Eta Carinae and the Luminous Blue Variables

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Abstract We evaluate the place of Eta Carinae (η Car) amongst the class of luminous blue variables (LBVs) and show that the LBV phenomenon is not restricted to extremely luminous objects like η Car, but extends luminosities as low as log \( (L/L_\odot) \sim 5.4 \) – corresponding to initial masses \( \sim 25 M_\odot \), and final masses as low as \( \sim 10-15 M_\odot \). We present a census of S Doradus variability, and discuss basic LBV properties, their mass-loss behaviour, and whether at maximum light they form pseudo-photospheres. We argue that those objects that exhibit giant η Car-type eruptions are most likely related to the more common type of S Doradus variability. Alternative atmospheric models as well as sub-photospheric models for the instability are presented, but the true nature of the LBV phenomenon remains as yet elusive. We end with a discussion on the evolutionary status of LBVs – highlighting recent indications that some LBVs may be in a direct pre-supernova state, in contradiction to the standard paradigm for massive star evolution.

1 Introduction

Luminous Blue Variables (LBVs) are evolved, luminous hot stars that experience outbursts as well as periods of enhanced mass loss. During outburst they appear to make transits in the HR Diagram (HRD) from their normal hot quiescent state to lower temperatures. The LBVs include a number of famous stars such as P Cyg, S Dor, R127 and AG Car. Eta Car is often described as an LBV, although it is a more extreme example owing to its giant eruption.

During the late 1970’s, it was recognized that the distribution of the most luminous hot stars on the HRD defines a locus of declining luminosity with decreasing temperature [36][42][96]. Together with the fairly tight upper luminosity limit of the
yellow and red supergiants at \( \log (L/L_\odot) \approx 5.8 \) \[36\], this indicated that the most massive stars \((M > 60M_\odot)\) do not evolve to cooler temperatures: the Humphreys-Davidson (HD) limit \[36\]. Humphreys and Davidson \[36, 37\] suggested that high mass-loss episodes, represented by stars like \( \eta \) Car, P Cyg, S Dor and the Hubble-Sandage variables in M31 and M33 \[35\], prevented the evolution of the most massive stars to cooler temperatures. With this addition of a post-main sequence period of high mass loss \( \left(10^{-3} - 10^{-5} M_\odot\text{yr}^{-1}\right)\) the evolutionary tracks of the most massive stars were shown to turn bluwards, towards the core He-burning Wolf-Rayet (WR) phase. During the WR phase, stars are anticipated to explode as supernovae (SNe) type Ib/c. However, at the end of this chapter, we challenge the canonical view that LBVs are always transitional between the O and WR stars, and suggest that some massive stars may already suffer their final explosion during or at the end of the LBV phase. One of the most relevant questions is therefore do LBVs explode?

The term LBV was introduced to describe the diverse group of unstable evolved hot stars in the upper HRD. Today we distinguish between more than one type of LBV \[38\]: (i) the normal LBV variability cycles with visual magnitudes changes of 1-2 magnitudes at essentially constant luminosity – on timescales of years to decades – represented by the prototype of the class, S Dor, in the Large Magellanic Cloud, and (ii) the giant eruption LBVs represented by \( \eta \) Car and P Cyg with visual magnitudes changes of 3 magnitudes or more, during which the total bolometric luminosity increases \[38, 40\].

In this chapter, we focus on the S Dor-type variables and their transits in the HRD, the prime characteristics of the LBV class. Roughly 30 massive stars in the Galaxy \((\approx 10)\) and Local Group \((\approx 20)\) are known to be S Dor variables. By contrast, only two Galactic objects have been discovered to exhibit giant \( \eta \) Car-like eruptions: \( \eta \) Car itself and P Cygni, which suddenly appeared at naked-eye visibility in 1600. Due to their high luminosities at maximum, a significant number of LBV-like non-terminal eruptions have been discovered in external galaxies. Most are typical of giant eruptions whilst some appear to be more similar to S Dor type variables. These extragalactic LBVs are sometimes referred to as “SN imposters” (see the contribution by Van Dyk and Matheson, this volume).

The circumstellar nebulae seen around many Galactic and MC LBVs \[68, 108\] may also have resulted from giant \( \eta \) Car eruptions, although stationary winds from prior evolutionary phases may constitute an alternative scenario for their creation \[25\]. Given the association of many LBVs with nebulae and ejecta and the close proximity of both the S Dor variables and the \( \eta \) Car-like variables to the Eddington limit, it is often suggested (though not proven) that their instabilities represent different manifestations of the same underlying evolutionary state. The fact that the giant eruptor P Cyg is also subject to small amplitude S Dor variability \[18, 62\] and that \( \eta \) Car’s second outburst (during 1888-1895) was like that of a normal S Dor variable \[40\] lends support to this possibility.

We emphasize, however, that neither the \( \eta \) Car-type eruptions, nor the S Dor variations are understood. Worse still, we do not know whether all LBVs are subject to both types of variability, or in which order they may occur. Two pertinent questions
are thus whether “η Car is unique among the LBVs?” and “what is the root cause of the S Doradus variations?”

2 Basic properties of LBVs

Variability LBVs show significant spectroscopic and photometric variability on timescales of years (short S Dor phases) to decades (long S Dor phases, cf. van Genderen [100]). For completeness, we note that LBVs also show smaller amplitude “micro” variability, on shorter timescales (weeks, months), but this aspect of their variability is also a common feature of supergiants in general (see [58, 54] and references therein).

Luminosities The classical LBVs have log \((L/L_\odot)\) larger than 5.8 with bolometric magnitudes in the range \(M_{\text{bol}} \approx -9\) to \(-11\). There is an apparent “gap” in their luminosities just below log \((L/L_\odot) = 5.8\), and a separate group of less luminous LBVs with log \((L/L_\odot) = 5.4-5.6\), corresponding to bolometric magnitudes in the range \(M_{\text{bol}} \approx -8\) to \(-9\) [38]. We note that this separation in luminosity (see Fig. 1) may not be real, but due to small number statistics. As the less luminous LBVs are below the HD limit, they have presumably been red supergiants where they may already have shed a lot of mass. As a result, they may not be further away from their Eddington limit than the classical LBVs.

One of the most important properties of LBVs is that they all appear to be close to the Eddington limit for stability against radiation pressure for their luminosities and current masses (see the subsection on stellar masses). The Eddington luminosity \(L_e\), is defined:

\[
L_e = \frac{4\pi GcM}{\kappa_F}
\]  

where \(\kappa_F\) is the flux-mean opacity and the other symbols have their usual meaning.

The dimensionless Eddington parameter for electron scattering: \(\Gamma_e\) is defined as the ratio between the gravitational acceleration and the radiative acceleration due to electron scattering, and scales as luminosity over mass:

\[
\Gamma_e = \frac{L\sigma_e}{4\pi cGM} = 7.66 \times 10^{-5} \sigma_e \left(\frac{L}{L_\odot}\right) \left(\frac{M}{M_\odot}\right)^{-1}
\]

where \(\sigma_e\) is the electron scattering cross-section.

Temperatures LBV temperatures are not only time-variable, but accurate \(T_{\text{eff}}\) determination requires sophisticated non-LTE spectral analyses for hot stars with extended envelopes and winds. Furthermore, it should be noted that for extreme objects like η Car we cannot even estimate the radius based on \(T_{\text{eff}}\) as the wind is
Fig. 1 The location of the LBVs (black circles) and candidates (open circles) in the Hertzsprung-Russell Diagram. The cool yellow hypergiants are indicated with pluses. The slanted and vertical grey bands represent visual minimum and maximum respectively. The dashed vertical line at 21 000 K indicates the location of the bi-stability jump (see Sect. 3). The figure has been adapted from Smith et al. [87] and is similar to e.g. Fig. 9 in [38].

optically thick. In such a case, $T_{\text{eff}}$ refers to the position in the wind where $R_{\text{ph}} > R_{\text{sonic}}$ (see below for a more extended discussion).

Fig. 1 shows the confirmed and candidate LBVs on a schematic HRD with their transits (the dotted horizontal lines) between quiescence and their outburst state or visual maximum. At quiescence, or visual minimum, they appear to lie along a fairly narrow slanted band: the “S Dor instability strip” [111]. Their effective temperatures vary from over 30 000 K, corresponding to spectral type late O/early B, for the luminous classical LBVs to only $\simeq 15$ 000 K, corresponding to late B spectral types, for the less luminous LBVs. Objects from both subgroups transit redwards to $T_{\text{eff}}$ not higher than $\simeq 8$ 000 K, corresponding to spectral types A to F, when they are “in outburst” or visual maximum. Wolf [111] noted that the amplitudes of the S Dor excursions become larger with increasing luminosity, and suggested that the most luminous LBVs could be cosmological distance indicators. Normal blue supergiants are also observed in and to the right of the S Dor instability strip. They are not close to their Eddington limit and are therefore not subject to the instability that characterizes LBVs. The cool or yellow hypergiants (YHGs) just below the HD limit [36, 38] are included as these might somehow represent the “missing” LBVs [37] – a possibility which will be discussed further in Sect. 3.
Membership Whether a particular blue hypergiant is a member of the select group of LBVs (see Table 1) is often a matter of debate (see [38, 7, 64]). In general, spectral resemblance to the P Cygni type spectrum of a known LBV is not a sufficient criteria for a star to be called an LBV. For this reason we include a group of LBV candidates (LBVc) listed in Table 2. To officially qualify as an LBV, an object should at least have shown the combination of spectral-type/photometric variations characteristic of S Dor-type variability due to changes in the star’s apparent temperature. Spectral variability, e.g. due to mass-loss changes, on its own is not a criterion, as almost all massive stars would qualify. Changes in photometric color could be the result of $T_{\text{eff}}$ changes, however obscuration by circumstellar dust may also give rise to color changes. Finally, the association of a supergiant with a circumstellar nebula is also not a criterion for an object to be added to the list of LBVs. The famous pistol star and LBV 1806−20 are thus strictly not LBVs. These objects remain candidates until they have shown the expected spectral-type variations.

Table 1 The confirmed LBVs.

| Galaxy: | η Car | AG Car | HR Car | P Cygni | HD 160529 |
|---------|-------|--------|--------|---------|-----------|
|         | HD 168607 | FMM 362 | AFGi 2298 | G24.73+0.69 | W243 |
| LMC: GCIRS 34W | R71 | R 110 | R 116 | R127 |
| S Dor | HD 269582 | HD 269929 | |
| R 143 | |
| SMC: R40 | HD 5980 | |
| M31: AE And | AF And | Var A-1 | Var 15 |
| M33: Var B | Var C | Var 2 | Var 83 | GR 290 |
| I 1 | I 2 | I 3 |
| M101: V 1 | V 2 | V 10 |
| NGC 2403: V 12 | V 22 | V 35 | V 37 | V38 |

When LBVs are discussed in an evolutionary context, we should be aware that the LBV phenomenon is likely to be intermittent and that part of the population might be dormant. Disregarding this could lead to incorrect interpretations with respect to their relative numbers and their evolutionary state. When we discuss the LBV phenomenon, however, we should only include the confirmed LBVs.

Abundances As massive stars evolve on the main sequence their atmospheric abundances are expected to undergo a transition in chemical abundances from solar
Table 2 The LBV candidates.

| Galaxy | Star | HD 168625 | HD 326823 | HD 316285 |
|--------|------|-----------|-----------|-----------|
| Cyg OB2#12 | Pistol star | | | |
| He3-519 | HD 80077 | | | |
| AS 314 | G25.5+0.2 | G79.29+0.46 | G26.47+0.02 | Wra 17-96 |
| Wra 751 | WR102ka | LBV1806−20 | Sher 25 | W51 LS1 |
| GCIRS 16NE | GCIRS 16C | GCIRS 16SW | GCIRS 16NW | GCIRS 33SE |
| LMC: | | | | |
| R 4 | R 66 | R 74 | R 78 | R 81 |
| R 84 | R 85 | R 99 | R 123 | R 128 |
| R 149 | S 18 | S 22 | S 61 | S 119 |
| S 134 | | | | |

He and CNO abundances to He-enriched and nuclear-equilibrium CNO abundances (with N enhanced, C/O depleted) \[60\]. For massive stars with \(\sim 60 M_\odot\), this transition occurs rather rapidly after about 2 Myr of evolution \[113\]. LBVs show a wide span of CNO ratios. Davidson et al. \[13\] showed that the ejecta around \(\eta\) Car are enhanced in both nitrogen and helium, and Pasquali et al. \[73\] found that the shell ejected by the LBVc HD 168625 is also N-enriched compared to the interstellar medium by a factor of several. Smith et al. \[83\] studied a sample of LBV nebulae and found the ejecta to be generally N-enhanced, although most nebulae have not reached abundances characteristic of CNO equilibrium.

The origin of the circumstellar nebulae associated with some LBVs however is uncertain. Photospheric abundance measurements might therefore provide a more direct means to constrain the LBV evolutionary state. These abundances however depend not only on the details of the atomic physics but also on the complexities of non-LTE spectral analyses. For example, Hillier et al. \[33\] showed that the H/He ratio in the wind of \(\eta\) Car is ambiguous due to a strong coupling with the mass-loss rate. Eta Car however, could be an exception with its huge luminosity and high mass-loss rate. Najarro et al. \[66\] studied the atmospheric He abundance of P Cygni and quoted a best value of \(n(\text{He})/n(H)\) of 0.3, corresponding to a mass fraction \(Y = 0.63\). However, they noted a huge uncertainty due to the trade-off in ionization and He abundance and provided a He abundance range of \(n(\text{He})/n(H) = 0.25-0.55\). Hillier et al. \[33\] also ruled out a solar He abundance for the extreme P Cygni star HD 361285, but admitted that the uncertainty in \(n(\text{He})/n(H)\) could be as large as a factor 20! Evidence for advanced CNO processing was found by Lennon et al. \[57\] for the LBV R71, but this is not a well-established result for LBVs in general. Although most LBVs have He and N enhanced atmospheres, it seems unlikely that all of them have reached equilibrium CNO values in their outer atmospheres.

**Stellar masses** Masses are most accurately determined using detached binary systems. However, almost all LBVs are single. Eta Car is the best-known exception to this rule, with its 5.5y periodicity \[110\] attributed to a companion. The current mass of \(\eta\) Car is thought to be at least 90 \(M_\odot\), to avoid violating the Eddington Limit at its high luminosity (see Davidson this volume, Owocki and Shaviv this volume).
LBVs with $\log (L/L_\odot) > 5.8$, are usually assumed to be evolved from the most massive stars with $M > 50M_\odot$ (e.g. [81]). Mass measurements for these high-luminosity objects are scarce and uncertain. Pauldrach & Puls [76] quote a mass of $23M_\odot$ for P Cyg. Vink & de Koter [104] estimated LBV masses from time-variable mass-loss rates and found a mass of $35M_\odot$ for AG Car. These results suggest that classical LBVs have already lost a significant fraction of their initial mass probably through the combined effects of line-driven mass loss during the OB and LBV phase, and/or through prior major eruptions. The quoted mass estimates are highly model dependent. For instance, wind clumping was not considered for the mass estimate of AG Car. However, if these objects have lost half their initial mass, their $L/M$ ratio is quite large, with $\Gamma_e \simeq 0.5$, and they are close to the Eddington Limit for their luminosities.

The initial masses of the less luminous LBVs, $\log (L/L_\odot) \simeq 5.4$, is of the order $M \sim 25M_\odot$; e.g. [81]). Comparing this mass with current-day mass estimates of $M \sim 12M_\odot$ for R71 [56], $M \sim 10M_\odot$ for R110 [94], and $M \sim 13M_\odot$ for HD 160529 [97], suggests that these low-luminosity LBVs may already have lost more that half of their initial mass (e.g. during a prior RSG phase). The low-luminosity LBVs are equally close to their Eddington limit with $\Gamma_e \simeq 0.6$. All of these empirical mass estimates are uncertain by at least a factor two.

Interestingly, Martins et al. [63] recently reported that the LBVc GCIRS 16SW may be an eclipsing binary, with both components weighing $\sim 50M_\odot$. If it is a genuine LBV, it may be a key object for constraining massive star evolution models, because current models with rotation [65] suggest such massive objects will not pass through the LBV phase at all during their evolution.

3 Mass-loss properties – do LBVs form pseudo-photospheres?

With its current mass-loss rate of order $10^{-3} M_\odot \text{yr}^{-1}$ it is clear that $\eta$ Car has formed an optically-thick wind and a pseudo-photosphere, but whether the S Dor-type variables have optically thick winds is less well established. It has been suggested that the temperature changes during S Dor cycles do not represent true stellar temperature changes, but are due to the formation of the dense, optically-thick wind. As the mass-loss rate increases, the effective photosphere of the moves out into the wind, and the apparent effective temperature of the star drops, whilst the apparent stellar radius increases – without an actual expansion of the star [3, 45, 12]. Davidson [12] also showed that the minimum temperature the wind can achieve as the mass loss increases is $\sim 7000K$, in rough agreement with the apparent temperatures of the LBVs at visual maximum.

Normal OB stars have winds that are optically thin in the continuum and we see through the entire wind – down to the photosphere. In other words, the wind is formed outside the photosphere. However, when the mass-loss rates increases, the wind becomes less transparent, and the photosphere from which the optical light originates is now at larger radii. When the wind has become optically thick, the pho-
tosphere is formed above the sonic velocity. In other words, the wind is accelerated “inside” the photosphere – forming an opaque wind with $R_{\text{ph}} > R_{\text{sonic}}$.

Leitherer et al. [56] and de Koter et al. [21] performed detailed NLTE modelling of this process, showing that the extent of a pseudo-photosphere that results from increased mass loss is relatively modest in comparison to that of a WR star. The conclusion was that the underlying LBV radius itself must become larger due to an as yet unidentified sub-photospheric mechanism. Furthermore, it became clear that empirical mass-loss rate during S Dor redward excursion do not always increase during outburst [55, 104]. More recently, Smith et al. [87] showed that pseudo-photospheres might be feasible under certain special circumstances discussed later in Sect. 3.3. Before we provide a more detailed account of the possibility of pseudo-photosphere formation, we give an overview of our current knowledge of stationary LBV mass loss. The radiative forces that may be responsible for giant eruptions are discussed elsewhere (Owocki and Shaviv, this volume).

### 3.1 Observed mass-loss rates

A commonly used method to determine mass-loss rates from massive stars is through the analysis of the H$\alpha$ emission line. In P Cygni, many of the optical emission lines, including H$\alpha$, show an additional blue-shifted absorption component, i.e. a P Cygni profile.

![AG Car spectrum](image.png)

**Fig. 2** The appearance of double-split absorption components in H$\alpha$ in the spectrum of AG Car during the years 1996 to 1999. The spectra are marked in Julian days. The figure has been taken from Stahl et al. [95].
**Terminal velocities**  The terminal velocities of LBV winds measured from the blue edge of the P Cygni absorption component are in the range 100-250 km s\(^{-1}\), with \(\eta\) Car having a \(v_\infty\) of \(\sim 500\) km s\(^{-1}\) (cf. [55]). These wind velocities are significantly lower than those of normal OB supergiants, which have \(v_\infty\) \(\sim 1000-3000\) km s\(^{-1}\). The mass-loss rates of LBVs are also a factor of 10-100 larger than those of normal supergiants, so their wind densities, \(\rho(r) = \dot{M}/4\pi r^2 v(r)\), are much higher, giving the line profiles their characteristic P Cygni shapes. As the LBV mass-loss rate is variable, some LBVs exhibit profile shape changes and variability in the absorption profile, such as the split blue-shifted absorption components seen in the H\(\alpha\) line of AG Car (see Fig. 2) and other LBVs such as R 127 [92], P Cyg, R 66, and HD 160529 also exhibit shell components in their Fe \(\text{II}\) lines (cf. [49] for P Cyg).

**Mass-loss rates**  Mass-loss rates of most LBVs have been determined using non-LTE models such as CMFGEN [32]. The very high mass-loss rate for \(\eta\) Car (\(3 \times 10^{-3}\) \(M_\odot\) yr\(^{-1}\)) has been determined by several methods using radio, mm-wavelength, and Hubble Space Telescope data [109, 8, 14], and the non-LTE model results for \(\eta\) Car [34] yield a similar answer. Sophisticated NLTE mass-loss determinations for other LBVs include a value of \(3 \times 10^{-5}\) \(M_\odot\) yr\(^{-1}\) for the extreme twin of P Cyg: HD 316285 [53], while Najarro et al. [66] derived \(3 \times 10^{-5}\) \(M_\odot\) yr\(^{-1}\) for P Cyg itself, using similar analysis tools. These results are all much higher than for normal OB supergiants of comparable temperatures.

![Fig. 3](image-url)  Time-variable empirical mass-loss rates for AG Car as a function of \(T_{\text{eff}}\), as analyzed by Stahl et al. [95]. Figure taken from Vink & de Koter [104].
The non-LTE model based mass-loss determinations however are based on assumed spherical winds, but the wind of η Car, is bipolar [86, 99]. Whether non-spherical winds have a large effect on the mass-loss determination, remains to be shown. A more serious assumption may be homogeneity. Davies et al. [15] performed a linear spectropolarimetry survey of Galactic and MC LBVs and found large line polarizations in over half of their survey targets. This is a higher incidence of polarization line effects than in O and WR stars where asphericities of resp. \( \sim 25\% \) [31] and \( \sim 15\% \) [30, 104] have been reported. Rather than attributing the polarization to large-scale axi-symmetry (e.g. [82]), Davies et al. [15] attribute the linear polarization of LBVs like AG Car to wind clumping, because the position angle in the polarization was shown to vary significantly, as was the case for P Cyg [67]. A similar conclusion regarding overall sphericity of LBV winds was drawn by Guo & Li [28] on the basis of modelling LBV continuum energy distributions.

The LBV polarization variability implies that the clumps must arise close to the photosphere, and many small clumps predominate over a few larger ones [16]. The quantitative implications of wind clumping for the absolute mass-loss rate of LBVs and in early-type stars, in general, have yet to be established [29]. Although most LBVs have been monitored photometrically, only a handful have been subject to quantitative spectroscopic analysis at various epochs, and mass-loss rates have rarely been reported for different S Dor phases. In this respect, AG Car is the best studied LBV. Stahl et al. [95] investigated AG Car’s mass-loss behavior over the period December 1990 – August 1999 and modelled the H\( \alpha \) profiles in detail. Their empirical mass-loss rates for the cycle from visual minimum to maximum – and back to minimum – are plotted against apparent temperature in Fig. 3. The mass-loss rate rises, drops, and rises again towards visual maximum (solid line) due to ionization changes of the Fe lines that drive the wind [104]. We note that there is a difference in mass-loss behavior from visual minimum to maximum and in the opposite direction (dotted line). We suspect that this is due to the breakdown of the assumption of stationarity from outburst to quiescence. Due to the larger radii, the dynamical flow times are much longer at maximum than they are at minimum light, which implies that material that was lost in this phase may still be near the photosphere, which may significantly affect the mass-loss determinations, resulting in erroneously large mass-loss rates for the route back to minimum. A second reason for the difference may be related to the release of gravitational energy when the star returns to quiescence. If this plays a role, the assumption of constant bolometric luminosity may no longer hold. Due to the above-mentioned complexities, we focus the comparison of mass-loss predictions to empirical mass-loss rates for the outburst phase (solid line) only.

3.2 Theoretical mass-loss rates

Mass loss from a star with a stationary stellar wind is assumed to be due to an outward acceleration larger than the inward directed gravitational acceleration. For
early-type stars, this acceleration has been identified with the radiation force, which depends on both the available photospheric flux and the cross section of the particles that can intercept this radiation.

In hot-star winds, nearly all H is ionized by the strong radiation field, which implies that there is an enormous number of free electrons present which are the main contributors to the continuum opacity. The radiative acceleration due to photon scattering off free electrons is subject to the same $1/r^2$ radius dependence as is the gravitational acceleration, and for this very reason cannot drive a stellar wind by itself. Lucy & Solomon [59] showed that a stationary wind would occur when scattering by optically thick spectral lines was included. The interested reader is referred to the introductory book on stellar winds by Lamers & Cassinelli [48] for an overview of the line acceleration of optically thin and thick lines.

The line acceleration due to all spectral lines is often expressed in terms of the radiative acceleration due to electron scattering times a certain multiplication factor: the force multiplier $M(t)$. Using this method, one can parametrize the line force, and solve the equation of motion in a rather straightforward manner [6]. In this approach, the radiation is assumed to emerge directly from the star. The effects of diffuse radiation and multiple scatterings are not taken into account.

Abbott & Lucy [1] showed that calculated mass-loss rates can also be obtained using Monte Carlo simulations, counting the cumulative radiative accelerations due to photon interactions with gas particles of different chemical species (mostly Fe). However, the main challenge in radiation-driven wind dynamics is that the line acceleration $g_{\text{line}}$ depends on the velocity gradient $dV/dr$, but the velocity $V(r)$, hence $dV/dr$, in turn depends on $g_{\text{line}}$. Due to its non-linear character, the dynamics of line-driven winds is quite complex. Fortunately, observational analyses provide accurate information on wind velocities, which can be used to constrain the wind dynamics.

Vink & de Koter [104] adopted an empirical velocity stratification, $V(r)$, and predicted stationary mass-loss rates for LBVs as a function of $T_{\text{eff}}$ in a similar vein to their mass-loss prescriptions for OB supergiants [106]. They studied the effects of lower masses and modified He/H and CNO abundances in comparison to normal OB supergiants and found that the main difference in mass-loss rate is attributable to the lower masses of LBVs compared to OB supergiants, resulting in a larger Eddington parameter $\Gamma_e$. The increase in He abundance changed the mass-loss properties by only very small amounts (up to about 0.2 dex in log $\dot{M}$). CNO processing also had only a minor effect on the mass-loss rate, because Fe was found to be the dominant contributor to the line force in the inner wind. CNO lines contribute mostly to the line force in the outer wind where the terminal velocity is set [105, 79].

They [104] also compared their LBV mass-loss predictions with observational analyses and showed that the mass-loss variability during the S Dor cycles may arise from changes in the ionization balance of Fe: the bi-stability mechanism, first noticed in model calculations of the wind of P Cygni [76]. The wind either had a high $v_\infty$ and low $\dot{M}$, or visa versa. The location of the jump near spectral type B1 (21 000 K) was established by Lamers et al. [50] from a $v_\infty$ study of OB supergiants and improved by Crowther et al. [9]. The nature of the jump was originally attributed
Fig. 4 Predicted (dotted line) and empirical (dashed line) mass-loss rates versus $T_{\text{eff}}$ for the LBV AG Car. Note that both the qualitative behaviour and the amplitude of the mass-loss variations are well reproduced, provided the predictions are shifted by $\Delta T_{\text{eff}} = -6000$ K. See [104] for details.

to the optical thickness of the Lyman continuum [47], but Vink et al. [105] showed that most of the line driving for both the hot and cool side of the jump was due to Fe in the Balmer continuum, with the jump in mass loss being the result of the recombination of Fe IV, as Fe III has more lines available to drive the wind. The first empirical evidence for a jump in $\dot{M}$ may have been found by Benaglia et al. [5], even though the rates at later spectral types appear to drop below those predicted [106, 92, 61].

The intriguing case of AG Car is depicted in Fig. 4 where we compare the predictions with the Stahl et al. [95] rates when the apparent temperature decreased from 24 000 to 9 000 K. In these computations, it was assumed that $\log (L/L_\odot) = 6.0$; $M = 35 M_\odot$; the He mass fraction $Y = 0.60$, and the ratio of the terminal over escape velocity was 1.3. The luminosity and He abundance are similar to those assumed by Stahl et al. We used the mass-loss behavior to constrain the stellar mass of the LBV. Unfortunately, the terminal velocity is poorly constrained by observations, as the $v_\infty$ determination from H$\alpha$ only allowed for a lower limit [95]. We note that the adopted ratio of the terminal over the effective escape velocity may impact the mass determination. Furthermore, the Fe recombination temperatures show an offset compared to empirical constraints from the drop in terminal velocities at spectral type B1 in OB supergiants.
Figure 4 shows that after accounting for a corrective shift $\Delta T_{\text{eff}}$, the observed and predicted mass loss agree within $\approx 0.1$ dex. As $\dot{M}(T_{\text{eff}})$ shows a complex behavior, with fluctuations of over 0.5 dex, this is a satisfactory result, confirming that AG Car’s mass-loss variability is the result of changes in the ionization of the dominant line-driving element Fe.

### 3.3 Do S Dor variables form pseudo-photospheres?

Now that we have gathered information on the empirical and theoretical mass-loss rates of LBVs, we can start addressing the question of whether these rates are large enough to be capable of forming a pseudo-photosphere. In most modern non-LTE atmosphere codes, the core radius follows from the relation $L = 4\pi R^2 \sigma T_{\text{in}}^{-4}$. As the inner boundary is chosen to be deep in the stellar photosphere the input temperature does not necessarily equal the output effective temperature. The effective temperature $T_{\text{eff}}$ is defined at the position where the thermalization optical depth at 5555 Å equals $1/\sqrt{3}$. We intentionally choose the thermalization optical depth over purely thermal optical depth, as we wish to include the effects of dilution by scattering (see [21] and references therein for more extensive discussions). For stars with modest mass fluxes, such as normal O stars, the winds are optically thin and $T_{\text{eff}}$ is only slightly lower than $T_{\text{in}}$. For LBVs, with $M \sim 10^{-4} M_\odot \text{yr}^{-1}$, there may be a significant difference between these temperatures. If the wind is so strong that the optical light originates from the depth of rapid acceleration, the object is considered to be forming a pseudo-photosphere.

The formation of pseudo-photospheres in LBVs may be favored by their lower masses, providing an increased mass-loss rate and an increase of the photospheric scale-height. Leitherer et al. [56] and de Koter et al. [21] assessed whether variable wind properties might explain $\Delta V \approx 1$ to 2 mags during S Dor cycles, and concluded that pseudo-photospheres are unlikely to form in LBVs. However, they did not investigate the effect of an order of magnitude change in the wind density of a star that is close to the bi-stability and Eddington limit.

Smith et al. [87] investigated the thermalization optical depth in the inner wind and showed that models on the cool side of the bi-stability jump may start to form optically thick winds which could lead to the formation of a pseudo-photosphere — if the objects are close to the Eddington limit. Figure 5 shows that for stars with log $(L/L_\odot) = 5.6$-5.8, if the current mass is below $\sim 12 M_\odot$, corresponding to $\Gamma_e = 0.8$, the star would start to form an extended optically thick wind when it crosses the bi-stability jump, and for stars with masses below $10.5 M_\odot$ (at log $(L/L_\odot) = 5.7$) the pseudo-photosphere starts to form at $T_{\text{eff}}$ 13000K. Applying the $\Delta T_{\text{eff}}$ shift of -6000 K to match the empirical temperature of the bi-stability jump would bring the effective temperature on the cool side of the bi-stability jump down to $\sim 7000$ K, which agrees with the location of LBVs in eruption and the YHGs.

The scenario described above hinges critically on the large value of $\Gamma_e$ of $> 0.8$, but it remains to be seen if these high $\Gamma_e$ values are realistic for LBVs. We quoted...
Fig. 5 The possible formation of a pseudo-photosphere. The figure shows the drop in apparent temperature that results from crossing the bi-stability jump which causes an order of magnitude increase in wind density. The apparent temperature drop from $T_m = 25000$ K is shown as a function of the stellar mass – for objects with $\log (L/L_\odot) = 5.7$. The computed effective output temperatures are denoted with ◆. When the stellar mass drops below $M \sim 10.5 M_\odot$, the objects starts to form an extended pseudo-photosphere, which results in an effective temperature of $\sim 13000$ K. Applying a corrective shift of 6000 K [104] this comes down to $T_{\text{eff}} \sim 7000$ K – corresponding to the location of the YHGs. The figure indicates that supergiants that have lost significant mass during prior (e.g. RSG) phases may be susceptible to pseudo-photosphere formation. The figure has been adapted from [87].

earlier $\Gamma_e$ values in the range $\Gamma_e \simeq 0.5$ for classical, and $\Gamma_e \simeq 0.6$ for low-luminosity LBVs. It is indeed possible that the missing LBVs had larger $\Gamma_e$ values, but clearly, more work is needed to determine LBV masses and luminosities to reliably establish the proximity of LBVs to the Eddington limit.

4 Theoretical models for S Dor variability

In the previous section we addressed the issue of whether the S Dor variability is the result of a sub-photospheric effect that actually increases the radius resulting in a decrease in $T_{\text{eff}}$, or whether the apparent decrease in temperature is due to an increase in the mass-loss rate and the formation of an the optically thick wind. It appears that the jury is still out on this, and we should thus consider both atmospheric as well as sub-photospheric mechanisms (see also [38]).
In those cases where a pseudo-photosphere would form as a result of increased mass loss, the root cause of such a sudden $M$ increase still needs to be established. The bi-stability mechanism is a good candidate because it can account for observed LBV mass-loss behavior. In the following discussion we include bi-stability under the more general topic of “radiation pressure instabilities”.

To investigate which atmospheric mechanism might be responsible for the large visual brightness and spectroscopic variations in S Dor variables it is useful to consider the momentum balance:

$$\frac{dv}{dr} + \frac{1}{\rho} \frac{dP}{dr} = -g_{\text{eff}}$$

where the quantities have their usual meanings and $g_{\text{eff}}$ is a combination of the Newtonian, $g_N$, minus the outward directed radiative, $g_{\text{rad}}$, and turbulent, $g_{\text{turb}}$, accelerations.

**Radiation pressure instability** Luminous evolved stars have reduced stability with respect to radiation pressure due to their reduced mass for their luminosity and are thus close to the Eddington limit. However massive stars are also rotating. The critical velocity is defined as $v_{\text{crit}}^2 = GM(1 - \Gamma)/R$. When rotation is included via the $v_{\text{rot}}$ term in the equation of motion, objects may become unstable when $\Omega = v_{\text{rot}}/v_{\text{crit}} > 1$, before arriving at the classical or opacity-modified Eddington limit \[52\]. For example, the projected rotational velocity for AG Car in the hot phase, of $190 \pm 30$ km s$^{-1}$ \[27\] is close to its critical velocity. Thus LBVs are considered to be in close proximity to both the Eddington and the Omega limits. The $\Omega$-limit is really the Eddington limit plus rotation. In the following we include the Omega ($\Omega$), Eddington ($\Gamma$), and Eddington-Omega ($\Gamma \Omega$) limits all under the general topic of the “Eddington limit”.

Radiation-pressure driven instabilities occur because as the temperature drops, the opacity rises (e.g. due to bi-stability), and the radiative acceleration $g_{\text{rad}}$ increases. The opacity–modified Eddington limit was initially introduced to explain the great eruption of $\eta$ Car \[11\], and subsequently for the temperature dependence of the HD limit \[37, 45\], and the instability of LBVs \[3, 4\]. Lamers & Fitzpatrick \[46\] computed the location of the opacity-modified Eddington limit, including metal-line opacities from model atmospheres in addition to electron scattering. They suggested that S Dor variations could result from a conflict between a star’s tendency to expand (following core H-burning) and strong mass loss close to the Eddington limit, requiring the star to shrink as the mass decreases. However there are issues with this simplified approach. When the ratio of radiative to gravitational force approaches 1, an instability could be expected, but as the atmosphere expands and density decreases, the ionization increases thereby reducing the absorptive opacity, and instead it approaches the classical Eddington limit due to electron scattering (which is not temperature dependent). However, if the instability would occur at $\Gamma$ somewhat less than 1, the density decrease would not eliminate absorption, and the concept of the modified Eddington limit might nonetheless work.
The attraction of scenarios based on the Eddington limit are clear; they naturally explain the temperature dependent luminosity limit in the HRD, the S Dor variability, and the two states of LBVs, their high $T_{\text{eff}}$ (just on the hot side of the bi-stability jump), and their low $T_{\text{eff}}$ limits. They could also lead to enhanced mass loss, increased density in the winds and the formation of a pseudo-photosphere. However, there are no self-consistent models that provide a sound theoretical basis for for scenarios involving pseudo-photospheres [21].

**Turbulent pressure instability**  As a star approaches the Eddington limit, the outermost layers of the envelope become convective (e.g. Cantiello, in prep.) and turbulent pressure gradients may provide an additional acceleration, $g_{\text{turb}}$ to the momentum equation. De Jager [19] showed how supersonic turbulence may destabilize the atmosphere, and as the mechanism becomes more efficient at higher luminosity, the mass-loss rate increases. This is also true for radiation pressure forces and it may be difficult to distinguish between these two atmospheric instabilities.

**Vibrations and dynamical instability**
Together with the radiation pressure-based instabilities, sub-photospheric dynamical mechanisms are the most promising explanation for the LBV/S Dor variability. In these models, “strange modes” and dynamical instabilities are caused by the bump or increase in the opacity due to iron at the base of the photosphere leading to a strong ionization-induced instability in the outer envelope as stars transit the HRD after the end of core H-burning. In the models of Stothers & Chin [98] the star keeps re-adjusting itself on thermal timescales after periods of strong mass loss, whilst shrinking in radius. These models provide the correct S Dor timescales and also appear to “behave” properly at constant bolometric luminosity. The strange mode calculations by Glatzel and Kiriakidis [26] reproduce the the S Dor instability strip and the upper luminosity boundary in the HRD quite well. Dynamical instability thus remains one of the more promising candidates to explain LBV variability.

Vibrational or pulsational instability was once thought to be one of the main contenders for instability and mass loss in the most massive stars (e.g. [2]), but the $\varepsilon$-mechanism is energized in the core, appears to grow too slowly (e.g. [71]) and is therefore no longer considered valid for LBVs. Another sub-photospheric instability, the $\kappa$ mechanism responsible for pulsation in massive stars such as the $\beta$ Cephei pulsators may cause pulsations in the outer envelope. It may be responsible for some of the micro-variability seen in LBVs and other supergiants (54 and references therein) which occur on timescales of weeks to months. The timescale of the S Dor variations however is much longer and therefore unlikely to be due to pulsations.

**Binarity**  Most LBVs are apparently single, and although, $\eta$ Car may have a companion, it seems clear that binarity can neither be the root cause of the S Dor variations, or for the giant eruptions, as the only other local example, P Cyg, is single (unless it formed through merging, cf. [78]).
5 Evolutionary State

There is no doubt that LBVs are evolved, unstable massive hot stars. The more massive classical LBVs have apparently evolved off the main sequence, while the less luminous LBVs may be post-red supergiants. In the generally accepted view of massive star evolution, the classical LBVs are considered “transitional” objects in a phase before entering the He-burning WR stage [53], by the end of which the star is anticipated to explode as a type Ib/c supernova. Many LBVs are known to be N and He rich compared to O stars, but H rich compared to the more evolved WR stars. This situation is somewhat more complex as there is also a group of high-luminosity late-type H-rich WR stars, which appear closely related to many classical LBVs in quiescence the Ofpe/WN stars [107]. These and other luminous stars, the B[e] supergiants [51], and and the cool or yellow Hypergiants (YHGs) [20], that show evidence for high mass loss and instabilities which may be related to the LBV state.

5.1 The evolutionary neighbours

Ofpe/late-WN stars  The so-called “slash” stars are a group of luminous hot stars with very strong emission lines due to their strong mass loss. They have He and N enhanced atmospheres indicative of an evolved state [72], but are generally not believed to be highly variable. These stars however may be closely related to the LBVs in quiescence. The S Dor-type variable, R127, was a late-WN star prior to its long-term outburst beginning in the early 1980s [93]. Either the late-WN stars evolve into LBVs, or they may represent a dormant phase of LBV evolution. Either way, Ofpe/late-WN stars are thought to be evolved massive stars in a transitional stage for objects with initial masses \( M > 50-60 \, M_\odot \). Since no evolved stars are observed redwards of the Humphreys-Davidson (HD) limit at these high luminosities and masses, high mass loss during the Ofpe/late-WN and LBV phases may reverse the evolutionary track back to the hotter part of the HRD, where they should appear as He-burning WR stars.

B[e] supergiants  The spectra of the B[e] stars [51] show an abundance of high-excitation permitted and forbidden emission lines that are thought to arise from an equatorially enhanced outflowing disk. Zickgraf et al. [114] proposed a 2-component wind with a normal fast polar wind and a dense slow outflowing equatorial “disk”. A popular mechanism to explain this 2-component wind is the rotationally induced bi-stability mechanism [47, 77]. The pole is hotter than the equator, due to the Von Zeipel gravity darkening effect which could lead to a fast, low \( \dot{M} \), polar wind driven by Fe IV lines, and a slow, high \( \dot{M} \), equatorial wind driven by the more effective Fe III lines [105]. This mechanism is expected to occur predominantly at spectral type B. However the star is expected to rotate rapidly but \( v_{\text{rot}} \) measurements are difficult for B[e] stars, with most of the lines in emission.
The B[e] supergiants may represent a subset of massive stars with high rotational velocities. The B[e] supergiants were originally not thought to be variable, but there is now evidence for large amplitude variability for some B[e] supergiants \[101\], suggesting a closer evolutionary link between LBVs and B[e] supergiants than previously acknowledged.

**Yellow or cool hypergiants** YHGs are found just below the HD-limit \[36, 38\] at intermediate temperatures with A to G spectral types. Many of these stars show spectroscopic and photometric variability, high mass-loss rates, large infrared excesses and visible circumstellar ejecta, all evidence for instability. The YHGs are often assumed to be post-RSGs \[23, 70\], although the evolutionary state is not established for all of them. The intriguing object IRC +10420 has been shown to be a post-RSG \[43, 69\] and numerous studies have revealed its complex ejecta \[39, 41\] and large-scale asymmetry \[75, 22, 17\]. Given their variability and high mass loss, the YHGs are likely close to their Eddington limit, with a large \(\Gamma_e\), and it is thus probable that many of them are post-RSGs. Nevertheless, it is not clear whether objects like IRC +10420 are on an evolutionary blueward journey towards the WR phase \[69, 41\], or bouncing against the yellow void \[20\] or the blue side of the bi-stability jump \[87\]. Smith et al. \[87\] suggested that some of the YHGs might be LBVs on the cool side of the bi-stability jump.

### 5.2 Do LBVs explode?

The picture of the LBVs as a high mass loss, relatively short-lived (some \(10^4\) yrs) and presumably core H-burning phase prior to a much longer (a few times \(10^5\) yrs) core He-burning WR phase seemed well established – until recently.

There is increasing observational evidence that LBVs could be direct progenitors of some SNe. Kotak & Vink \[44\] proposed that the quasi-periodic modulations seen in the radio light curves of transitional SNe such as SN 2001ig and SN 2003bg are the manifestation of variable mass loss during S Dor excursions. Although several other possibilities have been put forward to explain these modulations \[80, 89\], none has been entirely satisfactory. The recurrence timescale of the variability, as well as the amplitude of the radio modulations are consistent with those of S Dor variables and their scenario \[44\] provides a rather natural explanation for a behaviour that is expected on theoretical grounds \[104\].

The same wind bi-stability mechanism may be able to account for wind-velocity variations seen spectroscopically in SN 2005gj \[91\] in which the variable winds are inferred from double P Cygni components (see Fig. 6) which appear almost identical to those seen in the Hα profiles of S Dor variables like AG Car and HD 160529. Both the timescales and the spectroscopically measured wind velocities of SN 2005gj, with \(v_{\infty} \approx 100-200\) km s\(^{-1}\), are consistent with those of LBVs, but not with those of the much slower RSG winds (\(~10\) km s\(^{-1}\)), or the much faster WR winds (\(\approx 1000-5000\) km s\(^{-1}\)). See Van Marle et al. \[102\] and \[91\] for more information.
The progenitor star of the recent supernova SN 2006jc had a giant eruption just two years before its terminal explosion. Foley et al. [23] and Pastorello et al. [74] suggested that the progenitor star was either a WR star that exhibited an “LBV or η Car-like” eruption, or that the progenitor was part of a binary system including both an LBV and a WR star, with the WR star exploding and the giant eruption attributable to the LBV, as WR stars have never been observed to have an η Car type eruptions. A more direct application of Occam’s razor would be to accept that the progenitor object exploded during or at the end of the LBV phase or an η Car-like giant eruption [44].

Gal-Yam et al. [24] discovered a luminous source (with $M_{bol} = -10.3$) in the pre-explosion image of SN 2005gl. Although, the properties of the progenitor are consistent with those of LBVs, they are equally consistent with a luminous blue supergiant that has not exhibited spectral type variations (see the membership discussion in Sect.2), and the progenitor of SN 2005gl may potentially be classified as an LBVc. The resulting SN explosion was of type IIIn, indicating the presence of a dense circumstellar medium, additional evidence for prior η Car-type eruptions.

Other hints that LBVs may explode come from similarities in the morphology of LBV nebula and the circumstellar medium of SN 1987A [84], while the very luminous SN 2006gy – hypothesized to be an exotic pair-instability SN – may also have undergone an η Car-type eruption before exploding [88]. An alternative scenario for
a giant $\eta$ Car-type outburst was suggested by Woosley et al. [112] who attributed the dense shells around this luminous SN to pulsational pair instability.

We emphasize that the evolutionary status of LBVs remains uncertain. Evolutionary models have been constructed to allow LBVs in a transitional phase between a core H-burning main sequence and a core He-burning WR phase. This model naturally accounts for the chemical abundances (He, N) of LBVs which are intermediate between those of O and WR stars. The concept of an LBV exploding is certainly at odds with current stellar evolution models and an exploding LBV scenario was until recently considered “wildly speculative” [85]. Nevertheless, the evolutionary models do not provide a straightforward explanation for the wide range of phenomena described above and a simple explanation for this could be that at least some massive stars in an LBV state could precede the terminal explosion. This would allow some massive stars to skip the WR phase – in contradiction to the basic framework of massive star evolution. This also suggests that LBVs are already in the core He-burning phase of evolution. Given the intriguing variations seen in radio lightcurves and especially the double absorptions seen spectroscopically in P Cygni line profiles, I suggest that the changing winds of LBVs may help addressing the issue of whether the LBV phase may indeed represent the evolutionary endpoint for some of the most massive stars.

6 Outlook

We have examined observational, atmospheric modelling, and theoretical aspects of the current status of our knowledge of the LBV instability and their role in massive star evolution. Although radiation pressure as well as a dynamical instability are strong candidates for explaining S Dor variability, we conclude that the mechanism at the origin of the LBV phenomenon remains elusive. One of the most relevant issues to be addressed relates to the nature of the S Dor variability itself. With respect to massive star evolution, and in particular whether LBVs are in a transitional or final phase of evolution, the last few years have seen a flurry of activity, but we should not yet draw any definitive conclusions regarding their evolutionary state.

Progress is expected to be made on a number of fronts. First of all, the number of known LBVs is small and for a proper understanding of any individual member, photometric, polarimetric, and spectroscopic monitoring on the timescale of the S Dor variations is required. Atmospheric modelling is necessary to determine the stellar parameters and place the LBVs properly onto the HRD. There are still enormous uncertainties in the values shown in Fig. 1. Furthermore, LBV masses, nor their proximity to the Eddington limit, are known with any level of certainty, with profound consequences for theoretical interpretation. Therefore, binary searches, orbit determinations, and spectroscopic modelling are strongly encouraged to determine this most basic parameter.

As is the case for the normal OB supergiants, the LBV mass-loss rates are uncertain due to wind clumping. Progress will undoubtedly be made regarding the role of
of wind clumping and its impact on mass-loss rates in OB stars and LBVs. However, the LBVs themselves provide an ideal laboratory for studies of wind clumping, because the polarization variability is most extreme, due to the combined effect of low outflow velocities and high mass-loss rates \cite{15}. Mass-loss variability – in conjunction with $T_{\text{eff}}$ determinations – could also be utilized to constrain the stellar masses, as was exemplified for the object AG Car \cite{104}.

Further theoretical work on the formation of pseudo-photospheres and the more general question regarding the origin of the LBV variations are badly needed. Such studies may result in a better understanding of the origin of the variability which is necessary to place the LBV phase correctly in the evolution of massive stars.

The final message to emerge from this chapter is that $\eta$ Car may be one of the most extreme LBVs but it is not unique among the LBVs. Intriguing objects like P Cyg that have shown $\eta$ Car like eruptions in the past currently exhibit S Dor variations. The key to our understanding of $\eta$ Car’s great eruption may thus not exclusively lie in the study of $\eta$ Car itself, but pivotal clues will be obtained through better understanding of the more typical S Dor variations that define the LBVs as a class among the most massive stars.

The most outstanding question for all these stars, S Dor-type LBVs and the giant eruptions like $\eta$ Car, is still, what is the underlying origin of their instabilities?

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