Exploring the binary origin of B and Be rapid rotators

Jonathan Labadie-Bartz[1,2*], Mark Suffak[3], Carol Jones[3†], Yaël Nazé[4†],
Ken Gayley[5†], Geraldine Peters[6†], Rina Rast[3†], Anusha Ravikumar[3†],
Asif ud-Doula[7†], Coralie Neiner[2†], Jeremy J. Drake[8†]

[1] DTU Space, Technical University of Denmark, Elektrovej 327, Kgs., Lyngby, 2800, Denmark.
[2] LIRA, Paris Observatory, PSL University, CNRS, Sorbonne University, Université Paris Cité, CY Cergy University, 5 place Jules Janssen, 92195 Meudon, France.
[3] Physics and Astronomy, The University of Western Ontario, 1151 Richmond Street, London, N6A 3K7, Ontario, Canada.
[4] STAR Institute, Univ. of Liège, Allée du 6 Août 19c, Bât B5C, Liège, B4000, Belgium.
[5] Department of Physics & Astronomy, University of Iowa, 203 Van Allen Hall, Iowa City, 52242, IA, USA.
[6] Department of Physics and Astronomy, University of Southern California, 825 Bloom Walk, ACB 439, Los Angeles, 90089-0484, CA, USA.
[7] Penn State Scranton, 120 Ridge View Drive, Dunmore, PA 18512, USA.
[8] Advanced Technology Center, Lockheed Martin, 3251 Hanover St, Palo Alto, 94304, CA, USA.

*Corresponding author(s). E-mail(s): jbartz@udel.edu;
Contributing authors: msuffak@uwo.ca; cejones@uwo.ca; ynaze@uliege.be;
ken.gayley@gmail.com; gpeters@usc.edu; krast@uwo.ca; araviku4@uwo.ca; auu4@psu.edu;
coralie.neiner@obspm.fr; jeremy.1.drake@lmco.com;
†These authors contributed equally to this work.

Abstract

Observational evidence has continued to mount that a significant fraction of rapidly rotating early-B type stars are products of binary mass transfer. However, very few mid- and late-type B stars with rapid rotation have been demonstrated to be post-interaction products, despite a growing sample of SB1 binaries among stars within this range of spectral types. By considering the currently available information over the entire range of rapidly rotating B-type binaries, we argue that a significant fraction of the mid- and late-type rapid rotators found in binaries are also likely the result of past mass transfer episodes. The observed properties of this sample are compared to the predictions from the Binary Population and Spectral Synthesis code (BPASS), with attention given to the expected evolutionary pathways of stripped stars and the stellar and binary properties of both components of post-interaction systems across a range of initial conditions. Prospects for directly detecting and characterizing the stripped cores of the previous mass donors in such systems are described, and the implications for the role of binary interaction in causing rapid rotation are discussed. An

accurate description of prevalence of binary interaction, the physics of mass transfer, and the post-interaction configuration of systems over a range of initial conditions has far-reaching implications including double-degenerate binaries and their eventual mergers, the output of ionizing UV flux of stellar populations, and the supernova explosions that can arise from stripped or rapidly-rotating progenitors.

1 Introduction

B-emission or Be stars, for short, are B-type stars that produce Balmer emission lines in their spectra due to the presence of a geometrically thin disk of material in the equatorial region of the star, sometimes extending radially out to tens of stellar radii. The disk material is ejected from the star likely due, in part, to rapid stellar rotation (see Collins 1987 for a commonly quoted definition and the article by Rivinius et al 2013 for an extensive review of these stars).

These star/disk systems have been studied for over 150 years since they were discovered in 1866 when Angelo Secchi observed the Be star γ Cassiopeiae (Secchi, 1866), but there remain two major unanswered questions. The first asks what physical process(es), in addition to rotation, act to supply surface material with sufficient angular momentum (AM) to achieve Keplerian orbital velocities leading to the formation of a disk, usually through discrete "outburst" episodes. The second relates to the origin of their rapid rotation and high AM content, and how this is maintained through their main sequence (MS) and further evolution.

The focus of this paper is on the second question, namely the origin of rapid rotation. Generally, there are two scenarios that can give rise to the rapid rotation that we observe in Be stars today: such stars may have emerged on the MS already as rapid rotators (e.g. Martayan et al, 2006; Martin et al, 2007), perhaps with evolutionary processes acting to accelerate the surface rotation and keeping in mind that the critical rotational velocity decreases with age as the star expands (Ekström et al 2008; Georgy et al 2013; Hastings et al 2020) – this is the single-star evolutionary channel, or they may have acquired an excess of AM during binary mass transfer (the binary interaction evolutionary channel). Evidence continues to mount that a sizable fraction of Be stars were spun up to near-critical via binary mass transfer (van Bever and Vanbeveren, 1997; Hastings et al, 2021; Wang et al, 2021). Jones et al (2022, and references therein) provide a description of theoretical and observational efforts addressing the role of binarity interaction (or lack thereof) leading to rapid rotation, so this is not repeated here. Instead, a brief overview of the key points are discussed below. There is no physical reason to suggest the origin of rapid rotation is an "either/or" scenario – both single- and binary-star evolution are capable of leading to rapid rotation. The question remains as to the relative importance of these channels.

There are many reasons why the rapid rotation of these stars, and its origin, is important. Rapid rotation impacts the internal structure, not least by making the star non-spherical. It also increases the size of the convective core (Neiner et al, 2012) and thus the amplitude of pulsations stochastically-excited in the core (Neiner et al, 2020). Rotation is believed to enhance mixing of fusion fuel into the core, extending the main sequence and altering stellar evolution, as well as changing surface abundances (Maeder and Meynet, 2000b). It can also increase mass loss from the most luminous stars (Maeder and Meynet, 2000a), and change the nature of their ultimate supernova (Yamasaki and Yamada, 2005; Summa et al, 2018). If rapid rotation is related to binary interaction, as explored further in this paper, it also implies a tight connection between the appearance of rapid rotation, and the birth of massive stars via mass transfer from a companion. Such rejuvenated stars, and their stripped companions, change in important ways the ionizing radiation and supernova yields from what would otherwise be expected from a single-star initial mass function (IMF), especially in later times after an initial burst of star formation (Götberg

et al, 2019, 2020). Hence, understanding the origin of rapid rotation can fill in important details about many aspects of massive-star populations.

Also, this paper focuses on binary mass transfer leading to stripped companions of rapidly rotating B stars. These helium-rich stripped companions can be sdOB stars with masses between about $0.3 - 2$ M$_\odot$, or high-mass stripped stars between about $2 - 8$ M$_\odot$, such as those recently detected by Drout et al (2023). The somewhat arbitrary distinction is that the latter group can lead to phenomena like core collapse supernovae of hydrogen-free stars and gravitational waves from neutron star mergers, whereas the former can lead instead to binary helium white dwarfs that merge to produce He-rich sdO stars (Pandey and Lambert, 2017; Dorsch et al, 2022) or double-degenerate type Ia supernovae. Nevertheless, they are both drawn from the same population of stars generated by mass transfer, and their impact on the release of ionizing radiation long after episodes of star formation is related and should be understood together as a unit.

It is important to note that binary mass transfer can result in a rapidly rotating B-type star that does not create a decretion disk because rapid rotation is not a sufficient ingredient to create a Be star. For simplicity, we will refer to rapidly-rotating B-type stars that have never been observed with emission as Bn[1] stars, and rapid rotators in general (whether or not they posses a disk) as Be/n stars.

Binarity is important in the upper main sequence, and Be stars are not an exception. However, the observed binary properties of Be stars differ significantly from their non-Be (or more generally, slower rotating) counterparts. For example, there are no known relatively close (P$_{\rm orb} \lesssim 300$ d) early-Be+MS binaries (Bodensteiner et al, 2020b). Instead, nearly all known binary companions to Be stars are evolved. Less attention has been given to the Bn stars in this regard, so the binary properties of the Bn population are poorly understood. It remains an open question if the rapid rotation

in Be and Bn stars arises from binary interaction in a similar proportion.

There are several methods for direct and indirect detection of binarity for Be/n stars. Direct detection of companions typically involves recovering their spectroscopic signature in either UV or visible light (in addition to the rotationally-broadened lines of the Be/n component), or resolving a binary pair with interferometry. Eclipsing binaries (EBs) are also a possibility and detectable through orbital modulation in brightness. In the aforementioned cases, the nature of the companion (whether a stripped star or on the MS) can be determined. In the following cases, the evolutionary status of a companion is not revealed. Radial velocity (RV) measurements of Be/n stars can enable SB1 orbital solutions, providing orbital periods, RV semi-amplitudes of the Be/n star, eccentricity, and a mass function from which the secondary mass can be estimated. For Be stars, their disks can be used to indirectly probe for the presence of a companion. In particular, tidal forces from a companion both truncate the disk (Klement et al, 2019), and cause spiral density waves (called $m = 2$ modes, e.g. Panoglou et al, 2016, 2018; Cyr et al, 2020; Miroshnichenko et al, 2023). While disk truncation may hint at the presence of a companion and indicate an approximate orbital separation, $m = 2$ modes can provide an estimate of the orbital period (although the signature of an $m = 2$ mode may be observed at $P_{\rm orb}$ or $0.5 \times P_{\rm orb}$). In some cases, when a companion is very hot (as a high temperature stripped star), its radiation field can strongly impact the disk leading to observational features that support the system being a post-interaction binary, such as localized He I emission with RV motion in phase with the orbit (Hummel and Štefl, 2001; Koubský et al, 2012; Peters et al, 2013).

The aim of this paper is to gather information from the literature about the many individual Be/n stars that are confirmed binaries, and compare this to the MS B+B binary population, while also exploring similarities and differences over the range of Be/n spectral types. To aid in this, the binary population synthesis code BPASS (Eldridge et al, 2017) is employed to recover the range of initial binary configurations that could result in the sort of post-interaction Be/n binaries that are known, and in particular to make inferences about where low-luminosity stripped stars

---

[1]The "n" and "nn" designations date back to the early days of spectral classification, which was done from photographic plates. Broadened, or "blurred" photospheric lines from elements heavier than H or He were seen if the $v\sin i$ of the star was $\geq$ to the plate dispersion in Å /mm (Jaschek and Jaschek, 1990). "n" meant that blurred (nebulous) lines were observed, while "nn" meant the lines were very nebulous.

may be found in the Hertzsprung-Russell diagram (HRD) to guide observational efforts to detect and characterize such objects. Emphasis is given to systems that may have interacted in the past, or may interact in the future – that is, very wide binaries are not in general considered.

Section 2 provides an overview of the various types of relevant systems in a pre-interaction, ongoing-interaction, and post-interaction configuration. Section 3 then examines stellar and binary information from known or candidate Be/n binaries, and compares these to the MS B+B population while also giving consideration to the range of properties within the binary Be/n sample. Section 4 describes the Be/n binaries (including any known information about the companion star) on the HRD, along with BPASS evolutionary tracks of stripped stars, and Section 5 provides an outlook for observational strategies that can fill in the predicted parameter space that stripped stars are expected to occupy. Conclusions are given in Section 6.

2 Overview of current knowledge of Be/n binaries

When considering the role of binarity in causing a star to spin up to near critical, the discussion should be focused on relatively close binary systems that can physically interact at some point in the MS or post-MS phase via mass transfer or a merger. Here, we focus only on these cases. There are, however, many examples of Be stars with very wide companions, such as the well-known system β Cephei, with a magnetic slowly-rotating pulsating B2III primary, and a mid-type (B5Ve) Be star on an $\sim$81 year orbit (Pigulski and Boratyn, 1992; Wheelwright et al, 2009). These two stars have not and will not interact, so that the primary plays no direct role in shaping the rotational properties or evolution of the Be star; therefore, we exclude such systems from this study.

In a broad sense, there are two classes of (close) Be/n binaries – pre-interaction, and post-interaction. There may also be currently interacting systems with accretion disks, but these should be comparatively rare due to the short timescales involved. There can also be genuinely single Be/n stars[2], but these are difficult to confirm as it is challenging to rule out the possibility of faint low-mass companions. The following subsections describe what is currently known about these classes.

2.1 Pre-interaction binaries

Possible evidence for single-star or pre-interaction evolution into a Be phase would come from relatively short-period Be+MS systems, but these are apparently extremely rare. In these cases, it may be presumed that the Be star has evolved as single. Presently, the two shortest period Be+MS systems are α Eri (Achernar, B6) with an early-A secondary in an eccentric (e = 0.73) seven-year orbit (Kervella et al, 2022) and δ Sco (B0) in a highly eccentric (e=0.94) 11 year orbit with a main-sequence B2 companion (Tango et al, 2009; Tycner et al, 2011). However, it should be noted that the presence of a main-sequence companion at $\sim$10 AU separation (as in α Eri and δ Sco) does not necessarily preclude binary interaction in a tight inner binary with separation <1 AU. For example, HD 150136 exhibits a massive inner binary with separation $\sim$0.1 AU, and a slightly lower mass tertiary companion at 12 AU (Sana et al, 2013), which could in time lead to a rapid rotator coupled to a main-sequence star at larger distance as seen in α Eri and δ Sco.

It is notable that α Eri and δ Sco are the two brightest Be stars in the sky, leaving open the possibility that many more such systems could exist. However, detecting the MS components of α Eri and δ Sco is intrinsically difficult without the use of interferometry. The radial velocity (RV) variations of the Be star due to binary motion is very small (typically a few km s^{-1}), and owing to the long periods and wide Be absorption lines (broadened by their rapid rotation), long time series of high-SNR spectroscopy are required to detect and characterize such orbits. However, interferometric surveys (e.g. Klement et al, 2024) have recently expanded the limited distances to which main-sequence companions could be detected, yet failed to discover new Be+MS binaries. This is the basis for regarding such binary configurations as rare, especially since those same interferometric surveys

---

[2]However, see Section 2.3.7 for a brief overview of runaway Be stars, which are presently single but widely believed to be post-interaction systems.

have succeeded in detecting the key alternative: stripped subdwarf companions over a range of luminosities (see Sections 2.3.2 and 2.3.3).

Some recent works have started to discover and characterize pre-interaction systems with rapidly-rotating OB star primaries in short orbital periods. Nazé et al (2023) describe three massive (O7, B0, and B3) rapid rotators ($v\sin i > 200$ km s^{-1}) in short period (days) binaries with pre-MS companions, indicating that these are young pre-interaction systems where the rapid rotation of the primary is an intrinsic property of the star. Other qualitatively similar examples include the rapidly rotating ($v\sin i = 216$ km s^{-1}) early-B primary in HD 149834 with a ~ 1.2 M$_\odot$ companion (Stassun et al, 2021), HD 165246 with an O8 primary with $v\sin i = 243$ km s^{-1} (Johnston et al, 2021), and γ Lupi A (B5) with $v\sin i = 236$ km s^{-1} (Jerzykiewicz et al, 2021). Others include HD 163892 (O9.5IV(n), Mahy et al, 2022) and HD 152200 (O9.7IV(n), Britavskiy et al, 2024), all with $v\sin i > 200$ km s^{-1}. A dozen more B+pre-MS cases have been reported in Naze et al (2025) and the vast majority of them also show supersynchronous rotation. While none of these systems include Be stars, their existence demonstrates that binary interaction is not required for achieving rapid rotation. Some other works indeed argue that a significant fraction of B-type stars emerge on the ZAMS with a relatively high rotational velocity (e.g. Huang et al, 2010; Wang et al, 2022), but the true initial rotational velocity distribution for massive stars remains difficult to ascertain, as it requires distinguishing between stars that have evolved as single versus those that have experienced binary interaction (de Mink et al, 2013).

2.2 Interacting systems

There are many types of interacting binaries across the HRD, but the ones that concern us here are primarily the massive Algol systems. Algol-type binaries are the class of eclipsing binary stars comprising an early-type MS star and a late-type, secondary sub-giant or giant star that fills its Roche lobe. The evolutionary state of Algol systems was first explained by a mass transfer model more than 70 years ago (Crawford, 1955; Plavec, 1970), but details concerning the mass transfer process have slowly emerged only over the past 40

years (Peters et al, 2022, and references therein). The *massive* systems typically have total masses greater than 5 $M_\odot$. For the B-type systems, the Roche lobe-filling (secondary) star, usually has a mass less than 2 $M_\odot$. Secondaries in the O-type systems often show masses greater than 10 $M_\odot$. Less than one-third of the semi-detached binaries listed in recent catalogs (e.g. Malkov, 2020) are massive Algols according to our definition. X-ray emission is typically observed in Algol systems and is due to activity on the surface of the late-type giant (e.g., Chung et al, 2004). Highly ionized species (e.g. N V, C IV, Si IV) tend to be seen in absorption or emission at the phase interval 0.4-0.6 during the mid-latter stages of post-mass reversal mass transfer and are likely a result of shock heating from the impacting gas stream (Peters and Polidan, 1984).

It is reasonable to suspect that the massive Algols may eventually evolve into OBe/n + sdO systems. For example, the Algol binary RY Per (B3Ve + F7II-III), which presently has a systemic mass of $8M_\odot$ (Barai et al, 2004), could become a system like 28 Cyg (Klement et al, 2024) or 59 Cyg (Peters et al, 2013), but its orbital separation would have to increase by a factor of 13.5 or 4.1 to resemble 28 Cyg or 59 Cyg, respectively. The RY Per system is approaching mass transfer shutoff and the donor star is already less than 2 $M_\odot$, so there is not that much mass left to transfer. Furthermore, the rotational velocity of the mass gainer is only 215 km s^{-1}, which is less than half the critical velocity needed to form the Be star's disk but still significantly faster than if the star were tidally synchronized. The Algols may be on their way to becoming Be/n + sdOB binaries but the angular momentum transfer needs further study.

A (limited) number of systems with an accreting B star paired to a red giant have also been spotted. They are interpreted as binaries in which mass transfer is currently occurring, i.e. in which the emission line arises from active accretion of material from the companion by the B star. Harmanec et al (2015) lists nine such systems, with periods in the range 6 to 36 d and low mass ratios of ~ 0.06 to 0.30 (as expected after mass ratio reversal although UX Mon, with a ratio of 1.15, is a rare pre-reversal case). There are also other examples such as, AX Mon (Be+KIII, $P \sim 232$d,

Elias et al 1997) and V644 Mon (B1 V+K0 I-II, $P \sim 121$d, Aufdenberg and Bopp 1994). Table 8 in Harmanec et al (2015) lists ten other systems that he describes as possible semi-detached emission-line binaries. The B-type mass gainers in these systems rotate significantly faster than the orbital period, but in general seem sub-critical.

2.3 Post-interaction systems

In post-interaction systems that now contain a Be/n star, it is generally understood that the originally more massive star transferred mass and angular momentum causing the spin-up of the mass gainer eventually leading to the rapidly rotating B star becoming a Be/n star and leaving a stripped-envelope companion star (the mass donor). There are several classes of post-interaction systems that are observed. These are described in the following subsections, which are listed roughly in order of increasing luminosity of the stripped star, followed by post-supernova systems.

2.3.1 Supersoft X-ray emitters

In recent years, a dozen OBe stars (mostly belonging to the Magellanic Clouds) were found to be associated with bright, flaring, and very soft X-ray sources (e.g. Cracco et al, 2018). Since the X-ray emission properties appear typical of nuclear burning on a WD surface, these systems were identified as Be+WD binaries. Orbital periods could be determined only in two cases: 17d for both Swift J011511.0-725611 (Kennea et al, 2021) and CXOU J005245.0-722844 (Gaudin et al, 2024; Marino et al, 2025). The optical components of these two systems are early-type Be stars. Although apparently rare, there are also binary systems with fast-rotating B-type stars (plausibly Be) that present nova behavior, where the accreting star is necessarily a WD (Chamoli et al, 2025; Schaefer et al, 2025).

2.3.2 Low-luminosity low-mass companions

The post-interaction system Regulus includes a near critically-rotating (but diskless) MS B8 star, and a low-luminosity pre-WD on a circular 40 d orbit. Although the binary nature was known for some time (Gies et al, 2008), detecting the

stripped companion required a considerable quantity of high-SNR spectroscopy due to the very low luminosity of the ~ 0.3 M$_\odot$ stripped star (Gies et al, 2020). A similar system is KOI-81, found to be a rapidly rotating diskless B8V star in a circular 23.88 d eclipsing binary with a ~ 0.2 M$_\odot$ stripped star (Matson et al, 2015). These are the only two near critically-rotating Bn stars with published stellar and binary parameters that we are aware of.

The relatively well studied class of Be+sdOB binaries now includes about 20 members (e.g. Gies et al, 1998; Peters et al, 2013, 2016; Wang et al, 2018, 2021, 2023). The stripped stars are generally understood to be helium-fusing hot subdwarfs with temperatures similar to main sequence O-type stars ($\gtrsim 40$ kK) and masses of about 0.5 – 2 M$_\odot$. While hot, their small size (~ 0.5 R$_\odot$) makes them difficult to detect and characterize against the glare of their much more luminous MS companions. Be+sdO binaries tend to have near-circular orbits, but in 60 Cyg and 59 Cyg the eccentricities are 0.2 and 0.14, respectively (Peters et al, 2013; Klement et al, 2024). Orbital periods range from about 30 – 300 d. In all but two such systems (κ Dra and HD 92406), the rejuvenated component is an early-type Be star. κ Dra (B6) has a slightly cooler-than-typical subdwarf with a temperature typical of a MS B star, making this the first Be+sdB type system discovered (Klement et al, 2022a). HD 92406 is an eclipsing system first reported by Hauck (2018) with a late-type Be star and a ~ 0.5 M$_\odot$ stripped star that lies between the temperature and luminosity of the stripped star in κ Dra and those from the bulk of the known Be+sdO population (de Amorim et al, 2025).

2.3.3 High-luminosity low-mass companions

Stripped stars of around one solar mass can have a similar temperature and size (and therefore luminosity) as the much more massive mass gainer during a short-lived evolutionary phase after the cessation of mass transfer (e.g. Villaseñor et al, 2023; Rivinius et al, 2025). These "bloated" stripped stars tend to have slow rotation and near-circular orbits, although it is possible, for reasons yet unclear, that high eccentricities are allowed (e.g. HIP 15429, Müller-Horn et al, 2025). It is presumed that in such systems, the stripped

star will contract to become a core helium burning subdwarf, joining the more populated class of Be+sdOB binaries (Section 2.3.2).

2.3.4 High-luminosity higher-mass companions

At higher stripped star masses ($\sim 2 - 8$ M$_\odot$), the stripped star can be more luminous than the mass gainer, appearing as a lower-mass analog of Wolf Rayet (WR) stars. Such objects are expected to remain highly luminous until exploding as a supernova, rather than evolving to become a low-luminosity hot subdwarf (Hovis-Afflerbach et al, 2025). About a dozen such systems have been detected in the Magellanic Clouds (Götberg et al, 2017; Drout et al, 2023; Ramachandran et al, 2024). One qualitatively similar Galactic case is known, HD 96670, with a stripped star of ~ 4.5M$_\odot$ and an evolved O-type star in an orbital period of only 5.28 d (Nazé and Rauw, 2025). The mass gainer in HD 96670, with $v\sin i \sim 175$ km s^{-1}, may not be a 'proper' rapid rotator, but may have been spun down by some combination of evolution, AM loss through winds, and tidal effects. The temperature, luminosity, and mass of the stripped star in HD 96670 are similar to the sample from the Magellanic Clouds, although the O-type mass-gainer dominates the total flux of the system. The full sample of Drout et al (2023) includes stripped stars with presumed main-sequence companions with undetected, moderate, and large contributions to the optical flux. It should be noted that the stripped stars analyzed in Götberg et al (2017), which is the sub-sample of systems from Drout et al (2023) that are without detected companions, possibly underwent a common envelope phase where the presumed main-sequence lower-mass companion did not accrete much material or angular momentum. More detailed information about the systems with stripped stars and signatures of a luminous MS star (which may be post mass-transfer binaries) from Drout et al (2023) are not currently available.

2.3.5 Wolf-Rayet companions

Classical Wolf-Rayet (WR) stars are hot envelope-stripped stars with high initial masses in a late stage of evolution. Some fraction of WR stars have lost their envelope via binary interaction, while others (especially with relatively high initial masses) may strip their envelopes via strong winds and/or eruptive mass loss episodes (Shenar, 2024). The relative frequency of these two evolutionary paths for producing WR stars is still an open question (Neugent and Massey, 2014; Shenar et al, 2019, 2020b).

For WR stars that have been stripped via Roche lobe overflow (RLOF), the mass gaining component, which is typically an O-type star, may be spun up in the process. Typical rotation rates of these mass gainers are super-synchronous, where typical post-RLOF orbital periods may be anywhere from days to months, with rotation rates found to be about $\sim 50\%$ of critical (e.g. Shara et al, 2017, 2020).

However, Reeve and Howarth (2018) argue that the rotation rates of the O stars in WR+O binaries can be systematically overestimated by a factor of ~ 2, due to the complexity of the composite spectra of such systems and difficulties in identifying the pseudo-continuum from which to measure absorption line properties. Nevertheless, evidence suggests that the O-type companions of binary-stripped WR stars rotate faster than apparently single O-type stars, but perhaps not much more than $\sim 30\%$ of critical (barring some exceptions; Shenar et al, 2019). Some physical processes, such as magnetic braking during the mass transfer phase (Reeve and Howarth, 2018) and/or tidal interactions, act to quickly slow the rotation of the mass- and AM-gaining O-type star.

2.3.6 Be/X-ray binaries

Be/X-ray binaries (BeXRBs) are a subclass of Be binaries made up of a Be star and a neutron star (NS; Reig, 2011). The primary stars in these binaries are always early-type Be stars (Reig, 2011). As emitters of high energy X-rays, they represent the largest class of high-mass X-ray binaries (Fortin et al, 2023). They are among the brightest X-ray sources in the sky (Reig, 2011), with X-ray luminosities on the order of 10^{36-37} erg s^{-1} or larger. The X-ray flux is produced by the accretion of disk material onto the NS. Both the X-ray and visible flux in such systems are highly variable, and orbits are often eccentric and misaligned with respect to the Be star's equator (Hughes and Bailes, 1999; Martin et al, 2011; Salvesen and Pokawanvit, 2020; Marcussen et al, 2024). It is generally accepted

that the supernova event that creates the NS in such a system produces a kick that also sets the NS on a new, disrupted orbital path. Martin et al (2009) found that while such a kick can explain the observed misalignment angles of BeXRBs, the eccentricities may be influenced by more complex events (such as circularization over the lifetime of the system). There are more than 70 known BeXRBs in the Galaxy (Fortin et al, 2023), with roughly 100 more found in the SMC and LMC (Coe and Kirk, 2015; Antoniou and Zezas, 2016). It is possible that Bn stars may exist in similar binary configurations, however they will not emit in X-rays due to the lack of circumstellar material (the accretion of which powers the X-ray emission in BeXRBs).

Black Hole (BH) companions, which may have very low X-ray luminosities (Sen et al, 2024), are also starting to be discovered orbiting massive OB stars, which at least in some cases rotate rapidly (Shenar et al, 2022). The system MWC 656 was claimed to be a Be+BH binary (Casares et al, 2014), but this has been challenged by more recent analysis of this system which instead suggests the companion to the Be star is consistent with being a hot stripped star (Janssens et al, 2023; Rivinius et al, 2024). To our knowledge there are currently no confirmed Be+BH binaries in the literature.

2.3.7 Runaway Be stars

Runaway stars (or 'walkaway stars', being less extreme but qualitatively the same) are systems with anomalously high space velocities and/or found at large distances from their birth environment compared to what is expected from typical kinematics. Generally, runaways were imparted with high space velocities either through dynamical scattering (e.g. multiple-body interactions in a dense cluster environment), or by having a binary companion that explodes as a SN. Some fraction of Be stars are runaways, although the statistics depend on the environment being studied. Boubert and Evans (2018), for instance, determined that about 13% of Galactic Be stars are runaways, and interpreted this as evidence for a high fraction of Be stars being post-interaction products. Dorigo Jones et al (2020) analyzed the runaway populations of the Small Magellanic Cloud and reached a similar conclusion – a high fraction of runaways with high $v\sin i$ (including Be stars)

suggests that binary interaction is a major contributor to rapid rotation. However, it should be emphasized that rapidly-rotating runaways are not all guaranteed to have been spun up by binary interaction, since dynamical scattering can be a major contributing factor to the runaway population in general (Carretero-Castrillo et al, 2023).

3 Comparing binary populations

It is now well established that some fraction of Be/n stars have been spun up via binary interaction as demonstrated by the growing number of confirmed Be+sdO and similar post-interaction systems (Section 2.3). We have attempted to compile information from the literature for as many known post-interaction Be/n binaries as possible in Appendix A. However, these lists are probably not exhaustive, and this is a rapidly advancing field such that there are likely to be newly discovered systems and improved/updated parameters by the time of publication.

The large majority of confirmed post-interaction systems with a Be star (including all BeXRBs and runaways) contain an early-type Be star (∼B3 and earlier), and a stripped star mass of about 0.5 $M_\odot$ and above. One aim of this section is to test whether or not there is reason to believe there is a similar population of post-interaction late-type Be/n+stripped binaries which have so far avoided direct detection. Another is to compare the SB1 Be/n population to the confirmed Be/n+stripped population. In this Section, only systems that could plausibly be post-interaction are considered. That is, very wide binaries (visual doubles, or with orbital periods on the order of many years) are ignored.

First, it is useful to compare certain binary parameters measured for Be/n stars to those of the normal B star binary population. The most readily available orbital parameters are the period (P_{orb}), eccentricity (e), and radial velocity semi-amplitude (K_1), as these can be measured for SB2 and SB1 systems. Figure 1 plots e and K_1 versus P_{orb} for main sequence (non-Be/n) B stars from the SB9 binary catalog (Pourbaix et al, 2004), and for the early and late Be/n binaries for which this information is currently available (see
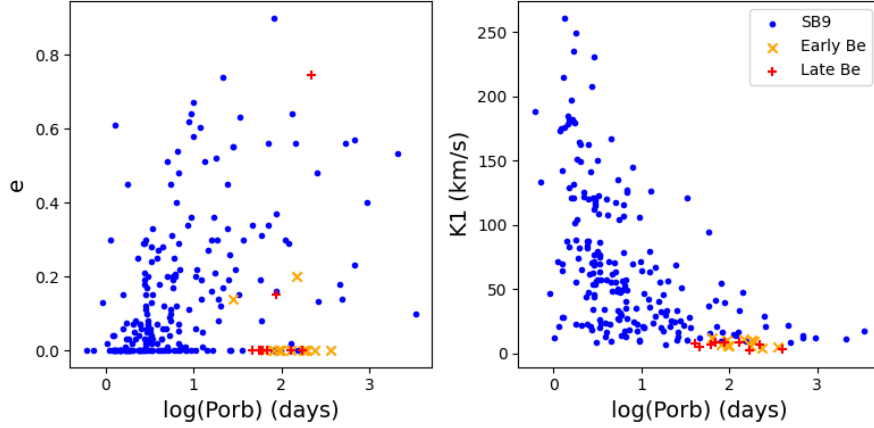
Fig. 1 Eccentricity (left) and radial velocity (right) vs. orbital period for main sequence B-type stars from the SB9 catalog. Early-type and late-type Be/n stars are indicated as in the legend. The two early-type outliers in the left panel are 59 Cyg and 60 Cyg, and the two late-type outliers are Pleione and 88 Her (see Appendix A). Of these, 88 Her is the only case where the eccentricity may be unreliable.

Appendix A). Although there are several additional factors that contribute to the SB9 sample (a range of secondary masses, selection biases, etc.), it is evident that the Be/n binary population stands apart. Be/n binary orbital periods are found only between about $30 - 300$ d[3], even though shorter periods are in principle easier to detect (while the absence of longer periods may be partly a detection bias). With a few exceptions, the eccentricity of Be/n orbits is very close to zero, which is rare for main sequence B star binaries in the period range occupied by the Be/n stars. The RV semi-amplitudes for Be/n stars are consistently low, implying lower-mass companions compared to the SB9 sample over this period range. In this view, there are no major differences between the early- and late-type Be/n binaries, but overall the Be/n binaries differ from the B stars in general.

Figure 2 compares the distribution of orbital periods for the known early- and late-type Be/n binaries (left panel). The p value of the two-sided Kolmogorov-Smirnov (KS) test is 0.01, indicating that if the two samples are drawn from the same distribution the probability of obtaining a KS statistic at least this extreme is 1%. However, given the inhomogeneous data and unknown sampling biases, no inferences can be made from

this simplistic comparison. Although the range in periods is similar, at present there is a relative excess of late-type Be/n binaries at shorter orbital periods compared to early-type Be/n binaries. Or, perhaps, there is a dearth of detected longer-period late-type Be/n binaries as a consequence of selection effects, especially since less observational resources have historically been applied to late-type Be/n stars.

The right panel of Figure 2 compares the orbital periods for confirmed post-interaction Be/n+stripped star binaries (Tbls. A1, A3, A4), with the orbital periods of Be/n binaries where the nature of the companion is not yet known (the SB1 sample, Tbl. A4). In this comparison, the distribution of orbital periods of these two samples are consistent with being identical (the p value of the two-sided Kolmogorov-Smirnov test is 0.35).

Figure 3 investigates relationships between primary and secondary masses and orbital periods. The top two panels in Figure 3 examine correlations between the orbital periods and the primary (left) and secondary (right) masses. There is significant scatter in both correlations, and it is not clear that there is any correlation between orbital period and primary and secondary masses. The bottom panel of Figure 3 shows a strong correlation between the mass of the secondary and that of the Be/n star. There does not seem to be any qualitatively different behavior in systems with early-type Be/n stars (with primary masses $\gtrsim 6$ M$_\odot$) compared to late-type. Neither

---

[3]Excluding the two OBe+WD binaries with shorter orbits, Sec. 2.3.1, and Sk -71 35 which is likely still undergoing mass transfer, Tbl. A4.
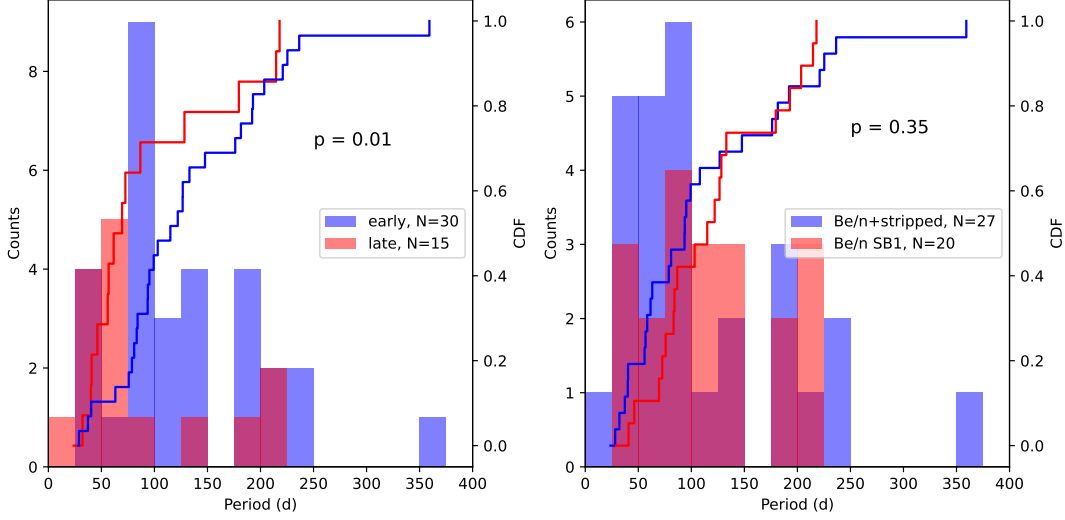
Fig. 2 *Left:* Histogram of orbital periods for early- (blue) and late-type (red) binaries with Be/n star primaries, including both SB1 systems and those containing confirmed stripped stars. *Right:* Histogram for Be/n binaries confirmed as post mass-transfer (with directly detected stripped stars, blue) and for SB1 Be/n binaries (red). The cumulative distribution function (CDF) is plotted as solid lines for these two samples. The p value of the two-sided Kolmogorov-Smirnov comparing each pair of samples is given in both panels.

are there any glaring differences in the above correlations between systems of different types (e.g. SB1 systems and those with more- or less-luminous stripped stars). However, in the comparison between primary and secondary masses, the SB1 systems including early-type Be/n stars tend to have somewhat lower estimated secondary masses, which again may be a selection effect as lower-mass stripped stars are generally of lower luminosity and thus harder to detect.

Figure 4 (left panel) plots a histogram of the mass ratio (q) for the same sample as in Figure 3 showing that the early- and late-type populations are similar. The mean values and their standard deviations are $q = 0.10 \pm 0.04$ (early) and $q = 0.10 \pm 0.03$ (late). The right panel of Fig. 4 is similar, but comparing the different categories of binaries. There are two outliers with less extreme mass ratios (omitted from the calculation of the mean q values and not shown in Fig. 4). These are the systems 2dFS 163 ($q = 0.4$) and 2dFS 2553 ($q = 0.5$), both containing a high-mass stripped star and an early-type Be/n star (Ramachandran et al, 2024).

From the above, a few inferences can be drawn. There appear to be no major differences between Be/n binaries when comparing early versus late

spectral types in terms of orbital period, eccentricities, mass ratios, and trends between these quantities. However, the orbital period distribution for late-type Be/n binaries may skew towards shorter periods, although this may be related to a selection bias. The same can be said when comparing confirmed post-interaction Be/n binaries with stripped stars, and the SB1 systems where the nature of the secondary is unknown. It therefore is reasonable to assume that a significant fraction of late-type Be binaries are post-mass transfer products (as well as early-type SB1 systems), with the secondary being a stripped low-mass star, rather than a low-mass MS star. From an observational point of view, the problem remains that very few stripped stars have yet been directly detected orbiting late-type rapid rotators, and there are several very well studied early-type binaries, especially the γ Cas analogs (early-type Be stars with characteristic X-ray emission, Nazé and Motch, 2018; Rauw, 2022), whose companions still evade direct detection. Potential reasons for this are explored in the next section.
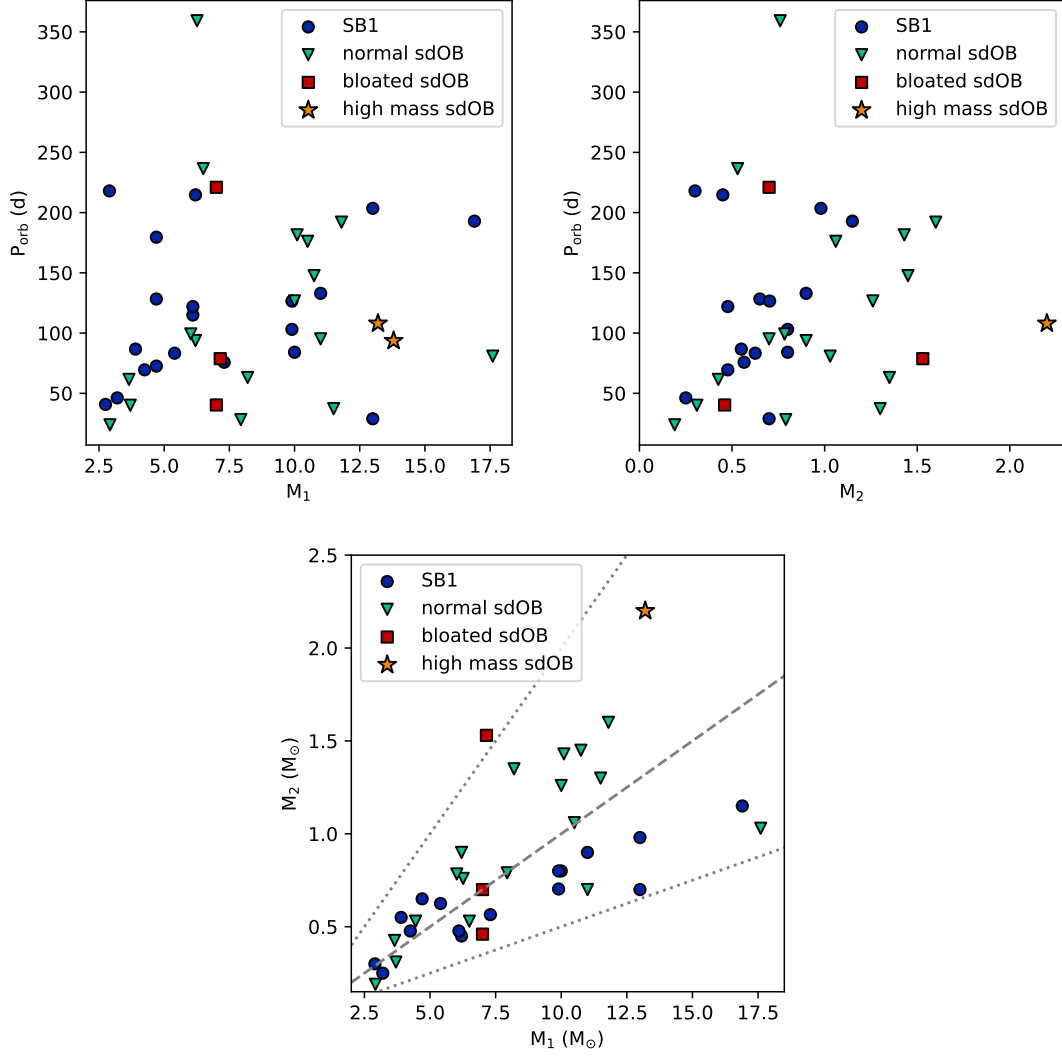
Fig. 3 *Top-left:* Comparison of the mass of the primary Be/n stars (M1) to the orbital period. *Top-right:* Comparison of the mass of the lower-mass secondary star (M2) to the orbital period. *Bottom:* Comparison of the secondary to primary mass. In the bottom panel, the dotted lines correspond to mass ratios of 0.2 and 0.05, and the dashed line to 0.1. In all panels, systems containing secondaries whose nature is unknown (SB1), and secondaries confirmed as being normal stripped stars, bloated stripped stars, and high mass stripped stars are indicated with different symbols. We further note that B4 and later types correspond to stars of $\sim 5\ M_\odot$ and lower. Two systems, 2dFS 163 ($q = 0.4$) and 2dFS 2553 ($q = 0.5$), both containing a high-mass stripped star and an early-type Be/n star (Ramachandran et al, 2024) are not shown in these figures.

4 Be/n binaries on the Hertzsprung–Russell diagram

4.1 Observations

While the rapidly-rotating mass gainers in Be/n+stripped binaries populate the near-MS, the stripped stars are found in several different regions in the Hertzsprung–Russell diagram (HRD). The temperature and luminosity of a stripped star depends primarily on its mass and evolutionary stage (i.e. how much time has passed since the end of mass transfer). Figure 5 examines the temperature and luminosity of near-MS Be/n
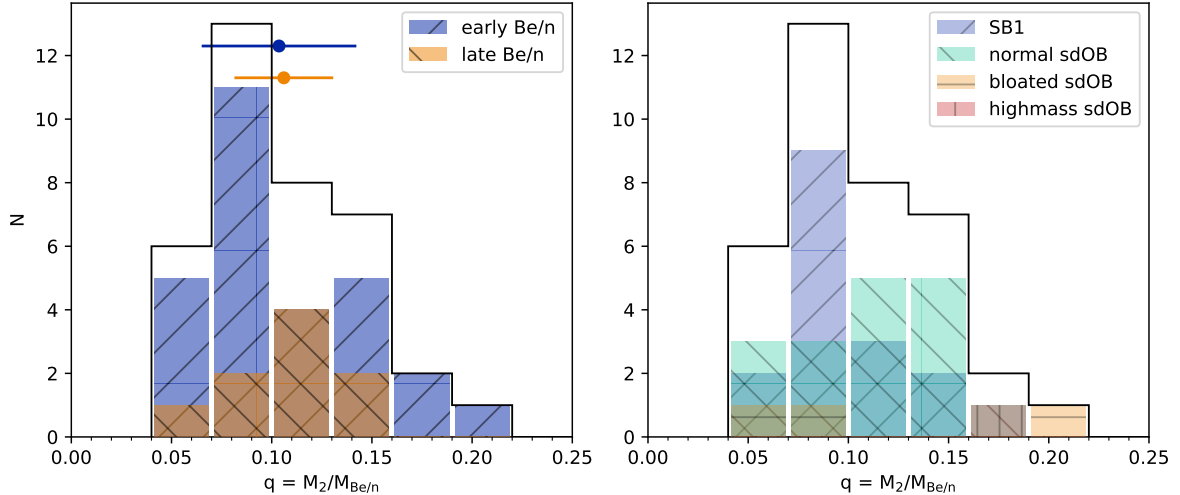
Fig. 4 *Left:* Histogram of mass ratios ($M_{stripped}/M_{Be}$) for the early- and late-type binaries, and their sum (black solid line). The mean and standard deviation for the early- and late-type mass ratios are plotted, with values of q = 0.10 ±0.04 (early), and q = 0.10 ±0.03 (late). *Right:* The same, but divided into the four different categories of binary systems as indicated in the legend, but without regard to spectral type.

stars (primarily Be) and their stripped companions in the HRD, whenever such measurements or estimates are available.

The most well-observed subset of non-NS stripped stars are the helium-burning sdOB stars (Sec. 2.3.2). These are generally found along the 'helium main sequence', running roughly parallel to the MS, but offset at lower luminosity and higher temperature. This helium main sequence is probably a continuum that spans from the lowest-mass to highest-mass stripped stars, although studies with differing science objectives often focus on specific regions.

The first stripped star that was directly detected orbiting a Be star is in the system ϕ Per (Gies et al, 1998). It is the hottest and most luminous stripped star among the 'intermediate mass' sdOB population. Many other qualitatively similar systems (but with less luminous sdO components) have since been discovered (Sec. 2.3.2). The sdB star in κ Dra has the lowest luminosity (and lowest temperature) of this population (Klement et al, 2022a). Fig. 5 illustrates an obvious lack of confirmed sdB stars, which should be located somewhere between the stripped star of κ Dra and the remainder of the sdO components.

The bloated stripped stars (Sec. 2.3.3) are near-indistinguishable from MS B stars in the HRD. Their very low surface gravity, as inferred

through spectroscopic analysis and/or their dynamical mass is what sets them apart as low-mass stripped stars (Bodensteiner et al, 2020a; Rivinius et al, 2025). It is generally understood that these will quickly evolve to the He MS after their short-lived 'bloated' stage. Due to their high luminosity and narrow lines (being slow rotators), they are relatively easy to discover, but intrinsically rare as this is a short evolutionary stage.

The high-mass stripped stars (Sec. 2.3.4) can be found at similar or higher luminosity than their MS companion. Considering the broad lines of the mass gainer in these systems, the typical challenge is reversed – it can be more difficult to obtain spectroscopic quantities of the MS mass gainer. Although several high-mass stripped stars are now known from the SMC and LMC (see Sec. 2.3.4), these are recent discoveries and in most cases the mass gainer has not been characterized. Nevertheless, these stripped stars lie along the same helium main sequence as the sdOB population.

Finally, the lowest-mass stripped stars ($\lesssim 0.4$ $M_\odot$) are unable to fuse helium in their core (Sec. 4.2). After their envelope has been stripped and there is insufficient hydrogen available for fusion, they evolve towards becoming a WD and do not loiter on the He MS. The two known examples (the lowest-luminosity stripped stars in
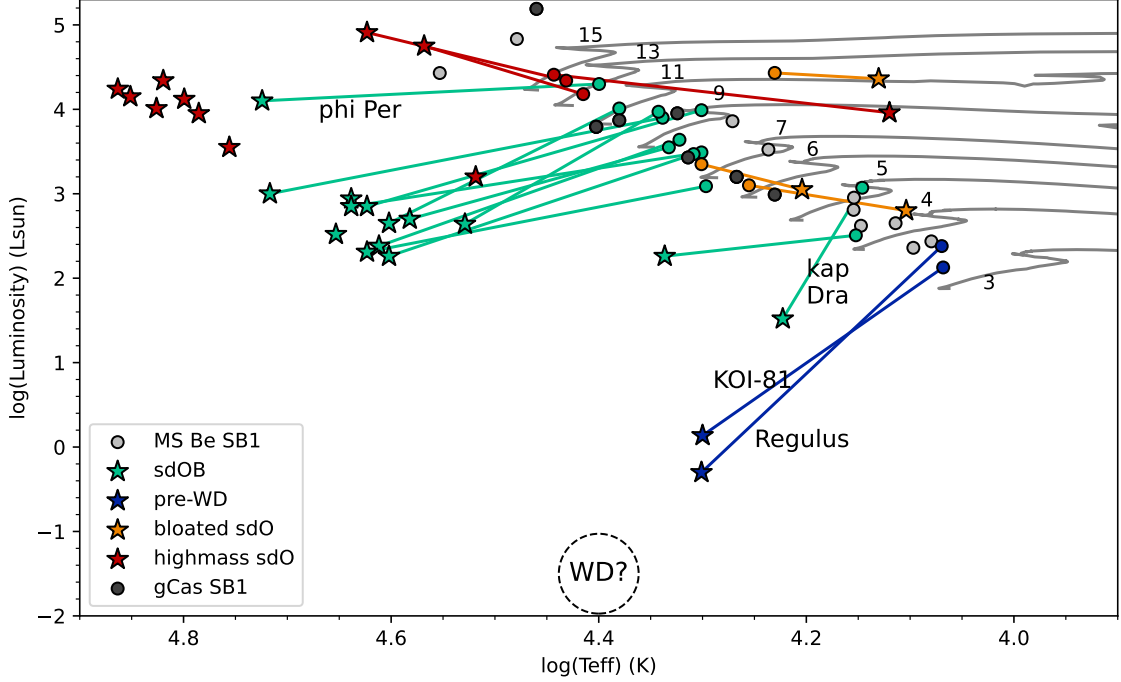
Fig. 5 Observational Hertzsprung–Russell diagram for known Be/n binaries. The filled circles represent the near-MS rapidly-rotating B-type stars, and the star symbols represent stripped stars. Whenever the luminosity and temperature of both components for a Be/n+stripped binary are known, the location of the MS star and stripped star are connected by a solid line. Different colors represent different classes of stripped stars, as represented in the legend. SB1 Be/n stars are indicated by light gray circles, and the SB1 systems that are γ Cas analogs are indicated by dark gray circles. MS evolutionary tracks from the Geneva stellar models (Georgy et al, 2013) from 3 – 15 $M_\odot$, with rotation rates at 95% of critical (here defined as $\Omega/\Omega_{\rm crit}$) and Z = 0.014 are plotted as gray lines. All high-mass sdO stars are from the Magellanic clouds, with the remainder of systems being Galactic.

Fig. 5) are ∼2 orders of magnitude fainter than any other known stripped stars with rapidly-rotating B-type primaries.

One population that is perhaps missing from the observational HRD of Fig. 5 are 'proper' WDs, with luminosities even less than the two known pre-WDs. Perhaps counter-intuitively, these may evolve from relatively high-mass stripped stars in a 'sweet spot' – too low mass to explode as SNe (leaving behind a NS; $\lesssim$2.6 $M_\odot$), but massive enough that they evolve relatively quickly and can exhaust their supply of helium before their companion evolves off the MS (at which point it will no longer be identifiable as a rapid rotator). Although no such WDs have been observed directly, there is circumstantial evidence that suggests that at least some of the γ Cas analogs have WD companions (Gies et al, 2023). There is additionally the population of likely Be+WD systems in the Magellanic Clouds (Sec. 2.3.1), although these cannot

be placed in the HRD. This remains an active and challenging field of study, as the origin of the anomalous X-ray emission of γ Cas stars is still unknown. Not only would such WDs have a low intrinsic luminosity, but those with massive Be hosts (e.g. the γ Cas analogs) would have such an extreme contrast ratio as to make the WDs undetectable in UV/visible spectroscopy even in principle.

4.2 Binary model predictions

If the companions to the SB1 Be stars plotted in Figure 5 are stripped stars, where would they be located on the HRD? To investigate this question, we used the Binary Population and Spectral Synthesis code (BPASS, Eldridge et al, 2017) and the Hoki package (Stevance et al, 2020) to examine evolutionary tracks for systems that would undergo mass transfer and result in (presumably

rapidly rotating) B stars on the MS and lower-mass stripped stars. When filtering the BPASS models, we searched the binary models at solar metallicity (Z = 0.02), with an initial orbital period of 100 days or less, that must have undergone mass transfer resulting in a B-type star (3 to 18 $M_\odot$) with a low mass companion (0.2 to 5 $M_\odot$), the ranges of which are consistent with the observed masses in Figure 3. We then also removed systems where the final orbital period was less than the initial orbital period, indicating highly non-conservative mass transfer. In total, there were 443 BPASS models which met the selection criteria.

To generate the binary population, BPASS bases the initial mass function on Kroupa et al (1993), adopting a power-law slope from 0.1 to 0.5 $M_\odot$ of -1.3, and a slope of -2.35 at higher masses. A flat distribution is prescribed for the initial mass ratio and for the logarithm of the orbital period.

In Figure 6 we plot the evolutionary tracks of the mass donors of these 443 models, colored by donor star mass, along with the observed Be/n+stripped systems. There are essentially two categories of stripped stars that are relevant. Higher mass stripped stars ($\gtrsim 0.35$ $M_\odot$) undergo core helium burning and usually maintain a relatively higher luminosity for a long time on the He MS, while lower mass stripped stars ($\lesssim 0.35$ $M_\odot$) cannot fuse helium and instead directly evolve along a cooling sequence. Examples of each are shown in Figure 7, where we see a $0.31\,M_\odot$ non-helium burning stripped star (left column) evolve directly onto a cooling track to become a WD, while a $0.85\,M_\odot$ stripped star (right column) fuses helium in the sdO region of the HR diagram, increases in luminosity, and then moves along a wider cooling track to eventually become a higher mass CO WD.

Figure 7 is colored by the normalized timestep length, for one low-mass and one high-mass donor star in the left and right columns respectively. The low-mass system started with masses of 2.5 $M_\odot$ and 1.5 $M_\odot$ for the mass donor and gainer respectively, and an orbital period of 1.6 days, and ended with masses 0.31 $M_\odot$, 3.42 $M_\odot$, and a period of 59.9 days. The high-mass system started with masses of 6.5 $M_\odot$ and 3.9 $M_\odot$ for the mass donor and gainer respectively, and an orbital period of 2.5 days, and ended with masses 0.85 $M_\odot$, 8.16
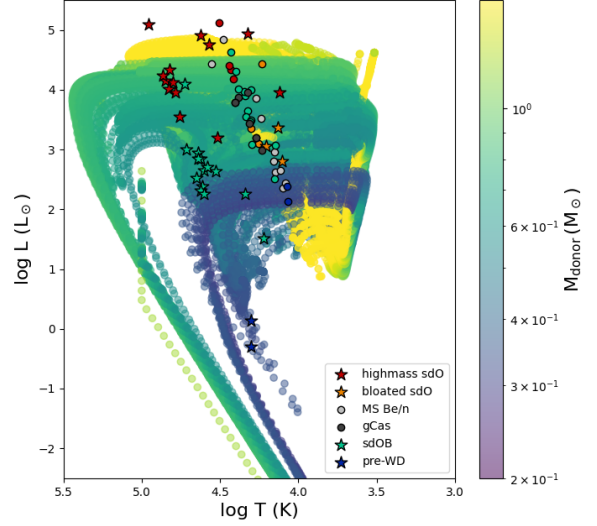

Fig. 6 HR diagrams showing the evolutionary tracks of the donor star, coloured by mass, for the BPASS models that met our search criteria as described in Section 4.2. The position of the observed mass gainer stars and their companions from Figure 5 are also plotted for reference.

$M_\odot$, and a period of 65 days. The timestep-colored tracks are plotted until the approximate end of the mass gainer's MS. This timespan is set by the MS lifetime of the equivalent single-star BPASS model that matches the post-interaction mass of the accreting star.

We find that we can divide the post-MS evolution of the higher-mass stripped stars (i.e. those capable of sustaining core helium fusion) into three sections: the first left-moving track, between the end of the MS to the start of the helium main sequence, the right-moving track, from the start of He burning to the tip of the second low-temperature loop, and the tip of this loop to the WD stage (around $\log(L) = 0$). Across our selected BPASS models that exhibit this behavior, these stages last on average 29 million years, 4.5 million years, and 1.7 million years, respectively, with the majority of this time concentrated at the start of He burning. This points to one possible reason why many companions are found in the sdO stage of their evolution – they simply spend most of their post-MS life as a hot subdwarf prior to becoming a WD. As for the low-mass donor stars that do not go on to fuse helium, the average time from the end of MS to the WD stage (again defined here as $\log(L) = 0$) is about 170 million years. Aside from the long time spent on
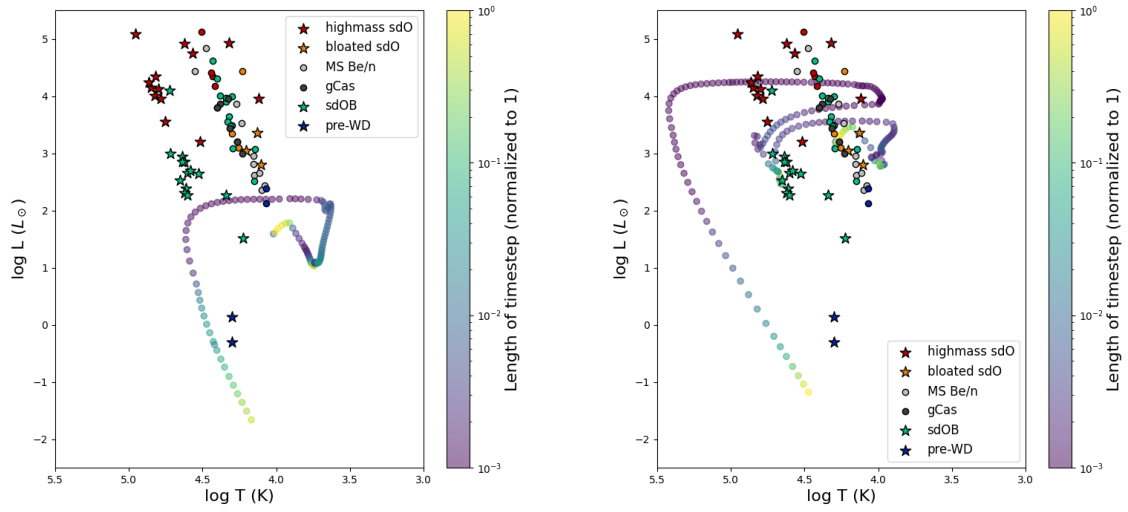
Fig. 7 Example evolutionary tracks for a lower mass ($0.31\,\mathrm{M_\odot}$) stripped star (left), and higher mass stripped star ($0.85\,\mathrm{M_\odot}$ right), colored by normalized timestep length indicated by the color bar. The same observations as Figure 6 are overplotted.

the MS, stars on the high-mass track spend a considerable amount of time in the helium burning phase, around the region of observed sdO companions, as well as at the WD phase. The low-mass stripped star, however, does not have a long pause in this sdO region, and instead progresses to the longer WD phase (after gradually passing through the 'pre-WD' phase).

To get an overall representation of the relative time where stripped stars occupy different regions of the HRD in our selected models, Figure 8 shows a heatmap of where the donor stars in the 443 BPASS models are found, up to the estimated end of the gainer star MS. In this representation, we see that there are three main strips in the HRD where the donor spends the most time: the MS track (upper right), the subdwarf track or "helium main sequence" (middle track), and the WD track (lower left). We can see that the dichotomy of high-mass and low-mass subwarfs creates a continuous distribution between the observed high mass subdwarfs (sdO), and the few observed low mass subwarf (sdB) and pre-WD companions, stretching roughly between $4.0 < \log(T) < 4.75$ and $0.5 < \log(L) < 5$. The high-luminosity region of the He MS is relatively less populated, due to these higher-mass stripped stars being intrinsically less common and also exhausting their He fuel relatively rapidly. We note that the number

of models where the donor ends as a WD while the mass gainer is still on the MS may be overestimated due to the following two reasons. It is possible that the MS lifetimes of the mass gainers is overestimated, as we calculate this value assuming that the star begins on the ZAMS with its post-interaction mass. Additionally, the rejuvenated star MS lifetimes would be shorter if mass transfer is more conservative than prescribed in BPASS (as discussed later in this section). On the other hand, this may be partly offset by the notion that rapid rotation extends the MS lifetime by enhancing mixing of H into the core, which is not accounted for in the BPASS evolution of the mass gainers.

To compare the helium-fusing stripped stars with their main-sequence companions, we have separated the helium main sequence into five sections, as denoted by the boxes in Fig. 8. Within a given box, we select all donor tracks that began to fuse helium, and find the mass of the gainer star at the time of He ignition. This mass is then converted to a position on the HR diagram using the BPASS single-star models. The average position and standard deviation is plotted, with an arrow connecting each box to its average gainer position. From this method, we can see that along the helium main sequence, higher mass stripped
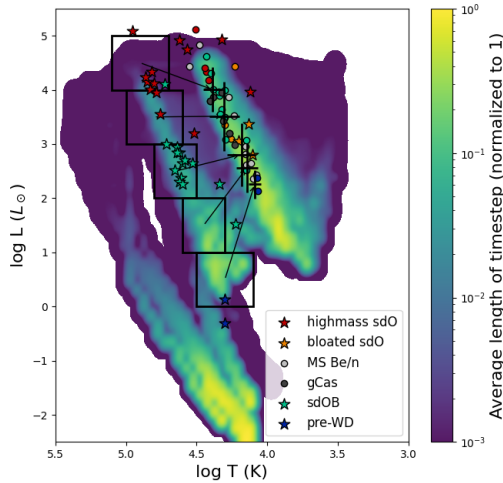
Fig. 8 Heatmap of the 443 analyzed BPASS models, showing the average length of each timestep, normalized to 1 for each individual model. The observed Be/n and companion stars are overplotted as indicated by the legend. The helium MS has been broken down into five boxes. These boxes are connected by arrows to points showing the average position of the MS mass-gainer for models that begin fusing helium in each box. The error bars indicate the standard deviation of the average mass-gainer position.

stars will tend to have higher mass MS companions, while lower mass stripped stars will have lower mass MS companions.

It is noteworthy that the middle box, containing the 'normal' observed sdO population, points approximately to the middle of the B-star MS, while from observations we know their Be companions are of higher temperature and luminosity (Fig. 5). This may suggest that the observed Be+stripped population demands more conservative mass transfer than is prescribed in BPASS for this parameter space. This notion seems supported by other recent work, (e.g. Lechien et al, 2025), which indicates that the mass transfer that produces early-type Be stars is more conservative than is often assumed. The prescription for mass transfer rates implemented in BPASS is limited by the thermal timescale of the accretor, $\dot{M}_2 \leq M_2/\tau_{KH}$, where the mass loss rate from the primary via Roche lobe overflow is described in Eqs. 1 – 3 in Eldridge et al (2017).

Figure 9 shows the distribution of orbital period versus donor mass, and the gainer star (presumed to be a Be star) mass versus donor mass, at the subdwarf/pre-WD stage (after crossing the ZAMS from right to left after mass transfer), along with the observed data from Figure 3. There is no obvious correlation between the mass of the stripped star and the orbital period, neither in the BPASS models nor in the observed sample. However, there is a clear relationship between gainer mass and donor mass in both the models and observations. The BPASS models also predict a short-period tail that is not observed in the Be/n binaries, as well as higher values of q compared to the observed systems.

A histogram of the mass ratio (q) is shown in Fig. 10. For each pair of stripped+B star, q was calculated at the first timestep where the donor track crosses the ZAMS moving left across the HR diagram (i.e. beginning to emerge as an sdOB or pre-WD). The average values and standard deviations of q for the early- and late-type B stars are 0.148 ± 0.064 and 0.166 ± 0.064, respectively. The distribution in q generated from BPASS skews towards higher values than the observed population (Fig. 4), again suggesting that mass transfer is more conservative than prescribed in BPASS.

We have shown observationally the correlation between the mass of the stripped star and the mass gainer (Figure 3). The higher mass Be stars therefore tend to have higher mass companions that spend a significant amount of the Be star MS lifetime in the core helium burning stage and appear as sdO stars. On the other hand, the companions of lower mass Be stars cool to become sdB or WD stars. The BPASS models predict that the stripped stars in our prescribed parameter space spend a long time fusing helium along a region in the HRD that is below but parallel to the MS (Fig. 8). The known stripped sdO stars lie along the upper half of this region in good agreement with the models (excluding the bloated stripped stars which are presumed to be evolving towards this region). BPASS predicts that the lower half of this region is well populated by stripped sdB stars and pre-WDs with mid- and late-type Be/n companions. However, to date there are only four such lower-luminosity stripped stars with rapidly rotating B-type companions known – two sdB
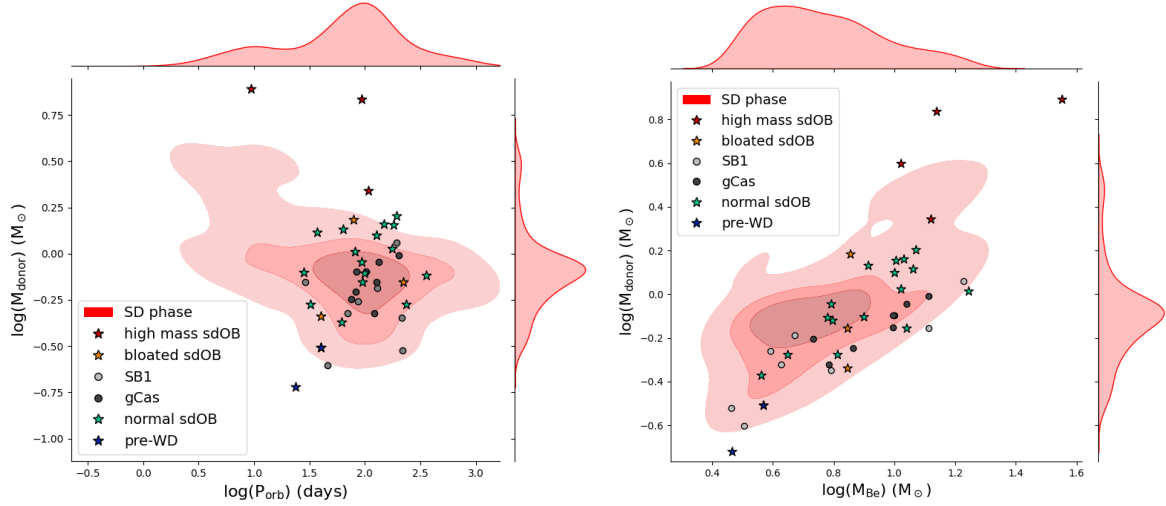
Fig. 9 Left: log-log plot of orbital period versus donor star mass. Right: log-log plot of Be star mass versus donor star mass (right). Both plots show the distribution of our selected BPASS models at the subdwarf/pre-WD phase (after crossing the ZAMS from right to left after mass transfer). The marginal graphs show the 1-dimensional distribution of the x and y axes. Plots were made using the seaborn package (Waskom, 2021). The observed systems from Figure 3 are also plotted on both panels.
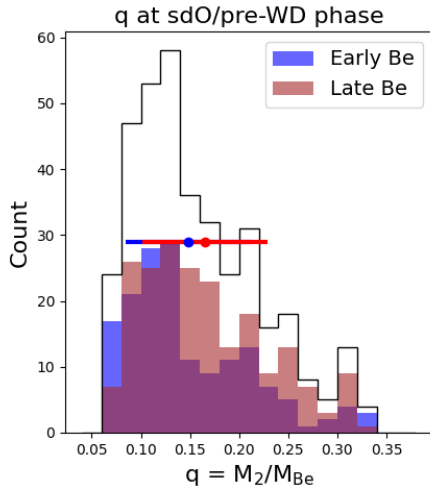
5 Observational methods for detecting low-mass stripped companions

Fig. 10 Histograms of the mass ratio for our selected BPASS models when the donor is at the sdO/pre-WD phase. The histograms are separated into early ($\geq 6\ M_\odot$) and late ($< 6\ M_\odot$) mass gainer stars, and the combined histogram is plotted in black. The mean and standard deviation of the early and late-type distributions are plotted as error bars.

stars (with mid/late Be companions), and two pre-WDs (with late Bn companions). Observational efforts are therefore required to fill in this parameter space to paint a more complete picture of the continuum of post-interaction systems.

The detection of stripped companions to Be stars can be done through several techniques. For NS and potential WD companions, this is done in the X-rays (Sec. 2.3.6 2.3.1). UV spectroscopy has historically been the tool of choice for sdOB stars (Wang et al, 2021, 2023), but some systems are also detectable in optical spectroscopy (Chojnowski et al, 2018). Bloated stripped stars are easily detectable in optical spectroscopy (Sec. 2.3.3), and hot high-mass stripped stars can be characterized by their photometric UV excess, and with UV and/or visible spectroscopy (e.g. Drout et al, 2023; Ramachandran et al, 2024).

Long time-series of optical spectroscopy has provided the known SB1 orbits of Be stars, thanks to dedicated monitoring of the short-intermediate- and long-time scale variations of this population (e.g. Harmanec et al, 2000; Vennes et al, 2011; Nazé et al, 2022a). However, such efforts have not been made for Bn stars, which lack disks and thus are much less obviously variable. It should be noted that Bn stars do seem to pulsate in a similar manner as Be stars (Nazé et al, 2024), and that at least some are post-interaction products (Sec. 2.3.2). Dedicated monitoring of Bn

17

stars is certainly warranted, both to conduct a binary census of the population, as well as to better understand their pulsational behavior and how this compares to that of Be stars. This may help to elucidate the processes by which Be stars create disks, while Bn stars do not.

Despite the relative dearth of good observational datasets suitable for the subtle binary analysis of Bn stars, the two lowest-luminosity stripped stars yet known belong to late-type Bn systems. In the case of KOI-81, this was rather serendipitous, with eclipses being found in Kepler photometry (Matson et al, 2015). The lack of a disk (which would otherwise increase complexity) in KOI-81 likely aided in the detection and characterization of this system. The companion to Regulus, on the other hand, was detected by sheer brute force through the analysis of an extensive set of high-quality optical spectra of this very bright star (Gies et al, 2020). This was made possible by the knowledge derived from its SB1 orbit (Gies et al, 2008).

As demonstrated with KOI-81 (Matson et al, 2015) and HD 92406 (de Amorim et al, 2023), finding Be/n stars with eclipses is in principle an excellent method for detecting binaries. However, owing primarily to the relatively long orbital periods and small stripped star sizes, an inclination angle very close to $90°$ is required to produce eclipses, and thus eclipsing systems are intrinsically rare.

Recently, interferometry has been established as a powerful tool for detecting and characterizing Be/n+stripped binaries (Klement et al, 2024), and is the only technique capable of providing a model-independent astrometric orbit. For example, the stripped star in κ Dra was first identified in interferometric measurements, and with knowledge of its orbital properties was recovered in IUE UV spectroscopy (Klement et al, 2022a). This was the first confirmed Be+sdB system, indicating that not all stripped stars in Be binaries are hot sdO stars (with temperatures between about 40000 – 50000 K). For systems with magnitudes below about 7, the CHARA interferometric array is capable of reaching contrast ratios as low as $\sim$0.3% (e.g. in the H/K bands with the MIRC-X/MYSTIC instruments) in ideal conditions, corresponding to a magnitude difference of $\sim$6.4 (Gallenne et al, 2015), and capable of achieving an angular resolution of $\sim$0.5 mas. The VLTI

interferometric facility offers similar capabilities for detecting high contrast close binaries. While interferometry is now a well established technique for discovering and characterizing Be+sdOB systems, very high contrast ratios as in Regulus (with a V-band flux ratio of about 0.06%, Gies et al, 2020) remain out of reach.

There is no single 'best' technique for discovering and characterizing Be/n binaries. Instead, the best results are achieved when combining different dataset and techniques which can depend on the specifics of the system(s) being analyzed. Nevertheless, UV spectroscopy has historically been the primary driver of this field, and remains an indispensable tool in directly detecting and characterizing stripped stars. The current lack of high-quality UV spectroscopy of a large sample of Be/n stars may be the main bottleneck in the advancement of this field.

One advantage of working with UV spectroscopy compared to visible and IR wavelengths is that in all observed cases (excluding the bloated stripped stars) the stripped star is hotter than the Be/n star and so the contrast is most favorable at UV wavelengths. Another is that the UV regime is exceptionally rich with absorption lines for hot stars. Figure 11 compares the UV and visible regimes for a synthetic spectrum of an object qualitatively similar to an sdB or pre-WD star, with $T_{\rm eff}$ = 20000 K, $\log g$ = 5, and $v\sin i$ = 15 km s^{-1}, using the line-by-line stellar atmosphere models (Shulyak et al, 2004) as implemented in the PYSME[4] package. The multitude of features in the UV greatly enhance the power of cross correlation techniques that can be used to detect and characterize faint stripped stars in spectra dominated by a slightly cooler MS star. In practice, an additional advantage is that stripped stars generally have a very low $v\sin i$ ($\lesssim$15 km s^{-1}) so that their lines are considerably sharper than those from rapidly rotating Be/n stars, assisting in efforts to disentangle the signatures of both components (Wang et al, 2023).

Historically, the limiting factor in detecting stripped stars with hot MS primaries with UV spectroscopy is the signal to noise ratio (SNR). In this sense, it is remarkable that the majority of known Be+sdO systems were first discovered in archival IUE spectra with typical SNR of $\sim$10

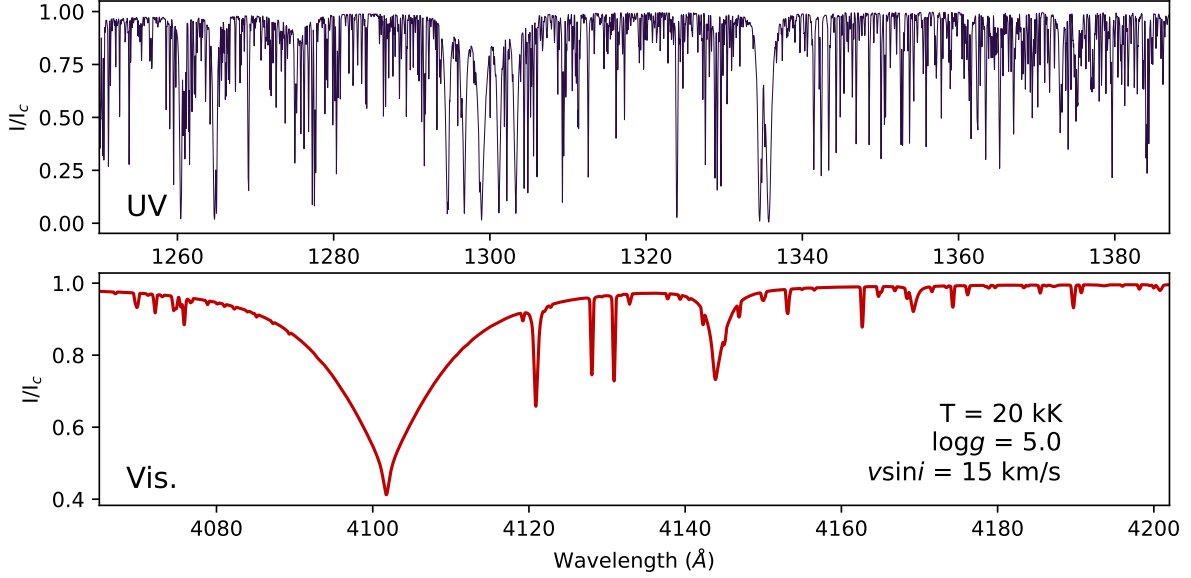[4]https://github.com/MingjieJian/SME

Fig. 11 Synthetic spectrum for an atmosphere with $T_{\text{eff}} = 20000$ K, $\log g = 5$, and broadened to $v\sin i = 15$ km s^{-1}. The upper and lower panels show a 137 Å portion of the UV and visible regions, respectively.

(Wang et al, 2018), and later confirmed with higher quality data (e.g. from HST with SNR~30, Wang et al, 2023). However, from the archival IUE data, it was only possible to detect the most favorable such systems with relatively bright stripped stars. In this sense, the archival IUE UV spectroscopic database is likely nearly exhausted in its utility for discovering stripped stars, although it may continue to be useful for 'pre-covery' of stripped stars following information derived from other methods (as in e.g. Klement et al, 2022a). HST currently provides the gold standard of UV spectroscopy, but tends to be used to confirm and better characterize Be/n+stripped systems after they have already been identified (perhaps as candidates) through other means (e.g. Gies et al, 1998; Wang et al, 2021; Matson et al, 2015). Future high-resolution UV spectrographs will be needed to continue to investigate this field. For example, the UVI and Pollux instruments (Muslimov et al, 2018) considered for the Habitable Worlds Observatory (HWO) would be excellent facilities for this science topic, as well as smaller UV spectrographs or spectropolarimeters such as those planned on the SMEX candidate PolStar (Scowen et al, 2022) and the ESA mission candidate Arago (Muslimov and Neiner, 2022).

5.1 Filling in the gaps in the Be/n+stripped population

The current known population of Be/n+stripped systems may represent only the tip of the iceberg. Naturally, the brightest stars with the most favorable flux ratios are the easiest systems for detecting stripped companion. For example, the Be/n+sdOB stars plotted in Fig. 5, the median V_{mag} is 5.7 (omitting bloated and high-mass companions). There is an obvious dearth of sdB and pre-WD stars, with only four that are published, to the best of our knowledge. Considering also the large number of Bn stars that exist, which remain poorly observed (including by IUE, which led to the discovery of most of the Be+sdO systems), it now seems essential to properly explore the parameter space where Be/n+stripped binaries may be found.

Progress can be made towards better understanding this population on several fronts. Spectroscopic monitoring for RV motion, especially when combined with the often large archival databases for Be stars, is promising for discovering new binaries and determining orbital periods and eccentricities. Interferometry can continue to detect close binaries, or rule out certain types of companions. To better populate the current observational gaps, attention should especially be

given to (non-emission line) Bn stars of all spectral types, and mid- to late-type Be stars.

For directly detecting stripped companions, Fig. 8 provides a guide for the expected luminosity and temperature contrast for potential or candidate Be/n+stripped binaries. Although we note that comparing the BPASS population to the observed sample, stripped companions around a Be/n star of a given spectral type may be less luminous than the models predict. UV spectroscopy of moderate SNR (∼30) has proven sufficient to detect sdO systems around early-type Be stars (e.g. Wang et al, 2021, 2023), but higher SNR may be required for detecting helium fusing sdB stars with less favorable contrast ratios in the FUV. It should be noted that for some systems at certain orbital phases, the stripped companion is not detected, likely due to obscuration from circumstellar material (Peters et al, 2016; Wang et al, 2021). Stripped companions around Bn stars then should not suffer from this issue.

High-SNR far UV (FUV) spectroscopy is a viable pathway towards detecting low-mass stripped stars at high contrast ratios, especially for stripped stars unable to fuse helium. Figure 12 shows a synthetic FUV spectrum that emulates the Regulus system (Gies et al, 2020) by co-adding a spectrum of a main-sequence B star with $T_{\mathrm{eff}} =$ 12 kK and $\log g = 3.5$, and a stripped star with $T_{\mathrm{eff}} = 20$ kK and $\log g = 5.0$, with a flux ratio of 0.5% at 1500 Å. For comparison, the sdB component of κ Dra contributes ∼2.3% of the FUV flux (Klement et al, 2022a). The B-type spectrum was broadened to 300 km s^{-1}, and the stripped star to 15 km s^{-1}. The spectrum was degraded to a resolving power of $R = 20000$, with noise added to simulate a SNR of 100 and 300. Employing cross correlation function (CCF) techniques, at a SNR of 100 the pre-WD in Regulus is marginally detectable, but at a SNR of 300, it is confidently detected. A UV spectroscopic survey at high SNR targeting the nearby population of rapid rotators would be a significant step forward in understanding the implications of binary interaction in high- and intermediate-mass stars.

6 Discussion and Conclusions

Comparing the binary parameters of Be/n+stripped systems, SB1 Be stars, and the MS B+B binary population (Sec. 3) suggests
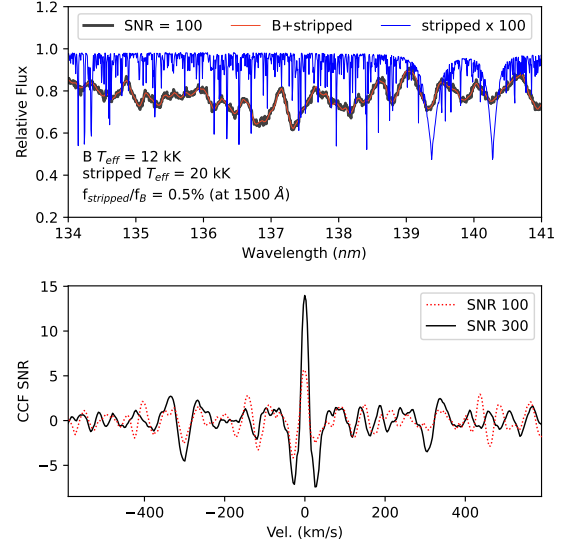

Fig. 12 Top: A portion of a synthetic UV spectrum emulating the Regulus system, with the primary having $v\sin i$ = 300 km s^{-1}, T_{eff} = 12 kK, $\log g$ = 3.5, and the stripped star having $v\sin i$ = 15 km s^{-1}, T_{eff} = 20 kK, $\log g$ = 5.0, with zero radial velocity offsets. Spectra from the two templates were co-added so that the stripped star contributes 0.5% of the flux at 1500 Å, consistent with the expected UV flux ratio based on the information in Gies et al (2020). The resolving power of the coadded spectrum was set to 20000. Bottom: The Cross Correlation Function (CCF) signal found after smoothing out the wide features (from the rapidly rotating primary) and using the stripped star spectrum as a template. The stripped star is marginally detected at a SNR of 100, and confidently detected at a SNR of 300.

the following. The SB1 systems are likely post-interactions binaries where the stripped star may be found along the helium MS and thus is expected to be detectable, or may be closer to a WD. For post-interaction binaries, the most likely nature of the companion depends on the spectral type of the Be/n star. For early-type primaries, the companion should either be an sdO star, or a (pre-)WD depending on the evolutionary stage. For mid-type primaries, the companion is most likely an sdB star. For later-type primaries, the companion may be a lower-mass sdB star fusing helium, or a (pre-)WD at low luminosity. However, the range of possible initial conditions that can lead to mass transfer and a Be/n+stripped configuration, the amount of time that has passed after the mass transfer stage, as well as parameters such as the degree to which mass transfer

is conservative, prevent accurate predictions for the present-day configuration of a given specific system. Nevertheless, these trends seem to hold at the population level.

Given the above, there is likely a cooler population of stripped stars, in the sdB and pre-WD regime that to date have hardly been observed. Direct detection of these sdB stars is possible with interferometry, UV spectroscopy, and possibly optical spectroscopy, while the pre-WDs can likely only be detected with high-SNR UV spectroscopy (Sec. 5.1). Filling in these observational gaps is important to map the continuum of post-interaction evolutionary products, which for non-degenerate stripped stars ranges from the low-mass pre-WDs up to the high-mass quasi-WR stars (Sec. 4). These higher-mass stripped stars may explode as SNe, producing NSs, which if they remain bound will become high-mass BeXRB systems (Sec. 2.3.6) when the companion is a Be star, or can cause runaways (Sec. 2.3.7). The eventual fate of intermediate- and lower-mass stripped stars ($\lesssim 2$ M$_\odot$) is most likely a WD.

While this work focused primarily on the interacting systems that produce a rapidly-rotating B type star, it is worth considering a broader perspective. Binary interaction is even more frequent in O-type stars, but these spin down quickly. This makes using rapid rotation as a potential indicator of past interaction difficult. Relative to higher masses, binary interaction is understood to be less common in lower-mass stars. Nevertheless, some fraction of A- and F-type stars do experience binary interactions including mass transfer (e.g. G et al, 2024), and there is also a rapidly rotating sub-population of A- and F-type stars (Royer et al, 2007). However, the Be phenomenon (where a star creates an outflowing gaseous decretion disk) is typically observationally limited to stars of spectral type $\sim$A2 and earlier, although may extend to slightly later stars (Anusha et al, 2021). Stars spun up by binary interaction, however, are under no obligation to create an outflowing gaseous disk. The low fraction of Ae stars (and absolute lack of F-type disk makers) cannot be used as an argument against binary interaction producing rapid rotation in this lower mass regime. In this scenario, any stripped companions would surely be too low-mass to reach the He MS, and probably appear as (pre-)WDs.

Recently, Lechien et al (2025) explored the properties of 16 Be+sdOB binaries to evaluate the efficiency of mass transfer during the interaction phase. Their results indicate that mass transfer is relatively efficient, such that most of the mass lost by the initial primary is gained by the accretor, strongly disfavoring a scenario where accretion is limited by a centrifugal barrier (i.e. when mass transfer only proceeds until the accretor is spun up to critical). Their results also appear to be in tension with mass transfer prescriptions limited by the thermal timescale of the accretor. The mass transfer prescription employed by BPASS is of this variety, with the accretion rate being limited by $\dot{M_2} \leq M_2/\tau_{\rm KH}$, where M_2 and $\tau_{\rm KH}$ are the mass and thermal timescale of the accretor, respectively (Eldridge et al, 2017).

Although the qualitative agreement is good, our analysis also suggests tension between the observed Be/n+stripped population and the BPASS models. The average predicted post-interaction mass ratios, q, are about $30\% - 60\%$ higher than in the observed sample (Figs. 4, 10). Likewise, for a given region in the He MS, the corresponding mass gainer in BPASS is of lower mass (or L and $T_{\rm eff}$) compared to what is observed (Fig. 8). In other words, for a given stripped star, the observations suggest a MS star with a $\sim$30% – 60% higher mass than predicted by the BPASS models. These tensions may be be alleviated by incorporating a higher mass transfer efficiency in BPASS. An increased efficiency of mass transfer in population synthesis models will result in a larger number of higher-mass stars, which in turn will produce a greater number of SNe.

Accurate and precise measures of post-interaction stellar and binary properties and better statistics can then be used to improve parameters (such as how conservative mass transfer is) in binary stellar population synthesis codes. More accurate models, coupled with a better observational view of the Be/n+stripped population should allow for a reliable determination of what fraction of rapid rotators have been spun up by binary mass transfer. This has important implications for stellar astrophysics in general, and also at larger scales, such as the ionizing flux in clusters and star forming regions (Götberg et al, 2019, 2020). Multiple aspects of the sort of binary interaction discussed in this paper contribute to a higher amount of ionizing UV flux than would

be produced were both stars to evolve as single. The stripped star will be significantly hotter, albeit much smaller. The mass gainer will also have a higher effective temperature by virtue of its increased mass, while very rapid rotation will increase the polar temperature up to an additional $\sim30\%$ (e.g. Paxton et al, 2019). If rotational mixing is efficient and the mass-accretion efficiency is not too low, then the main sequence lifetime may be extended by up to $\sim30\%$ (Maeder and Meynet, 2000b).

It is worth mentioning the final fate of the massive post-interaction binaries. Modern gravitational wave (GW) instruments, such as LIGO, have recently begun to explore black hole (BH) physics via observing the mergers of BH/NS+BH/NS pairs as they dynamically warp the fabric of spacetime (Abbott et al, 2017). This is an exciting new frontier in probing nature at its most extreme. Such mergers are a possible outcome for the higher-mass post-interaction binaries, after both stars have exploded as a SN (or perhaps collapsed directly into a BH). The lower-mass post-interaction binaries may form very close WD+WD pairs before merging and igniting a SN explosion, which may also lead to GW signals detectable by future instruments such as LISA (Korol et al, 2024). It is therefore crucial to improve our understanding of the evolutionary pathways starting from the initial conditions of massive binaries, through their interaction and post-interaction stages in order to predict the final outcome of such systems, which will better enable us to trace back the history of observed GW events.

---

[5] http://www.astropy.org

Appendix A Tables of confirmed binaries

This appendix contains tables describing the basic stellar and orbital properties of the post-interaction binaries gathered from the literature. Table A1 includes the Be/n+sdOB systems, Tbl. A2 the SB1 Be binaries, and Tbl A3 the Be+bloated binaries. Table A4 lists the high-mass stripped stars recently confirmed to be binaries. However, the stellar properties of the non-stripped companions in Tbl. A4 are in general poorly determined. For the last nine entries in Tbl. A4 the non-stripped star has not been directly observed, but RV motion of the stripped star indicates its binarity. In these cases, it is possible that the systems have evolved through a common envelope phase, rather than Roche lobe overflow, so that the non-stripped component is cannot at present be presumed to be rapidly rotating Götberg et al (2023).

Table A1 Basic properties of confirmed Be/n+sdOB binaries.

HD	ID	ST	P_{orb} (d)	e	K_1 (km s^{-1})	M_1 ($M_\odot$)	$\log(T_{eff,1})$ (K)	$\log(L_1)$ ($L_\odot$)	M_2 ($M_\odot$)	$\log(T_{eff,2})$ (K)	$\log(L_2)$ ($L_\odot$)	i (°)
200310	60 Cyg	B1Ve	147.68[1,2,3]	0.2[3]	11.2[3]	10.75[3]	4.43[1]	4.13[4]	1.45[3]	4.62[5]	3.14[4,5,A]	84.6[3]
200120	59 Cyg	B1.5Vnne	28.2[6,7]	0.14[7]	11.7	7.94[7]	4.34[7]	3.90[7]	0.79[7]	4.72[7]	3.00[7]	54.2[3]
194335	V2119 Cyg	B2IIIe	63.146[2,3]	0[3]	12.2[3]	8.2[3]	4.41[8]	3.98[8]	1.35[3]	4.64[9]	2.94[9]	49.5[3]
55606	HD 55606	B0.5Vnnpe	93.8[10]	0[10]	10.74[10]	6.2[10]	4.32[10]	3.64[10]	0.9[10]	4.61[9]	2.38[9]	80[10]
58978	FY CMa	B0.5IVe	37.3[11]	0[11]	17.4[11]	11.5[11]	4.44[11]	4.88[8]	1.3[11]	4.65[11]	4.11[8,11,B]	68[8]
41335	HR 2142	B1.5IV-Vnne	80.9[3,12]	0[3]	7[3]	17.6[3]	4.32[12]	4.37[8]	1.03[3]	4.63[12]	-	77.7[3]
10516	phi Per	B1.5 V:e-sh	126.7[13]	0[13]	9.97[14]	10[14]	4.40[14]	4.30[14]	1.26[14]	4.72[13]	4.10[14]	82[13]
157042	iota Ara	B2Vnne	176.17[15]	0[15]	5.8[15]	10.5[15]	4.34[16]	3.97[C]	1.06[15]	4.53[9]	2.64[9]	46[15]
137387	kap01 Aps	B2Vnpe	192.1[15]	0[15]	9.09[15]	11.8[15]	4.38[8]	4.01[8]	1.6[15]	4.60[9]	2.65[9]	60[15]
113120	LS Mus	B2IVne	181.54[15]	0[15]	10.66[15]	10.1[15]	4.36[8]	3.91[8]	1.43[15]	4.65[9]	2.52[9]	74[15]
152478	V846 Ara	B3Vnpe	236.5[15]	0[15]	4.33[15]	6.5[15]	4.30[8]	3.09[8]	0.53[15]	4.62[9]	2.31[9]	60[15]
191610	28 Cyg	B3IVe	359.26[2,3]	0[3]	5.4[3]	6.26[3]	4.31[8]	3.83[8]	0.76[3]	-	-	118.7[3]
161306	EM* MWC 271	B3/5Vnne	99.3[3,17]	0[3]	5.6[3]	6.02[3]	4.21[C]	2.89[C]	0.784[3]	-	-	34[3]
109387	Kap Dra	B6IIIe	61.55[18]	0[18]	6.9[18]	3.65[18]	4.15[18]	3.07[18]	0.426[18]	4.22[18]	1.52[18]	40[18]
183537	7 Vul	B5Vne	69.5[3]	0[3]	8.7[3]	4.25[3]	4.19[19]	2.91[19]	0.477[3]	-	-	>70[19]
92406	V658 Car	Bpsh	32.185[20]	0[20]	12.2[20]	4.45[20]	4.15[20]	2.51[20]	0.53[20]	4.34[20]	2.26[20]	88[20]
87901	Regulus	B8IVn	40.102[21]	0[21]	7.58[21]	3.7[21]	4.07[22]	2.38[23]	0.31[21]	4.30[21]	-0.30[21,D]	86.3[24]
-	KOI-81	B8V	23.876[25]	0[25]	6.74[25]	2.92[25]	4.07[25]	2.13[25]	0.19[25]	4.30[25]	0.14[25]	89[25]
60855	V378 Pup	B3Ve	-	-	-	5.4[C]	4.30[9]	3.99[26]	-	4.62[9]	2.85[9]	-
43544	HR 2249	B2/B3Ve	-	-	-	8.5[9]	4.33[27]	3.55[26]	-	4.58[9]	2.70[9]	46[8]
51354	QY Gem	B3ne	-	-	-	5.4[C]	4.30[9]	3.49[26]	-	4.64[9]	2.85[9]	-
29441	V1150 Tau	B2.5Vne	-	-	-	6.1[C]	4.31[28]	3.47[26]	-	4.60[9]	2.26[9]	-

In the column labels, the subscript "1" indicates the Be/n star, and "2" the stripped sdOB star. Note that when ranges of values are provided in a given paper, the average value is listed. References for these parameters are indicated by superscript numbers, and further notes with capital letters according to the following. 1 = Koubský et al (2000), 2 = Klement et al (2022b), 3 = Klement et al (2024), 4 = Harmanec (2000), 5 = Wang et al (2017), 6 = Tarasov and Tuominen (1987), 7 = Peters et al (2013), 8 = Zorec et al (2016), 9 = Wang et al (2021), 10 = Chojnowski et al (2018), 11 = Peters et al (2008), 12 = Peters et al (2016), 13 = Mourard et al (2015), 14 = Gies et al (1998), 15 = Wang et al (2023), 16 = Arcos et al (2018), 17 = Koubský et al (2014), 18 = Klement et al (2022a), 19 = Harmanec et al (2020), 20 = de Amorim et al (2023), 21 = Gies et al (2020), 22 = Borisov et al (2023), 23 = Anderson and Francis (2012), 24 = Che et al (2011), 25 = Matson et al (2015), 26 = Nazé et al (2022b), 27 = Levenhagen and Leister (2006), 28 = Hohle et al (2010), A = Estimated from parameters in Wang et al (2017), considering luminosity from Harmanec (2000). B = Estimated from parameters in Peters et al (2008) and Zorec et al (2016). C = Estimated from spectral type from the table of Eric Mamajek https://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt. D = Estimated from Fig. 8 in Gies et al (2020).

Table A2 Basic properties of confirmed SB1 Be binaries.

HD	ID	ST	P_{orb} (d)	e	K_1 (km s^{-1})	M_1 ($M_\odot$)	$\log(T_{eff,1})$ (K)	$\log(L_1)$ ($L_\odot$)	M_2 ($M_\odot$)	i (°)
205637	eps Cap	B3Vpe	128.3[1]	0[1]	8.4[1]	9.6[2]	4.27[2]	3.86[2]	0.98[B]	68[2]
142926	4 Her	B9pe	46.2[3]	0[3]	4.8[3]	3.2[3]	4.10[3]	2.36[3]	0.25[3]	77[4]
23862	Pleione	B8Vne	218[5]	0.745[5]	6.39[5]	2.9[5]	4.08[2]	2.44[2]	0.27[5]	68[2]
162732	88 Her	B8e	86.7[6]	0.15[6]	8.91[6]	2.9[2]	4.15[2]	2.62[2]	0.41[6,B]	62[2]
183656	V923 Aql	B7III	214.716[7]	0[7]	3.02[7]	6.2[2]	4.15[2]	2.95[2]	0.45[7,C]	88[2]
184279	V1294 Aql	B0.5IVe	192.9[8]	0[8]	6.3[8]	16.9[2]	4.48[2]	4.83[2]	1.15[8]	37[2]
63462	omi Pup	B1IV:nne	28.9[9]	0[9]	10.3[9]	13[9]	4.55[2]	4.43[2]	0.7[9]	67[2]
212571	pi Aqr	B1III-IVe	84.1[10,11,12]	0[11,12]	8.1[11,12]	10[12]	4.38[10]	3.87[12]	0.8[12,D]	56[4]
5394	gamma Cas	B0.5IVe	203.523[13,14]	0[13]	4.3[13]	13[15]	4.46[15]	5.19[2]	0.98[13]	45[16]
37202	zeta Tau	B1IVe-shell	133[17,18,19]	0[18]	7.4[18]	11[18]	4.32[2]	3.95[2]	0.9[18]	85[20]
45995	HD 45995	B2Vnne	103.1[19]	0[19]	6.7[19]	10[19]	4.40[2]	3.79[2]	1[19]	45[2]
183362	V558 Lyr	B3Ve	83.3[19]	0[19]	8.2[19]	8[19]	4.23[21]	2.99[21]	0.75[19]	-
12882	V782 Cas	B2.5III	122[19]	0[19]	5.2[19]	9[19]	4.27[21]	3.20[21]	0.6[19]	-
220058	V810 Cas	B1	75.8[19]	0[19]	6.4[19]	12.5[19]	4.41[A]	4.13[A]	0.75[A]	-
-	V2156 Cyg	B1.5V	126.6[19]	0[19]	5.5[19]	11[19]	4.39[A]	3.91[A]	0.75[19]	-
157832	V750 Ara	B2Vne	95.23[22]	0[22]	6.25[22]	11[22]	4.40[23]	3.91[A]	0.75[22]	-

References for these parameters are indicated by superscript numbers, and further notes with capital letters according to the following. 1 = Rivinius et al (2006), 2 = Zorec et al (2016), 3 = Koubsky et al (1997), 4 = Sigut and Ghafourian (2023), 5 = Nemravová et al (2010), 6 = Duemmler et al (1988), 7 = Wolf et al (2021), 8 = Harmanec et al (2022), 9 = Koubský et al (2012), 10 = Bjorkman et al (2002), 11 = Nazé et al (2019), 12 = Tsujimoto et al (2023), 13 = Nemravová et al (2012), 14 = Rauw et al (2022), 15 = Harmanec et al (2000), 16 = Klement et al (2024), 17 = Harmanec (1984), 18 = Ruždjak et al (2009), 19 = Nazé et al (2022a), 20 = Carciofi et al (2009), 21 = Pecaut and Mamajek (2013), 22 = Wang et al (2023), 23 = Lopes de Oliveira and Motch (2011). A = Estimated from spectral type from the table of Eric Mamajek https://www.pas.rochester.edu/~emamajek/EEM_dwarf_UBVIJHK_colors_Teff.txt. B = Estimated from mass function and inclination angle. C = Average value from a range of solutions. D = Estimated from their Fig. 8.

Table A3 Basic properties of confirmed Be binaries with stripped bloated companions.

HD	ID	ST	P_{orb} (d)	e	K_1 (km s^{-1})	K_2 (km s^{-1})	M_1 (M$_\odot$)	$\log(T_{eff,1})$ (K)	$\log(L_1)$ (L$_\odot$)	M_2 (M$_\odot$)	$\log(T_{eff,2})$ (K)	$\log(L_2)$ (L$_\odot$)	i (°)
-	LB-1	B3V	78.78[1]	0[1]	11.2[1]	52.94[1]	7.15[1]	4.26[1]	3.10[1]	1.53[1]	4.10[1]	2.80[1]	39[1]
167128	HR 6819	B3IIIe	40.3315[2,3,4]	0[3]	4[3]	62.13[3]	7[3]	4.30[3]	3.35[3]	0.46[3]	4.20[3]	3.05[3]	32[3]
-	HIP 15429	B5Ib	221[5]	0.52[5]	5[5]	75[5]	7[5]	4.23[5]	4.43[5]	0.7[5]	4.13[5]	4.36[5]	-
190467	V1362 Cyg	B3e	56.82[6]	0[6]	-	82[6]	-	-	-	-	-	-	-
698	V742 Cas	B7:Ib-II(e)	55.93[6]	0[6]	-	86.9[6]	-	-	-	-	-	-	-
173219	V447 Sct	B1:V:npe	58.41[6]	0[6]	-	87.4[6]	-	-	-	-	-	-	-
235679	V2174 Cyg	BN2.5Ib:e	225.33[6,7]	0.075[6,7]	-	61.1[6,7]	-	-	-	-	-	-	-
44637	MWC 139	B3III:[n]e	>180[6]	–	-	>30[6]	-	-	-	-	-	-	-

In the column labels, the subscript "1" indicates the Be/n star, and "2" the stripped star (which is lower mass but may be the more luminous component). The spectral types may be misleading, as such classifications may have been made prior to understanding the intricacies of these systems. References for these parameters are indicated by superscript numbers. 1 = Shenar et al (2020a), 2 = Rivinius et al (2020), 3 = Bodensteiner et al (2020a), 4 = Frost et al (2022), 5 = Müller-Horn et al (2025), 6 = Rivinius et al (2025), 7 = Bolton and Hurkens (2001).

Table A4 Basic properties of binaries with high-mass stripped stars.

ID	ST	P_{orb} (d)	e	K_1 (km s^{-1})	M_1 (M$_\odot$)	$\log(T_{eff,1})$ (K)	$\log(L_1)$ (L$_\odot$)	M_2 (M$_\odot$)	$\log(T_{eff,2})$ (K)	$\log(L_2)$ (L$_\odot$)
2dFS 163[1]	O6.5Ib(f)+B0-1Ve	-	-	-	10.5	4.41	4.18	3.96	4.57	4.75
2dFS 2553[1]	O4III(f)+B0-1Ve	93.6	-	-	13.8	4.43	4.34	6.86	4.62	4.91
Sk -71 35[1]	B1Ia+O9Ve	9.398	-	-	35.7	4.51	5.12	7.8	4.32	4.93
VFTS 291[2]	B5II-Ib+BV-IV	108.03	0	<15	13.2	4.44	4.41	2.2	4.12	3.96
1[3,4]		-	-	-	-	-	-	8.45	4.95	5.09
2[3,4]		-	-	-	-	-	-	3.31	4.80	4.12
3[3,4]		-	-	-	-	-	-	3.38	4.85	4.15
4[3,4]		-	-	-	-	-	-	3.04	4.83	4.01
5[3,4]		-	-	-	-	-	-	4.06	4.82	4.34
6[3,4]		-	-	-	-	-	-	3.74	4.86	4.24
7[3,4]		-	-	-	-	-	-	2.91	4.79	3.95
8[3,4]		-	-	-	-	-	-	2.14	4.76	3.55
16[3,4]		-	-	-	-	-	-	1.63	4.52	3.20

In the column labels, the subscript "1" indicates the Be/n star, and "2" the stripped star (which may be the more luminous component). The IDs for the last several columns are those used in Drout et al (2023). The first two entries in this table may have a classical Be star component (Ramachandran et al, 2024). Sk -71 35 is possibly still undergoing mass transfer, so may be of a different nature than the rest of this sample. In most cases, details of the non-stripped companion are not yet known. References for these parameters are indicated by superscript numbers. 1 = Ramachandran et al (2024), 2 = Villaseñor et al (2023), 3 = Götberg et al (2023), 4 = Drout et al (2023).

References

Abbott BP, Abbott R, Abbott TD, et al (2017) Multi-messenger Observations of a Binary Neutron Star Merger. ApJL 848(2):L12. https://doi.org/10.3847/2041-8213/aa91c9, arXiv:1710.05833 [astro-ph.HE]

Anderson E, Francis C (2012) XHIP: An extended hipparcos compilation. Astronomy Letters 38(5):331–346. https://doi.org/10.1134/S1063773712050015, arXiv:1108.4971 [astro-ph.GA]

Antoniou V, Zezas A (2016) Star formation history and X-ray binary populations: the case of the Large Magellanic Cloud. Monthly Notices of the RAS 459(1):528–553. https://doi.org/10.1093/mnras/stw167, arXiv:1603.08011 [astro-ph.HE]

Anusha R, Mathew B, Shridharan B, et al (2021) Identification of new classical Ae stars in the Galaxy using LAMOST DR5. MNRAS 501(4):5927–5937. https://doi.org/10.1093/mnras/staa3964, arXiv:2012.09782 [astro-ph.SR]

Arcos C, Kanaan S, Chávez J, et al (2018) Stellar parameters and H α line profile variability of Be stars in the BeSOS survey. MNRAS 474(4):5287–5299. https://doi.org/10.1093/mnras/stx3075, arXiv:1711.08675 [astro-ph.SR]

Astropy Collaboration, Robitaille TP, Tollerud EJ, et al (2013) Astropy: A community Python package for astronomy. A&A 558:A33. https://doi.org/10.1051/0004-6361/201322068, arXiv:1307.6212 [astro-ph.IM]

Astropy Collaboration, Price-Whelan AM, Sipőcz BM, et al (2018) The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. AJ 156(3):123. https://doi.org/10.3847/1538-3881/aabc4f, arXiv:1801.02634 [astro-ph.IM]

Aufdenberg JP, Bopp BW (1994) Anisotropic Outflow in the Symbiotic/Be Star V644 Monocerotis. In: Shafter AW (ed) Interacting Binary Stars, p 364

Barai P, Gies DR, Choi E, et al (2004) Mass and Angular Momentum Transfer in the Massive Algol Binary RY Persei. ApJ 608(2):989–1000. https://doi.org/10.1086/420875, arXiv:astro-ph/0309734 [astro-ph]

Bjorkman KS, Miroshnichenko AS, McDavid D, et al (2002) A Study of π Aquarii during a Quasi-normal Star Phase: Refined Fundamental Parameters and Evidence for Binarity. Astrophysical Journal 573(2):812–824. https://doi.org/10.1086/340751, arXiv:astro-ph/0203357 [astro-ph]

Bodensteiner J, Shenar T, Mahy L, et al (2020a) Is HR 6819 a triple system containing a black hole?. An alternative explanation. A&A 641:A43. https://doi.org/10.1051/0004-6361/202038682, arXiv:2006.10770 [astro-ph.SR]

Bodensteiner J, Shenar T, Sana H (2020b) Investigating the lack of main-sequence companions to massive Be stars. A&A 641:A42. https://doi.org/10.1051/0004-6361/202037640, arXiv:2006.13229 [astro-ph.SR]

Bolton CT, Hurkens R (2001) A perplexing binary system containing a supergiant Be star. Publications of the Astronomical Institute of the Czechoslovak Academy of Sciences 89:23–27

Borisov SB, Chilingarian IV, Rubtsov EV, et al (2023) New Generation Stellar Spectral Libraries in the Optical and Near-infrared. I. The Recalibrated UVES-POP Library for Stellar Population Synthesis. ApJS 266(1):11. https://doi.org/10.3847/1538-4365/acc321, arXiv:2211.09130 [astro-ph.IM]

Boubert D, Evans NW (2018) On the kinematics of a runaway Be star population. MNRAS 477(4):5261–5278. https://doi.org/10.1093/mnras/sty980, arXiv:1804.05849 [astro-ph.SR]

Britavskiy N, Renzo M, Nazé Y, et al (2024) Tracing the evolution of short-period binaries with super-synchronous fast rotators. A&A 684:A35. https://doi.org/10.1051/0004-6361/202348484, arXiv:2401.11304 [astro-ph.SR]

Carciofi AC, Okazaki AT, Le Bouquin JB, et al (2009) Cyclic variability of the circumstellar disk of the Be star ζ Tauri. II. Testing the 2D global disk oscillation model. A&A 504(3):915–927. https://doi.org/10.1051/0004-6361/200810962, arXiv:0901.1098 [astro-ph.SR]

Carretero-Castrillo M, Ribó M, Paredes JM (2023) Galactic runaway O and Be stars found using Gaia DR3. A&A 679:A109. https://doi.org/10.1051/0004-6361/202346613, arXiv:2311.01827 [astro-ph.SR]

Casares J, Negueruela I, Ribó M, et al (2014) A Be-type star with a black-hole companion. Nature 505(7483):378–381. https://doi.org/10.1038/nature12916, arXiv:1401.3711 [astro-ph.SR]

Chamoli S, Basu J, Barway S, et al (2025) Challenging Classical Paradigms: Recurrent Nova M31N 2017-01e, a BeWD System in M31? ApJ 991(2):174. https://doi.org/10.3847/1538-4357/adf843, arXiv:2508.02227 [astro-ph.SR]

Che X, Monnier JD, Zhao M, et al (2011) Colder and Hotter: Interferometric Imaging of β Cassiopeiae and α Leonis. ApJ 732(2):68. https://doi.org/10.1088/0004-637X/732/2/68, arXiv:1105.0740 [astro-ph.SR]

Chojnowski SD, Labadie-Bartz J, Rivinius T, et al (2018) The Remarkable Be+sdOB Binary HD 55606. I. Orbital and Stellar Parameters. ApJ 865(1):76. https://doi.org/10.3847/1538-4357/aad964, arXiv:1806.06843 [astro-ph.SR]

Chung SM, Drake JJ, Kashyap VL, et al (2004) Doppler Shifts and Broadening and the Structure of the X-Ray Emission from Algol. ApJ 606(2):1184–1195. https://doi.org/10.1086/383195, arXiv:astro-ph/0401583 [astro-ph]

Coe MJ, Kirk J (2015) Catalogue of Be/X-ray binary systems in the Small Magellanic Cloud: X-ray, optical and IR properties. Monthly Notices of the RAS 452(1):969–977. https://doi.org/10.1093/mnras/stv1283, arXiv:1506.01920 [astro-ph.HE]

Collins IGeorge W. (1987) The Use of Terms and Definitions in the Study of be Stars (review Paper). In: Slettebak A, Snow TP (eds) IAU Colloq. 92: Physics of Be Stars, p 3

Cracco V, Orio M, Ciroi S, et al (2018) Supersoft X-Ray Sources Identified with Be Binaries in the Magellanic Clouds. ApJ 862(2):167. https://doi.org/10.3847/1538-4357/aacefb, arXiv:1806.08971 [astro-ph.SR]

Crawford JA (1955) On the Subgiant Components of Eclipsing Binary Systems. ApJ 121:71. https://doi.org/10.1086/145965

Cyr IH, Jones CE, Carciofi AC, et al (2020) Spiral density enhancements in Be binary systems. Monthly Notices of the RAS 497(3):3525–3536. https://doi.org/10.1093/mnras/staa2176, arXiv:2107.06230 [astro-ph.SR]

de Amorim T, Carciofi A, Labadie-Bartz J, et al (2023) The unique Be system HD 92406 with two stellar and two disk eclipses. Bulletin of the Astronomical Society of Brazil 34:119–123

de Amorim TH, Carciofi AC, Labadie-Bartz J, et al (2025) X-Raying a Be star disk: fundamental parameters of the eclipsing binary Be star V658 Car. arXiv e-prints arXiv:2507.20053. https://doi.org/10.48550/arXiv.2507.20053, arXiv:2507.20053 [astro-ph.SR]

de Mink SE, Langer N, Izzard RG, et al (2013) The Rotation Rates of Massive Stars: The Role of Binary Interaction through Tides, Mass Transfer, and Mergers. ApJ 764(2):166. https://doi.org/10.1088/0004-637X/764/2/166, arXiv:1211.3742 [astro-ph.SR]

Dorigo Jones J, Oey MS, Paggeot K, et al (2020) Runaway OB Stars in the Small Magellanic Cloud: Dynamical versus Supernova Ejections. ApJ 903(1):43. https://doi.org/10.3847/1538-4357/abbc6b, arXiv:2009.03571 [astro-ph.SR]

Dorsch M, Reindl N, Pelisoli I, et al (2022) Discovery of a highly magnetic He-sdO star from a double-degenerate binary merger. A&A 658:L9. https://doi.org/10.1051/0004-6361/202142880, arXiv:2201.08146 [astro-ph.SR]

Drout MR, Götberg Y, Ludwig BA, et al (2023) An observed population of intermediate-mass helium stars that have been stripped in binaries. Science 382(6676):1287–1291. https://doi.org/10.1126/science.ade4970, arXiv:2307.00061 [astro-ph.SR]

Duemmler R, Kubicela A, Doazan V, et al (1988) The development and weakening of the shell spectrum of 88 Herculis (1977-1987). I. A radial velocity study. A&AS 75:311–316

Ekström S, Meynet G, Maeder A, et al (2008) Evolution towards the critical limit and the origin of Be stars. A&A 478(2):467–485. https://doi.org/10.1051/0004-6361:20078095, arXiv:0711.1735 [astro-ph]

Eldridge JJ, Stanway ER, Xiao L, et al (2017) Binary Population and Spectral Synthesis Version 2.1: Construction, Observational Verification, and New Results. Publ. Astron. Soc. Australia 34:e058. https://doi.org/10.1017/pasa.2017.51, arXiv:1710.02154 [astro-ph.SR]

Elias NMII, Wilson RE, Olson EC, et al (1997) New Perspectives on AX Monocerotis. ApJ 484(1):394–411. https://doi.org/10.1086/304299

Fortin F, García F, Simaz Bunzel A, et al (2023) A catalogue of high-mass X-ray binaries in the Galaxy: from the INTEGRAL to the Gaia era. A&A 671:A149. https://doi.org/10.1051/0004-6361/202245236, arXiv:2302.02656 [astro-ph.HE]

Frost AJ, Bodensteiner J, Rivinius T, et al (2022) HR 6819 is a binary system with no black hole. Revisiting the source with infrared interferometry and optical integral field spectroscopy. A&A 659:L3. https://doi.org/10.1051/0004-6361/202143004, arXiv:2203.01359 [astro-ph.SR]

G VK, Devarapalli SP, Parthasarathy M, et al (2024) Investigative study of five low mass ratio semi-detached binaries. Ap&SS 369(10):105. https://doi.org/10.1007/s10509-024-04368-6

Gallenne A, Mérand A, Kervella P, et al (2015) Robust high-contrast companion detection from interferometric observations. The CANDID algorithm and an application to six binary Cepheids. A&A 579:A68. https://doi.org/10.1051/0004-6361/201525917, arXiv:1505.02715 [astro-ph.SR]

Gaudin TM, Coe MJ, Kennea JA, et al (2024) CXOU J005245.0-722844: discovery of a Be star/white dwarf binary system in the SMC via a very fast, super-Eddington X-ray outburst event. MNRAS 534(3):1937–1948. https://doi.org/10.1093/mnras/stae2176, arXiv:2408.01388 [astro-ph.HE]

Georgy C, Ekström S, Granada A, et al (2013) Populations of rotating stars. I. Models from 1.7 to 15

$M_\odot$ at Z = 0.014, 0.006, and 0.002 with Ω/Ω_{crit} between 0 and 1. A&A 553:A24. https://doi.org/10.1051/0004-6361/201220558, arXiv:1303.2321 [astro-ph.SR]

Gies DR, Bagnuolo WGJr., Ferrara EC, et al (1998) Hubble Space Telescope Goddard High Resolution Spectrograph Observations of the Be + sdO Binary φ Persei. ApJ 493(1):440–450. https://doi.org/10.1086/305113

Gies DR, Dieterich S, Richardson ND, et al (2008) A Spectroscopic Orbit for Regulus. ApJL 682(2):L117. https://doi.org/10.1086/591148, arXiv:0806.3473 [astro-ph]

Gies DR, Lester KV, Wang L, et al (2020) Spectroscopic Detection of the Pre-White Dwarf Companion of Regulus. ApJ 902(1):25. https://doi.org/10.3847/1538-4357/abb372, arXiv:2009.02409 [astro-ph.SR]

Gies DR, Wang L, Klement R (2023) Gamma Cas Stars as Be+White Dwarf Binary Systems. ApJL 942(1):L6. https://doi.org/10.3847/2041-8213/acaaa1, arXiv:2212.06916 [astro-ph.SR]

Götberg Y, de Mink SE, Groh JH (2017) Ionizing spectra of stars that lose their envelope through interaction with a binary companion: role of metallicity. A&A 608:A11. https://doi.org/10.1051/0004-6361/201730472, arXiv:1701.07439 [astro-ph.SR]

Götberg Y, de Mink SE, Groh JH, et al (2019) The impact of stars stripped in binaries on the integrated spectra of stellar populations. A&A 629:A134. https://doi.org/10.1051/0004-6361/201834525, arXiv:1908.06102 [astro-ph.GA]

Götberg Y, de Mink SE, McQuinn M, et al (2020) Contribution from stars stripped in binaries to cosmic reionization of hydrogen and helium. A&A 634:A134. https://doi.org/10.1051/0004-6361/201936669, arXiv:1911.00543 [astro-ph.GA]

Götberg Y, Drout MR, Ji AP, et al (2023) Stellar Properties of Observed Stars Stripped in Binaries in the Magellanic Clouds. ApJ 959(2):125. https://doi.org/10.3847/1538-4357/ace5a3, arXiv:2307.00074 [astro-ph.SR]

Harmanec P (1984) Re-Investigation of the Periodic and Long-Term Radial-Velocity Variations of the Be Star ζ Tau (HD 37202). Bulletin of the Astronomical Institutes of Czechoslovakia 35:164

Harmanec P (2000) Physical Properties and Evolutionary Stage of Be Stars. In: Smith MA, Henrichs HF, Fabregat J (eds) IAU Colloq. 175: The Be Phenomenon in Early-Type Stars, p 13

Harmanec P, Habuda P, Štefl S, et al (2000) Properties and nature of Be stars. XX. Binary nature and orbital elements of gamma Cas. A&A 364:L85–L88. https://doi.org/10.48550/arXiv.astro-ph/0011516, arXiv:astro-ph/0011516 [astro-ph]

Harmanec P, Koubský P, Nemravová JA, et al (2015) Properties and nature of Be stars. 30. Reliable physical properties of a semi-detached B9.5e+G8III binary BR CMi = HD 61273 compared to those of other well studied semi-detached emission-line binaries. A&A 573:A107. https://doi.org/10.1051/0004-6361/201424640, arXiv:1411.5651 [astro-ph.SR]

Harmanec P, Lipták J, Koubský P, et al (2020) A new study of the spectroscopic binary 7 Vul with a Be star primary. A&A 639:A32. https://doi.org/10.1051/0004-6361/202037964, arXiv:2005.11089 [astro-ph.SR]

Harmanec P, Božić H, Koubský P, et al (2022) V1294 Aql = HD 184279: A bad boy among Be stars or an important clue to the Be phenomenon? A&A 666:A136. https://doi.org/10.1051/0004-6361/

202244006, arXiv:2206.11649 [astro-ph.SR]

Hastings B, Wang C, Langer N (2020) The single star path to Be stars. A&A 633:A165. https://doi.org/10.1051/0004-6361/201937018, arXiv:1912.05290 [astro-ph.SR]

Hastings B, Langer N, Wang C, et al (2021) Stringent upper limit on Be star fractions produced by binary interaction. A&A 653:A144. https://doi.org/10.1051/0004-6361/202141269, arXiv:2106.12263 [astro-ph.SR]

Hauck N (2018) Eclipsing binary V658 Carinae (HD 92406) containing a shell star and a hot low-mass star in the post-Algol stage. BAV Rundbrief - Mitteilungsblatt der Berliner Arbeits-gemeinschaft fuer Veraenderliche Sterne 67:41–48. https://doi.org/10.48550/arXiv.1805.04318, arXiv:1805.04318 [astro-ph.SR]

Hohle MM, Neuhäuser R, Schutz BF (2010) Masses and luminosities of O- and B-type stars and red supergiants. Astronomische Nachrichten 331(4):349. https://doi.org/10.1002/asna.200911355, arXiv:1003.2335 [astro-ph.SR]

Hovis-Afflerbach B, Götberg Y, Schootemeijer A, et al (2025) The mass distribution of stars stripped in binaries: The effect of metallicity. A&A 697:A239. https://doi.org/10.1051/0004-6361/202453185, arXiv:2412.05356 [astro-ph.SR]

Huang W, Gies DR, McSwain MV (2010) A Stellar Rotation Census of B Stars: From ZAMS to TAMS. ApJ 722(1):605–619. https://doi.org/10.1088/0004-637X/722/1/605, arXiv:1008.1761 [astro-ph.SR]

Hughes A, Bailes M (1999) Constraints on Natal Pulsar Kicks from Eccentric Binary Pulsars. Astrophysical Journal 522(1):504–511. https://doi.org/10.1086/307605

Hummel W, Štefl S (2001) The circumstellar structure of the Be shell star φ Persei. II. Modeling. A&A 368:471–483. https://doi.org/10.1051/0004-6361:20000559

Janssens S, Shenar T, Degenaar N, et al (2023) MWC 656 is unlikely to contain a black hole. A&A 677:L9. https://doi.org/10.1051/0004-6361/202347318, arXiv:2308.08642 [astro-ph.SR]

Jaschek C, Jaschek M (1990) The Classification of Stars

Jerzykiewicz M, Pigulski A, Michalska G, et al (2021) BRITE observations of ν Centauri and γ Lupi, the first non-eclipsing members of the new class of nascent binaries. MNRAS 503(4):5554–5568. https://doi.org/10.1093/mnras/stab846, arXiv:2104.11770 [astro-ph.SR]

Johnston C, Aimar N, Abdul-Masih M, et al (2021) Characterization of the variability in the O+B eclipsing binary HD 165246. MNRAS 503(1):1124–1137. https://doi.org/10.1093/mnras/stab488, arXiv:2102.08391 [astro-ph.SR]

Jones CE, Labadie-Bartz J, Cotton DV, et al (2022) Ultraviolet Spectropolarimetry: on the origin of rapidly rotating B stars. Ap&SS 367(12):124. https://doi.org/10.1007/s10509-022-04127-5, arXiv:2111.07926 [astro-ph.IM]

Kennea JA, Coe MJ, Evans PA, et al (2021) Swift J011511.0-725611: discovery of a rare Be star/white dwarf binary system in the SMC. MNRAS 508(1):781–788. https://doi.org/10.1093/mnras/stab2632, arXiv:2109.05307 [astro-ph.HE]

Kervella P, Borgniet S, Domiciano de Souza A, et al (2022) The binary system of the spinning-top

Be star Achernar. A&A 667:A111. https://doi.org/10.1051/0004-6361/202244009, arXiv:2209.07537 [astro-ph.SR]

Klement R, Carciofi AC, Rivinius T, et al (2019) Prevalence of SED Turndown among Classical Be Stars: Are All Be Stars Close Binaries? Astrophysical Journal 885(2):147. https://doi.org/10.3847/1538-4357/ab48e7, arXiv:1909.12413 [astro-ph.SR]

Klement R, Baade D, Rivinius T, et al (2022a) Dynamical Masses of the Primary Be Star and Secondary sdB Star in the Single-lined Binary κ Dra (B6 IIIe). ApJ 940(1):86. https://doi.org/10.3847/1538-4357/ac98b8, arXiv:2210.03090 [astro-ph.SR]

Klement R, Schaefer GH, Gies DR, et al (2022b) Interferometric Detections of sdO Companions Orbiting Three Classical Be Stars. ApJ 926(2):213. https://doi.org/10.3847/1538-4357/ac4266, arXiv:2112.05073 [astro-ph.SR]

Klement R, Rivinius T, Gies DR, et al (2024) The CHARA Array Interferometric Program on the Multiplicity of Classical Be Stars: New Detections and Orbits of Stripped Subdwarf Companions. ApJ 962(1):70. https://doi.org/10.3847/1538-4357/ad13ec, arXiv:2312.08252 [astro-ph.SR]

Korol V, Buscicchio R, Pakmor R, et al (2024) Expected insights into Type Ia supernovae from LISA's gravitational wave observations. A&A 691:A44. https://doi.org/10.1051/0004-6361/202451380, arXiv:2407.03935 [astro-ph.HE]

Koubsky P, Harmanec P, Kubat J, et al (1997) Properties and nature of Be stars. XVIII. Spectral, light and colour variations of 4 Herculis. A&A 328:551–564

Koubský P, Harmanec P, Hubert AM, et al (2000) Properties and nature of Be stars. XIX. Spectral and light variability of 60 Cygni. A&A 356:913–928

Koubský P, Kotková L, Votruba V, et al (2012) o Puppis: another Be+sdO binary? A&A 545:A121. https://doi.org/10.1051/0004-6361/201219679

Koubský P, Kotková L, Kraus M, et al (2014) HD 161306: a radiatively interacting Be binary? A&A 567:A57. https://doi.org/10.1051/0004-6361/201424022

Kroupa P, Tout CA, Gilmore G (1993) The Distribution of Low-Mass Stars in the Galactic Disc. MNRAS 262:545–587. https://doi.org/10.1093/mnras/262.3.545

Lechien T, de Mink SE, Valli R, et al (2025) Binary stars take what they get: Evidence for Efficient Mass Transfer from Stripped Stars with Rapidly Rotating Companions. arXiv e-prints arXiv:2505.14780. https://doi.org/10.48550/arXiv.2505.14780, arXiv:2505.14780 [astro-ph.SR]

Levenhagen RS, Leister NV (2006) Spectroscopic analysis of southern B and Be stars. MNRAS 371(1):252–262. https://doi.org/10.1111/j.1365-2966.2006.10655.x, arXiv:astro-ph/0606149 [astro-ph]

Lopes de Oliveira R, Motch C (2011) A Hard and Variable X-ray Emission from the Massive Emission-line Star HD 157832. ApJL 731(1):L6. https://doi.org/10.1088/2041-8205/731/1/L6, arXiv:1102.4625 [astro-ph.SR]

Maeder A, Meynet G (2000a) Stellar evolution with rotation. VI. The Eddington and Omega -limits, the rotational mass loss for OB and LBV stars. A&A 361:159–166. https://doi.org/10.48550/arXiv.astro-ph/0006405, arXiv:astro-ph/0006405 [astro-ph]

Maeder A, Meynet G (2000b) The Evolution of Rotating Stars. ARA&A 38:143–190. https://doi.org/10.1146/annurev.astro.38.1.143, arXiv:astro-ph/0004204 [astro-ph]

Mahy L, Sana H, Shenar T, et al (2022) Identifying quiescent compact objects in massive Galactic single-lined spectroscopic binaries. A&A 664:A159. https://doi.org/10.1051/0004-6361/202243147, arXiv:2207.07752 [astro-ph.SR]

Malkov OY (2020) Semidetached double-lined eclipsing binaries: Stellar parameters and rare classes. MNRAS 491(4):5489–5497. https://doi.org/10.1093/mnras/stz3363

Marcussen ML, Albrecht SH, Winn JN, et al (2024) The BANANA Project. VII. High Eccentricity Predicts Spin–Orbit Misalignment in Binaries. ApJ 975(1):149. https://doi.org/10.3847/1538-4357/ad75fa, arXiv:2408.03072 [astro-ph.SR]

Marino A, Yang HN, Coti Zelati F, et al (2025) Einstein Probe Discovery of EP J005245.1-722843: A Rare Be–White Dwarf Binary in the Small Magellanic Cloud? ApJL 980(2):L36. https://doi.org/10.3847/2041-8213/ad9580, arXiv:2407.21371 [astro-ph.HE]

Martayan C, Frémat Y, Hubert AM, et al (2006) Effects of metallicity, star-formation conditions, and evolution in B and Be stars. I. Large Magellanic Cloud, field of NGC 2004. A&A 452(1):273–284. https://doi.org/10.1051/0004-6361:20053859, arXiv:astro-ph/0601240 [astro-ph]

Martin RG, Pringle JE, Tout CA (2007) Alignment and precession of a black hole with a warped accretion disc. Monthly Notices of the RAS 381(4):1617–1624. https://doi.org/10.1111/j.1365-2966.2007.12349.x, arXiv:0708.2034 [astro-ph]

Martin RG, Tout CA, Pringle JE (2009) Supernova kicks and misaligned Be star binaries. Monthly Notices of the RAS 397(3):1563–1576. https://doi.org/10.1111/j.1365-2966.2009.15031.x, arXiv:0905.2362 [astro-ph.SR]

Martin RG, Pringle JE, Tout CA, et al (2011) Tidal warping and precession of Be star decretion discs. Monthly Notices of the RAS 416(4):2827–2839. https://doi.org/10.1111/j.1365-2966.2011.19231.x, arXiv:1106.2591 [astro-ph.SR]

Matson RA, Gies DR, Guo Z, et al (2015) HST/COS Detection of the Spectrum of the Subdwarf Companion of KOI-81. ApJ 806(2):155. https://doi.org/10.1088/0004-637X/806/2/155, arXiv:1505.00817 [astro-ph.SR]

Miroshnichenko AS, Chari R, Danford S, et al (2023) Searching for Phase-Locked Variations of the Emission-Line Profiles in Binary Be Stars. Galaxies 11(4):83. https://doi.org/10.3390/galaxies11040083

Mourard D, Monnier JD, Meilland A, et al (2015) Spectral and spatial imaging of the Be+sdO binary ¡ASTROBJ¿ϕ Persei¡/ASTROBJ¿. A&A 577:A51. https://doi.org/10.1051/0004-6361/201425141, arXiv:1503.03423 [astro-ph.SR]

Müller-Horn J, El-Badry K, Rix HW, et al (2025) HIP 15429: a newborn Be star on an eccentric binary orbit. arXiv e-prints arXiv:2504.06973. https://doi.org/10.48550/arXiv.2504.06973, arXiv:2504.06973 [astro-ph.SR]

Muslimov E, Neiner C (2022) Spectropolarimeter's optical design for the Arago space mission project. arXiv e-prints arXiv:2211.09931. https://doi.org/10.48550/arXiv.2211.09931, arXiv:2211.09931 [astro-ph.IM]

Muslimov E, Bouret JC, Neiner C, et al (2018) POLLUX: a UV spectropolarimeter for the LUVOIR space telescope project. In: den Herder JWA, Nikzad S, Nakazawa K (eds) Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, p 1069906, https://doi.org/10.1117/12.2310133, 1805.09067

Nazé Y, Motch C (2018) Hot stars observed by XMM-Newton. II. A survey of Oe and Be stars. A&A 619:A148. https://doi.org/10.1051/0004-6361/201833842, arXiv:1809.03341 [astro-ph.SR]

Nazé Y, Rauw G (2025) Another one (BH+OB pair) bites the dust. A&A 696:A84. https://doi.org/10.1051/0004-6361/202453493, arXiv:2503.08190 [astro-ph.SR]

Nazé Y, Rauw G, Smith M (2019) Surprises in the simultaneous X-ray and optical monitoring of π Aquarii. A&A 632:A23. https://doi.org/10.1051/0004-6361/201936307, arXiv:1910.11050 [astro-ph.SR]

Nazé Y, Rauw G, Czesla S, et al (2022a) Velocity monitoring of γ Cas stars reveals their binarity status. MNRAS 510(2):2286–2304. https://doi.org/10.1093/mnras/stab3378, arXiv:2111.09579 [astro-ph.SR]

Nazé Y, Rauw G, Smith MA, et al (2022b) The X-ray emission of Be+stripped star binaries. MNRAS 516(3):3366–3380. https://doi.org/10.1093/mnras/stac2245, arXiv:2208.03990 [astro-ph.SR]

Nazé Y, Britavskiy N, Rauw G, et al (2023) Extreme mass ratios and fast rotation in three massive binaries. MNRAS 525(2):1641–1656. https://doi.org/10.1093/mnras/stad2280, arXiv:2308.02368 [astro-ph.SR]

Nazé Y, Britavskiy N, Labadie-Bartz J (2024) TESS observations of non-Be fast rotators. A&A 689:A320. https://doi.org/10.1051/0004-6361/202450966, arXiv:2407.08305 [astro-ph.SR]

Naze Y, Rauw G, Kolaczek-Szymanski PA, et al (2025) A family of binaries with an extreme mass ratio. arXiv e-prints arXiv:2510.15393. https://doi.org/10.48550/arXiv.2510.15393, arXiv:2510.15393 [astro-ph.SR]

Neiner C, Mathis S, Saio H, et al (2012) Seismic modelling of the late Be stars HD 181231 and HD 175869 observed with CoRoT: a laboratory for mixing processes. A&A 539:A90. https://doi.org/10.1051/0004-6361/201118151

Neiner C, Lee U, Mathis S, et al (2020) Transport of angular momentum by stochastically excited waves as an explanation for the outburst of the rapidly rotating Be star HD49330. A&A 644:A9. https://doi.org/10.1051/0004-6361/201935858, arXiv:2007.08977 [astro-ph.SR]

Nemravová J, Harmanec P, Kubát J, et al (2010) Properties and nature of Be stars. 27. Orbital and recent long-term variations of the Pleiades Be star Pleione = BU Tauri. A&A 516:A80. https://doi.org/10.1051/0004-6361/200913885, arXiv:1003.5625 [astro-ph.SR]

Nemravová J, Harmanec P, Koubský P, et al (2012) Properties and nature of Be stars. 29. Orbital and long-term spectral variations of γ Cassiopeiae. A&A 537:A59. https://doi.org/10.1051/0004-6361/201117922, arXiv:1111.3761 [astro-ph.SR]

Neugent KF, Massey P (2014) The Close Binary Frequency of Wolf-Rayet Stars as a Function of Metallicity in M31 and M33. ApJ 789(1):10. https://doi.org/10.1088/0004-637X/789/1/10, arXiv:1405.1810 [astro-ph.SR]

Pandey G, Lambert DL (2017) Non-local Thermodynamic Equilibrium Abundance Analyses of the Extreme Helium Stars V652 Her and HD 144941. ApJ 847(2):127. https://doi.org/10.3847/1538-4357/

aa88bb, arXiv:1708.07945 [astro-ph.SR]

Panoglou D, Carciofi AC, Vieira RG, et al (2016) Be discs in binary systems - I. Coplanar orbits. Monthly Notices of the RAS 461(3):2616–2629. https://doi.org/10.1093/mnras/stw1508, arXiv:1605.06674 [astro-ph.SR]

Panoglou D, Faes DM, Carciofi AC, et al (2018) Be discs in coplanar circular binaries: Phase-locked variations of emission lines. Monthly Notices of the RAS 473(3):3039–3050. https://doi.org/10.1093/mnras/stx2497, arXiv:1704.06751 [astro-ph.SR]

Paxton B, Smolec R, Schwab J, et al (2019) Modules for Experiments in Stellar Astrophysics (MESA): Pulsating Variable Stars, Rotation, Convective Boundaries, and Energy Conservation. ApJS 243(1):10. https://doi.org/10.3847/1538-4365/ab2241, arXiv:1903.01426 [astro-ph.SR]

Pecaut MJ, Mamajek EE (2013) Intrinsic Colors, Temperatures, and Bolometric Corrections of Pre-main-sequence Stars. ApJS 208(1):9. https://doi.org/10.1088/0067-0049/208/1/9, arXiv:1307.2657 [astro-ph.SR]

Peters GJ, Polidan RS (1984) Evidence for a high-temperature accretion region in Algol-type binarysystems. ApJ 283:745–759. https://doi.org/10.1086/162359

Peters GJ, Gies DR, Grundstrom ED, et al (2008) Detection of a Hot Subdwarf Companion to the Be Star FY Canis Majoris. ApJ 686(2):1280–1291. https://doi.org/10.1086/591145, arXiv:0806.3004 [astro-ph]

Peters GJ, Pewett TD, Gies DR, et al (2013) Far-ultraviolet Detection of the Suspected Subdwarf Companion to the Be Star 59 Cygni. Astrophysical Journal 765(1):2. https://doi.org/10.1088/0004-637X/765/1/2, arXiv:1301.0257 [astro-ph.SR]

Peters GJ, Wang L, Gies DR, et al (2016) The Hot Companion and Circumbinary Disk of the Be Star HR 2142. ApJ 828(1):47. https://doi.org/10.3847/0004-637X/828/1/47, arXiv:1607.01829 [astro-ph.SR]

Peters GJ, Gayley KG, Ignace R, et al (2022) Ultraviolet spectropolarimetry: conservative and non-conservative mass transfer in OB interacting binaries. Ap&SS 367(12):119. https://doi.org/10.1007/s10509-022-04106-w, arXiv:2111.14047 [astro-ph.SR]

Pigulski A, Boratyn DA (1992) The orbit of beta Cephei derived from the light-time effect. A&A 253:178–184

Plavec M (1970) Mass Exchange in Binary Stars. PASP 82(489):957. https://doi.org/10.1086/128996

Pourbaix D, Tokovinin AA, Batten AH, et al (2004) S_{B^9}: The ninth catalogue of spectroscopic binary orbits. A&A 424:727–732. https://doi.org/10.1051/0004-6361:20041213, arXiv:astro-ph/0406573 [astro-ph]

Ramachandran V, Sander AAC, Pauli D, et al (2024) X-Shooting ULLYSES: Massive stars at low metallicity: VIII. Stellar and wind parameters of newly revealed stripped stars in Be binaries. A&A 692:A90. https://doi.org/10.1051/0004-6361/202449665, arXiv:2406.17678 [astro-ph.SR]

Rauw G (2022) X-Ray Emission of Massive Stars and Their Winds. In: Bambi C, Sangangelo A (eds) Handbook of X-ray and Gamma-ray Astrophysics. p 108, https://doi.org/10.1007/978-981-16-4544-0_79-1

Rauw G, Nazé Y, Motch C, et al (2022) The X-ray Emission of γ Cassiopeiae During the 2020-2021 Disc

Eruption. A&A 664:A184. https://doi.org/10.1051/0004-6361/202243679, arXiv:2206.08730 [astro-ph.SR]

Reeve D, Howarth ID (2018) Are the O stars in WR+O binaries exceptionally rapid rotators? MNRAS 478(3):3133–3137. https://doi.org/10.1093/mnras/sty1296, arXiv:1805.03481 [astro-ph.SR]

Reig P (2011) Be/X-ray binaries. Astrophysics and Space Science 332(1):1–29. https://doi.org/10.1007/s10509-010-0575-8, arXiv:1101.5036 [astro-ph.HE]

Rivinius T, Štefl S, Baade D (2006) Bright Be-shell stars. A&A 459(1):137–145. https://doi.org/10.1051/0004-6361:20053008

Rivinius T, Carciofi AC, Martayan C (2013) Classical Be stars. Rapidly rotating B stars with viscous Keplerian decretion disks. Astronomy and Astrophysics Reviews 21:69. https://doi.org/10.1007/s00159-013-0069-0, arXiv:1310.3962 [astro-ph.SR]

Rivinius T, Baade D, Hadrava P, et al (2020) A naked-eye triple system with a nonaccreting black hole in the inner binary. A&A 637:L3. https://doi.org/10.1051/0004-6361/202038020, arXiv:2005.02541 [astro-ph.SR]

Rivinius T, Klement R, Chojnowski SD, et al (2024) MWC 656: A Be+BH or a Be+sdO? In: Mackey J, Vink JS, St-Louis N (eds) Massive Stars Near and Far, pp 332–333, https://doi.org/10.1017/S1743921322002976, 2208.12315

Rivinius T, Klement R, Chojnowski SD, et al (2025) Newborn Be star systems observed shortly after mass transfer. A&A 694:A172. https://doi.org/10.1051/0004-6361/202347275, arXiv:2412.09720 [astro-ph.SR]

Royer F, Zorec J, Gómez AE (2007) Rotational velocities of A-type stars. III. Velocity distributions. A&A 463(2):671–682. https://doi.org/10.1051/0004-6361:20065224, arXiv:astro-ph/0610785 [astro-ph]

Ruždjak D, Božić H, Harmanec P, et al (2009) Properties and nature of Be stars. 26. Long-term and orbital changes of ζ Tauri. A&A 506(3):1319–1333. https://doi.org/10.1051/0004-6361/200810526

Salvesen G, Pokawanvit S (2020) Origin of spin-orbit misalignments: the microblazar V4641 Sgr. Monthly Notices of the RAS 495(2):2179–2204. https://doi.org/10.1093/mnras/staa1094, arXiv:2004.08392 [astro-ph.HE]

Sana H, Le Bouquin JB, Mahy L, et al (2013) Three-dimensional orbits of the triple-O stellar system HD 150136. A&A 553:A131. https://doi.org/10.1051/0004-6361/201321189, arXiv:1304.3457 [astro-ph.SR]

Schaefer BE, Pearce A, Love T, et al (2025) FQ Circini: An Ordinary Nova with a High-mass B1 V(n)(e) Companion Whose Decretion Disk Transfers Mass to the White Dwarf via Roche-Lobe Overflow. arXiv e-prints arXiv:2511.16594. https://doi.org/10.48550/arXiv.2511.16594, arXiv:2511.16594 [astro-ph.SR]

Scowen PA, Gayley K, Ignace R, et al (2022) The Polstar high resolution spectropolarimetry MIDEX mission. Ap&SS 367(12):121. https://doi.org/10.1007/s10509-022-04107-9, arXiv:2108.10729 [astro-ph.IM]

Secchi A (1866) Schreiben des Herrn Prof. Secchi, Directors der Sternwarte des Collegio Romano, an den Herausgeber. Astronomische Nachrichten 68:63. https://doi.org/10.1002/asna.18670680405

Sen K, El Mellah I, Langer N, et al (2024) Whispering in the dark: Faint X-ray emission from black holes with OB star companions. A&A 690:A256. https://doi.org/10.1051/0004-6361/202450940, arXiv:2406.08596 [astro-ph.HE]

Shara MM, Crawford SM, Vanbeveren D, et al (2017) The spin rates of O stars in WR + O binaries - I. Motivation, methodology, and first results from SALT. MNRAS 464(2):2066–2074. https://doi.org/10.1093/mnras/stw2450

Shara MM, Crawford SM, Vanbeveren D, et al (2020) The spin rates of O stars in WR+O Magellanic Cloud binaries. MNRAS 492(3):4430–4436. https://doi.org/10.1093/mnras/staa038, arXiv:2001.01012 [astro-ph.SR]

Shenar T (2024) Wolf-Rayet stars. arXiv e-prints arXiv:2410.04436. https://doi.org/10.48550/arXiv.2410.04436, arXiv:2410.04436 [astro-ph.SR]

Shenar T, Sablowski DP, Hainich R, et al (2019) The Wolf-Rayet binaries of the nitrogen sequence in the Large Magellanic Cloud. Spectroscopy, orbital analysis, formation, and evolution. A&A 627:A151. https://doi.org/10.1051/0004-6361/201935684, arXiv:1905.09296 [astro-ph.SR]

Shenar T, Bodensteiner J, Abdul-Masih M, et al (2020a) The "hidden" companion in LB-1 unveiled by spectral disentangling. A&A 639:L6. https://doi.org/10.1051/0004-6361/202038275, arXiv:2004.12882 [astro-ph.SR]

Shenar T, Gilkis A, Vink JS, et al (2020b) Why binary interaction does not necessarily dominate the formation of Wolf-Rayet stars at low metallicity. A&A 634:A79. https://doi.org/10.1051/0004-6361/201936948, arXiv:2001.04476 [astro-ph.SR]

Shenar T, Sana H, Mahy L, et al (2022) An X-ray-quiet black hole born with a negligible kick in a massive binary within the Large Magellanic Cloud. Nature Astronomy 6:1085–1092. https://doi.org/10.1038/s41550-022-01730-y, arXiv:2207.07675 [astro-ph.HE]

Shulyak D, Tsymbal V, Ryabchikova T, et al (2004) Line-by-line opacity stellar model atmospheres. A&A 428:993–1000. https://doi.org/10.1051/0004-6361:20034169

Sigut TAA, Ghafourian NR (2023) Comparing Be Star Inclination Angles Determined from Hα Fitting and Gravitational Darkening. Astrophysical Journal 948(1):34. https://doi.org/10.3847/1538-4357/ac940c, arXiv:2209.06885 [astro-ph.SR]

Stassun KG, Torres G, Johnston C, et al (2021) Discovery and Characterization of a Rare Magnetic Hybrid β Cephei Slowly Pulsating B-type Star in an Eclipsing Binary in the Young Open Cluster NGC 6193. ApJ 910(2):133. https://doi.org/10.3847/1538-4357/abe5a8, arXiv:2102.06151 [astro-ph.SR]

Stevance H, Eldridge J, Stanway E (2020) Hoki: Making BPASS accessible through Python. The Journal of Open Source Software 5(45):1987. https://doi.org/10.21105/joss.01987, arXiv:2001.11069 [astro-ph.SR]

Summa A, Janka HT, Melson T, et al (2018) Rotation-supported Neutrino-driven Supernova Explosions in Three Dimensions and the Critical Luminosity Condition. ApJ 852(1):28. https://doi.org/10.3847/1538-4357/aa9ce8, arXiv:1708.04154 [astro-ph.HE]

Tango WJ, Davis J, Jacob AP, et al (2009) A new determination of the orbit and masses of the Be binary system delta Scorpii. Monthly Notices of the RAS 396(2):842–848. https://doi.org/10.1111/j.1365-2966.2009.14272.x, URL https://doi.org/10.1111/j.1365-2966.2009.14272.x, https://academic.oup.com/mnras/article-pdf/396/2/842/3395685/mnras0396-0842.pdf

Tarasov AE, Tuominen I (1987) Duplicity of the Be star 59 Cyg. Publications of the Astronomical Institute of the Czechoslovak Academy of Sciences 5:127–129

Tsujimoto M, Hayashi T, Morihana K, et al (2023) X-ray and optical spectroscopic study of a γ Cassiopeiae analog source π Aquarii. PASJ 75(1):177–186. https://doi.org/10.1093/pasj/psac099, arXiv:2211.10803 [astro-ph.HE]

Tycner C, Ames A, Zavala RT, et al (2011) The Revised Orbit of the δ Sco System. Astrophysical Journall 729(1):L5. https://doi.org/10.1088/2041-8205/729/1/L5, arXiv:1101.5152 [astro-ph.SR]

van Bever J, Vanbeveren D (1997) The number of B-type binary mass gainers in general, binary Be stars in particular, predicted by close binary evolution. A&A 322:116–126

Vennes S, Kawka A, Jonić S, et al (2011) On the nature of the Be star HR 7409 (7 Vul). MNRAS 413(4):2760–2766. https://doi.org/10.1111/j.1365-2966.2011.18350.x, arXiv:1101.2622 [astro-ph.SR]

Villaseñor JI, Lennon DJ, Picco A, et al (2023) The B-type Binaries Characterisation Programme - II. VFTS 291: a stripped star from a recent mass transfer phase. MNRAS 525(4):5121–5145. https://doi.org/10.1093/mnras/stad2533, arXiv:2307.07766 [astro-ph.SR]

Wang C, Langer N, Schootemeijer A, et al (2022) Stellar mergers as the origin of the blue main-sequence band in young star clusters. Nature Astronomy 6:480–487. https://doi.org/10.1038/s41550-021-01597-5, arXiv:2202.05552 [astro-ph.SR]

Wang L, Gies DR, Peters GJ (2017) Detection of the Ultraviolet Spectrum of the Hot Subdwarf Companion of 60 Cygni (B1 Ve) from a Survey of IUE Spectra of Be Stars. ApJ 843(1):60. https://doi.org/10.3847/1538-4357/aa740a, arXiv:1705.07165 [astro-ph.SR]

Wang L, Gies DR, Peters GJ (2018) Detection of Additional Be+sdO Systems from IUE Spectroscopy. ApJ 853(2):156. https://doi.org/10.3847/1538-4357/aaa4b8, arXiv:1801.01066 [astro-ph.SR]

Wang L, Gies DR, Peters GJ, et al (2021) The Detection and Characterization of Be+sdO Binaries from HST/STIS FUV Spectroscopy. Astronomical Journal 161(5):248. https://doi.org/10.3847/1538-3881/abf144, arXiv:2103.13642 [astro-ph.SR]

Wang L, Gies DR, Peters GJ, et al (2023) The Orbital and Physical Properties of Five Southern Be+sdO Binary Systems. AJ 165(5):203. https://doi.org/10.3847/1538-3881/acc6ca, arXiv:2303.12616 [astro-ph.SR]

Waskom ML (2021) seaborn: statistical data visualization. Journal of Open Source Software 6(60):3021. https://doi.org/10.21105/joss.03021, URL https://doi.org/10.21105/joss.03021

Wheelwright HE, Oudmaijer RD, Schnerr RS (2009) The close Be star companion of β Cephei. A&A 497(2):487–495. https://doi.org/10.1051/0004-6361/200811105, arXiv:0902.4356 [astro-ph.SR]

Wolf M, Harmanec P, Božić H, et al (2021) Long-term, orbital, and rapid variations of the Be star V923 Aql = HD 183656. A&A 647:A97. https://doi.org/10.1051/0004-6361/202039740, arXiv:2102.00631 [astro-ph.SR]

Yamasaki T, Yamada S (2005) Effects of Rotation on the Revival of a Stalled Shock in Supernova Explosions. ApJ 623(2):1000–1010. https://doi.org/10.1086/428496, arXiv:astro-ph/0412625 [astro-ph]

Zorec J, Frémat Y, Domiciano de Souza A, et al (2016) Critical study of the distribution of rotational velocities of Be stars. I. Deconvolution methods, effects due to gravity darkening, macroturbulence, and binarity. A&A 595:A132. https://doi.org/10.1051/0004-6361/201628760

Declarations

All authors contributed to the study conception and design. JLB collected and analyzed the observationally-determined information from the literature, with assistance from several authors (YN, KG, GP, RR, AR), and MS did the binary population synthesis modeling and subsequent analysis. All authors contributed text and expertise related to these topics, provided detailed comments which shaped the structure of the manuscript. All authors commented on previous versions of the manuscript, and have read and approved the final manuscript.

Ethics declaration: not applicable.