Massive Stars Near and Far
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Multiplicity of Galactic Luminous Blue Variable stars

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Abstract. Luminous Blue Variable stars (LBVs) are rare and enigmatic. Often cited as evolutionary stages in the single-star evolution, the idea that binary evolution produces the LBV state was already considered, 30 years ago.

It is now commonly accepted that a significant part of massive stars are born in multiple systems. One aspect that also emerged is that massive stars have on average at least two companions, i.e. they are triples. This immediately implies that a number of LBVs should have evolved as part of multiple systems.

While some LBVs are confirmed as binaries, different methods were used to derive their multiplicity, with different results. We report on a systematic search for multiplicity using spectroscopy, interferometry in a sample of 20 LBVs. Spectroscopy provides us with a bias-corrected binary fraction of 62^{+38}_{-24}%, and a percentage of $50-70$% is found from interferometry. This has a high impact on the way that these objects might be formed.

Keywords. stars: variables: S Doradus; stars: evolution; binaries: general; stars: massive; Astrophysics - Solar and Stellar Astrophysics

1. Introduction

Luminous Blue Variable stars (LBVs) are enigmatic objects in Astrophysics that are important to understand massive star evolution and their final fate. The classical LBVs experience outbursts, characterised by photometric and spectroscopic variability over periods from years to decades (the so-called S-Doradus cycle). During these cycles, the stars show visual magnitude changes of the order of one or two magnitudes, and they transit from cool to hotter regions in the Hertzsprung-Russell diagram. Their spectra vary from A- or F-type star when they are in a cool phase to B supergiant, O or even WR star when they are in a hot phase. Some LBVs also exhibit giant eruptions with visual magnitude changes higher than $2-3$ magnitudes, mimicking the appearance of type IIn supernovae (SNe). Finally, some stars also present common characteristics with the classical LBVs, but have never been detected to show S-Doradus variability or giant eruption: the dormant or candidate LBVs (Humphreys & Davidson 1994).

LBVs are traditionally thought to be an evolved stage of massive O- or B-type stars, in a transitory phase toward that of the Wolf-Rayet (WR, Conti 1984). Although O and

WR stars have high mass-loss rates, when integrated over the stellar lifetime, these rates are not sufficient to enable a smooth direct evolution. The stars must have gone through a phase of extreme mass loss (the LBV phase) to reveal the bare core that becomes the WR star. This short and extreme mass-loss phase is thought to occur for stars with masses higher than $25M_{\odot}$ stars and ranges in duration from 10^4 to 10^5 yrs.

However, the role of LBVs in massive star evolution appears not so simple. Their identification as progenitors of some high luminosity type IIb and IIn SNe challenged the traditional view of LBVs. Observational and theoretical evidences seem to indeed suggest that LBVs might be formed through binary interactions (e.g. Gal-Yam et al. 2007; Kiewe et al. 2012; Groh et al. 2013, 2020; Justham et al. 2014). While main-sequence O- and B-type stars are mainly found in young open clusters, the relative isolation of LBVs was also pointed out as possible evidence that LBVs are not the product of single-star evolution, but were in fact rejuvenated through mass transfer or merger events (Smith & Tombleson 2015; Smith 2016, 2019; Aghakhanloo et al. 2017, 2022). That claim was however strongly debated in the literature (Humphreys et al. 2016; Davidson et al. 2016; Aadland et al. 2018; Mehner et al. 2021), so that many challenges to understand the role of LBVs in massive star evolution remain.

While the majority (if not all) of massive O- and B-type stars are born in binary or multiple systems (Sana et al. 2012; Bodensteiner et al. 2021; Banyard et al. 2022; Bordier et al. 2022), the multiplicity of LBVs has not been clearly stated. Only a few LBVs in the Milky Way were detected as binaries: η Car (Damineli 1996), HR Car (Boffin et al. 2016, 2022 in prep.), MWC 314 (Lobel et al. 2013), HD 326823 (Richardson et al. 2011), and Pistol star (Martayan et al. 2012) but a general census on the multiplicity fraction was not obtained. Through their X-ray survey, Nazé et al. (2012) detected four objects (η Car, Schulte 12, GAL 026.47+00.02, and Cl* Westerlund 1 W 243) for which the X-ray detections are reminiscent of wind-wind collisions in binary systems, and five objects (P Cyg, AG Car, HD 160529, HD 316285, and Sher 25) in which the X-ray detections reach a strong limit that can be due to binarity, among other explanations. From this study, a binary fraction between 26 and 69% was claimed. Using high-resolution infrared images and adaptive optics, Martayan et al. (2016) investigated the close environments around seven LBVs to search for wide-orbit companions. Such companions were found for two out of seven objects (HD 168625 and MWC 314) but their physical link to the LBVs was not confirmed. From low-number statistics, Martayan et al. (2016) deduced a binary fraction for LBVs of about 30%.

If one accounts for the luminosities and the effective temperatures of LBVs, their radii are expected to be ranged from a few tens of solar radii to several hundreds. At their distances the best observing technique to unveil their multiplicity is the combination of spectroscopy and interferometry (see Fig. 1). We set up an observational campaign to collect new interferometric data of all the LBVs (classical and dormant) brighter than $V = 12.5 - 13.5$ mag and $H = 7.5 - 8$ mag, using VLTI/PIONIER and CHARA/MIRC-X. We combined these data with archival and new spectroscopic observations. Most of these results were presented in Mahy et al. (2022).

2. Data and methods

We built our sample from the LBV catalogues of Clark et al. (2005), Nazé et al. (2012), and Richardson & Mehner (2018). The spectroscopic sample gathers all the Galactic (classical and dormant) LBVs with V magnitudes brighter than 13.5 mag, plus Cl* Westerlund 1 W 243 and the Pistol star, which are fainter, because of the availability of archival data. We removed AG Car because the spectra in the archives are too strongly affected by the S-Doradus cycle to measure the RVs accurately. The interferometric sample gathers all the stars brighter than $H = 7.5$ mag in the northern and $H = 8$ mag in

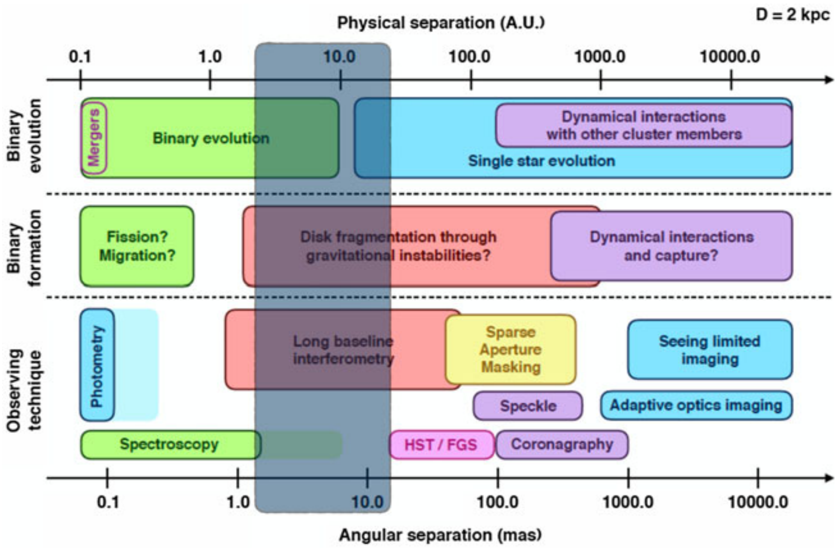

Figure 1. Sketch of the typical physical and angular separations covered by LBVs. A distance of 2 kpc is adopted, as representative of most objects (adapted from Fig. 1 of Sana 2017). Shaded blue area shows the typical separations expected with respect to LBV radii.

the southern hemisphere, because the sensitivities of PIONIER and MIRC-X are different. We collected interferometric snapshots for 20 stars (ESO Programme IDs: 0102.D-0460, 105.20AC, 109.231M, PI: Mahy). To extend this sample, we also used the published interferometric results for η Car (Gravity Collaboration et al. 2018), HR Car (Boffin et al. 2016), and Pistol star (Martayan et al. 2012). The final samples are shown in the left panel of Fig. 2. We stress that more objects are included for the present work than published by Mahy et al. (2022). We also refer the reader to Mahy et al. (2022) for more information about the sample, and the data reduction.

3. Results

3.1. *Spectroscopy*

The detection of secondary components orbiting around LBVs from spectroscopy is difficult because of (1) the difference in luminosity between the components and (2) the strong variability characterising the LBVs (Weis & Bomans 2020). Furthermore, given the LBV radii, their possible companions are expected to be on wide orbits and spectroscopy is not ideal to detect them. We measure the radial velocities (RVs) of the LBVs by focusing on spectra that do not show strong variability due to the S-Doradus cycle (i.e. we focus on spectra taken during the same quiescent/hot phase). We use a cross-correlation technique presented by Zucker (2003).

To classify a star as a likely spectroscopic binary, we use two criteria:

(a) $\frac{|\mathrm{RV}_i - \mathrm{RV}_j|}{\sqrt{\sigma_i^2+\sigma_j^2}} > 4.0$,

(b) $\Delta\mathrm{RV} = |\mathrm{RV}_i - \mathrm{RV}_j| > \Delta\mathrm{RV}_{\mathrm{min}}$,

where RV_i and RV_j are the individual RV measurements and σ_i and σ_j the respective 1σ errors on the RV measurements at epochs i and j. If and only if at least one pair of RVs measured at different epochs simultaneously satisfies these criteria, the star is reported as spectroscopic binary. The observed binary fraction as a function of the $\Delta\mathrm{RV}_{\mathrm{min}}$ value

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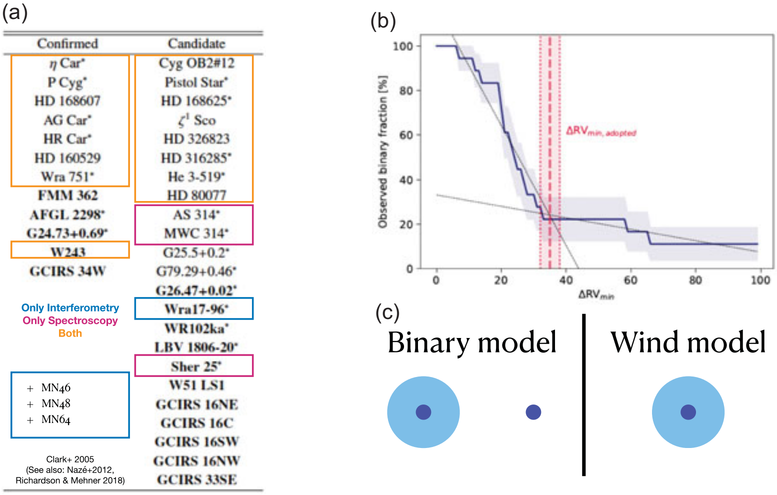

Figure 2. a) List of Galactic classical and dormant LBVs observed for this work, b) Observed binary fraction as a function of the adopted RV-variability threshold ΔRV_{min}. The vertical dotted line gives the adopted threshold value $\Delta RV_{min} = 35 \pm 3$ km s^{-1}, indicated by the red line (the shaded area represents the 1σ error), and c) Interferometric models used for CANDID (left), and LITPro (right).

is displayed in the top right panel of Fig. 2. A kink is clearly visible at 35 km s^{-1}. We adopted this value as threshold, considering all the variability under that threshold dominated by intrinsic variability, and everything above that threshold dominated by binarity. The observed spectroscopic binary fraction is equal to $f_{obs} = 26^{+16}_{-10}\%$, where binomial statistics have been used to compute the uncertainty.

To obtain the intrinsic spectroscopic binary fraction for the Galactic LBVs, the observed binary fraction needs to be corrected for the observational biases. We run simulations following the approach described in Sana et al. (2013) to compute an estimate of the sensitivity of our observations and this provides us with a correction factor (see more details in Mahy et al. 2022). Once we correct for the observational biases, the intrinsic spectroscopic binary fraction rises to $f_{int} = 62^{+38}_{-24}\%$.

3.2. *Interferometry*

To search for astrometric companions among LBVs, we used the CANDID (Gallenne et al. 2015) and the Lyons Interferometric Tool prototype (LITPRO, Tallon-Bosc et al. 2008) codes. CANDID is a set of python tools that was specifically created to systematically search for high-contrast companions. It assumes a disc for the primary, an unresolved secondary, and additional background flux. However, because LBVs are characterised by strong winds, a wind model, composed of a disc or point-like source and a Gaussian profile to model the winds and centred on the star) also needed to be tested using LITPro (see the bottom right panel of Fig. 2). For ten stars in our sample (HD 160529, P Cyg, HD 168625, ζ Sco, Schulte 12, Cl* Westerlund 1 W 243, HD 326823, WRAY 15-751, MWC 930 and WRAY 17-96), the fits performed by CANDID provide a lower chi-square, suggesting that these objects are binary systems. For five stars (AG Car, [GKF2010] MN46, and [GKF2010] MN48, WR 31a, and HD 168607), the measured chi-squares with CANDID and LITPro are equivalent and the difference between the two models become insignificant. If we also consider HR Car, the Pistol star, and η Car (already reported as interferometric binaries), our analysis shows that the binary fraction among the Galactic LBVs is between 50 and 75%.

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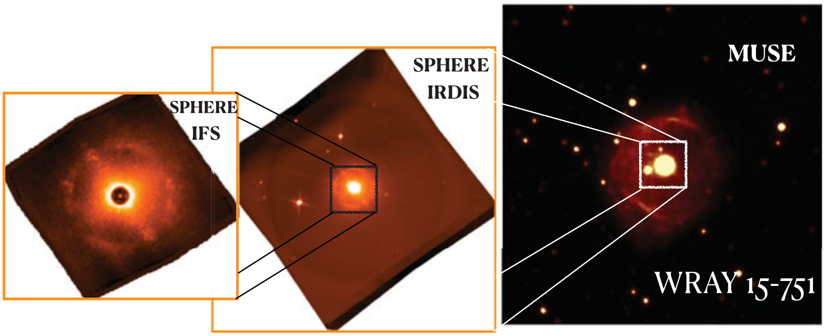

Figure 3. Newly acquired SPHERE/IFS+IRDIS and MUSE/WFM images of WRAY 15-751, with respective field-of-views of 1.73″, 11″, and 1′.

4. Conclusions

Massive stars predominantly live their lives in binary or multiple systems (Sana et al. 2014; Moe & Di Stefano 2017) with on average more than two companions. As a consequence, the presence of a companion severely impacts the evolution of these stars with a significant percentage of stellar mergers ($\sim 24\%$), accretion and spin up or common envelope evolution ($\sim 14\%$), and envelope stripping ($\sim 33\%$). Binary star evolution must therefore be considered as a possible channel to form LBVs (Gallagher 1989). Furthermore, the idea of merger events was proposed to explain the giant eruption observed for η Car (Smith et al. 2018; Hirai et al. 2021).

The search for binarity among the Galactic LBV population could provide a quantitative test to understand how these objects are formed. Our study shows that a large fraction of Galactic LBVs are binary systems, most of them being detected with interferometry. We stress, however, that so far the physical association of these detections with the LBVs (classical or dormant) only relies on statistical arguments and further observations are still needed to derive the orbital parameters of these possible systems. It is also interesting to investigate larger separations to probe their close environments (Fig. 3).

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