Chapter VII: Unsteady mass loss

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Luminous blue variables and B[e] supergiants

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Abstract. Luminous blue variables (LBVs) and B[e] supergiants (B[e]SGs) are some of the most massive stars that display extreme and puzzling behavior. Their rarity indicates that they belong to short evolutionary phases or short-lived phenomena in the post-main sequence evolution of massive stars. However, their strong mass loss and episodic mass eruptions may be crucially impacting massive star evolution. LBVs are a group of evolved massive stars that exhibit irregular variability and eruptive mass loss. Various subtypes, including S Doradus variables, giant eruptions, and pre-supernova outbursts, exist. The physical cause of the LBV phenomenon remains heavily debated. B[e]SGs have strong forbidden line emission and infrared excess from dust that are thought to arise in a circumstellar disk or torus. The formation mechanism of their disk-like structures is yet to be settled. The evolutionary phases of LBVs and B[e]SGs and their connection to other evolved massive stars are important unanswered questions in massive star evolution.

Keywords. stars: emission-line, Be, stars: evolution, (stars:) circumstellar matter, stars: winds, outflows, stars: variables: other

1. Introduction

The upper Hertzsprung-Russell (HR) diagram is populated by evolved, luminous, and variable massive stars. Many of them show evidence for strong stellar winds and periods of enhanced or eruptive mass loss. Prominent stellar groups are the luminous blue variables (LBVs) and the B[e] supergiants (B[e]SGs). Extensive observing campaigns and theoretical studies have been conducted over the past decades to investigate these massive evolved stars. LBV studies centered on identifying the instability mechanism, potential triggers of the instability, and the mass-loss drivers of their enhanced mass-loss episodes. B[e]SG studies focused on understanding the formation mechanism of their dusty circumstellar environments. The low-number statistics and the complexity of the physics involved, such as the impact of initial mass, metallicity, mass-loss history, rotation, and binarity, are major challenges to the understanding of their place in massive star evolution and eventual fate.

The term LBV was introduced to describe the diverse group of unstable evolved luminous hot stars in the upper HR diagram (Conti 1984). Because of the observed diversity of the LBV phenomenon and lack of understanding of the underlying physics, we distinguish three LBV subtypes in this review; classical LBVs, giant eruption LBVs, and LBV-like pre-supernova eruptions. The B[e] phenomenon describes B-type stars with strong Balmer emission, low excitation permitted emission, forbidden emission, and a strong near- or mid-infrared excess due to hot circumstellar material (Kraus 2019). Stars of different mass and different evolutionary stages can exhibit the B[e] phenomenon (Lamers et al. 1998). We only discuss the B[e]SGs, because we restrict this review to evolved massive stars.

1.1. *Classical and giant eruption LBVs*

Classical LBVs, often called S Doradus variables, experience "outbursts" and episodes of enhanced mass loss on timescales of years to decades. During an outburst, they transit in the HR diagram from a hot quiescent state ($T_{\rm eff} \sim 12\,000 - 30\,000$ K) to lower temperatures ($T_{\rm eff} \sim 7\,000 - 8\,000$ K), i.e., their spectral appearance changes from a hot supergiant to a much cooler A or F-type supergiant. Their visual magnitudes change by $1 - 2$ mag at almost constant bolometric luminosity. Classical LBVs are very rare with only about $40 - 50$ known (e.g., HR Car, AG Car, RMC 71; Richardson & Mehner 2018). They are generally divided into high-luminous LBVs ($log\ L/L_\odot > 5.8$), which evolve from the most massive stars with $M > 50\ M_\odot$, and less-luminous LBVs, which have initial masses of the order $M \sim 25 - 40\ M_\odot$ and which have presumably lost more than half of their initial mass during a red supergiant (RSG) phase.

Giant eruption LBVs, represented by the famous Galactic stars η Car and P Cygni, exhibit eruptions with visual magnitude changes of $2 - 3$ mag or more, during which their bolometric luminosity increases. Supernova (SN) surveys are finding increasingly such transients in other galaxies, which are referred to as "SN imposters," as they mimic the appearance of SN IIn.

The terminal velocities of LBV winds are in the range of $100 - 250$ km s^{-1}, significantly lower than those of normal OB supergiants. LBV mass-loss rates are up to $10^{-5} - 10^{-4}\ M_\odot$ yr^{-1} a factor of $10 - 100$ larger than those of normal supergiants. During quiescent phases, LBVs lose mass most likely via ordinary line-driving and the bistability mechanism is a good candidate to account for their transitional mass-loss variations (Vink 2021). The large mass-loss rates and giant eruptions observed in some LBVs suggest that also continuum-driven winds and/or explosions could play a role (Shaviv 1998; 2001, Owocki et al. 2004, Smith & Owocki 2006, Rest et al. 2012, Davidson & Humphreys 2012, Owocki & Shaviv 2016, González et al. 2022). As the different mechanisms can produce the same observables, the question remains whether the LBV giant eruptions are better understood in terms of a continuum-driven wind, an explosive model, or a combination of both.

Classical and giant eruption LBVs show evidence for extensive circumstellar matter. The morphology, kinematics, and chemical composition of these nebulae trace the star's mass-loss history and evolution. Typically, LBV nebulae have sizes of $0.2 - 5$ pc, ionized masses of $1 - 4\ M_\odot$, and expansion velocities of several tenths to a few hundreds km s^{-1} (Weis 2003). Bordiu et al. (2021) found that molecular gas may account for $> 30\%$ of the total mass lost around LBVs. Most LBV nebulae exhibit axisymmetric morphologies. At least 50% of the LBV nebulae are bipolar and several nebulae show in addition equatorial ring-like structures. To explain the observed nebular morphologies, a range of models have been proposed (see, e.g., Nota et al. 1995, Frank 1999, Frank et al. 1998, Owocki & Gayley 1997, Dwarkadas & Owocki 2002, Maeder & Desjacques 2001, Soker 2004).

Chemical abundances are consistent with material processed in the CNO cycle, and were the first proof that LBVs are post-main-sequence objects. Several abundance studies have attempted to infer the evolutionary phase in which the material was ejected (Smith et al. 1997; 1998, Lamers et al. 2001), but results range from potential ejections during a previous RSG phase, a yellow supergiant (YSG) phase, or a blue supergiant (BSG) phase. The dust grains in LBV nebulae are unusually large and have an unusual composition compared to grains in the interstellar medium and the asymptotic giant branch stars. They may trace the cool outbursts or giant eruptions (Kochanek 2011) or they could have formed in a prior RSG phase (Waters et al. 1997). Agliozzo et al. (2021)

found that the dust mass of individual LBVs does not correlate with their stellar parameters, which suggests that the dust production mechanism is independent of the initial stellar mass or that the stars have different evolutionary paths and mass-loss histories.

1.2. *LBV-like pre-SN eruptions*

Several SNe have displayed precursor eruptive events (Smith 2017). The responsible mechanism could be the same as those of the classical or giant eruption LBVs or may be triggered by core instabilities in the very final burning stages of massive stars. The most dramatic and well-studied case so far has been SN 2009ip. Similar transients have been observed, which are characterized by a long-lasting phase of erratic variability that ends with two luminous outbursts a few weeks apart. SN 2009ip descended from a very luminous progenitor consistent with a $50-80\ M_{\odot}$ star (Smith et al. 2010, Foley et al. 2011). On the other hand, the progenitor of AT 2016jbu, which has been classified as a SN 2009ip-like transient, was identified as a YHG of only $\sim 20\ M_{\odot}$ (Brennan et al. 2022). There is much debate about the nature of these transients and their final state. If they are true SNe and not impostors (Smith et al. 2022), the progenitors could be LBVs or YHGs. To match the ejecta mass and energy would require giant LBV eruptions. However, such events are very infrequent and many LBVs and YHGs have massive shells that are thousands of years old. It seems thus more likely that the pre-SN eruptions are related to the imminent core collapse.

There is increasing observational and theoretical evidence that LBVs could be direct progenitors of some high-luminosity type IIb and IIn SNe as signatures in the SN spectra indicate dense circumstellar material, which requires eruptive pre-SN mass-loss (Groh et al. 2013, Justham et al. 2014, Smith 2014, Groh 2017, Ustamujic et al. 2021). This poses a serious challenge for the traditional single-star evolutionary picture of LBVs as the transitional phase leading to Wolf-Rayet (WR) stars.

1.3. *B[e] supergiants*

LBVs and B[e]SGs are spectroscopically similar, but can be distinguished based on spectral lines and spectral energy distribution (Humphreys et al. 2017b, Agliozzo et al. 2021). B[e]SGs appear to originate from a lower initial mass population with $M \sim 15-40\ M_{\odot}$, compared to LBVs. They show two components in their circumstellar environment with a hot, fast (~ 1000 km s^{-1}) line-driven polar wind and a cool, slow (~ 100 km s^{-1}), dense equatorial wind (Zickgraf et al. 1985). The fast wind in the polar region is similar to the winds of normal BSGs. Strong near- and mid-infrared excess emission is indicative of hot circumstellar dust.

Imaging and interferometry have spatially resolved the environment of the closest and brightest Galactic objects, providing precise measurements of the disk inclinations and disk sizes (e.g., Domiciano de Souza et al. 2007; 2008, Wheelwright et al. 2012). The kinematics of the equatorial gaseous material favor Keplerian rotation (Kraus et al. 2007; 2010, Millour et al. 2011, Wheelwright et al. 2012), likely accumulated in multiple, partial rings and possible spiral arm-like structures and not a smooth disk (Aret et al. 2012, Kraus et al. 2016, Maravelias et al. 2018). Several B[e]SGs have been discovered to be in short-period binary systems and the dynamical and spatial information indicates that the prevalent geometry is a circumbinary ring or disk (Kraus et al. 2013, Porter et al. 2022). Large dust shell structures and nebulae are detected around some objects, hinting at major mass-loss events (Liimets et al. 2022).

2. LBV instability mechanisms

It is yet unclear what causes the transitions of LBVs across the HR diagram, the giant LBV eruptions, and the LBV-like pre-SN eruptions. Arguments in favor of instabilities in the outer layers use the facts that (1) LBVs are close to the Eddington limit (Sanyal et al. 2015), (2) the distinction between less- and high-luminous LBVs with potentially different evolutionary phases, and (3) the timescales, mass, and energy of ejecta of classical LBV outbursts. Arguments in favor of core instabilities are (1) the total mass and energy of giant LBV eruptions and (2) the timescales of LBV-like pre-SN eruptions. A single mechanism may be operating over a wide range of energy and mass, different mechanisms may produce the same observables, or several mechanisms may cooperate. Apart from this, rotation, binary interaction, and stellar mergers may also play a crucial role in shaping the LBV phenomenon.

Radiation and turbulent pressure instabilities. One of the first suggestions to explain the LBV phenomenon was that stars become unstable near the Humphreys-Davidson limit due to radiation pressure (Humphreys & Davidson 1984, Lamers 1986). As massive stars ($M > 40\ M_{\odot}$) evolve, their photospheres become increasingly unstable against radiation pressure and eventually reach a critical point where the radiation pressure and gravity are balanced, leading to mass loss, which ends their redward evolution. Turbulent pressure may ease the requirement for radiative instability (Stothers 2003). These two mechanisms may be working together with the opacity-modified Eddington limit (Lamers & Fitzpatrick 1988, Ulmer & Fitzpatrick 1998).

Ionization-induced dynamical instabilities. There is a large family of proposed ionization-induced instabilities related to the iron, helium, and hydrogen opacity peaks at different temperatures in the stellar layers. However, several are unable to explain the LBV outbursts. A geyser-like model (Maeder 1992) is not applicable for the highest temperature LBVs. Dynamical instabilities (Stothers & Chin 1993; 1994; 1997) and strange modes (Glatzel & Kiriakidis 1993, Kiriakidis et al. 1993) can likely only account for some of the observed photometric microvariations (Glatzel & Kiriakidis 1998, Lovekin & Guzik 2014).

Jiang et al. (2018) found with physically realistic three-dimensional global radiation hydrodynamic simulations that the physical mechanism responsible for the LBV phenomenon may be the interaction of the large radiative flux with the opacity peaks in the optically thick envelope as these stars expand and cool. Grassitelli et al. (2021) found unstable configurations in time-dependent hydrodynamic stellar evolution models due to feedback between the wind mass loss and the stellar envelope structure, which reproduce the observed LBV variability. Inflated envelopes (Gräfener et al. 2012) and the bistability mechanism (Vink et al. 1999, Petrov et al. 2016) are key ingredients in their models (cf., Björklund et al. 2022).

Pulsational pair instability (PPI). Woosley et al. (2007) noted the potential of PPI in the stellar core for powering pre-SN and giant LBV eruptions. PPI appears only in the final years to decades before core collapse. However, the ages of LBV nebulae is $10^2 - 10^4$ yr, indicating that the stars survived longer than expected if PPI was at play. In addition, the PPI is predicted to occur only for extremely massive stars at low metallicity. Thus, PPI is not a viable explanation for LBV giant eruptions, but it could be an option for the pre-SN eruptions.

Deep rooted energy release or addition. A large amount of extra energy can be deposited deep in a massive star's envelope by a number of mechanisms, including unsteady burning (Smith & Arnett 2014), explosive shell burning instabilities (Dessart et al. 2010, Smith & Arnett 2014), wave-driven mass loss (Meakin & Arnett 2007, Quataert & Shiode 2012, Shiode & Quataert 2014), and stellar collisions or mergers

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in a binary system (Podsiadlowski et al. 2010, Smith & Arnett 2014). For energy releases or additions that are on the order of the envelope binding energy, partial envelope ejection can result, reminiscent of LBV giant eruptions (Dessart et al. 2010, Owocki et al. 2019). In case of the even more energetic pre-SN LBV-like eruptions, late nuclear burning instabilities may be applicable.

Stellar rotation. Rotation modifies drastically the evolution of stars and some LBVs exhibit very rapid rotation, near their break-up rates (Groh et al. 2006; 2009). LBV outbursts might be associated with luminous stars encountering the critical rotation limit (Langer 1998), but it is not clear how reaching this limit could induce a sudden mass loss eruption. Nevertheless, rotation may play a key role as an instability trigger and for the resulting asymmetric mass-loss geometry. Recent studies found rotationally driven instabilities that could potentially trigger LBV outbursts, such as centrifugal instabilities (Zhao & Fuller 2020) and viscous instabilities (Shi & Fuller 2022).

Binarity. Most massive stars reside in multiple systems and the processes of mass loss and mass transfer in binary systems impact the evolution and fate (De Marco & Izzard 2017, Sana et al. 2012, de Mink et al. 2014; 2013). LBVs were long considered as single stars, but this picture is subject to discussion. Eta Car and HR Car are confirmed binary systems (e.g., Corcoran et al. 1997, Boffin et al. 2016) and Mahy et al. (2022) found that the spectroscopic and interferometric binary fraction of Galactic LBVs is similar to other massive stars, albeit with wide orbits.

Interacting binaries and stellar mergers offer many free parameters to explain the diversity in LBV eruptions. Proposed binary scenarios include common envelope evolutionary phases (Kenyon & Gallagher 1985, Gallagher 1989), violent periastron non-merger collisions (Smith 2011, Owocki et al. 2019, Quataert et al. 2016), mass accretion by the secondary star (Soker 2001; 2004; 2007, Kashi & Soker 2009), and tidal influence of the companion star near periastron (Smith et al. 2003, Koenigsberger 2004). The scenario of a stellar merger in a triple system has gained attention to explain the giant LBV eruptions (Iben 1999, Portegies Zwart & van den Heuvel 2016, Hirai et al. 2021).

Binary evolution for LBVs? The topic of a single versus binary evolutionary path for LBVs has been developing into a lively scientific discussion in the past years. The crucial question is whether binary interactions are the key to the LBV phenomenon, or whether they are only modifying or triggering a single-star instability. Smith & Tombleson (2015), Smith (2016), Aghakhanloo et al. (2017), Smith (2019), Aghakhanloo et al. (2022) claimed that LBVs reside outside young massive clusters with early O-type stars and inferred that LBVs may thus be primarily the product of binary evolution. In this scenario, LBVs are rejuvenated mass gainers that get enriched, spun up, and sometimes kicked far from their birth sites by a SN of their companion. Humphreys et al. (2016), Davidson et al. (2016), Aadland et al. (2018), Mehner et al. (2021) claimed the contrary, that indeed LBVs are associated with luminous young stars and supergiants appropriate for their luminosities and position in the HR diagram.

3. B[e]SG disk formation

The origin of the B[e] phenomenon is still uncertain. Generally, dust formation in the winds of single hot stars is inhibited by the low particle densities and the harsh ultraviolet environment. Thus, the formation of dust and its continuous presence close to the hot B[e]SGs are intriguing.

The formation of a slowly expanding, rotating disk (or ring) has been linked to near-critical rotation combined with bistable radiation-driven winds (Zickgraf et al. 1986, Lamers & Pauldrach 1991, Oudmaijer et al. 1998, Pelupessy et al. 2000, Curé et al. 2005, Kraus 2006, Madura et al. 2007, Kraus et al. 2010). Optical and infrared spectroscopic observations showed that the circumstellar material of B[e]SGs is concentrated in multiple, clumpy rings on stable Keplerian orbits and pulsations might thus play a role (Kraus 2017). Evidence between the occurrence of the B[e] phenomenon and binarity in B-type supergiants is growing (Podsiadlowski et al. 2006, Wang et al. 2012, Maravelias et al. 2018, Miroshnichenko et al. 2020) and circumbinary Keplerian rings are the most probable geometry for the equatorial outflows. Merger products, maybe in triple systems, are good candidates for B[e]SGs (Podsiadlowski et al. 2006, Pasquali et al. 2000, Wu et al. 2020). Several different scenarios may lead to the B[e] phenomenon, with binarity and mergers appearing to be preferable for several objects.

4. The role of LBVs and B[e]SGs in massive star evolution

Initial mass, metallicity, mass-loss, rotation, and binarity may all crucially affect the outcome of massive star evolution. In particular, the effects of mass loss complicate the model predictions (Chiosi & Maeder 1986, Langer 2012). Observations and theory find that mass-loss is too weak to expel the hydrogen-envelopes to form WR stars. As a result, an important open question is whether massive star evolution is facilitated mainly by mass loss through stellar winds or whether episodic mass loss is required, e.g., during an eruptive LBV phase.

Stars of different masses and different evolutionary stages can exhibit the B[e] phenomenon. In the case that LBV outbursts depend also only on the physical conditions within their stellar envelopes, the LBV phenomenon could also appear in different evolutionary phases. Thus, for a discussion on the evolutionary stages and the relationships of LBVs and B[e]SGs to other massive stars, it is critical to note the possibility that they are spectroscopic and not evolutionary phases.

LBVs. LBVs are generally assumed to be post-main-sequence stars. Their hydrogen surface abundances and luminosities indicate properties between O-type and WN stars. The LBV phenomenon appears to be intermittent and part of the population might be dormant (e.g., the Ofpe/WN stars). In the traditional view, LBVs have been interpreted as a transitional phase of evolution when a massive star moves from core-hydrogen burning to core-helium burning (Conti 1978, Chiosi & Maeder 1986, Humphreys & Davidson 1994). The upper luminosity boundary to the HR diagram provides a valuable clue and constraint on the understanding of these stars.

Above an initial mass of $40 - 50\ M_{\odot}$, stars do not evolve across the HR diagram to become RSGs. Groh et al. (2014) found that LBVs arise naturally in their single-star evolution models at the end of the main sequence when the mass-loss rate increases as a consequence of crossing the bistability limit. Lower mass supergiants evolve across the HR diagram through BSG and YSG phases, before reaching the RSG phase. High mass loss during the RSG stage causes the star to evolve again bluewards, through a second YSG phase, and possibly becoming a post-RSG warm hypergiant, an LBV, or WR star (Maeder 1982, Lamers et al. 1983, Chiosi & Maeder 1986, Stothers & Chin 1996, Groh et al. 2013).

B[e]SGs. Most of the B[e]SGs lie below the LBV instability strip in the HR diagram, which suggests that the phenomena are not related in an evolutionary sense and that B[e]SGs may be more common at lower stellar masses. Several studies support a post-RSG state (Kastner et al. 2010, Aret et al. 2012, Humphreys et al. 2017a), while others concluded that the C12/C13 ratios support a post-main-sequence state in a likely pre-RSG stage (Oksala et al. 2013). This analysis depends strongly on stellar evolution models and on the rotational speed of the stars.

In summary, LBVs and B[e]SGs are likely post-main-sequence objects. There are sufficient differences in their spectra, their luminosities, spatial distribution, and the presence of circumstellar dust, to conclude that they are not related in an evolutionary sense. However, overlap between these two classifications may occur since the B[e]SGs are a spectroscopic phase (and the LBVs could be as well). The less-luminous LBVs are post-RSGs, maybe post-warm hypergiants. There may be more than one path to become a B[e]SG. Some B[e]SGs may be pre-RSGs and some may be post-RSGs. Hot supergiants, warm and cool hypergiants, B[e]SGs, and Of/late-WN stars may be evolutionary neighbors or even quiescent LBVs as they are neighboring in the HR diagram and show all evidence for high mass loss and instabilities.

5. Outlook

The diversity and rarity of massive stars and their descendants challenge our understanding of their evolution and fate. Despite considerable advances in the past decades, many questions remain. On a positive outlook, due to their brightness and extended nebulosities, massive stars are excellent targets for almost any observing technique and wavelength range, enabling a multi-wavelength approach that provides different diagnostics and consistency checks. Upcoming large survey missions (e.g., Euclid, Roman, Rubin) will provide an improved census of evolved massive stars, massive star transients, and SN precursors. High-multiplex spectroscopic surveys (e.g., MOONS and 4MOST at the VLT, WEAVE at the WHT) will allow classification and follow-up of the candidates identified in those surveys. Increasingly sophisticated computational methods and connecting observations to theory will be a major task, but with statistically meaningful observational samples it may be possible to unveil the nature and fate of these fascinating objects.

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