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Luminous Blue Variables: a step towards exploring a critical phase in massive star evolution

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Abstract

Luminous Blue Variables (LBVs) are a rare class of earlytype, bright variable stars of late O to A spectral types that represent one of the most enigmatic phases in the evolution of massive stars. Optical spectra of LBVs display prominent emission lines of HI, HeI, FeII, and [FeII], often showing P Cygni type profiles indicating mass loss. Traditionally, LBVs have been viewed as a transitional phase between massive O-type and Wolf-Rayet stars, marked by significant mass loss, 10 to 100 times compared to normal supergiant stars having similar luminosity, through episodes of eruptions and strong winds. However, these enigmatic objects still remain mysterious but important to better understand the life cycle of massive stars, motivating further investigations to unravel their true nature. In this article, we provide an introduction to the various observable properties of LBVs and explore both traditional and alternate models of their origin. The article is written to motivate both young readers and scholars of the astronomy community by highlighting the importance of exploring these rare but exotic stars, the LBVs.

Keywords: Luminous Blue Variables, , massive stars, stellar evolution

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1. Introduction

Stars in the universe exhibit a remarkable diversity in colours, temperatures, sizes and chemical compositions, making each one unique in some way. However, they are broadly classified into seven spectral types based on their general properties, particularly their effective temperatures. These spectral types are O, B, A, F, G, K and M, arranged in order from the most massive and hottest O-type to the least massive and coolest M-type stars (Banerjee 2021).

O-type stars are among the most massive and hottest stars, with surface temperatures ranging between 25,000 K and 50,000 K (Heap et al. 2006). Their spectra are distinguished by prominent lines of ionised helium. In contrast, M-type stars occupy the cooler end of the stellar spectrum, with temperatures dropping as low as 3,000 K. These cooler conditions allow for the formation of molecules, such as titanium oxide, in their atmospheres (Rajpurohit et al. 2019). While the evolutionary pathways of low-mass stars are relatively well established, the evolution of massive OB-type stars follow a different trajectory and remains less understood (see Suda & Fujimoto 2010; Martins & Palacios 2013). High-mass stars undergo several evolutionary phases, each with its own distinct timescale, beginning from the Zero-Age Main Sequence (ZAMS) line. The ZAMS is the stage when a star first begins hydrogen fusion in its core. At this point, the star reaches a balance between the inward pull of gravity and the outward pressure from fusion. ZAMS stars form a clear line that astronomers use to study how stars evolve over time. However, the overall lifespan and evolutionary path are determined by their initial mass. Stars with more than eight times the solar mass burn through their nuclear fuel in just a few million years (typically 3–10 million years) before concluding their lives in powerful supernova explosions (Woosley et al. 2002). These explosions leave behind either a neutron star or a black hole.

Massive stars are potent engines that significantly influence the evolution of star-forming galaxies over cosmic time (Bresolin et al. 2008). However, their evolution (Martins & Palacios 2013) and their impact on the surrounding stellar environment (Freyer & Hensler 2001) are still not fully understood and remain active areas of research. These stars are characterised by their high intrinsic luminosity, large masses, and intense winds, which set them apart from intermediate- and low-mass stars. Among these massive stars, Luminous Blue Variables (LBVs hereafter) represent a critical, yet short-lived, transitional phase characterized by various forms of variability that distinguish them from other massive stars. Studying LBVs is crucial for understanding the late evolutionary stages of massive stars and their role as potential progenitors of certain types of core-collapse supernovae. A core-collapse supernova is a powerful and luminous explosion that occurs at the end of a star's life cycle. It marks the violent death of a massive star. During a supernova, the star releases an immense amount of energy, often outshining its entire host galaxy for a short time. These explosions play a crucial role in enriching the interstellar medium with heavy elements and can trigger the formation of new stars (Scannapieco et al. 2006).

1.1 Luminous Blue Variables: an overview

LBVS are a rare class of early-type, bright variable stars of late O to A spectral types that have an absolute bolometric magnitude brighter than -9. Having high intrinsic luminosity ($10^6 L_\odot$) and characterised by significant spectroscopic and photometric variability, i.e. variations happening in luminosity and time scales (Humphreys & Davidson 1994), these stars occupy the upper-most region in the Hertzsprung Russell diagram (HR diagram or HRD). Figure 1 depicts a HR diagram showing the evolutionary tracks of stars with varying initial masses. Developed independently by Ejnar Hertzsprung in 1911 and Henry Norris Russell in 1913, this diagram was a groundbreaking advancement in our understanding of stellar evolution. The HR diagram is a fundamental tool in stellar astrophysics that plots stars according to their absolute magnitude (or luminosity) and spectral type (or surface temperature). It reveals distinct stellar groupings such as the main sequence, giants, supergiants, and white dwarfs, illustrating various stages of stellar evolution.

Such variations are attributed to their apparent photospheric temperature, which can range between 12,000 (during visual minimum i.e. 'quiescent state' when these stars are hotter) and 8000 K (during visual maximum i.e. 'eruptive state' when they are cooler) as calculated by Leitherer et al. (1989). LBVs also exhibit prominent emission lines of HI, HeI, FeII and [FeII], often showing P Cygni type profiles. The P Cygni (originating from the spectral line profiles observed in the famous LBV star P Cygni) profiles seen in emission lines infer large mass-loss rates in the case of LBVs. During active phases, their massloss rates are within a range of $10^{-4} M_\odot$ to $10^{-6} M_\odot$ yr^{-1} (Lamers 1989). These are 10 to 100 times compared to normal supergiant stars having similar luminosity. Examples of some famous LBV stars in our Milky Way Galaxy are eta Car, P Cygni and AG Car. Another notable LBV in our neighbouring galaxy, namely the Large Magellanic cloud (LMC) is S Dor.

The LBV phase is a short-lived stage in massive stars, lasting for around 25,000 years (Humphreys 1991). Traditionally, LBVs were viewed

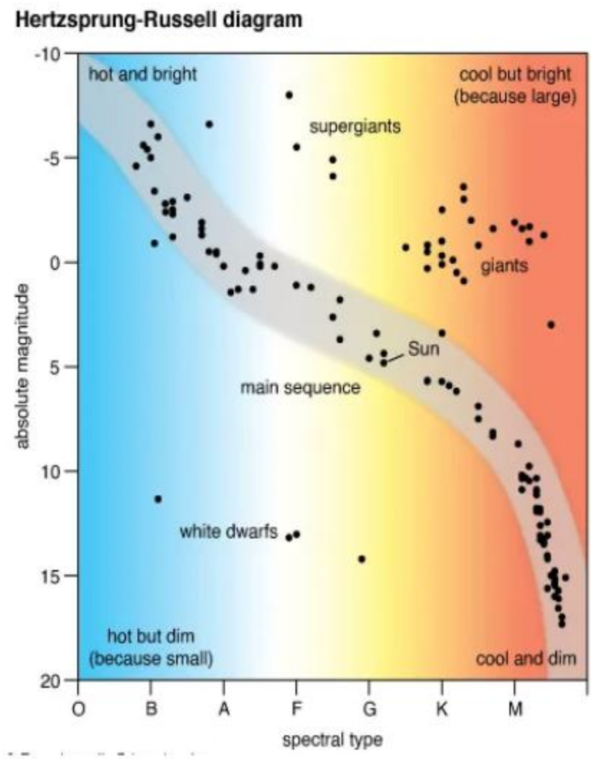

Figure 1. The HR diagram, which plots absolute magnitude against spectral type for stars with known surface temperatures. Based on these attributes, it is observed that in an HR diagram, most of the stars in the universe fall into some key evolutionary groups, including the main sequence, giants, supergiants, and white dwarfs. The colour gradient reflects stellar temperature, with hot, blue stars on the left and cool, red stars on the right. The Sun is located roughly in the middle of the main sequence. Figure has been adapted from https://kids.britannica.com/students/assembly/view/149080

as transitional phases in single-star evolution, from core hydrogen-burning to the helium-burning phase. However, recent studies suggest that LBVs may also result from binary evolution, potentially 'kicked' out of their binary system due to the supernova of their companion star. In this context, LBVs might be considered massive evolved blue stragglers formed through binary interactions rather than single-star evolution.

1.2 Nomenclature for Luminous Blue Variables

Historically, LBVs were not initially recognised as a subclass. Stars like eta Car, P Cygni and S Dor were studied individually until Hubble & Sandage

(1953) conducted a study in 1953, analysing five irregular blue variable stars in the neighbouring galaxies M31 and M33.

These variables are now called Hubble-Sandage variables. These stars showed irregular light curves with 2–3 magnitude variability over decades and F-type spectra with strong Balmer emission lines. These properties resemble LBV-like behaviour and mark an early step in grouping them as a subclass. However, by the 1970s, similarities among Hubble-Sandage variables, S Dor variables, and Eta Carinae type stars became evident through different spectroscopic and photometric studies, (Humphreys & Davidson 1994). Then in 1984, Peter Conti formally coined the term 'Luminous Blue Variable' (Conti 1984). Peter Conti wrote in the paper 'These objects—despite their different discovery histories and names—are all very luminous, blue in colour, and highly variable. Because of these shared characteristics, it is appropriate to group them under a single term: Luminous Blue Variables.'Despite advancements, the mechanisms driving LBV variability remain unclear to this day, including whether there is a direct connection between the S Dor cycle (Section 5.1) and giant eruptions (Section 5.2) or if all LBVs experience both in a specific sequence. This uncertainty challenges the classification of these stars as unified 'LBV phenomena', as giant eruptions and S Dor cycles may signify different LBV subclasses. Nevertheless, these instabilities, occurring on distinct timescales, remain defining features that distinguish LBVs from other massive stars.

1.3 Significance of studying LBVs

In the context of single star evolution, if the initial mass M_{ZAMS} of an LBV lies in the range $25M_{\odot} < M_{\mathrm{ZAMS}} < 40M_{\odot}$, it is believed to be a supernova progenitor, Wherein LBV phase is believed to occur in the later stages of evolution i.e. after the Red Supergiant phase (Groh et al. 2013). For massive stars with masses $M_{\mathrm{ZAMS}} > 40M_{\odot}$, the LBV phase is thought to occur as an intermediate evolutionary stage between massive main sequence stars and Wolf–Rayet (WR) stars i.e. transition from Hydrogen core burning to Helium core burning (Groh et al. 2014) phase. WR stars are evolved, massive stars characterised by strong, broad emission lines in their spectra (Schmutz et al. 1989), indicating powerful stellar winds and significant mass loss. They are typically hotter and more luminous than most stars, with surface temperatures ranges from 20,000 to 210,000 K (Sander & Vink 2020). WR stars are thought to represent a late stage in the evolution of massive stars, often following the LBV phase (Massey et al. 2001).

A majority of massive stars are found in binary systems with separations small enough that they exchange mass (Gies 1987; Hillwig et al. 2006; Mahy et al. 2009; Sana et al. 2012). This has led many to argue that LBVs might be a product of binary evolution rather than single-star evolution, challenging the traditional view where LBVs are considered a transitional phase between massive O-type stars and WR stars. It has been proposed that LBVs are the mass gainers in binary interactions. Through binary mass transfer, their mass becomes enriched (for more insights on this topic, Smith & Tombleson 2014; Smith 2017).

The well-established fact that massive stars can trigger star formation and enrich the surrounding interstellar medium (ISM) with CNO-processed material (Vink 2008) motivates us to further investigate this particular evolutionary phase. LBVs are known for their slow, dense stellar winds with high mass-loss rates ($10^{-5} M_{\odot}$ yr^{-1} to $10^{-6} M_{\odot}$ yr^{-1}; Lamers 1989) and lower terminal velocities than other stars of the same spectral type Due to the high mass loss, LBVs readily form circumstellar nebulae (for a review, see Weis 2001), which sometimes can completely obscure the central star. Because of the brightness of the central star, it is extremely difficult to observe LBV nebulae at visual wavelengths. However, they are quite bright at infrared wavelengths (Robberto & Herbst 1998). Eta Car, one of the most famous LBVs, is the brightest IR source outside our solar system at 10-20 μm.

Recent studies, such as Sana et al. (2012), have concluded that the majority of massive stars reside in binary systems. This suggests that most LBVs are likely part of binary systems, making these systems prime candidates for studying gravitational wave events. In their final stages, massive stars leave behind black holes or neutron stars (Heger et al. 2003), which, when in binary systems, are known to emit gravitational waves (Gröbner et al. 2020). One such interesting system is HD 5980, a prominent multiple star system in the Small Magellanic Cloud. It consists of three stars: a primary star that exhibited an LBV-like eruption (Koenigsberger et al. 2014), a secondary WR star, and a tertiary component, which is a distant O-type supergiant. So the LBV phase represents an unstable and critical transition in the life of a massive star, potentially leading to either the WR stage or directly to a core-collapse supernova. One of the defining characteristics of LBVs is their intense mass loss, which significantly enriches the surrounding interstellar medium with heavy elements, particularly nitrogen-enhanced, carbon- and oxygen-depleted material processed through the CNO cycle (Wiescher 2018). These stars also exhibit powerful stellar winds that can shape their immediate environment, influence nearby star formation, and contribute to large-scale feedback processes in galaxies. In addition to their evolutionary importance, LBVs are considered likely progenitors of Type IIn supernovae, which are a subclass of core-collapse supernovae marked by narrow hydrogen emission lines in their spectra (Taddia et al. 2013). These features suggest that the supernova shock interacts with a dense, hydrogen-rich circumstellar medium that was ejected prior to the explosion, likely during the LBV phase. Despite their importance, many aspects of LBVs—including the mechanisms behind their instability and eruptive behaviour—remain poorly understood.

Our main goal with this review is to introduce LBVs to those who are new to the field. These stars hold a fascinating yet mysterious place in the evolution of massive stars, making them an exciting and sometimes puzzling subject of research. Their unpredictable nature, extreme variability, and uncertain evolutionary paths can make them challenging to grasp, especially for newcomers. With this article, we aim to provide a clear and structured introduction to LBVs—what they are, why they matter in stellar evolution, and the ongoing debates about their origins and fate. By bringing together insights from both foundational and recent studies, we hope to create an engaging and accessible resource for researchers, students, and anyone curious about these extraordinary stars.

In this research article, we explore LBVs, their defining characteristics, and the evolutionary scenarios they are believed to follow. Section 2 outlines the general properties of LBVs, including their photometric variability, observed spectral features, multi-wavelength observations, and variability patterns. In Section 3, we examine the methods used to identify LBVs. Section 4 highlights well-known LBVs both within our Galaxy and in nearby galaxies. In Section 5, we discuss the various evolutionary pathways of LBVs—such as the S Doradus phase, giant eruptions, the influence of binarity, mass-loss and morphology, and their potential role as supernova progenitors. Section 6 focuses on the environments surrounding LBVs. Finally, Section 7 presents our conclusions along with future research directions in this field.

2. General properties of LBVs

2.1 Photometric variability

Photometry is the measurement of a star's brightness over time, typically across different wavelengths or filters. It helps astronomers study variability, detect outbursts, and analyse stellar properties such as temperature and luminosity by tracking how light changes with time.

Photometry of LBVs is particularly important because these stars exhibit significant brightness variations over timescales ranging from days to decades. Monitoring their photometric behaviour helps identify different variability phases, which are essential for confirming the LBV status of any star. According to the observed time scale, Lamers (1987) classified the variations into three types:

Type 1: The change in visual magnitude during these eruptive events is $\Delta V \geq 3$. This type of variation is associated with the giant eruptions observed in stars like Eta Car and P Cygni. The time interval between these outbursts is estimated to be on the order of centuries.

Type 2: The moderate change in $\Delta V \approx 1$ or 2 occurs on a time scale of years to decades and is mostly associated with the S Dor cycle, as seen in stars like AG Carinae and S Dor.

Type 3: The small-scale micro-variation of $\Delta V \approx 0.1$ to 0.2 magnitudes occur on a time scale of weeks to months. This variation is caused by non-radial pulsations commonly observed in giant stars.

As expected, there are certain difficulties in finding the type 1 variability because of the time scale. But the Type 2 and 3 variations are readily seen in LBVs. Specifically, the Type 2 variation is of utmost importance because it is one of the hallmarks to distinguish LBVs from other variable stars. Type 2 and 3 variations happen at approximately constant bolometric luminosity but the case is different for Type 1 variations. It is also important to emphasise that these values are derived using galactic LBVs and may vary in the case of other galaxies with different metallicity.

2.2 Spectral features observed in LBVs

LBVs exhibit distinctive spectral features across the ultraviolet (UV), optical, and infrared (IR) bands, reflecting their unstable atmospheres and strong stellar winds. In the UV, their spectra often show prominent P Cygni profiles in lines such as NV, SiIV, and CIV, indicative of highvelocity outflows. The optical spectra of LBVs are rich in emission lines, including hydrogen Balmer lines (especially Hα), FeII, HeI, and sometimes [NII] and [FeII], which vary with the star's temperature and eruptive phase. During outbursts, cooler temperatures lead to enhanced low-ionisation lines and a shift in spectral type toward late- A or even F-type supergiants. In the near-IR, strong emission from Paschen and Brackett series lines is common, along with HeI and metal lines like FeII, and occasionally molecular bands if dust forms. These multi-wavelength spectral features provide crucial insights into the mass-loss processes, wind structures, and circumstellar environments of LBVs.

2.2.1 LBV spectra during quiescence stage

During the quiescent or visual minimum phase, LBVs exhibit spectral features similar to those of hot, early-type supergiants. The spectra in this phase are dominated by emission lines from hydrogen, such as Hα (6563) and Hβ (4861), along with Paschen series lines spanning wavelengths from approximately 8200 to 10000 Å . Prominent neutral helium (HeI) lines are also observed, particularly at 5876 and 6678 Å, as well as lines from singly or doubly ionized metals, including SiIII, NIII, and FeIII. A hallmark of LBV spectra in this phase is the presence of P Cygni profiles, especially in hydrogen and HeI lines, which indicate strong, high-velocity stellar winds and ongoing mass loss. The HeII 4686 Å line may also be present in hotter LBVs, although it is typically weak. Additionally, a dense forest of forbidden emission lines, particularly [FeII], is commonly seen during this phase (Massey et al. 2001 and references therein). The overall ionisation structure corresponds to higher effective temperatures, generally ranging from 12,000 to 30,000 K (Kogure & Leung 2007), and reflects a relatively less dense stellar atmosphere compared to the outburst phase.

2.2.2 LBV spectra during outburst phase

In their outburst or visual maximum phase, LBVs exhibit significant changes in their spectral properties, closely resembling those of cooler A- or F-type supergiants. This apparent transformation is not due to a drop in core temperature, but rather the formation of a dense, optically thick pseudo-photosphere caused by enhanced mass loss. As a result, the effective temperature appears reduced, typically ranging between 8,000 and 12,000K (Kogure & Leung 2007), and the spectral energy distribution shifts from the ultraviolet to the optical region. The spectra become dominated by low-ionisation species, with strong hydrogen emission lines—particularly Hα—often showing broad electron-scattering wings. Lines from neutral and singly ionised metals, such as FeII and TiII, become more prominent, while high-ionisation features like HeII disappear entirely. In contrast, HeI lines at 5876 Å and 6678 Å with broad absorption wings become more noticeable. Additionally, NI lines appear around 8000 Å, and nebular forbidden lines of [NII] at 5755 Å and 6584 Å may also become prominent. Forbidden emission lines such as [FeII] are typically weakened or absent due to the increased optical depth of the expanding stellar wind.

2.2.3 P Cygni profile observed in LBVs

The P Cygni profile is a spectroscopic feature observed in the spectra of different massive stars having strong stellar winds, including LBVs and WR stars. It is characterised by a combination of broad emission and blueshifted absorption, indicative of expanding stellar material (Kuan & Huhi 1975). The emission component originates from the outer layers of the wind, while the absorption arises as the observer views light travelling through the outflowing material along the line of sight. The shape of the P Cygni profile provides critical insights into the velocity, density, and ionisation structure of stellar winds, making it an essential diagnostic tool for understanding mass-loss processes in massive stars. Figure 2 illustrates the formation mechanism of a P Cygni profile, assuming a spherically symmetric expanding envelope around the star. Figure 3 shows P Cygni profiles as seen in the optical spectra of cLBV WRAY16-232.

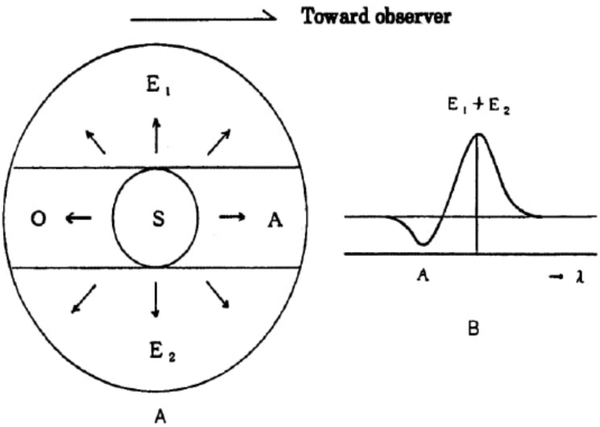

Figure 2. The figure illustrates the formation mechanism of P Cygni profiles in an expanding stellar envelope. The left panel depicts a star surrounded by an expanding envelope, which is divided into four regions: A, which emits light directly toward the observer; E1 and E2, located at the top and bottom of the envelope, respectively; and O, which is obscured by the star itself. The absorption component of the P Cygni profile originates from region A, where the expanding material absorbs light along the observer's line of sight. The emission component arises from regions E1 and E2, where scattered light from the envelope contributes to the observed spectrum. The right panel presents the resulting P Cygni spectral profile, displaying the combined effects of absorption and emission from different regions of the envelope. This figure is adapted from Kogure & Leung (2007).

Beals first proposed an explanation for the formation of P Cygni profiles (1929). In Figure 2, region A represents the absorbing area along the observer's line of sight, where light is absorbed by the circumstellar material and blue-shifted due to the Doppler effect. Regions E1 and E2 are the emitting areas responsible for the emission component of the P Cygni profile, while region O is the obscured part of the star that does not contribute to the observed profile. Some stars, such as S Dor, have also exhibited 'inverse P Cygni profiles' (Wolf & Stahl 1990), characterised by blue-shifted emission and a red-shifted absorption component. These profiles indicate an inward-moving envelope rather than expanding one.

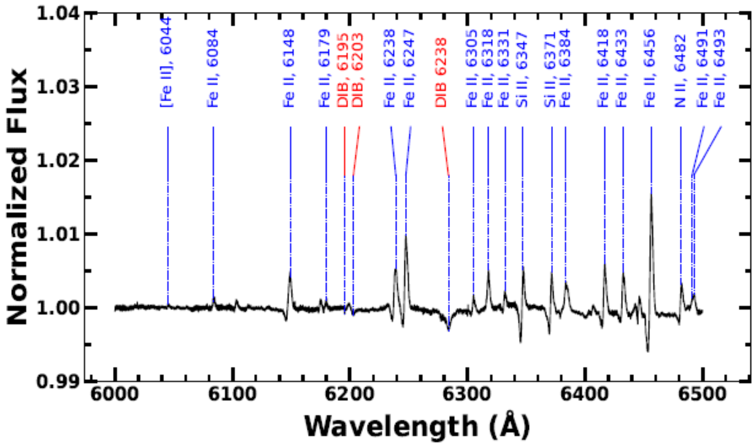

Figure 3. The figure illustrates the P Cygni profile observed in the candidate LBV WRAY 16-232 within the wavelength range of 6000 to 6500. The figure is adapted from Arun et al. (in preparation).

2.3 Spectroscopic observations of LBVs

Spectroscopic observations of LBVs provide crucial insights into their wind properties, temperature changes, and chemical composition. Key features such as P Cygni profiles and emission lines of HI, HeI, FeII and [FeII], as well as shifts in ionisation levels, help trace the variability phases of these stars.

2.3.1 UV spectroscopy

UV spectroscopy plays a crucial role in studying LBVs by providing insights into their extreme stellar winds, massloss rates, and ionisation conditions (Hillier et al. 2020). Their UV spectra reveal the interplay between radiation-driven winds and circumstellar material. The UV spectrum of LBVs is dominated by a variety of resonance lines from highly ionized species, which include SiIV (1393, 1402), CIV (1548, 1551), NV (1238, 1242), and FeII multiplets (Pasquali 1997). These lines frequently exhibit P Cygni profiles.

The presence of strong CIV and NV lines suggests highly ionised wind conditions, particularly during the hotter phases of LBV variability. Conversely, during the cooler phases, FeII and MgII (2800 doublet) lines become more prominent, indicative of lower ionisation. The SiIV doublet is particularly useful for tracing changes in wind density and ionisation balance, as its strength varies significantly during LBV spectral shifts. One of the key aspects of LBV UV spectra is the presence of broad, saturated absorption troughs in resonance lines, pointing to wind clumping and inhomogeneities. Figure 4 depicts the UV spectra of Eta Car in the wavelength range of 1700 to 2000 Å.

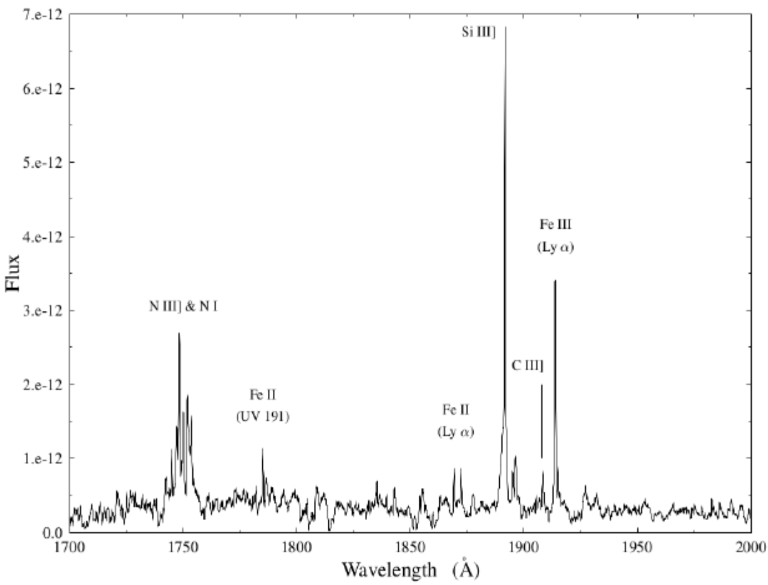

Figure 4. The figure shows the near UV spectrum of the well-known Galactic LBV, Eta Car, in the wavelength range of 1700 to 2000 Å. The figure is adapted from Zethson et al. (2012).

2.3.2 Optical spectroscopy

Optical spectroscopy of LBVS provides critical insights into spectral variability and the circumstellar environment. LBVs exhibit a rich and evolving optical spectrum, with prominent emission lines that vary between different phases of their instability cycle. One of the defining features of LBV optical spectra is the presence of strong hydrogen Balmer emission lines, particularly Hα, often accompanied by P Cygni profiles. In addition to hydrogen, their spectra prominently feature HeI, FeII, [FeII] and NI with the specific line strengths and profiles changing as the star undergoes variability. During the hotter quiescent phase, LBVs resemble Of/WN-type stars, showing strong HeII and FeIII lines, along with weak or absent FeII features. As they transition to their cooler eruptive phase, the spectrum shifts towards that of an A- or F-type supergiant, with enhanced FeII, TiII emission, along with increased continuum opacity due to a pseudo-photosphere forming in the dense stellar wind. The presence of forbidden lines such as [NII] and [FeII] is linked to circumstellar nebulae, which are remnants of previous mass-loss events and can be used to calculate the terminal velocities of the outflows. Figure 5 depicts the optical spectra of Eta Car around Hα in the wavelength range 6000 to 7400 Å.

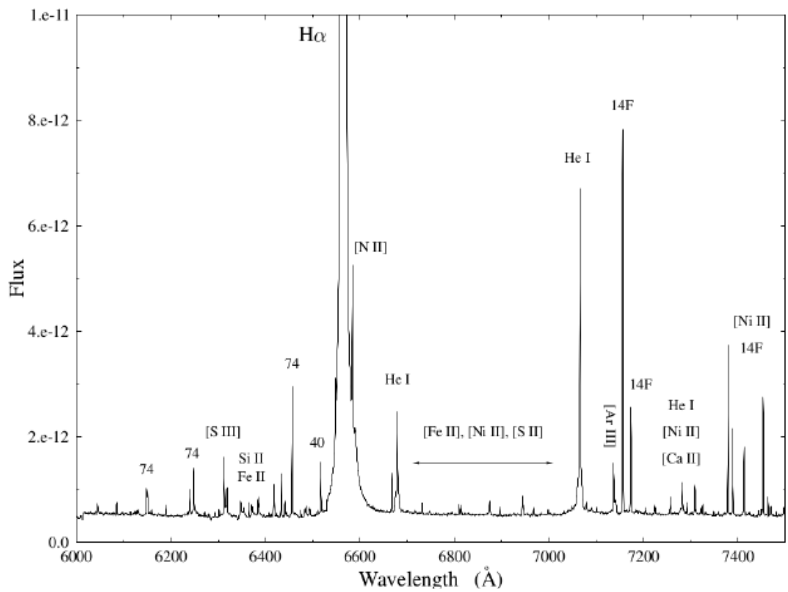

Figure 5. The figure shows the near optical spectrum of the well-known Galactic LBV, Eta Car, in the wavelength range of 6000 to 7400 Å. The figure is adapted from Zethson et al. (2012).

2.3.3 IR spectroscopy

IR spectroscopy plays a crucial role in studying LBVs by revealing insights into their circumstellar environment and dust formation processes. LBVs often exhibit strong infrared excess due to thermal emission from dust, which forms in the material ejected during their episodic mass-loss events. This excess is particularly prominent in stars like Eta Car, where a dense circumstellar nebula absorbs stellar radiation and re-emits it in the infrared (Westphal & Neugebauer 1969).

The IR spectrum of LBVs is characterised by prominent emission lines of molecular hydrogen lines, as well as [FeII]. In some cases, molecular CO first-overtone bands at 2.3 μm and SiO emission have been detected, providing evidence for cool, dense environments that allow molecular formation McGregor et al. (1988b). Forbidden lines such as [SiIV], [NeII], [NeIII], [NeV], [SII] and [SIII] (Umana et al. 2009) are often observed in LBVs with extended nebulae. The presence of Polycyclic Aromatic Hydrocarbon (PAH) features in the mid-infrared suggests complex circumstellar chemistry (Guha Niyogi et al. 2014), particularly in evolved LBVs surrounded by dusty nebulae. Figure 6 shows the spectrum of HD168625, highlighting prominent PAH features in the mid-IR.

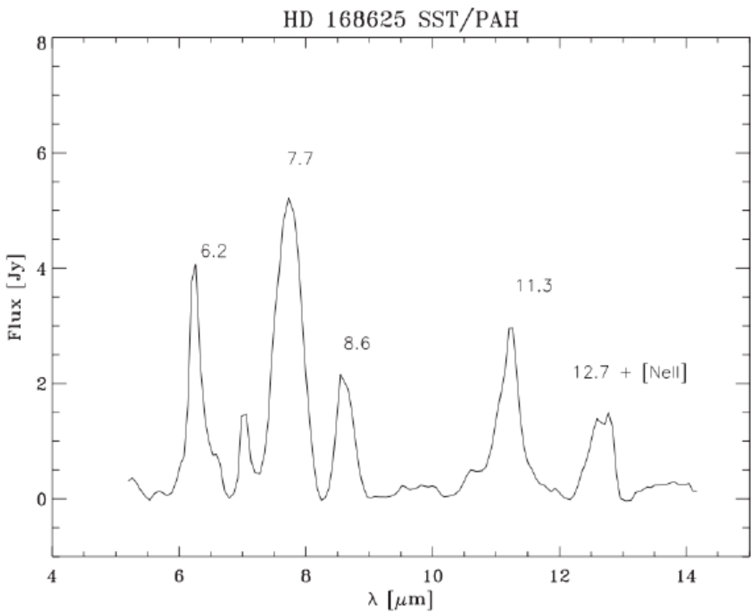

Figure 6. The figure shows the mid-IR spectrum of HD 168625, taken from Umana et al. (2010), displaying prominent PAH features at 6.2, 7.7, 8.6, 11.3 and 12.7μm.

2.4 *Variability in LBVs*

In addition to photometric changes, LBVs exhibit variability in their spectra, mass-loss rates, and stellar winds. These variations can occur over different timescales and are often linked to underlying instabilities in the star's envelope (Discussed in greater detail in section 5). Changes in the velocity and intensity of P Cygni profiles and pure emission lines, shifts in spectral classification from early type to late type giants, and variations in mass ejection rates are commonly observed. Such variability provides critical insight into the internal processes driving LBV phenomena, reinforcing the importance of long-term observations of LBVs.

A very recent study by Spejcher et al. (2025) analysed photometric time-series data from the TESS mission for 37 LBVs across our Milky Way Galaxy, Large Magellanic Cloud (LMC) and Small Magellanic Cloud (SMC). Using Fourier analysis with semi-Lorentzian fits, they extracted characteristic frequencies, red noise amplitudes, and white noise components, and compared these parameters to stellar properties such as $B - V$ colour, apparent g magnitude, and Hα equivalent widths. They found no significant correlation between the variability parameters and any of the stellar characteristics, suggesting that LBV microvariability is likely a stochastic phenomenon akin to α Cygni-type variations (van Genderen et al. 1992; Guzik et al. 2024). The study concludes that LBVs may not require variability-based classification, and that their short-term variability could be intrinsic to all massive evolved stars in the relevant region of the HR diagram.

Spectral variations in LBVs are always accompanied by photometric variations, both of which are evidently driven by changes in temperature. To distinguish LBVs from other variable stars, both spectral and photometric analyses are essential. This analysis must be conducted over at least one S Dor cycle, during which the LBV transitions from visual maximum to minimum state or vice versa. Only then can we confidently identify the star as an LBV. Until confirmed, the star is referred to as a c-LBV.

3. Identification methods for LBVs

Confirming LBV status requires continuous monitoring over years or even decades, which is a demanding task. Furthermore, the number of massive stars that can evolve into LBVs is very low, and the LBV phase itself is short-lived, resulting in a small number of confirmed LBVs. This scarcity demands caution when adding a new LBV to the list, as even a single incorrect candidate can hinder the overall statistical properties. As a result, researchers often revisit the same LBVs repeatedly to ensure accuracy, which limits the scope of studies and, in our opinion, slows further progress in the field.

3.1 Photometric variability

One of the most distinctive features of LBVs is their irregular photometric variability, which occurs over different timescales. The two main types of variations include the S Doradus cycle, where the star brightens by 1–2 magnitudes over years to decades at nearly constant bolometric luminosity, and giant eruptions, which result in dramatic outbursts exceeding 3 magnitudes.

3.2 Spectroscopic features

Spectroscopy is a crucial tool in LBV identification. LBV spectra typically exhibit strong hydrogen Balmer emission lines (e.g., $H\alpha$ and $H\beta$), HeI, FeII, and [FeII] lines, often with P Cygni profiles. The spectral classification of LBVs varies depending on their phase: in the quiescent state, they resemble Of/WN-type stars, while during eruptions, they appear as cooler A- or F-type supergiants. The presence of forbidden emission lines such as [NII] and [FeII] suggests the existence of a circumstellar nebula formed by past mass-loss events.

3.3 Infrared and mid-infrared excess

LBVs often exhibit infrared excess due to dust formation in their expelled material. Mid-infrared observations using telescopes like Spitzer have been instrumental in identifying LBV candidates based on their strong thermal emission at 24 μm. Identifying dust-rich environments around LBVs provides insights into their mass-loss history and circumstellar interactions.

3.4 Multi-wavelength observations and long-term monitoring

Since LBVs exhibit significant variability across different wavelengths, combining data from UV, optical, IR and radio observations is essential for accurate classification. Long-term spectroscopic and photometric monitoring is crucial to capture both quiescent and eruptive phases, ensuring a reliable LBV classification.

3.5 Comparison with other variable stars

To confirm an LBV candidate, it is important to distinguish them from other massive variable stars such as WR stars, B[e] supergiants and Of/WN type stars. Of-type stars are massive and extremely hot, distinguished by strong and broad emission lines in their spectra, particularly those of ionised nitrogen (NIII) and helium (HeII). They are often regarded as a more evolved subclass of O-type stars, exhibiting enhanced mass-loss rates due to their powerful stellar winds. Similarly, WN-type stars are a subclass of WR stars characterised by strong emission lines of helium and nitrogen in their spectra, with little or no hydrogen present. These stars represent a late evolutionary stage of massive stars, having shed their outer hydrogen layers through powerful stellar winds. Unlike WR stars, LBVs show spectral shifts between hotter and cooler states. Compared to B[e] supergiants, LBVs have stronger Hα emission and do not exhibit persistent dense equatorial disks.

By utilizing a combination of photometry, spectroscopy, infrared imaging, and long-term monitoring, astronomers can effectively identify and classify LBVs.

4. Well-known LBVs in the Milky Way and Beyond

In this section, we highlight a few benchmark LBV stars that have been instrumental in advancing our understanding of this critical phase in the evolution of massive stars. A selection of LBVs from Smith et al. (2019) with their equatorial coordinates, visual magnitude ranges, and key references is provided in Table 1.

Table 1. The table lists 11 confirmed Galactic LBVs, as compiled from Smith et al. (2019), along with 6 well-known extragalactic LBVs. Among the extragalactic sources, S Dor, HD 269858, and HD 269006 reside in the LMC, while HD 6884 and HD 5980 are located in the SMC. BASW 19 is situated in the Andromeda Galaxy (M31). The table includes their equatorial coordinates (ordered by increasing Right Ascension), visual magnitude ranges, and key references. Note: The visual magnitude ranges represent the observed variability of each star and may differ across studies due to the dynamic nature of LBVs. Since LBVs are highly variable objects, their visual magnitudes are subject to change. As mentioned in Section 4.1.2, P Cyg has not exhibited significant magnitude changes over the past centuries; therefore, only a single magnitude value is provided. For Westerlund 1-243, V481 Sct, HD 269858, BASW 19, and HD 269006, exact values for magnitude variation could not be found or are based on very old data.

Star	Right Ascension (hh mm ss)	Declination (dd mm ss)	Visual Magnitude	Key references
		Galactic LBVs		
HD 90177	10 22 53	- 59 37 28	6.8 - 8.8	Machado et al. (2002)
AG Car	10 56 11	- 60 27 12	5.7 - 8	Davidson et al. (1989)
MR 35	11 08 38	- 60 42 54	10.5 - 12.5	Sterken et al. (2008)
Westerlund 1-243	16 47 07	- 45 52 29	-	Clark & Negueruela (2003)
[GKF 2010] MN48	16 49 37	45 35 59	10.1 - 11.2	Kniazev et al. (2016)
Brey 3	17 25 13	- 38 02 48	13.8 - 15.2	Kniazev et al. (2015)
HD 160529	17 41 59	- 33 30 13	6.3 - 6.9	Sterken et al. (1991)
HD 168607	18 21 14	- 16 22 31	8.05 - 8.41	Chentsov et al. (1980)
MWC 930	18 26 25	- 07 13 17	11.5 - 12.7	Miroshnichenko et al. (2014)
V481 Sct	18 33 55	- 06 58 38	-	Petriella et al. (2012)
P Cyg	20 17 47	+ 38 01 58	4.8	Conti et al. (1984)
		Extragalactic LBVs		
BASW 19	00 43 33	+ 41 12 10	-	Joshi et al. (2019)
HD 5980	00 59 26	- 72 09 53	8.8 - 11.9	Koenigsberger et al. (1998)
HD 269006	01 32 32	+ 30 30 25	-	Humphreys et al. (1987)
S Dor	05 18 14	- 69 15 01	8.6 - 11.5	Conti et al. (1984)
HD 269858	05 36 43	-69 29 47	-	Walborn et al. (2008)
HD 6884	05 39 28	- 69 45 36	7.9 - 9.2	Szeifert et al. (1993)

4.1 Prominent LBVs in the Galaxy

4.1.1 Eta Carinae

Eta Carinae, popularly known as Eta Car, is the most well-known Luminous Blue Variable (LBV) in our Galaxy, the Milky Way. It is renowned for the presence of the bipolar Homunculus Nebula and is also the most massive binary star system discovered to date. The system's primary star has an estimated mass between 80–120 $M_\odot$ (Davidson & Humphreys 1997; Hillier et al. 2001), with some estimates suggesting it could reach up to 200 $M_\odot$ (Kashi & Soker 2010). Its spectrum exhibits rich emission lines spanning from the UV to the infrared, with the most prominent features including HI, HeI, FeII, NI, SiII, NaI, MgII, CaII, and AlII, many of which appear as P Cygni profiles. A comprehensive line identification study for Eta Car was conducted by Zethson et al. (2012), covering the spectral range from 1700 to 10400 Å.

4.1.2 P Cygni

P Cygni is a well known LBV in our Galaxy, famously known for its distinctive P Cygni type line profiles (discussed in Section 2.2.3) observed in its spectra, which were first identified in its spectrum. P Cygni is a star of B spectral type and a prominent LBV known for its strong emission lines, which display typical P Cygni profiles. These include Balmer lines and ionised metallic lines such as FeIII, OII, NII, and SII. Additionally, forbidden lines such as [FeII], [TiII], and [NII] are observed. These forbidden lines appear as pure emission without a violet-shifted component, indicating their formation in the low-velocity regions outside the expanding envelope. Historical observations suggest an overall brightness increase of 0.15 ± 0.02 mag per century between 1700 and 1988 for this star (de Groot & Lamers 1992).

4.1.3 AG Carinae

AG Carinae (AG Car) is also considered as one of the most well-known LBVs in our galaxy, exhibiting a high luminosity of log $L/L_\odot \approx 6.0$ (Groh et al. 2006). AG Car is considered the prototype of the LBV class and has been extensively studied across a broad range of wavelengths, from ultraviolet to radio, using photometric, spectroscopic, and polarimetric techniques over several decades. Between 1981 and 1985, AG Car underwent a significant fading event, with its visual magnitude decreasing from V = 6 to 8. This change corresponds to a dramatic temperature variation, dropping from approximately 30,000 K to 10,000 K (Viotti et al. 1993). AG Car is surrounded by an elliptical ring nebula, measuring approximately 1.1 × 1.0 parsecs in size (Nota et al. 1992). The estimated nebular mass is about 4.2 $M_\odot$, with an expansion velocity of 70 km s^{-1} (Nota et al. 1992), suggesting that it was formed during a past eruptive event, potentially before the onset of the LBV phase. The spectrum of AG Car is rich in emission lines, including prominent features of HI, HeI, FeII, [FeII], and [NII]. Many of these lines appear as P Cygni profiles, indicative of strong stellar winds and significant mass-loss processes.

4.1.4 HD 160529

HD 160529 is a low-luminosity LBV exhibiting moderate photometric and spectral variability, placing it between classical LBVs and normal B/A supergiants. Confirmed as an LBV by Sterken et al. (1991), its spectral type shifts between B8 and A9, with corresponding temperature variations from 8,000 K to 12,000 K and radius changes between 150 and 330 $R_\odot$. The star shows S Doradustype variability with long-term cycles of approximately 20 years and short-term pulsations around 57 days. Spectroscopically, it displays strong Hα, HeI, FeII, and TiII lines, with P Cygni profiles indicative of mass loss, while forbidden lines of [NII] and [FeII] suggest the presence of a circumstellar nebula. NaI D line absorption indicates accelerating shells in the stellar wind. Its mass-loss rate is estimated at $10^{-5} M_\odot$ yr^{-1}, with a relatively low wind velocity of around 200 km/s, suggesting a weaker wind compared to more extreme LBVs. Evolutionarily, HD 160529 is likely transitioning from the Red Supergiant phase rather than following the classical O-type to WR star pathway (Sterken et al. 1991 and references therein).

4.2 Notable Extragalactic LBVs

4.2.1 S Doradus

S Doradus (S Dor) is an LBV and one of the brightest stars in the LMC galaxy. The S Dor cycle (The Type 2 variability discussed in Section 2.1), a hallmark to distinguish LBVs from other variable stars, is named after this star as such type of variability was first observed in S Dor.

Between 1983 and 1993, S Dor experienced significant brightening, reaching its peak in 1988 with a magnitude increase of more than 2 above its quiescent level. During this phase, S Dor initially displayed distinct P Cygni profiles in metallic lines. However, following the peak brightness, the star transitioned into a phase of inverse P Cygni profiles, lasting approximately two years. Wolf (1994) attributed this phenomenon to the ejection of a substantial amount of gas that formed an expanding envelope, which was subsequently followed by the fallback of the ejected material toward the star.

4.2.2 HD 269858

HD 269858, popularly known as R127 is a well-studied LBV in the LMC, known for its outburst that began in 1980. Initially classified as an Ofpe/WN9 star, it transitioned into a LBV phase, exhibiting long-term brightening and periodic declines. The light curve peaked in 1990, declined until 2008, and then unexpectedly brightened again, suggesting ongoing mass-loss episodes. Spectroscopically, R127 shifts between an early B-type supergiant at minimum and an A-type supergiant at maximum, with strong Hα P Cygni profiles, FeII emission, and forbidden [NII] and [FeII] lines, indicating interactions with a circumstellar nebula. It has a mass-loss rate of $10^{-5} M_{\odot}$ yr^{-1}. The resemblance of its photometric behaviour to Eta Car raises questions about the cyclic nature of massive star instabilities and whether LBVs can experience multiple outbursts before their final fate (Walborn et al. 2008 and references therein).

4.2.3 HD 5980

HD 5980 is a massive multiple-star system located in the Small Magellanic Cloud (SMC), known for its complex composition and dramatic variability. The system consists of at least three massive stars, with the primary components forming a close eclipsing binary with an orbital period of 19.3 days. These stars are among the most luminous in the SMC and have masses estimated to be around 61 and 66 solar masses. The primary star underwent a significant LBV-like eruption in 1994, during which its spectrum temporarily resembled that of a WR star.

Spectroscopically, HD 5980 displays strong emission lines of nitrogen and helium, with prominent P Cygni profiles indicating powerful stellar winds. The system is characterised by variable wind interactions, including wind-wind collisions that influence its emission-line profiles. A third component, identified as an O-type supergiant, follows a 96.5-day eccentric orbit around an unseen companion, suggesting that HD 5980 may be a hierarchical quadruple system. The complex interactions between these components make HD 5980 an important laboratory for studying massive star evolution and binary dynamics. Further long-term monitoring of HD 5980 is crucial to understanding the final evolutionary stages of massive stars in low-metallicity environments (Koenigsberger et al. 2014 and references therein).

4.2.4 BASW 19

BASW 19, popularly known as AF And is an extragalactic LBV located in M31 (the Andromeda Galaxy). It belongs to the Hubble–Sandage variables, a rare subclass of LBVs found in nearby spiral galaxies. AF is one of the most luminous stars in M31 and has exhibited significant photometric variability, including multiple major eruptions and several secondary outbursts. One of its most notable recorded eruptions occurred in 1999, during which its brightness increased by approximately 1.5 magnitudes, followed by a gradual decline over the next three years.

During its visual minimum, the photospheric temperature of AF And is estimated to be 33,000 ± 3,000 K, as determined through spectral energy distribution fitting. The star experiences a high mass-loss rate of $2.2 \times 10^{-4} M_{\odot}$ per year, characteristic of the intense stellar winds observed in LBVs. Its wind terminal velocity is approximately 280–300 km/s.

The spectrum of AF And is dominated by HI, HeI, FeII, and [FeII] emission lines, often exhibiting P Cygni profiles, which are characteristic features of LBVs and indicative of strong stellar winds and mass loss (Joshi et al. 2019 and references therein).

4.2.5 Variable A

Variable A (Var A) in M33 is an extragalactic hypergiant and a Hubble–Sandage variable. Its eruption, which began around 1950, lasted approximately 45 years, during which it transitioned from an F-type supergiant to a cool M-type phase due to the formation of an optically thick wind. Observations from 2003 to 2004 reveal that the star has returned to a warmer state, with a spectrum now resembling an early F- to early G-type supergiant. Spectroscopically, it displays strong hydrogen emission lines, the CaII infrared triplet, [CaII] forbidden lines, and KI. Photometric observations confirm significant variability, with a 3-magnitude drop in brightness since its 1950 maximum, followed by continued fading. The mass-loss rate during its dense wind phase in 1986 was estimated at $2 \times 10^{-4} M_{\odot} yr^{-1}$, but its recent transition to a warmer state has likely reduced it to $(2 - 3) \times 10^{-5} M_{\odot} yr^{-1}$, with wind velocities reaching 50–300 km/s. Despite its apparent return to a hotter phase, Var A remains visually obscured, likely due to circumstellar dust extinction. Its long-duration mass-loss event and recent recovery provide a rare opportunity to study the late evolutionary stages of massive stars (Humphreys et al. 1987 and references therein).

5. Evolutionary pathways of LBVs

The evolutionary pathways of LBVs are complex and not yet fully understood. This section outlines the key evolutionary phases and characteristic features commonly observed in LBVs.

5.1 S Doradus phase in LBVs

While LBVs prominently exhibit S Dor (SD) variability, this phase is not exclusive to LBVs; other giants may also display it (van Genderen 2001). Photometric studies of AG Car and S Dor have identified two distinct SD phases: a shorter cycle lasting less than 10 years, termed the normal (N)-SD phase, and a longer cycle exceeding 20 years, referred to as the very long-term (VLT)-SD phase (van Genderen et al. 1997). When both phases occur simultaneously, the shorter cycle overlays the longer one. Notably, no SD cycles have been observed with durations between 10 and 20 years. Langer et al. (1999) suggests that SD eruptions occur as the star nears the Eddington limit. Importantly, S Dor variables do not exhibit this variability throughout their lifetime, remaining inactive and unspectacular for at least 70 % of their lifespan (van Genderen 2001).

The criteria for classifying a star as an S-Dor variable are as follows:

1. The presence of visible ejecta around the star, resulting from one or more SD eruptions.
2. Spectroscopic variability, accompanied by high luminosity and mass-loss rates.
3. Photometric variability of approximately 1–2 magnitudes over timescales ranging from years to decades.

5.2 Giant eruptions in LBVs

Giant eruptions in LBVs, marked by a visual magnitude change of $\Delta V \geq 3$, involve the ejection of several solar masses of material. These events are thought to occur when a star's L/M ratio increases, potentially exceeding the classical Eddington limit, leading to catastrophic mass loss. Unlike the S Dor phase, bolometric luminosity during these eruptions does not remain constant. Notable Galactic examples include the eruptions of P Cygni and Eta Car.

P Cygni experienced an outburst in 1600, reaching 3rd magnitude and remaining at this brightness for six years before fading. It reappeared in 1654 and varied in brightness until 1683, gradually declining to 5.2 by 1780 (Israelian & de Groot 1999). The circumstellar shell around P Cygni is estimated to have a mass of 0.1 $M_{\odot}$ (Smith & Hartigan 2006). The P Cygni profile, first observed in this star's spectrum, derives its name from it. Likewise, a giant eruption was identified for Eta Car in 1837, which peaked in 1843 and then gradually faded out. During the peak, Eta Car became the second brightest star in the night sky, outshone only by Sirius (apparently the brightest star in the night sky). A second giant eruption, resembling an S Dor phase, occurred between 1888 and 1895 (Humphreys et al. 1999). The mass of the circumstellar shell was estimated to be 10 $M_{\odot}$ by Smith et al. (2003).

The varying shell masses of P Cygni and Eta Car underscore the diversity of LBV eruptions. Extragalactic examples include SN 1954J, an outburst from V12 in NGC 2403 (Tammann & Sandage 1968), and SN 1961V, which was initially classified as a Type V supernova. However, Goodrich et al. (1989) later suggested that SN 1961V may have been an Eta Car-like event in NGC 1058.

Despite significant research on LBVs during outbursts, more studies are needed to investigate their dormant phases, such as by Maryeva et al. (2022). Understanding what occurs during these quiet periods could provide valuable insights into the mechanisms driving their variability. However, identifying dormant LBVs is challenging, as they lack the variability typically used for classification.

5.2.1 S Dor phase vs giant eruptions

The S Doradus phase is a cycle that lasts from years to decades, during which the star appears to brighten by 1–2 magnitudes in the visible band. However, this does not mean the star is actually producing more energy; rather, the increased brightness is an illusion caused by the expansion and cooling of its outer layers. As the star swells, its temperature drops, shifting more of its radiation into the visible band, making it appear brighter even though its total energy output remains roughly constant. These cycles are driven by changes in opacity, which temporarily make the outer layers more efficient at scattering and emitting light. This process is relatively calm compared to giant eruptions, which are violent and short-lived.

Giant eruptions can last from a few months to several years, but unlike S Dor phases, they involve an actual increase in luminosity and a dramatic mass-loss event, where the star sheds several solar masses of material. These eruptions are so extreme that they can create entire nebulae, such as the famous Homunculus Nebula surrounding Eta Car (Summers et al. 2022). It is widely believed that these outbursts occur when an LBV approaches the Eddington limit, causing the outward pressure of radiation to overcome gravity, ultimately leading the star to expel its outer layers. While S Dor phases can be thought of as a star breathing in and out, giant eruptions are cataclysmic events that permanently reshape the star and its surroundings, possibly serving as a precursor to a supernova. In both cases, these events play a crucial role in shaping the final evolutionary stages of LBVs.

5.3 LBVs during quiescent and outburst phase

The diagonal strip in Figure 10 represents the quiescent phase of LBVs, also known as the 'visual minimum'. During this phase, the effective temperature of LBVs ranges generally 12,000 K, corresponding to a late B spectral type, to 30,000 K, showing late O/early B spectra. Mass-loss rates during the visual minimum are relatively lower, and the stellar winds are faster, although still not as fast as those of other supergiant stars.

Occasionally, LBVs enter the outburst phase, during which their effective temperature drops to approximately 7,500 K to 8,500 K. However, some LBVs can reach even lower temperatures, such as R40, which dropped to T_{eff} = 5,800 – 6,300 K during an eruption in 2016 (Campagnolo et al. 2018). This temperature decrease occurs irrespective of their effective temperature and luminosity during quiescence. In this 'visual maximum' phase, the star displays supergiant A to F type spectra. During this phase, their mass-loss rates and visual magnitudes increase at nearly constant luminosity (see Figure 10). Additionally, the winds become slower and denser, forming a 'pseudo-photosphere' that can sometimes be dense enough to obscure the entire star. This increases the star's effective radius, leading to a decrease in its surface temperature. These episodes of brightening and dimming are known as the S Dor cycle of LBVs.

It is important to note that the terms 'effective temperature' and 'radius' lose their conventional meaning for LBVs during the outburst phase. The actual photosphere becomes diffuse and lacks a clear definition. Consequently, the observable properties we derive, such as spectra, effective temperature, and radius, are characteristics of the pseudo-photosphere, not the star itself.

The spectral and photometric variability of LBVs is primarily driven by changes in mass loss, wind density, ionisation structure, and temperature.

During quiescence, LBVs exhibit a hot O/B-type spectrum, but during eruptions, increased mass loss leads to a denser wind, forming a pseudo-photosphere that expands outward. This expansion lowers the apparent effective temperature, shifting the spectrum toward cooler A/F-type supergiant characteristics while maintaining a nearly constant core temperature. Changes in the ionisation structure accompany these variations, as denser winds favour lower ionisation states, such as FeII and HeI, while lower-density phases allow for higher ionisation species like HeII and FeIII to dominate. Metallicity plays a crucial role, as higher metallicity environments enhance radiation-driven mass loss, increasing variability (Meynet & Maeder 2005). Pulsational instabilities, particularly strange-mode instabilities, contribute to short-term fluctuations and may trigger outbursts when interacting with radiation pressure near the Eddington limit. Some LBVs also experience dust formation following major eruptions, leading to infrared brightening and temporary optical dimming as the dust obscures the star.

5.4 Role of binarity

Recent studies, such as those by Sana et al. (2012), have concluded that the majority of massive stars exist in binary systems, suggesting that most LBVs are likely part of such systems. Additionally, a significant number of massive stars have separations small enough to facilitate mass exchange (Gies 1987; Hillwig et al. 2006; Mahy et al. 2009; Sana et al. 2012). This has led many researchers to argue that LBVs may originate from binary evolution rather than evolving as single stars, challenging the traditional view that LBVs represent a transitional phase between massive O-type stars and WR stars. It has been proposed that LBVs are the mass gainers in binary interactions, acquiring additional mass through binary mass transfer. As a result, they may become enriched and, in some cases, be ejected or 'kicked' from their binary system.

One of the most significant studies challenging the traditional view of LBVs while supporting the binary evolutionary pathway is that of Smith & Tombleson (2014), who examined the isolation of LBVs from O-type and WR stars. Figure 7 illustrates the projected separation of massive stars in the LMC, with stars clustered near O-type stars on the left side of the plot, while increasing separation is observed toward the right. According to the traditional view, LBVs should be positioned between O-type stars and WR stars, yet observations show that LBVs are located even farther away from WR stars. Based on this finding, Smith & Tombleson (2014) concluded that the observed population of LBVs cannot evolve directly into the currently observed population of WR stars. Instead, they proposed an alternative explanation for the apparent isolation of LBVs and suggested new evolutionary tracks for the evolution of massive stars:

$$\text{O star} \rightarrow \begin{cases} \text{WN} \rightarrow \text{WC} \rightarrow \text{SN Ibc (donor)} \\ \text{LBV/B[e]} \rightarrow \text{SN IIn (gainer)} \end{cases}$$

In these newly proposed evolutionary tracks, stars that ultimately explode as SN Ibc—a type of supernova that lacks hydrogen in its spectrum—are identified as mass donors. Throughout their evolution, these stars lose their hydrogen envelopes, a defining characteristic of WR stars. Conversely, stars that end their lives as SN IIn—a supernova distinguished by narrow emission lines indicative of interaction with dense circumstellar material—are classified as mass gainers. Over time, these stars accumulate mass and develop a circumstellar shell, a feature commonly associated with LBV and B[e] stars. For further insights, see Smith & Tombleson (2014) and Smith (2017).

5.5 *Mass-loss in LBVs*

As massive stars evolve, they shift from solar abundances to He-enriched and CNO equilibrium abundances, marked by nitrogen enrichment and carbon and oxygen depletion (Maeder 1983). While LBVs show varied CNO abundances, most studies indicate that their ejecta are nitrogen-enriched (Davidson et al. 1982; Smith et al. 1998; Pasquali et al. 2002) although CNO equilibrium abundances are generally not reached.

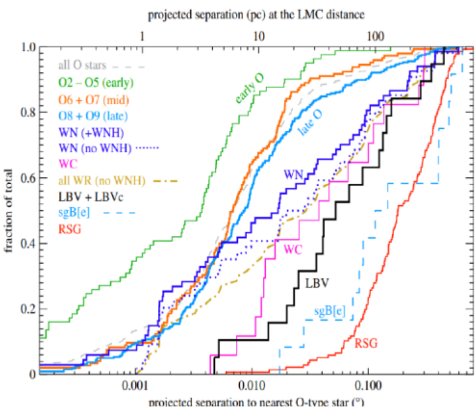

Figure 7. The figure illustrates the varying degrees of isolation among massive stars in the LMC (Smith & Tombleson 2014). The sample includes all O-type stars, WR stars, LBVs, sgB[e] stars, and RSGs within a 10◦ projected radius of 30 Doradus, excluding stars from the SMC. Stars positioned on the left are closest to O-type stars, while moving rightward indicates increasing isolation from O-type stars. Notably, LBVs appear to be even more isolated than WR stars, which raises questions, as the WR phase is expected to follow the LBV phase and should, theoretically, be spatially more distant from LBVs.

The high mass-loss rates of LBVs lead to the formation of circumstellar nebulae, though not all LBVs possess this feature. LBV nebulae typically form when slower winds from earlier S Dor cycles collide with faster winds from more recent ones. These nebulae contain nitrogen-rich, CNO-processed material, as evidenced by [NII] emission lines at 5755 and 6584 Å in LBV spectra. Their structures vary significantly, with 60-75 % of Galactic LBVs showing hourglass-shaped nebulae (Weis & Bomans 2020), while others display spherical nebulosity (Gvaramadze et al. 2010). Figure 8 shows HST images of the LBV R127 and the c-LBV S61 located in the LMC.

Dust in LBV nebulae forms in the cool, dense shells ejected during outbursts. This dust absorbs UV and optical radiation, re-emitting it as infrared light, making LBVs bright in the infrared spectrum. Most LBVs exhibit an infrared excess at 1-3 μm, with some also emitting at longer wavelengths (McGregor et al. 1988a). Notably, McGregor et al. (1988b) detected the CO first overtone at 2.3 μm in the infrared spectrum of HR Carinae, a Galactic LBV. In the case of Eta Car, dust is dense enough to completely obscure the star (Westphal & Neugebauer 1969).

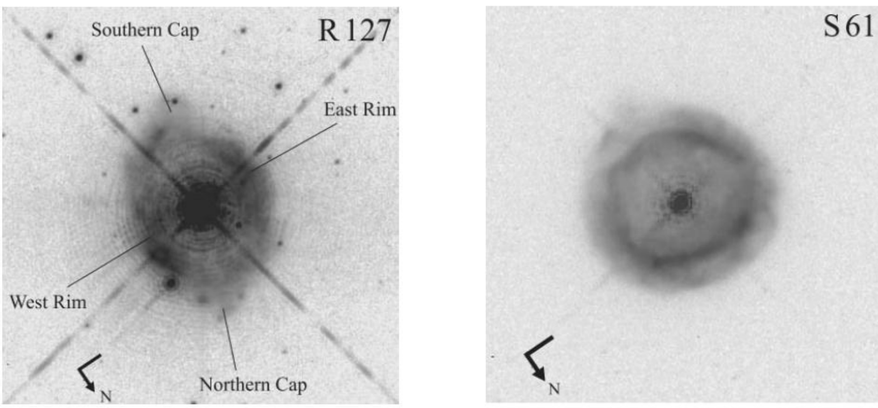

Figure 8. The HST image of R127 (classical LBV) reveals a bipolar structure, while S61 (c-LBV) displays a spherical morphology, as adopted from Weis (2003).

5.5.1 ***Morphology of LBV nebulae***

LBVs undergo intense mass-loss episodes, forming circumstellar nebulae that exhibit a wide range of morphologies, including spherical, irregular, and predominantly bipolar structures. Studies indicate that nearly 50 % of LBV nebulae display some degree of bipolarity, increasing to 75 % among Galactic LBVs, while in the LMC, bipolar structures are less frequent, with spherical nebulae being more common (Weis 2010). In general, about 40 % of LBV nebulae are spherical, 50 % are bipolar, and only 10 % exhibit irregular shapes. This distribution suggests an intrinsic formation mechanism influenced by factors such as stellar rotation, binarity, and wind interactions. The nebulae ejected by LBVs typically have diameters ranging from 0.5 to 2 pc, with expansion velocities between 25 and 140 km s^{-1}. Their estimated dynamical ages fall within the range of 5×10^3 to 5×10^4 years (Nota & Clampin 1997). However, notable exceptions include Eta Carinae and P Cygni. Bipolar nebulae often appear as hourglass structures, like in Eta Car and HR Car, or feature attached bipolar caps, as seen in WRA 751 and R 127. Rapid rotators like AG Car and HR Car provide key evidence for rotation-induced shaping. Notably, LBV nebulae in the LMC expand more slowly than their Milky Way counterparts, possibly due to lower metallicity affecting wind dynamics (Weis 2003). The strong resemblance between LBV nebulae and planetary nebulae suggests common hydrodynamic shaping processes, but the precise role of stellar winds, eruptions, and instabilities in sculpting these nebulae remains an open question.

Understanding these structures is crucial for understanding the final evolutionary stages of massive stars and their transition toward WR stars or supernovae.

5.6 *LBVs as supernova progenitors*

The connection between LBVs and supernovae remains one of the most debated topics in massive star evolution. Traditionally, LBVs were considered a transitional phase between massive OB-type stars and WR stars, with the expectation that they would shed their hydrogen envelopes through strong stellar winds and eruptive mass-loss events before evolving into WR stars and eventually exploding as Type Ibc supernovae. However, recent observations challenge this view, suggesting that some LBVs may instead explode directly as supernovae, particularly as Type IIn supernovae (Dwarkadas et al. 2011), which are characterised by narrow hydrogen emission lines indicative of interaction between the supernova ejecta and a dense circumstellar medium. This has led to the hypothesis that some LBVs retain enough of their hydrogen envelope at the time of collapse, rather than fully evolving into hydrogen-deficient WR stars.

Evidence supporting the LBV–supernova connection comes from observations of Type IIn supernovae, which often show pre-supernova outbursts resembling LBV giant eruptions. These transient events suggest that some LBVs experience instability-driven mass loss shortly before core collapse, leading to dense circumstellar environments similar to those seen around LBVs like Eta Car. Several Type IIn supernovae, including SN 2005gl (Gal-Yam et al. 2007), SN 2010jl (Smith et al. 2011), and SN 2009ip (Berger et al. 2009), have been linked to LBV-like progenitors based on pre-explosion imaging and spectral analysis. The case of SN 2009ip, which exhibited multiple outbursts before its terminal explosion, strongly resembles LBV variability, reinforcing the idea that at least some LBVs die as supernovae rather than transitioning into WR stars.

Additionally, the observed isolation of LBVs from young O-type stars raises questions about their evolutionary pathways. If LBVs were direct precursors to WR stars, they would be expected to be found in young massive clusters, yet many are instead observed in relative isolation. This has led to alternative theories suggesting that LBVs might be binary interaction products, such as mass gainers or post-merger remnants, rather than simple evolutionary descendants of single massive stars. In this scenario, LBVs could represent a distinct class of massive stars that fail to fully shed their hydrogen envelopes, leading to a direct explosion as Type IIn supernovae rather than transitioning through the WR phase.

While some LBVs may still follow the classical single-star evolutionary path leading to WR stars and Type Ibc supernovae, growing evidence supports an alternative track where LBVs explode as hydrogen-rich Type IIn supernovae. The distinction between these evolutionary channels is critical for understanding massive star evolution. Further long-term monitoring of LBVs and high-resolution pre-supernova imaging will be essential in resolving these uncertainties.

6. LBVs and their environments

LBVs in low-metallicity environments present significant challenges to traditional models of massive star evolution. The reduced efficiency of line-driven winds at low metallicity affects how these stars lose mass (Vink 2022), leading to uncertainties in their evolutionary pathways. In the SMC, a galaxy with metallicity approximately one-fifth that of the Milky Way, LBVs appear to be far less common than in higher-metallicity galaxies like the LMC or the Milky Way. A study of 64 blue supergiants in the SMC (Kalari et al. 2018) identified only one candidate exhibiting S Doradus variability, suggesting that either the LBV phase is much shorter than traditionally assumed, lasting only a few thousand years, or that LBVs are intrinsically different from normal blue supergiants.

The rarity of LBVs in the SMC has important implications for massive star evolution at low metallicity, particularly in the early universe, where most stars formed in metal-poor conditions. With lower wind efficiency at low metallicity, it is unclear whether these stars can shed sufficient mass to follow the classical LBV to WR to supernova pathway. Instead, some LBVs may skip the WR phase entirely and explode directly as supernovae, particularly as Type IIn supernovae.

Additionally, studies of the bi-stability jump, a temperature-dependent change in stellar wind properties (Smith et al. 2004), suggest that it is less pronounced at low metallicities, meaning that LBVs may not experience the same abrupt wind-driven transitions observed in metal-rich environments. This further complicates the picture of LBV evolution in the SMC and other metal-poor galaxies. The scarcity of LBVs in the SMC and their uncertain evolutionary status highlight the need for further observational studies in metal-poor environments. Increasing the number of confirmed LBVs in low-metallicity galaxies is essential for understanding whether they are truly a brief phase in massive star evolution or if they represent a separate evolutionary track influenced by binary interactions.

6.1 LBVs on HR diagram

LBVs occupy the uppermost regions of the HR diagram (Figure 9). They typically reside in two distinct regions of the HR diagram depending on their current phase. One region is a diagonal strip known as the S Dor instability strip, where LBVs are found during their quiescent phase. The other is a vertical region on the cooler side of the HR diagram, corresponding to the outburst phase of LBVs. Figure 10 shows an HR diagram with various Galactic and extragalactic LBVs plotted. Figure 10 also includes c-LBVs that have a circumstellar shell surrounding them. Additionally, it features yellow hypergiants (YHG) in the lower right corner of the diagram, which may represent missing 'LBVs' (Smith et al. 2004). Both LBVs and YHGs lie just below an empirical luminosity limit for hypergiants, known as the Humphreys-Davidson (HD) limit (Humphreys & Davidson 1979). This line represents the maximum luminosity a star can achieve before becoming unstable. Stars near the HD limit experience significant mass loss, a phenomenon observed in LBVs.

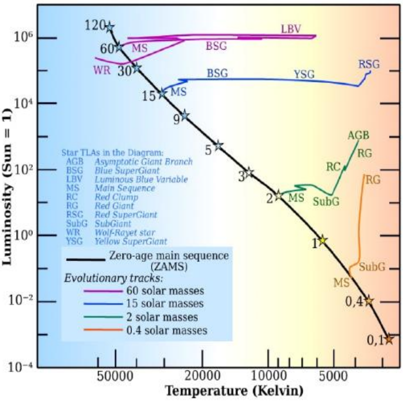

Figure 9. This figure presents a Hertzsprung–Russell diagram with evolutionary tracks illustrating how stars with different initial masses follow distinct paths throughout their evolution. LBVs are positioned at the very top of the diagram, consistent with the theory that they represent a transitional phase in the life cycle of massive stars (MS → BSG → **LBV** → WR). The following figure has been adapted from https://pages.uoregon.edu/imamura/122/lecture-8/UMS.html

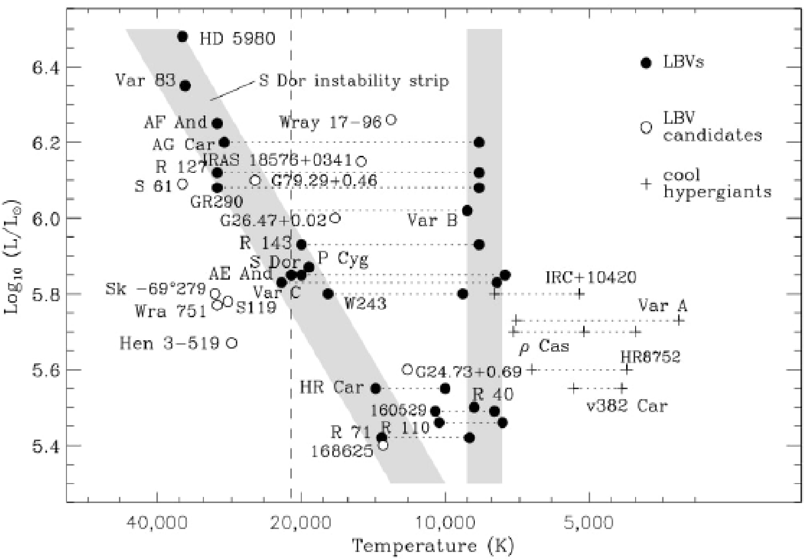

Figure 10. LBVs are plotted on the HR diagram in the figure, taken from Smith et al. (2004). Dark circles represent LBVs, hollow circles indicate c-LBVs, and the plus signs represent yellow hypergiants for comparison. The diagonal strip represents the quiescent phase of LBVs, while the vertical strip corresponds to the outburst phase. The dashed line at ≈ 21,000 K marks the bistability limit. The LBVs above the dashed line are classified as high-luminosity LBVs (classical LBVs), while those below the line are called low-luminosity LBVs.

A distinct gap was noticed just below 21,000 K on the S Dor instability strip, known as the bistability jump. Around 21,000 K, near spectral type B1, a discontinuity in the stellar wind property is observed. This discontinuity is accompanied by an increase in the mass-loss rate roughly by a factor of 10 (Vink 2018). This shift is linked to changes in the driving force of Fe III ion as the temperature decreases.

6.2 Spatial distribution

Figure 11 illustrates the spatial distribution of 11 confirmed and 12 candidate LBVs within the Milky Way. Although a greater number of LBVs are known, accurate distance determinations remain challenging due to high galactic extinction and additional obscuration caused by their own nebulae. The apparent grouping of LBVs and c-LBVs in Figure 11 is a result of selection bias, as the sample is based on the LBVs and c-LBVs listed in Smith et al. (2019). The distance measurements in that study are derived from data provided by Bailer-Jones et al. (2018). The background face-on Milky Way image was generated using the milkyway-plotPython package[1].

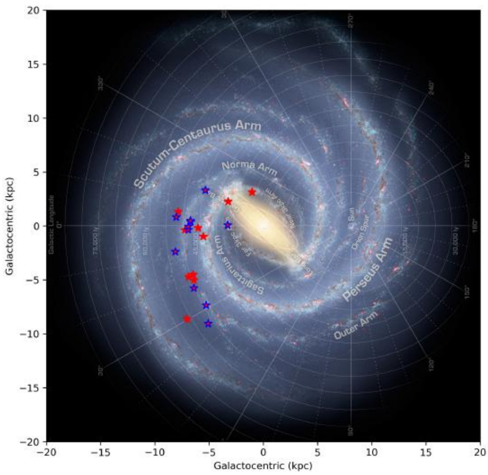

Figure 11. The figure above illustrates the spatial distribution of LBVs and candidate LBVs (c-LBVs) within the Galactic plane using Galactocentric Cartesian coordinates. The Galactic Centre is positioned at the origin (0,0). LBVs are represented by red stars, while c-LBVs are shown as blue stars. The background outlines the structure of the Milky Way, highlighting key features such as the major spiral arms and the Galactic bar for reference. The apparent clustering of LBVs and c-LBVs in his figure is due to selection bias. The data for LBVs and c-LBVs, including their distances, were taken from Smith et al. (2019).

Presently various techniques are being used to search for new c-LBVs. One of them is to search for mid-infrared circumstellar nebulae in Spitzer

[1] https://milkyway-plot.readthedocs.io/en/stable/

and Wise archives (Gvaramadze et al. 2010), and another is to look for objects with Hα emission like objects (Valeev et al. 2010).

7. Summary and prospects for future research

LBVs are a rare and highly variable class of massive stars known for their extreme photometric and spectroscopic variability. They undergo episodic mass-loss events, including S Doradus-type cycles and giant eruptions, which significantly influence their evolution and affect the surrounding interstellar medium. Traditionally considered a transitional phase between O-type stars and WR stars, LBVs were thought to shed their outer envelopes before evolving further. However, recent evidence suggests that some LBVs may bypass the WR stage altogether and explode directly as Type IIn supernovae, indicating a more diverse range of evolutionary outcomes.

Key points regarding LBVs:

- LBVs show two main types of variability: long-term S Doradus-type cycles, involving gradual changes in brightness and temperature, and short-term giant eruptions with sudden brightness increases of several magnitudes.
- Their spectra during quiescence resemble hot OB-type supergiants, while outburst phases exhibit features typical of A- or F-type stars due to a dense pseudo-photosphere.
- Strong hydrogen emission lines, HeI, FeII, [FeII] and P Cygni profiles are commonly observed, reflecting dense winds and ongoing mass loss.
- Mass-loss rates during eruptions can reach up to 10^{-4} $M_\odot$ yr^{-1}, contributing to the formation of nitrogen-rich circumstellar nebulae. • Increasing evidence points to the importance of binarity, with many LBVs possibly being products of mass transfer or stellar mergers.
- The spatial isolation of LBVs from O-type stars and OB associations challenges traditional single-star evolutionary pathways.
- Some LBVs may serve as direct progenitors of Type IIn supernovae, emphasizing the need to reconsider their endpoint in stellar evolution.
- Metallicity influences LBV behaviour; in low-metallicity environments, weaker line-driven winds may lead to different mass-loss histories and final outcomes.

7.1 Future prospects

Future research should focus on advancing both observational and theoretical understanding of LBVs, in order to address unresolved questions about their evolution, variability, and ultimate fate. Below are some key areas where further investigation is needed.

- *What triggers LBV variability?* — The physical mechanisms driving both S Doradus-type cycles and giant eruptions are still debated. It is unclear whether these are due to envelope instabilities, proximity to the super-Eddington limit, or a combination of factors such as pulsations and opacity effects.

- *Are LBVs a distinct evolutionary phase or a temporary state?* It is still not well established whether all massive stars pass through an LBV phase, or whether LBV behaviour arises only under specific circumstances, such as particular mass ranges, rotation rates, metallicity or binary interactions.

- *What is the connection between LBVs and supernovae?* — While some LBVs have been proposed as direct progenitors of Type Iin supernovae, observational evidence is still sparse. It remains uncertain whether these cases are rare exceptions or representative of a broader evolutionary path.

- *What role does binarity play?* — The extent to which LBVs are influenced by binary evolution, such as mass transfer or mergers, is not yet clear. Are LBVs primarily binary products, or do they emerge in both single and binary systems?

- *How does metallicity affect LBV evolution?* —While low-metallicity environments are thought to suppress line-driven winds, the exact influence on LBV lifetimes, variability, and explosion outcomes remains poorly constrained.

- *What is the internal structure of LBVs during outburst?* — The formation and structure of the pseudo-photosphere during outbursts is not well understood, limiting our ability to interpret spectroscopic observations accurately.

- *Do all LBVs form nebulae?* —While many LBVs are surrounded by circumstellar nebulae, the conditions required for their formation and their diversity in morphology and composition are still open for investigation.

In conclusion, LBVs remain one of the most fascinating and least understood phases of massive star evolution. Bridging the gap between theory and observation through comprehensive surveys and simulations will be key to uncovering the true nature and fate of these stellar giants.

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Author's contribution

1. Prasoon Ashok Singh: The author has developed this manuscript by reviewing and analyzing various research studies conducted on LBVs.
2. Gourav Banerjee: The author provided insightful suggestions since the beginning of the manuscript and thoroughly reviewed it multiple times to improve its quality.
3. Arun Roy: He is the supervisor of this project, and it was his initial idea to write a review paper on LBVs.
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