a number of input parameters which were adjusted so that a similar number of observables came out right. However, the resulting model then failed to reproduce other observables such as the Balmer line absorption components and the continuum flux.

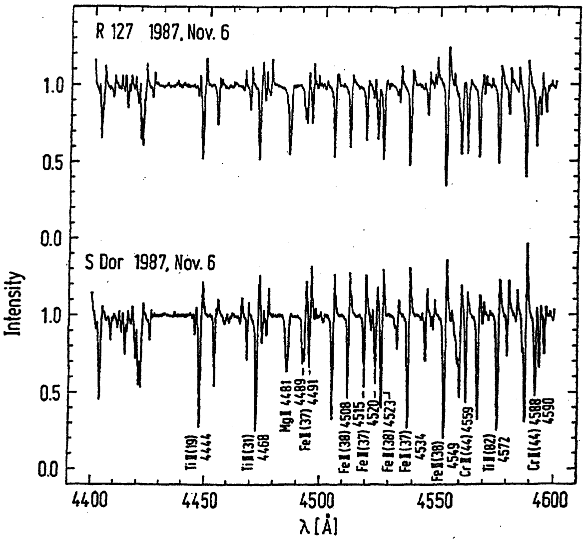

FIG. 8—High-resolution spectra of S Dor and R 127 reproduced from Wolf (1989b) with permission, showing their remarkable similarity at maximum light, eruption.

So what is the answer for He 3-519? The intrinsic visual color from the Smith et al. model, $B-V=-0.12$, may be about right because the wind must make $B-V$ redder than a hot star. (This disagrees with the intrinsic color implied by their adopted reddening.) With the observed $B-V$ of $+1.25$, we then find a reddening of $E(B-V)\approx1.37$ Adjusting the discussion by Davidson et al. accordingly, the characteristic temperature for the UV continuum shape is in the neighborhood of $T_{\mathrm{app}}\approx34{,}000$ K, and the most likely bolometric absolute magnitude is around $M_{\mathrm{Bol}}\approx-10.8$. He 3-519 is obviously an object in need of more observational work to resolve the discrepancies, especially concerning extinction.

He 3-519 has one curious observational peculiarity. The most conspicuous emission feature in its *IUE* spectrum is an emission line near 3010 Å, most likely a radiatively excited Fe III multiplet. It is surprising that this line is so prominent in He 3-519 but not in related LBV-like stars.

The above list includes only a few examples of the kind of behavior and properties typical of LBVs. In Table 4 we summarize the physical parameters of the better studied LBVs; that is those for which there are sufficient UV, optical, and infrared observations to estimate an apparent temperature and luminosity at either maximum or minimum light (quiescence) and therefore place it on the observational HR diagram.

4. LBVs ON THE HR DIAGRAM AND THEIR ROLE IN MASSIVE STAR EVOLUTION

In this section we discuss the role of LBVs from an empirical point of view. At the end of the section, we outline a

TABLE 4
Physical Parameters for Well-Studied LBVs

Star	$M_{\rm Bol}$	Apparent temp. (quiescence)	Apparent temp. (eruption)	$\dot{M}$ (in eruption)	Reference
Milky Way					
η Car	−11.6:	20,000–30,000	···	10^{-3}	Davidson et al. (1986, 1994)
P Cyg	−9.9	19,000	···	2×10^{-5}	Lamers et al. (1983, 1985)
AG Car	−10.5 to −11.2	30,000:	9000	3×10^{-5}	Wolf and Stahl (1982) Humphreys et al. (1990)
HD 160529	−8.9	11,000:	8000	···	Sterken et al. (1991)
HR Car	−8.9	14,000:	···	···	van Genderen et al. (1991) Hutsemekers and Von Drom (1991)
LMC					
S Dor	−9.8	20,000–25,000:	8000	5×10^{-5}	Stahl and Wolf (1986) Leitherer et al. (1985)
R 127	−10.5	~30,000:	8500	5×10^{-5}	Stahl et al. (1983) Stahl and Wolf (1986)
R 71	−8.8	13,600	9000:	6×10^{-5}	Wolf et al. (1981) Thackeray (1974)
R 143	−10.0	20,000:	8500:	···	Parker et al. (1993)
R 110	−8.9	10,250	7600:	3×10^{-6}	Stahl et al. (1990)
SMC					
R 40	−9.0	⩾10,000:	8700	8×10^{-6}	Szeifert et al. (1994)
M31					
AE And	−10.0:	~30,000:	···	1.7×10^{-5}	Humphreys et al. (1994)
AF And	−11.4:	>30,000:	···	2×10^{-5}	Humphreys et al. (1994)
M33					
Var B	−10.2	···	~9000	10^{-5}	Humphreys et al. (1994)
Var C	−9.8	20,000–25,000	7500–8000	5×10^{-5}	Humphreys et al. (1994) Humphreys et al. (1988)

likely evolutionary scenario which differs in some important ways from previous versions.

The upper HR diagram is characterized by an obvious upper envelope to stellar luminosities. This empirical luminosity boundary, known as the Humphreys–Davidson limit, was determined from the distribution of normal stars in the Milky Way and Magellanic Clouds (Humphreys and Davidson 1979, 1984; Fitzpatrick and Garmany 1990). The temperature dependence of the observed boundary for the hot stars (⩾10,000 K) and the well-defined temperature-independent upper luminosity limit for the late-type hypergiants (⩽8000 K) indicate that this is a critical locus in the HR diagram. Figure 9 shows a schematic HR diagram with the luminosity boundary for the hot and cool stars as a broad solid line.

The lack of cool, evolved supergiants above the luminosity limit (near $M_{\rm Bol}\simeq-9.5$ for $T_{\rm eff}<8000$ K) suggests that above some critical initial mass (~40–50 $M_\odot$), stars do not evolve to the region of the red supergiants. In 1979, we suggested that very massive stars (>40 $M_\odot$) in their post main sequence evolution encounter a limit to their stability, resulting in a period of very high mass loss—the LBV phase—which limits further evolution to cooler temperatures. Model calculations (de Loore et al. 1977; Chiosi et al. 1978; Maeder 1981) showed that if the mass loss is sufficient the evolutionary tracks for $M>40$–50 $M_\odot$ will reverse to the blue, toward warmer temperatures. The location and behavior of the LBVs on the HR diagram and the characteristics of the unstable cool hypergiants just below the luminosity limit have been critical to our current understanding of the final stages in the evolution of the most massive stars.

The LBVs in Table 4 are plotted in Fig. 9. The dashed lines illustrate the transits at constant luminosity from quiescence (maximum temperature) to visual maximum (minimum temperature) during the stars' outburst or eruption phase. At quiescence the LBVs lie near the temperature-dependent luminosity boundary for hot stars, in a region also occupied by normal hot supergiants. However, during the eruption phase many of the LBVs *appear* to both violate the luminosity boundary for the hot stars and lie above the luminosity limit for the evolved cool supergiants. During the eruption the expanded envelope mimics the photosphere of an evolved cooler supergiant. The actual "star" is embedded beneath this pseudo-photosphere. These apparent transits on the HR diagram are due entirely to changes in the outermost layers (variations in temperature and bolometric correction) and not to the evolution of the star.

It is clear from Fig. 9 that all of the LBVs during the eruption phase have essentially the same minimum temperature for the expanded pseudo-photosphere, near 8000–8500

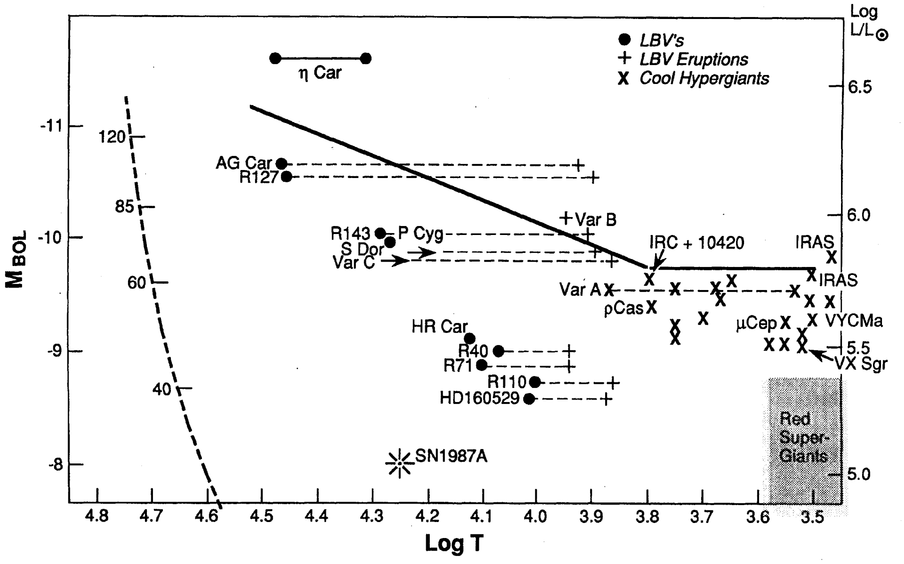

FIG. 9—A schematic HR diagram for the most luminous stars. The dashed lines represent the LBV transitions from quiescence (●) and to the eruption (+) stage. The most luminous cool hypergiants are also plotted. The empirical upper luminosity boundary is shown as a solid line.

K. Davidson (1987b) using a simple opaque-wind model, showed that during an LBV eruption at constant luminosity the temperature of the emergent radiation cannot easily fall below ≈7000 K, no matter how high the mass-loss rate.

An LBV instability strip? While there is a common minimum temperature for the LBVs, at quiescence they appear to lie along an inclined strip in the HR diagram such that the temperature of the LBV at quiescence is luminosity dependent—it increases with luminosity (see Fig. 10). Wolf (1989a,b) first pointed out that this distribution implies an amplitude-luminosity relation for LBV eruptions. Since the LBV eruptions occur at constant bolometric luminosity, the instability strip combined with the opaque wind limit means that the variation of the bolometric correction, or the amplitude of the visual light variations, from minimum to maximum temperature, depends on the absolute luminosity of the star. Thus LBVs may obey an amplitude-luminosity relation which could make them potential distance indicators. This behavior is a characteristic of normal LBV eruptions and consequently Wolf referred to it as the "S Dor instability strip."

The existence of an S Dor or LBV instability strip is an intriguing possibility, but many normal hot supergiants that are not LBVs are also found in or near the location of this strip on the HR diagram. Evidently, only certain stars that pass through this strip become unstable. Presumably, then, the LBVs are in a unique stage of their evolution that gives rise to the instability and the subsequent LBV eruptions.

The evolutionary state of LBVs—two types of LBVs? The LBV phenomenon is the most likely reason for the sloping boundary in the upper left of the empirical HR diagram. Rapid and high mass loss is necessary to explain the observed limit. The LBVs are conspicuously unstable and no other stars in that part of the HR diagram are known to have comparable mass-loss rates. However, the temperature-dependent empirical upper boundary for hot stars in the HR diagram is defined by relatively normal mass-losing supergiants, and does not necessarily coincide with the location of the stability limit. In this connection we note the presence of three very luminous A-type hypergiants: Cyg OB2 No. 12 in the Milky Way, HD 33579 in the LMC, and B 324 in M33. These are the visually brightest stars in their respective galaxies, with $M_v = -9.8$ and $M_{\rm bol} = -9.8$ to -10.2. Since only one is known per galaxy, these are obviously very rare stars in a short-lived phase. Massey and Thompson (1991) suggest that Cyg OB2 No. 12 may be an incipient LBV, based on light variations up to ~0.5 mag and small spectral variations, but these objects are not full-fledged LBVs. Perhaps they and the other apparently steady hot stars at the "upper boundary" are pre-LBVs. Very likely a sufficiently massive star first becomes unstable at temperatures somewhat *cooler* than the observed sloping upper boundary. The enhanced mass loss would then cause a modest relaxation to the left in the HR diagram as the LBV phase begins. We suppose that the LBVs then remain unstable because their L/M ratios have increased, but of course this depends on the instability mechanism (see Sec. 5).

We known from their high luminosities, high mass-loss rates, and the overabundance of processed elements like helium and nitrogen in their ejecta and atmospheres that the LBVs are evolved massive stars. With these characteristics plus their close association with the Of/WN9 stars R 127, AG Car, and HDE 269582), the LBVs are now commonly considered to be evolved objects in transition to the WR stars (Maeder 1983). The large amount of mass that may be lost during the LBV phase suggests that this is the critical stage that a very massive star (>40 $M_\odot$) must pass through before becoming a WR star.

While this scenario is a very reasonable one for the more massive or *classical* LBVs (those with $M_{\rm Bol}$ brighter than

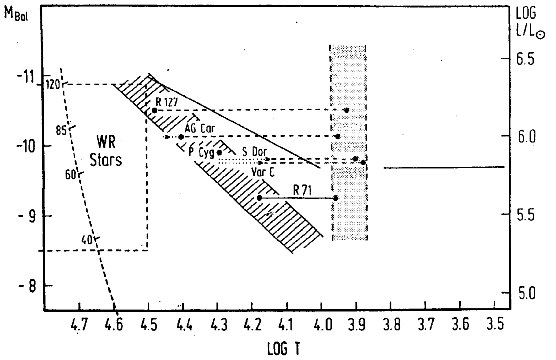

FIG. 10—The "S Dor instability strip" reproduced from Wolf (1989b) with permission. The opaque wind (cool) limit is also shown.

−9.5 mag and with initial masses presumably greater than 40 $M_\odot$), there is a group of five reasonably well observed LBVs at lower luminosity, below the upper luminosity limit for evolved supergiants. These stars also have smaller amplitudes in their variability, lower mass-loss rates, and lower maximum temperatures than the classical LBVs. Given their location on the HR diagram, these stars are either evolving to the red supergiant region or they have already been red supergiants. We suspect the latter because the masses implied for these stars from the atmospheric analysis yield unusually low masses for their luminosity; for example, R 71 has a He-enriched atmosphere and a current mass of only 8–10 $M_\odot$ (Kudritzki et al. 1989) though its initial mass must have been ~25 $M_\odot$ based on its location on the HR diagram. R 71 must have been through the red supergiant stage to have lost more than half its mass. Similarly, R 110 (Stahl et al. 1990) and HD 160529 (Sterken et al. 1991) have current masses of 10 to 13 $M_\odot$, respectively. Thus the two groups of LBVs have had very different evolutionary histories and the explanation for the instability cannot be a common evolutionary state.

An important clue to understanding this apparent instability strip and possibly even the origin of the LBV eruptions is the presence of a significant number of nonvariable stars or non-LBV stars in the instability strip. Thus there must be something unique about the lower luminosity LBVs at this location in the HR diagram. We suggest that this is their unusually low mass. Most of the likely explanations for the LBV instability discussed in the next section require L/M ratios near the Eddington limit. Assuming that there is an instability strip in this part of the HR diagram, the first time a star passes through, it has just left the main sequence and still has most of its mass. However, on its second passage through this region, the star is evolving back to warmer temperatures from the red supergiant region; it has already lost half of its initial mass but has essentially the same luminosity. With a much reduced mass, but the same luminosity, the star will be much closer to its Eddington limit and much more subject to radiation pressure induced instabilities.

The normal or S Dor-type eruptions in the more luminous classical LBVs may also be caused by their proximity to the Eddington limit for their mass, but they have probably not been red supergiants. However, they are more evolved (N- and He-enriched ejecta) and have lost more mass than the non-LBV stars in the same region of the HR diagram. This high mass loss may have occurred in a more violent LBV eruption like that of η Car of P Cyg.

Thus there appears to be a critical dividing line in the HR diagram above which the stars do not evolve to M supergiants but enter a highly unstable stage—the classical LBVs. Just below this limit we find a number of evolved supergiants including the most luminous M supergiants. These cooler, evolved supergiants (or hypergiants) that define the cool component of the upper luminosity limit are also highly unstable. These stars are the most luminous stars of spectral types F, G, K, and M in the Milky Way and the LMC. Some of the better known members are identified by name in Fig. 9. These stars all show light and spectral variability, and high mass loss, plus extensive circumstellar dust around many. Half of the most luminous M supergiants ($M_{\rm Bol}$ brighter than −9 mag) are known supergiant OH/IR stars, a well-known, rapid mass-loss stage ($\dot{M} \approx$ few$\times 10^{-4}$ $M_\odot$ yr^{-1}. Two of these cool hypergiants deserve special mention—Variable A in M33 and IRC +10420 in our galaxy.

Variable A in M33 was one of the original Hubble–Sandage variables but recent optical and infrared observations (Humphreys et al. 1987) show that it is not a classical LBV. At maximum light (1950) Var A was one of the visually brightest stars in M33 with an F-type spectrum. It is now faint and red with the spectrum of an M supergiant, not an emission-line hot star like other *H-S* variables or LBVs. It also has a large infrared excess and a mass-loss rate of ~2×10^{-4} $M_\odot$ yr^{-1}. Today it is as bright at 10 μ as it was at its visual maximum in 1950 (Fig. 11). We suggested that Var A is an evolved supergiant with an initial mass near 40 $M_\odot$ evolving to cooler temperature and encountering the stability limit, perhaps the same one that affects the LBVs. Given its luminosity, right at the luminosity boundary, we do not know whether or not Var A will eventually evolve into a stable red supergiant. The slightly less luminous galactic hypergiant Rho Cassiopeiae displayed similar but less dramatic behavior in the 1940s (Bidelman and McKellar 1957; Beardsley 1961).

In contrast, the peculiar galactic OH/IR source, IRC +10420, an equally luminous star, is a strong candidate for post-red supergiant evolution. In a recent analysis of its infrared polarization, optical and near-IR energy distribution, and the stellar radial velocity, Jones et al. (1993) conclude that its physical properties and photometric behavior in the optical and infrared are consistent with a highly evolved, luminous star dissipating its cocoon of gas and dust. They propose that IRC +10420 is a true core-burning supergiant evolving from the red supergiant stage to the blue side of the HR diagram perhaps to become a WR star. It is now in a phase of evolution that is analogous to the degenerate core giants evolving through the proto-planetary nebula stage but at a much higher luminosity.

We are seeing increasing evidence for post-red supergiant evolution for stars in the ≈20–40 $M_\odot$ range; IRC +10420, a highly unstable evolved star, is probably shedding its cocoon from an earlier OH/IR stage; the less luminous LBVs have very likely been through a high mass-losing red supergiant state, and of course the progenitor of SN 1987A had been a red supergiant. Given their proximity on the HR diagram to SN 1987A's progenitor, it is tempting to speculate that the less luminous LBVs may soon become supernovae. The recently discovered interlocking rings around SN 1987A are likely due to a fossil bipolar outflow similar to what we now observe in many LBVs.

We obviously observe some very dramatic behavior, high mass loss and the ejection of shells of matter in eruptions, among many stars in the upper HR diagram, including both the hot LBVs and the cool hypergiants. Massive star evolution in the HR diagram is the essential background to discussing the cause of their instabilities.

In summary, a plausible empirical scenario for the classical LBVs has the following steps: (1) a very massive star ($M > 40\ M_\odot$) first evolves in the familiar way, moving to the right in the HR diagram with only moderate mass loss. The L/M ratio for such a star will be more than half the classical Eddington limit. (2) Then, at some temperature or radius, the star suddenly becomes unstable, for reasons discussed in the next section. We suppose that the sloping *initial* instability line in the HR diagram is to the right of or cooler than the empirical "upper boundary" of observed normal stars, but not cooler than ~8000 K. (3) Rapid, irregular mass loss then occurs. This causes the star to move perceptibly back toward the left in the diagram, probably until it temporarily stabilizes again. (4) The rapid mass loss increases the star's L/M ratio, which reduces its stability, so the *instability line also moves to the left in the HR diagram.* (This point has seldom been emphasized in the past.) Therefore the instability will soon recur when the star evolves toward cooler temperatures again; the star has become an LBV. The left–right excursions of the star and the hypothetical leftward movement of the instability line in the HR diagram are important. (5) Eventually a Wolf–Rayet star results when enough mass has been lost.

The empirical scenario explains why a few normal stars are found in and to the right of the LBV strip in the HR diagram. In this view, these normal supergiants have not yet reached the *initial* instability line and therefore have smaller L/M ratios than LBVs. Instead of the two-dimensional HR diagram, *we must consider at least four evolving parameters: L, M, R, and composition* when exploring the LBV phenomenon and the upper HR diagram in general.

While this scenario may be simplified, it is plausible and provides a good provisional framework for discussion of two theoretical problems: the origin of the LBV instability (and the related upper luminosity boundary), and the bipolar symmetry in some LBVs.

5. THE CAUSE OF THE LBV PHENOMENON

Theoretical work on this topic has been far scarcer than observations. In this section we describe several proposed mechanisms for the basic LBV instability, but none of them has yet been analyzed properly and so far there is no good basis for choosing among them. Given the wide variety of observational clues that are already available, the LBV problem can now be viewed as a set of theoretical and phenomenological questions:

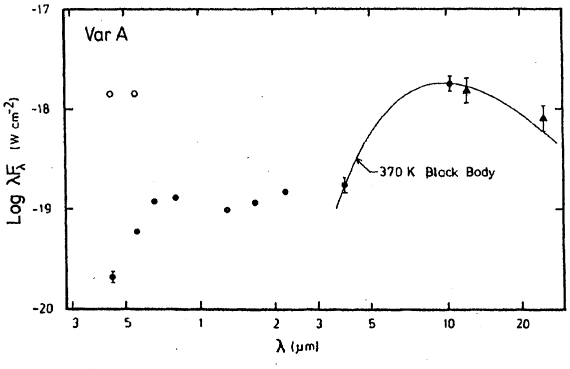

FIG. 11—The energy distribution of Var A in M33 from Humphreys et al. (1987).

(1) *What is the cause of the instability?* Sporadic, episodic, or chaotic behavior is required, not just pulsation or an enhanced steady mass-loss rate. Is more than one mechanism at work? What is the precise relationship between LBVs and the empirically observed upper luminosity boundary in the HR diagram? Do the less luminous LBVs have the same instability mechanism as the classical LBVs? (See Sec. 4 above.)

(2) What are the relative roles of giant and normal eruptions? Do they have similar causes? Which are more important for the total mass loss? Do most LBVs undergo giant eruptions, or do such events result from unusual circumstances? Do giant eruptions recur, or are they one-time catastrophes for each star?

(3) What is the *energy budget* in an LBV outburst? What parts of the star does the energy come from? If the *characteristic duration* of an LBV eruption is related to a thermal time scale, as often suggested, then to what depth in the star does this time scale refer? (Cf. Davidson 1987a, 1989; Maeder 1989.)

(4) How is the situation affected by stellar characteristics such as rotation, metallicity, and binarity? Would the upper HR diagram look different for stars with nearly primordial composition (i.e., with low metallicity)? Are some LBVs close binaries?

(5) Precisely how does the LBV phenomenon influence the upper luminosity boundary observed for cool hypergiants ($T_{\rm app} < 8000$ K)? These appear to be stars that are not quite massive enough to experience the LBV instability in their initial evolution to the right in the H-R diagram. However, the theoretical de Jager limit, involving turbulence in the photosphere of cool stars, may also play a role (de Jager 1980, 1984; see below). Therefore, does the LBV instability limit for hot stars merge with the de Jager limit for cool stars, and if so, how?

Various qualitatively plausible answers to these questions have been devised, but it is not easy to decide which answers are correct.

5.1 Core-Energized Pulsation

Historically the earliest instability mechanism to be envisioned for these stars (even before the LBV phenomenon was clearly recognized) was the ϵ mechanism that drives Ledoux or Ledoux–Schwarzschild pulsation (Ledoux 1941; Schwarzschild and Harm 1959; see also Eddington 1926; Maeder 1985; Appenzeller 1987; Stothers 1992). This phenomenon, loosely called pulsational or vibrational instability, is energized in the stellar core and depends on the nuclear reactions; we omit a fuller description here because it is no longer a leading explanation of LBVs. As explained in the historical appendix to this review (see below), the Ledoux–Schwarzschild mechanism was famous 25 or 30 years ago when it was thought to occur for masses above about 65 $M_\odot$. This process is no longer very appealing for LBVs because it applies mainly to young main-sequence stars; it is strongly damped by any internal composition gradient. The surface compositions of LBVs show that they are evolved, making them unlikely candidates for this instability (Luud 1967; Davidson et al. 1982, 1984, 1986; Dufour and Mitra 1987; Walborn 1982a, 1988, 1989).

There are other reasons to doubt the ϵ mechanism as an explanation for LBV eruptions. The critical mass now appears to be far above 65 $M_\odot$ even for the ZAMS stars, though there is still disagreement about the actual value (Appenzeller 1987; Klapp et al. 1987; Stothers 1992). Rotation inhibits this instability, but some LBVs are bipolar (see below). Stothers and Chin (1983) gave additional arguments against this as well as other deep-interior mechanisms. On the other hand, none of the stellar models used for analyses of Ledoux pulsation really corresponds to an LBV. (One might imagine an evolved, but well-mixed star; the critical mass would presumably decrease for higher He/H ratios, if only there were no composition gradient.) In summary, though we dare not reject it absolutely, this mechanism does not now rank among the likely possibilities.

5.2 Radiation Pressure and Photospheric Opacity

The next proposed LBV instability—one that we still like—is supposed to occur at the stellar surface. This is the hypothetical modified Eddington limit for the L/M ratio, where the word "modified" indicates that opacity is temperature and density dependent (see Sec. 2 above). (For the classical Eddington limit, opacity per unit mass is constant because it includes only scattering by free electrons in fully ionized gas; see remarks later below.) Variations in the opacity may conceivably lead to chaotic behavior, rather than just an enhanced steady wind. So far as we know, the earliest speculation of this type was inspired by a temperature estimate of $T_{\text{app}}\approx$30,000 K for η Car. Perceptible numbers of hydrogen atoms and other opacity-enhancing ions begin to appear as the local temperature decreases below 30,000 K, while η Car was presumed to be close to the Eddington limit, therefore: "If the temperature were slightly reduced, the surface opacity would rise, causing radiation pressure to overwhelm gravity" (Davidson, 1971). This idea is appealing because it suggests a possible reason for the slope of the upper luminosity limit in the HR diagram: Stars with higher luminosities have higher L/M ratios and therefore would become unstable with smaller amounts of "extra" opacity, i.e., at higher temperatures.

The modified Eddington limit was proposed explicitly by Humphreys and Davidson (1984) and later by Lamers (1986). In a more detailed qualitative discussion of the hypothesis, Appenzeller (1986, 1989) emphasized the possibility of relaxation oscillations between two states with different photospheric temperatures. Opacity tends to increase below 30,000 K, but reaches a peak around 12,000 K and then decreases toward lower temperatures. The atmosphere may therefore have two different quasi-stable states, one above 15,000 and one below 10,000 K—like the quiescent and eruptive states of an LBV. As Appenzeller noted, unpredictable jumps between states may occur.

Lamers and his colleagues have attempted to calculate the locus of the modified Eddington limit in the H-R diagram (Lamers and Fitzpatrick 1988; Gustafsson and Plez 1992; Lamers and Noordhoek 1993). We suspect that their approach is oversimplified (see below); the calculations require extrapolations to zero net force per unit mass. Even so, Lamers and Noordhoek's results are interesting with regard to the effect of initial chemical composition: The instability locus in the H-R diagram tends to be higher or cooler for stars with lower metallicity.

The modified Eddington limit hypothesis is really more subtle than one might gather from the above discussion and from most of the papers cited above (as noted by Humphreys and Davidson 1984; Davidson 1987a). For simplicity, consider an old-fashioned hydrostatic stellar atmosphere model without a wind (cf. Gustafsson and Plez 1992). Consider the parameter $\Upsilon_{\max}$, the maximum value of the ratio |*radiative force/gravitational force*| in this idealized static photosphere, where a simple effective opacity value is used to calculate the radiative force at each point. (Thus we ignore the normal line-driven stellar wind; we are concerned here with a more drastic hypothetical effect that involves all wavelengths, and which is supposed to occur in the photosphere proper rather than in the thin outer layers.) Naively, one expects an instability to occur when $\Upsilon_{\max}$ reaches a value of unity. As $\Upsilon_{\max}$ approaches unity in a series of static atmosphere models with successively larger L/M ratios, the density at a given temperature becomes smaller. Therefore the ionization becomes higher, which reduces the absorption contribution to the opacity. One finds that the absorption opacity is thereby almost eliminated in the critical layers of a model with $\Upsilon_{\max}\approx1$, so the total opacity is mainly due to scattering by free electrons after all! In other words, such models can approach the *classical* Eddington limit, a result that almost seems to invalidate the simplest concept of a temperature-dependent *modified* version.

Therefore, a workable modified Eddington limit must be a little more subtle and does not necessarily occur at $\Upsilon_{\max}=1$. Suppose that the hypothetical instability occurs at values of $\Upsilon_{\max}$ noticeably less than unity (perhaps 0.8 or 0.9, for example); this would still be consistent with Appenzeller's (1986, 1989) qualitative discussion of the problem. In that case the density decrease is not severe enough to eliminate the absorption opacity, and we would indeed find a sloping locus in the HR diagram that would resemble what is observed. But this is just one speculation; the important point is that a proper stability analysis has not yet been done, even though the basic conjecture has been expressed repeatedly for many years.

Obviously we need a detailed analysis showing whether or not radiation pressure really drives an instability of approximately this type. A simplified opacity function may be adequate for the basic phenomenon, and non-LTE effects may be irrelevant; but the hydrodynamics must be realistic. Either a classical stability analysis or a hydrodynamic model calculated with a supercomputer might work. The closest that anyone has come to this goal so far is the "bistable wind" model reported by Pauldrach et al. (1989, 1990), which resembles what is needed for LBVs but is still not sufficient. Calculating radiation-driven stellar winds, Pauldrach et al. found almost a discontinuity in the mass-loss rate as a function of stellar parameters, for reasons involving the optical thickness in the Lyman continuum. If this phenomenon can cause LBV eruptions, then it is close enough to the original idea to be considered at least a partial vindication of the modified Eddington limit.

5.3 Turbulent Pressure

Another relevant process at the stellar surface involves turbulence rather than radiation (de Jager 1980, 1984; Maeder 1983; Boer et al. 1988; Gustafsson and Plez 1992; Nieuwenhuijzen and de Jager 1992). If the outer layers of a star are convective, then the effective total pressure must include a contribution due to turbulence, i.e., random bulk motions. However, convective energy flux must be converted to radiation in or near the photosphere, and the resulting gradient in turbulent pressure implies an outward force on the gas. According to de Jager, this outward force balances gravity at some critical luminosity which is close to the observed upper luminosity limit for red supergiants. The de Jager theoretical limit is roughly analogous to the Eddington limit, with turbulent pressure substituting for radiation pressure.

Unfortunately, since convection and turbulent pressure are so difficult to calculate with any confidence, we do not yet know whether de Jager's theory is relevant to stars as hot as classical LBVs. One does not ordinarily associate outer convective zones with stars hotter than 10,000 K, but on the other hand, convection is easier to incite close to the Eddington limit; the situation is quite unclear. We have the uncomfortable feeling that this mechanism may be working together with the modified Eddington limit, inseparably, at least for temperatures below 20,000 K. Making the situation even more complicated, shear turbulence generated by differential rotation may also be significant (Sreenivasan and Wilson 1989). Conceivably these mechanisms and others mentioned below *all* have some validity, simultaneously!

5.4 Subphotospheric Instability

Some proposed instability mechanisms are located below the photosphere of an LBV. Note that the Eddington limit is not valid in a stellar interior, because there L represents total heat flow, not necessarily radiation. Wherever radiation pressure threatens to overwhelm gravity deep below the photosphere, convection may occur, carrying enough of the energy flux so that the radiation-pressure gradient remains less than the gravitational force per unit volume. (This is not possible in the photosphere, of course, because there L must emerge as radiation plus the bulk kinetic energy of mass loss.) A famous type of subphotospheric instability is the "κ mechanism" or value mechanism that drives Cepheid pulsations (see, e.g., Eddington 1926; Kippenhahn and Weigert 1990). This occurs if the heat transfers across a critical depth in the star decreases in the contraction phase of pulsation, and usually involves helium and hydrogen ionization zones. Moskalik and Dziembowski (1992) speculated that the κ mechanism might explain LBVs, but this has not been verified (cf. Glatzel and Kiriakidis 1993; Stothers and Chin 1993).

Maeder (1989, 1992) noted that a subphotospheric density inversion occurs in some stellar models with surface temperatures below 9000 K. This is caused by the same opacity dependences mentioned earlier in connection with the modified Eddington limit, but in deeper layers of cooler stars where the temperature is in the range 10,000–30,000 K. The Rayleigh–Taylor convection instability does not necessarily prevent such an inversion (see remarks by Glatzel and Kiriakidis 1993). Maeder argues that the situation is not fully understood, and that geyser-like eruptions might occur when a density inversion begins to arise in a calculated model. Aside from hydrodynamic doubts, unfortunately this idea does not provide a straightforward explanation of the appearance of the HR diagram for LBVs and other very luminous stars. LBV eruptions begin at surface temperatures far hotter than 9000 K, and the most luminous normal stars also have temperatures considerably above 9000 K. Thus, if a process like that suggested by Maeder is operative, then it must be supplemented by additional effects in order to explain why very luminous quiescent stars are not seen at temperatures around 10,000 K.

Maeder called his density inversion idea the "geyser model" because of the following geophysical analogies (which, however, also apply to other proposed LBV mechanisms). In a geyser on Earth, an eruption usually begins with minor burbles or splashes. Then, as water begins to be ejected at a high rate, a "boiling front" moves downward along the geyser pipe as the overlying layers of water are removed. This allows the eruption to continue, so the total mass ejected in the event greatly exceeds the mass of the layers where the instability began. Moreover, the duration of a geyser's quiescent period is correlated with the size of the preceding eruption. Since characteristics like these are shared by *most* LBV explanations, the term "geyser model" should be used to refer to the LBV phenomenon in general (cf. Davidson 1989).

Glatzel and Kiriakidis (1993) proposed that the LBV phenomenon is caused by "violent mode-coupling instabilities," which they found along a locus in the HR diagram that closely resembles the LBV strip and the observed upper boundary. Their linearized stability analysis included only radial pulsation modes. The unstable modes are inobvious and are not energized by the κ mechanism or by density inversions. Perhaps the main objection to this idea is that nonlinear effects may limit the instability, preventing any large effect (cf. Ledoux pulsation, mentioned earlier and in the appendix below). However, in a closing remark Glatzel and Kiriakidis stated that preliminary nonlinear analyses had given promising results: while even small-amplitude vibrations may effect some of the other possible mechanisms described above. The unstable modes are so complicated that we cannot say more than this possibility, pending further results (cf. Cox et al. 1993; Soukup et al. 1994).

Stothers and Chin (1993, 1994) have recently found yet another plausible mechanism for LBVs, reminiscent of the Glatzel–Kiriakidis idea. They calculated some modern evolution models for 60–120 $M_\odot$ stars with "normal" chemical composition, using improved (mostly increased) opacities that have lately become available. As a preliminary to the instability itself, they note that the end of the main sequence phase in each model occurs close to the observed upper luminosity boundary in the HR diagram. Evolution after that point is rapid (duration about 6000 yr), almost fast enough to account for that boundary without further ado.

Next, Stothers and Chin explain that the outer layers with temperatures below about 5×10^5 K are dynamically isolated from the stellar interior, because of high opacity due to iron around 2×10^5 K. The outer layers can become dynamically unstable if the following conditions occur: Zones of partial hydrogen and helium ionization near the surface must cause a sufficient decrease of the average adiabatic index, while L/M must be sufficiently large (partly due to mass loss). According to Stothers and Chin's calculations, the star's outer layers first become unstable in this way during rapid post-main-sequence evolution, at a surface temperature below 12,000 K. (Here it is assumed that a modified Eddington limit instability does not disrupt the surface first, and that the lack of observed very luminous stars far to the right of the upper limit in the HR diagram is simply due to rapidity of evolution in this stage.) When the outer layers become dynamically unstable, the resulting eruptive mass loss is extremely rapid until the star has become much smaller and hotter. Afterward, as in the empirical scenario described at the end of Sec. 4 above, the instability can recur at higher surface temperatures and the star may behave like an LBV.

The sequence of events described by Stothers and Chin is appealing but does not provide a perfect match with observations. The low surface temperature when the instability first occurs seems mildly objectionable; either this temperature has been underestimated in the calculations, or else the absence of very luminous late-B or A-type stars must be explained by a combination of rapid evolution and poor statistics (Cyg OB2 No. 12 may be relevant to this question). At first sight the giant 19th-century outburst of η Car appears to be a likely example of an initial eruption according to Stothers and Chin's scenario. However, if this star was cooler than 12,000 K before that great event, then it should have appeared consistently at second magnitude during the 17th and 18th centuries; in fact, it was often much fainter and therefore probably hotter (van Genderen and Thé 1985; Davidson 1989). The expected recurrence time between eruptions of an LBV seems too long in Stothers and Chin's theory. These discrepancies are not enormous, though, and the proposed instability is certainly worth more attention.

The Glatzel–Kiriakidis and Stothers–Chin mechanisms are bewildering in their complexity—indeed, they may even be fundamentally similar, but this is difficult to judge from the published papers. Presumably both occur mainly in the same outer layers of the star. The two mechanisms are said to begin at different values of $T_{\rm eff}$ (hence the observed upper boundary for normal stars in the HR diagram is explained differently by the two pairs of authors), but the calculations are obviously sensitive to details such as opacities, prior mass-loss rates, etc. For a third proposal in the same vein, see recent abstracts by Cox et al. (1993) and Soukup et al. (1994). It seems unfortunate that the unstable modes are not obvious, and that the instability is so sensitive to many parameters, but these are not good arguments against the proposed scenarios. Our own feeling is that the subphotosphere instability models and the modified Eddington limit ideas are now the leading contenders to explain the LBV instability and the top of the HR diagram. There is no reason to assume that they are mutually exclusive!

5.5 Close-Binary Models and/or Rapid Rotation

So far we have mentioned only single-star theories for LBVs. At present the wisest attitude toward models that invoke close binary systems may be a wary, tentative ambivalence. Very massive binary systems do exist, and LBV behavior is likely to be affected in close cases with orbital periods less than 100 or even 200 days. Some objects' observed bipolar structures may indicate that they are close binaries (see below, however). On the other hand, close binary models allow theorists to "ascend into free-parameter heaven" (as remarked by Gallagher 1989).

Bath (1979) proposed that an object like η Car is a close binary system whose components are *less* massive than 50 $M_\odot$. Most of the luminosity, he suggested, originates in an accretion disk rather than the stars themselves. However, this conjecture does not explain much; one or two special objects may be represented, but the model lacks strong constraints and provides no obvious explanations for the LBV strip in the HR diagram, the characteristics of LBV eruptions, or the upper boundary in the HR diagram. A modified version may be worth considering for particular objects (Kenyon and Gallagher 1985).

Mass transfer between components in a very massive binary system has been discussed, e.g., by Tutukov and Yungel'son (1980) and by Gallagher (1989). A common-envelope system can look like a single large star, and an unusual event like the giant eruption of η Car might occur when two components merge together. Binary models seem unlikely to provide a general explanation for the LBV strip and upper boundary in the LBV diagram, though, because not all massive stars are in binaries, and binaries have various separations and mass ratios. Moreover, mass transfer in a very massive binary is difficult for a reason noted in the next paragraph below. Additional work on binary models is nonetheless worthwhile, especially for unusual objects like η Car. It would be especially useful to discover better criteria to distinguish between binary and single-star systems.

One peculiarity of mass flow in a very massive binary has not received much attention. For simplicity, consider a system with synchronous rotation. Radiation pressure greatly reduces the effective gravity at the surface of the primary star, but this has no effect on the orbital period of its close companion. The Roche equipotential surfaces are thus altered in a remarkable way: the mass-outflow vertex is found on the side of the primary star that faces *away* from its companion star! (See Schuerman 1972; Kondo and McCluskey 1976; Vanbeveren 1977, 1978; Davidson 1993.) In effect, that part of the stellar surface is like the equator of an isolated rapid rotator, where the rapid rotation is enforced by the companion star. In these circumstances, a binary model for LBV behavior will probably resemble a rapidly rotating single-star model. Most of the ejected material presumably leaves the system rather than being transferred to the companion star.

Bipolar structure, even as dramatic as in η Car, does not require a binary star system, because rotation of a single star can also provide an axis of symmetry for the mass outflow. Effective gravity and temperature are reduced near the equator; ordinarily such effects tend to decrease as the evolving star expands, but the outcome is not obvious for a star near the Eddington limit. Suppose, for instance, that a surface instability occurs when the local temperature drops below some critical value. (Some of the mechanisms listed above may have suitable temperature dependences.) Then, even if the rotation rate appears to by dynamically modest, the LBV eruption would begin near the stellar equator and bipolar structure is likely to result.

B[e] supergiants are usually supposed to be fast rotators with luminosities comparable to LBVs (Zickgraf 1989, 1990). They have fast bipolar winds and slower, denser equatorial disks. Lamers and Pauldrach (1991) have explained how this can occur in a bistable wind model, which, as noted earlier, is related to the modified Eddington limit idea. Equatorial and polar zones represent the two phases or modes of the bistability. Bjorkman and Cassinelli (1993) and Owocki et al. (1994) have described another way of making an equatorial disk around a rotating massive star. In their wind-compression models the stellar wind curves toward the equatorial plane from both hemispheres. Since streamlines cannot intersect, the result is a dense equatorial disk confined by ram pressure. Cassinelli et al. (1994) have applied this model to WR stars and conclude that a rotation of only about 13% of the breakup velocity is sufficient to produce a "wind compressed zone" in the equatorial region. Moreover, turbulent energy flux generated by internal rotational shear may also affect the stability of the equatorial region of the star (Sreenivasan and Wilson 1989). Considering all these possibilities, since the distinctions between LBVs and B[e] stars are not understood, there is nothing very surprising about an equatorial disk around an isolated LBV. The disk-creating effects mentioned above may operate together, and they are accentuated near the Eddington limit; therefore modest rotation speeds may suffice. Rotation may also help to create a dipole magnetic field, but it seems premature to speculate about this until the other effects of rotation have been clarified.

To summarize this section: Several proposed mechanisms involving single, nonrotating stars appear to be qualitatively plausible as explanations for LBV eruptions. They occur either in the photosphere and just below it, or else in deeper layers at temperatures of the order of 200,000 K. Various authors disagree about the apparent stellar temperature when the instability first arises—values ranging from 8000 to 25,000 K have been mentioned. All of the proposed instabilities need far more theoretical exploration and especially clarification; more than one of them may be relevant. Pending such work there is no obvious need yet to invoke companion stars or rapid rotation to explain the basic LBV phenomenon. However, bipolar structure is seen in at least some LBV ejecta. This may be normal, or uncommon, or freakish (e.g., conceivably η Car is not a proper LBV); binarity or rotation probably enhances the LBV instability but it might inhibit it; more information is needed. We also need some criterion for distinguishing whether a bipolar case involves a binary system or a single rotating star; close to the Eddington limit these alternatives resemble each other more than usual. Altogether, few astrophysical topics present theoretical problems as little explored as the LBV phenomenon.

6. FINAL THOUGHTS AND SPECULATIONS

It is obligatory at the end of a review article to summarize the outstanding problems or questions. We think it is clear from the discussion in the previous section that the most pressing questions concerning LBVs are theoretical.

Routine monitoring (*photometry and spectroscopy* approximately once a year) of all known LBVs, candidate LBVs, and the cool hypergiants at the upper luminosity limit should continue. Among the candidate LBVs, we should include not only the Of/WN stars but also the A-type hypergiants (M_v brighter than -9 mag) and the very luminous hot supergiants that lie near the hot star upper luminosity boundary. Presumably these stars are evolving to cooler temperatures and eventually will encounter the stability limit. It would be especially exciting to catch a normal hot supergiant in transition to the LBV stage. With the discovery of the cluster of He I emission, high mass-losing stars at the center of our galaxy, there is also the intriguing possibility that LBV/Of-WN stars may be major contributors to the energetics of starburst galaxies. Imagine what a cluster of η Car-like stars, all erupting at about the same time, would be like!

Sandage (1983, 1984a,b) has suggested that the LBVs define an upper limit to blue supergiant luminosities and can be used as distance indicators on that basis. But it is clear from Fig. 10 that a given LBV can have a visual luminosity ranging from -8.5 to near -11 mag at maximum. Mixing them with the normal A-type hypergiants, which apparently do have a luminosity cap of -9.5 to -10 mag, could result in a significant error in the resulting distance modulus. But with a well-calibrated amplitude-luminosity relation (Wolf 1989b), the LBVs have some potential as extragalactic distance indicators. Given their very high luminosities, approaching $M_{\text{Bol}}=M_v\simeq-11$ mag during eruption for some LBVs, they could be identified at extremely large distances. However, they would have to be observed for many years, even a decade or more, to determine their amplitudes. In this sense they might not be practical as distance indicators. Furthermore, not all LBV eruptions are the same. For example, in Fig. 3 Var B shows a range of amplitudes. We also have to be careful not to confuse a giant LBV eruption (like η Car or SN 1961V) with a supernova.

Obviously, the historical record of LBV variability has been very important both for our appreciation and understanding of these highly unstable stars. The old records for P Cyg and η Car in particular raise the possibility that some LBV eruptions, especially the giant outbursts, may have been recorded in ancient records much like supernovae. More recently, some LBVs may have been mistaken for supernovae, SN 1961V, for example.

We thought it would therefore be interesting to retell a story from the myths of ancient Sumer.

The god Ea of Eridu (see Shklovskii and Sagan 1966) was credited with bringing the gifts of civilization and learning to the Sumerians. Ea (also called Oannes) was a fish god who every day rose from the waters and taught the people. At that time Eridu was on the coast of what is now the Persian Gulf. Ea was identified with a southern star or asterism, called the Ea star, which was said to be variable.

The early Sumerologist P. C. A. Jensen (1890) identified the Ea star with η Car! In 3000 B.C., η Car would indeed have risen above the Persian Gulf. The great eruption (and rapid fading) of η Car was well known to scholars in Jensen's time, so it was logical to make the identification with η Car. This doesn't necessarily mean that η Car was the Ea star; but proper motions of some of the outlying condensations suggest that previous eruptions have occurred, possibly several hundred years ago (Walborn et al. 1978).

With this possibility in mind, it would be interesting to check the ancient records of the Chinese and Babylonians for possible LBVs (most likely η Car), and given the extreme brightness of LBVs, to survey archival plates of resolved galaxies for additional examples. It would be especially good to identify more of these astrophysical geysers during their giant eruptions.

We are grateful to many colleagues for providing reprints and preprints and for permission to use their figures. We are especially grateful to Dennis Ebbets and Rick White for permission to publish the fantastic image of η Car.

HISTORICAL APPENDIX: EARLY VIEWS OF LBVs

Since the origins of this topic are already fading in astronomers' memories, a brief review of early ideas may be of interest.

Of course η Car, P Cyg, and S Dor were often discussed individually before 1950, but we are not aware of any early suggestions linking all three of these stars together in one class of objects. A paper by Hubble and Sandage (1953) is sometimes credited with the recognition of LBVs as a class, but in fact did not actually do that. Hubble and Sandage noted that five irregular variables in M31 and M33 were very luminous and "blue." By "blue" they really meant "not red," i.e., these stars were not in the more familiar class of red supergiant irregular variables. Like most other authors before the late 1970s, Hubble and Sandage considered LBVs to be essentially F-type supergiants fluctuating in radius without varying much in luminosity (see also Tammann and Sandage 1968; Rosino and Bianchini 1973). In early papers, the spectra were occasionally said to resemble that of Epsilon Aurigae. In a footnote, Hubble and Sandage remarked that S Dor might be in the same class; this star was famous at the time because it was occasionally cited as the most luminous star known. (They did not propose η Car or P Cyg as other possible examples.) Several of the stars in M31 and M33 that are now known as "Hubble–Sandage variables" were first noted in other papers by various authors—see references cited by Sharov (1975), Humphreys (1978a), and Stothers and Chin (1983).

Tammann and Sandage (1968) and other authors began to include η Car in this class of stars after Payne-Gaposchkin (1957) and Burbidge (1962) explicitly called it a likely supergiant with a very high luminosity. As Payne-Gaposchkin and Burbidge recalled, Bok (1930) had classified a spectrogram of η Car obtained during an eruption around 1890 as "type cF5" (F supergiant; see also Walborn and Liller 1977). This was not considered to settle the matter, though; some astronomers continued to regard η Car as a possible "slow supernova," or a supernova remnant, or some unfamiliar kind of nebulous or nonthermal object, or a protostar (e.g., see Thackeray 1956; Gratton 1963; Zwicky 1965; McCray 1967; Pagel 1969; Ostriker and Gunn 1971).

Meanwhile, the Ledoux–Schwarzschild pulsational instability or ϵ mechanism dominated theoretical views of the most luminous stars in the 1960s and even later. Discussed earlier by Ledoux (1941), this core-induced instability attracted attention when Schwarzschild and Harm (1959) estimated that it would occur for *main-sequence* stars with $M > 60\ M_\odot$. Schwarzschild and Harm warned that nonlinear effects might limit the pulsations and that more massive stars were suspected to exist; nevertheless, for years many astronomers thought that this phenomenon would destroy very massive stars. Stothers and Simon (1968) showed an empirical H-R diagram with a nearly level (constant luminosity) upper limit, consistent with the idea of disaster above $65\ M_\odot$. They used the LMC and SMC stars listed by Feast, Thackeray, and Wesselink (1960), but underestimated the bolometric corrections for the hot stars.

A natural interpretation of LBVs therefore seemed obvious (though they were not called LBVs then): A very massive main-sequence star would develop a fluctuating, pulsationally induced envelope that would look like an F supergiant. This explanation was favored by Tammann and Sandage (1968), for example. Perhaps the Ledoux instability even led astronomers to be complacent about the upper left corner of the H-R diagram in the 1960s, delaying recognition of the true LBV phenomenon. (On the other hand Burbidge 1962 proposed a somewhat different scenario for η Car, in which the star really was an evolved, type-F supergiant, but was pulsationally unstable nevertheless. During the same years theorists often speculated about hypothetical supermassive stars with $M > 1000\ M_\odot$, partly because of the interest in general relativity at that time.)

Appenzeller (1970a,b), Ziebarth (1970), Simon and Strothers (1970), and Talbot (1971) explored Ledoux–Schwarzschild pulsations, including nonlinear effects. In general they found that very massive stars would not necessarily be destroyed after all. During the following decade this mechanism was still sometimes mentioned in connection with LBVs (e.g., see Hoyle et al. 1973; Thackeray 1974; Humphreys and Davidson 1979; Stothers and Chin 1983), but it had begun to lose much of its appeal, for reasons noted in Sec. 5 above. Thus, in the years when the true locations of LBVs in the HR diagram were recognized, there was no longer an "obvious" theoretical explanation. (Ironically, the maximum luminosity for *red* supergiants does correspond to an initial mass near 60 $M_\odot$, as many astronomers would have expected 30 years ago. Their reasoning would have been fallacious, because the Ledoux–Schwarzschild limit is almost certainly not relevant. Today we think the explanation for the red supergiant maximum luminosity is quite different; see Sec. 4 above.)

In a theoretical paper on pulsational instability, Appenzeller (1970a) brought P Cyg into the discussion. "P Cyg spectra," i.e. emission lines with P Cyg profiles, had often been mentioned in the papers cited above, but Appenzeller may have been the first to discuss the star P Cyg itself in roughly the same context as the other LBVs mentioned above. This is retrospectively interesting because P Cyg was then known to be genuinely "blue" in the sense that we mean today, hotter than 15,000 K, not an F supergiant (Luud 1967). One might say that P Cyg, the first LBV known to have been observed, was also the first LBV to be put in the correct part of the H-R diagram.

The *second* LBV known to have been observed then took its own place (roughly) in the HR diagram soon after. Infrared observations of η Car by Westphal and Neugebauer (1969) had revealed its present luminosity, which indirectly helped to show that the core object is quite blue (Pagel 1969). Further consideration suggested that it really is a star, much hotter than an A- or F-type supergiant (Davidson 1971). Given the known history and ejecta of this star, the idea that an eruption would look like an F supergiant was then obvious. Thus by 1972 two stars, P Cyg and η Car, had illustrated the most dramatic features of the LBV phenomenon. (This statement will, ironically, remain true even if η Car is found to be atypical of LBVs.)

Further developments in the 1970s and early 1980s brought the topic into its modern form:

(1) Early UV observations of hot stars improved the bolometric corrections and revealed the prevalence of stellar winds (see many Refs. cited by de Jager 1980 and by Humphreys and Davidson 1984). Meanwhile, more authors consciously linked the "famous" LBVs while identifying additional examples including AG Car (see, e.g., Caputo and Viotti 1970; Thackeray 1974, 1977; Johnson 1976).

(2) Good-quality spectroscopy of supergiants in our galaxy and other nearby galaxies revealed the correct (albeit rough) location of the upper boundary of the HR diagram (Humphreys 1970; Osmer 1973; Hutchings 1976; Humphreys 1978b,c; Humphreys and Davidson 1979; de Jager 1980).

(3) Stellar evolution studies indicated that very high mass-loss rates, exceeding any observed steady values, would be needed to explain this boundary (de Loore et al. 1977; Chiosi et al. 1978; Stothers and Chin 1979; Maeder 1980, 1981).

(4) Then it was noticed that LBVs occur near the same line in the HR diagram, suggesting a plausible explanation in terms of sporadic events (Humphreys and Davidson 1979; see also e.g., Wolf et al. 1980).

(5) However, the physical nature of the LBV instability was far from obvious (Humphreys and Davidson 1979, 1984; de Jager 1980; Stothers and Chin 1983).

(6) Beginning in 1979 the *International Ultraviolet Explorer (IUE)* began to provide good ultraviolet spectroscopy of LBVs and other hot emission-line stars (see Shore and Sanduleak 1984, for example, and references therein). The star R 127 in the LMC obligingly provided a nice example of an LBV eruption in the early years of the *IUE* (Walborn 1982a,b, 1984; Stahl et al. 1983).

(7) CNO-processed chemical compositions were found at the surfaces of several LBVs (Luud 1967; Davidson et al. 1982; Walborn 1982a). This confirmed that the stars are evolved.

After these developments had occurred, by the mid-1980s, the topic had arrived in its "modern" state. Finally, concerning the term "LBV": although this modern usage traces directly back to Conti (1984), it is interesting to note that one section in Sandage and Tammann (1974) was titled "Irregular Luminous Blue Variables," and was indeed about LBVs.

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