Bull. Soc. R. Sci. Liège, 2024, **93**(3), 58–84
Peer-reviewed conference paper
doi:10.25518/0037-9565.12266

Caught *in flagrante delicto:* Evidence for Past Mass Transfer in Massive Binaries?

Gregor Rauw

STAR Institute, Université de Liège, Allée du Six-Août, 19c, Bât. B5c, 4000–Liège, Belgium
Correspondence to: g.rauw@uliege.be

*Paper presented at the 41st Liège International Astrophysical Colloquium on
“The eventful life of massive star multiples,” University of Liège (Belgium), 15–19 July 2024.*

Abstract

Many massive binary systems undergo mass and angular momentum transfer over the course of their evolution. This kind of interaction is expected to deeply affect the properties of the mass donor and mass gainer and to leave various observational signatures. The most common smoking guns of a past mass transfer episode are notably rapid rotation of the mass gainer and altered surface chemical abundances of the stripped mass donor star. Quantitative observational studies of evolved massive binaries are crucial to gain insight into poorly constrained parameters of binary evolution models such as the fraction of mass lost by the mass donor that is actually accreted by the mass gainer. Yet, drawing conclusions about a past mass transfer episode requires a detailed analysis of all aspects of a binary system which sometimes leads to unexpected results. In this contribution, we review the existing observational evidence for past mass exchange events in massive main-sequence and post main-sequence binaries.

Keywords: stars: early-type, binaries: close, stars: abundances, stars: evolution, stars: rotation

Résumé

Prises en flagrant délit: signatures d’épisodes passés d’échanges de matière dans des binaires massives? Beaucoup de systèmes binaires massifs traversent des épisodes de transfert de masse et de moment angulaire au cours de leur évolution. Ce type d’interaction affecte les propriétés des deux étoiles (donneur de masse et accréteur) et devrait imprégner plusieurs signatures observationnelles. Parmi les indices les plus probants d’un épisode passé d’échange de matière, il y a la rotation rapide de l’accréteur et la composition chimique altérée du donneur de masse. Des études observationnelles quantitatives de binaires massives évoluées sont cruciales pour contraindre certains paramètres clés des modèles d’évolution, tels que la fraction de la matière perdue par le donneur qui est effectivement accrétée par le compagnon. Toutefois, ce type d’étude requiert une analyse en profondeur de tous les aspects d’un système binaire, ce qui conduit parfois à des résultats inattendus. Dans cette contribution, nous passons en revue les indices observationnels d’épisodes passés d’échanges de masse dans des binaires massives de la séquence principale ou ayant quitté celle-ci récemment.

Mots-clés : étoiles massives, binaires serrées, étoiles: abondances, étoiles: évolution, étoiles: rotation

1. What Theoretical Models Predict

Contrary to single star evolution, which is mostly ruled by the initial mass of the star, its rotation rate, wind mass-loss rate, overshooting prescription and metallicity (e.g., Ekström et al., 2011; Martins and Palacios, 2013), the evolution of a massive binary system depends on a number of additional parameters, such as the orbital period, the primary/secondary mass ratio, and the orbital eccentricity. As a result, a wide variety of binary evolutionary channels can be distinguished (e.g., Podsiadlowski et al., 1992; Chen et al., 2024). These scenarios can be classified into three broad categories depending on the evolutionary phase of the initially more massive star at the time of the mass-transfer (Kippenhahn and Weigert, 1967; Vanbeveren et al., 1998; Marchant and Bodensteiner, 2024). If the mass donor is in the hydrogen core-burning phase, one speaks about Case A mass transfer. Case B concerns situations where the mass exchange occurs after the donor has completed its core hydrogen burning phase but prior to the ignition of core helium burning. Finally, Case C refers to situations where the primary has evolved beyond helium core-burning. About a quarter of the massive binaries have sufficiently short orbital periods to ensure that mass transfer occurs while the stars are still in the core hydrogen burning phase (de Mink et al., 2014; Sen et al., 2022). For a $25\,M_\odot$ primary, Case A mass transfer occurs in systems with initial $P_{\rm orb}$ below about 10 days (Langer et al., 2020; Sen et al., 2022). In wider systems, mass transfer occurs as Case B.

To guide the theoretical binary evolution models, it is crucial to collect as many observational diagnostics as possible for each of the evolutionary stages massive binaries go through. In some cases, we can directly observe the mass exchange taking place between the stars. In a Case A situation, the orbit shrinks as the more massive star expands and initiates the Roche lobe overflow (RLOF) process. This leads to a fast mass transfer episode occuring on the thermal timescale of the mass donor (e.g., Sen et al., 2022; Marchant and Bodensteiner, 2024). Once the mass ratio is inverted, the orbit widens. The second Case A mass exchange episode is then expected to be much slower as it occurs on the much longer nuclear timescale. Given the difference in timescale between the fast and slow Case A, the majority of the observable semi-detached systems, where mass exchange can be seen directly, are expected to be in the slow Case A phase. These systems, where the mass donor is now the less massive but more evolved star, are called massive Algol binaries. Some of these systems, those with very short orbital periods, enter a contact configuration during the slow Case A mass transfer and eventually experience mass loss through the L_2 point leading to significant losses of angular momentum and finally to the merger of the two stars.

In very massive binaries, the fast Case A mass transfer can end before the mass ratio has inverted (Sen et al., 2023). This occurs when the mass donor is stripped sufficiently for He-rich material to appear at the surface. Subsequent mass loss then leads to a shrinking of the donor. Moreover, wind mass loss increases and becomes so strong that the orbit widens already before the mass ratio is inverted (Sen et al., 2023). During the ensuing nuclear timescale evolution, many mass donors remain more massive than the accretors. Such systems appear as so-called reverse Algol systems. Actually, the slow (nuclear timescale) mass transfer may be interrupted or absent altogether. This scenario can lead to the formation of Wolf–Rayet (WR) binaries containing H-rich WN stars as the mass donors.

Observational diagnostics are however not restricted to the massive Algol or reverse Algol systems. The consequences of past RLOF episodes can also be diagnosed in other binaries. Moreover, in many of the binary evolutionary scenarios, a fraction of the binary systems either merge or break-up. Therefore, the signatures of past binary interactions also affect the properties of currently single stars. In general terms, binary evolution is expected to result in various observational signatures that we briefly discuss hereafter:

- spin-up of the mass gainer;
- altered chemical composition at the surface of the mass donor;
- overluminosities of the mass donor compared to main-sequence stars of same mass;
- and possibly magnetic fields.

Roche lobe overflow not only leads to the exchange of mass between the stars, but also to the transfer of angular momentum from the mass donor to the mass gainer. How this affects the accretion process depends on the efficiency of tidal interactions. Indeed, when the gainer is spun up to critical rotation it stops accreting (Packet, 1981), leading to a low mass transfer efficiency. Tides tend to synchronize the rotation and the orbital motion and thus to spin down the mass gainer, allowing for a more efficient mass transfer (e.g., Langer et al., 2020; Sen et al., 2022). Case A close binary systems evolve quickly into tidal locking and should thus have a high mass transfer efficiency. Conversely, tidal effects are negligible in wider systems. Case B systems, where the companion quickly reaches critical rotation, should thus have a low mass transfer efficiency. The spun-up mass gainer might then become an Oe/Be star (or a ‘normal’ rapidly rotating OB star; van Bever and Vanbeveren, 1997) paired with a hot He-burning subdwarf companion, a white dwarf, or a neutron star (e.g., Shao and Li, 2021, and references therein).

Another way to produce a rapidly rotating massive star could be through a binary merger: de Mink et al. (2013) argue that binary interactions account for 20% of all massive main-sequence stars having projected rotational velocities ($v \sin i$) exceeding $200\,\mathrm{km\,s^{-1}}$, either as a result of mass transfer or binary mergers. However, Schneider et al. (2019) rather predict that merger products, once they return to thermal equilibrium and settle on the main-sequence, should be rotating slowly.

The stripping of the mass donor reveals material at the stellar surface that was previously inside the convective core of this star. Therefore, one expects the mass donors to display enhanced nitrogen and helium abundances, along with depleted carbon and oxygen at their surface (e.g., Sen et al., 2022). Binaries that survive the entire Case A mass transfer phase are expected to reach the CNO equilibrium abundances. In single star evolution, rotational mixing plays a key role in chemical enrichment at the stellar surface. In contrast with this, in binary evolution, where the surface enrichment is due to envelope stripping, one does not expect a correlation between surface nitrogen enrichment and rotation rate of the donors.

The chemical enrichment of the mass gainer depends on the mass accretion efficiency. For instance, in Case B binaries, the mass gainer essentially maintains its original surface composition because it accretes only a small fraction of the material lost by the donor. Furthermore, regardless of the accretion efficiency, the accreted chemically enriched material is diluted by thermohaline mixing with unprocessed material of the accretor. As a result, any chemical enrichment of the accretor is generally expected to remain well below that of the mass donor (e.g., De Loore and Vanbeveren, 1994; Vanbeveren and De Loore, 1994; Langer et al., 2020; Sen et al., 2022). Nonetheless, the overall properties (chemical composition and rotation rate) of accretors are clearly distinct from those of single rotating stars (e.g., Renzo and Götberg, 2021).

The mass donors of massive Algol systems are expected to be overluminous compared to single stars of same mass and effective temperature (Sen et al., 2022). This is a consequence of the modified chemical composition of the stellar surface following the stripping of the hydrogen-rich envelope. Indeed, the stellar luminosity scales as $L \sim M^{\alpha}\,\mu^{\beta}$ with μ the mean molecular weight and β in the range 5–2.5 for stars between 10 and $30\,M_{\odot}$ (Sen et al., 2022). The value of μ increases by about a factor 2.2 during the hydrogen burning phase, thus leading to the overluminosity once the enriched material appears at the surface.

Depending on their mass, stripped envelope mass donors that have previously undergone Case B mass transfer should exhibit spectral characteristics ranging from hot subdwarfs to Wolf-Rayet (WR) stars (Vanbeveren, 1991; Götberg et al., 2018). These objects have their hot helium core exposed with only a thin residual layer of hydrogen on top. Götberg et al. (2018) found that these stripped stars display bolometric luminosities similar to those of their progenitors despite having lost about two third of the initial mass. This is because of their extreme temperatures that compensate for their small radii. These temperatures shift the peaks of the spectral energy distributions of the stripped stars into the extreme UV domain.

The magnetic fields that are detected in about 7% of the massive stars might be another consequence of binary interactions. In merger events involving two main-sequence stars, fresh nuclear fuel is mixed into the core of the merger product. This leads to a rejuvenation of the order of the nuclear timescale (Schneider et al., 2016). The products of such merger events should thus appear younger than other stars that formed simultaneously with their progenitors. Moreover, such events could lead to the formation of strong long-lived magnetic fields (Schneider et al., 2016, 2019). The magnetic field would be triggered by the shear of the massive accretion stream on the surface of the accretor, and would be further amplified by vortices occuring when the two stellar cores merge (Schneider et al., 2019).

From measurements of projected rotational velocities of O-star components in Galactic and Large Magellanic Cloud (LMC) WR + O binaries (Shara et al., 2017, 2020), Vanbeveren et al. (2018) noted that the O-star components of those systems are rejuvenated and rotate faster than synchronously, although significantly slower than their critical velocities. This situation was interpreted as evidence for spin-up by accretion combined with a mechanism to slow down the rotation. Indeed, the tidal interactions alone are not sufficient to slow down the mass gainers from near critical rotation to their current spin rates. Vanbeveren et al. (2018) accordingly suggest that accretion leads to differential rotation in the mass gainer, thereby triggering a Spruit–Tayler dynamo mechanism that generates a strong magnetic field. The magnetic field then forces the stellar wind of the accretor and the inflowing material into co-rotation with the star out to the Alfvèn radius. This leads to a substantial loss of angular momentum and thus a spin-down of the star (Ud-Doula et al., 2009).

2. The Broad Observational Picture

Systematic observing campaigns of massive stars have shown that a majority of them are located in binary or higher multiplicity systems (Sana et al., 2012, and references therein). Binary interactions should thus impact the overall properties of many massive stars. In this section, we discuss the observational signatures of RLOF interactions on populations of massive stars.

2.1. Fast rotators

The observed distribution of $v \sin i$ values of apparently single OB-type stars displays a bimodal shape consisting of a main peak at around 80–100 $\mathrm{km\,s^{-1}}$ flanked by a tail of rapid rotators ($v \sin i \geq 200\,\mathrm{km\,s^{-1}}$) extending up to $\sim 400\,\mathrm{km\,s^{-1}}$ (e.g., Ramírez-Agudelo et al., 2013; Dufton et al., 2013; Holgado et al., 2022, and references therein). The tail of rapid rotators could consist mostly of post-binary interaction products (de Mink et al., 2013). These would be either merger products or rejuvenated mass gainers possibly accompanied by a stripped star or a compact object.

Britavskiy et al. (2023) analysed a sample of 54 fast rotating O-type stars comparing it to a sample of 415 Galactic O-type stars spanning the full range of $v \sin i$ values. They concluded that there is a deficit of double-lined spectroscopic binaries (SB2) among fast rotating O-type stars (8–12% versus $\sim$ 33% for slow rotators). This is a likely consequence of the presence of binary evolution products among the population of rapid rotators. Indeed, many of the rapid rotators in binary systems are likely paired with a stripped companion or a compact object neither of which produces a strong spectral signature. Conversely, the higher fraction of SB2 systems among slow rotators indicates that these systems have not yet undergone binary interaction. Moreover, Britavskiy et al. (2023) found that the fraction of runaway stars with a runaway status, as diagnosed from their sole tangential velocity to avoid biases from uncertain radial velocities (RVs), is significantly higher among the fast rotators (47% versus 20–30%). The fraction of runaways is even higher among those fast rotating O-stars that are classified as presumably single stars. In this subsample, 64% (23 out of 36 objects) were found to be runaways. This result is in line with the interpretation that these rapid rotators were ejected from their birthplace as a consequence of the supernova explosion of a former mass donor in a binary system.

The rapidly rotating O9.5 star HD 93521, which is located about 1 kpc above the Galactic plane, could be an example of the outcome of binary evolution. Gies et al. (2022) showed that it would require about 39 Myr for this star to reach its current location starting from the Galactic plane. This is much longer than the estimated age of the star of about 5 Myr. Gies et al. (2022) therefore suggest that HD 93521 formed via the merger of two stars of nearly equal mass.

Classical Oe/Be stars are rapidly rotating OB stars surrounded by decretion disks. One possibility to explain their near-critical rotation is that the Be stars were spun up by mass and angular momentum accretion during a past RLOF episode in an interacting binary. A significant fraction of the mass donors are expected to be in the He-core burning stage and should appear as slowly rotating stripped hot subdwarf sdO/sdB stars (Götberg et al., 2018). Such objects are difficult to detect against the strong optical emission of the Be star, and many of them might even escape detection in the UV (Yungelson et al., 2024). Nevertheless, about 20 such sdO companions have been found via cross-correlation with far-UV spectra (Wang et al., 2021, 2023, and references therein). These results suggest that many Be stars could have such hot subdwarf companions, thereby supporting the binary scenario.

Since most of the stripped companions of Be stars predicted by theory are expected to be hot subdwarfs they should be too faint in the optical domain to be distinguished against the strong emission of the Be star. The situation could be different for bloated stripped companions, which represent an earlier evolution stage where the mass transfer is possibly still ongoing. El-Badry et al. (2022) performed a search for such Be + bloated stripped companion systems among the spectra of the APOGEE survey. They searched for Doppler shifts of narrow photospheric absorptions associated with the bloated stripped star. Out of a sample of 297 stars classified as Be stars, they identified one such binary system: HD 15124 consisting of a Be primary star ($T_{\rm eff} = 16000$ K) with a mass of about 5.3 $M_{\odot}$ and a low-mass (0.92 $M_{\odot}$) cool ($T_{\rm eff} = 6900$ K) subgiant companion revolving on a 5.47 days circular orbit. El-Badry et al. (2022) did not measure the RVs of the Be star. Hence they derived an SB1 orbital solution, and the mass of the primary was inferred from the spectroscopic $\log g$ value. The light curve of this system revealed a combination of ellipsoidal variations, due to the low-mass companion filling up its Roche lobe, and reflection of the B star light off the surface of the low-mass subgiant. El-Badry et al. (2022) showed that the emission lines in the spectrum arise from an accreting disk fed by the low-mass star which fills-up its Roche lobe, and that the mass gainer currently rotates at only 60% of its critical velocity. As such, the primary in HD 15124 is not yet a genuine classical Be star. El-Badry et al. (2022) further used stellar atmosphere models to constrain the chemical abundances. The He abundance was derived from the spectrum of the primary star and was found to be four times higher than solar. The CNO abundances were determined from the spectrum of the mass donor. Both C and O were found to be heavily depleted whilst N was found to be overabundant by a factor of six.

Conversely, fast rotation can also be primordial! Indeed, a group of rapidly rotating OB stars paired with a low-mass (typically 1 $M_{\odot}$) companion was found to most likely consist of stars that have not yet experienced any mass-exchange (Nazé et al., 2023, and references therein). Three such systems were studied in detail by Nazé et al. (2023): HD 25631 (B3 V, $P_{\rm orb} = 5.24$ days), HD 191495 (B0 V, $P_{\rm orb} = 3.64$ days), and HD 46485 (O7 V, $P_{\rm orb} = 6.94$ days). These systems display photometric light curves with a strong reflection effect and two narrow eclipses. Unlike HD 15124, they do not show strong ellipsoidal variations though, indicating that none of the binary components has a large Roche lobe filling factor. In contrast to systems consisting of Be stars paired with hot subdwarfs, the OB primary star is the hotter component in these systems. The ratios between the primaries' and the secondaries' masses, denoted $M_{\rm p}$ and $M_{\rm s}$ respectively, are rather extreme—$M_{\rm s}/M_{\rm p}$ range between 0.035 to 0.15 for the three systems studied by Nazé et al. (2023))—and the secondaries are likely non-degenerate, low-mass pre-main-sequence stars. To further understand the status of these systems, Britavskiy et al. (2024) performed evolutionary calculations testing different assumptions regarding the origin of the primary star's fast rotation. Assuming a primordial origin, Britavskiy et al. (2024) showed that the loss of angular momentum via wind mass-loss becomes only significant towards the end of the main-sequence phase. Likewise, tidal synchronisation also becomes effective only at the end of the main-sequence phase. This implies that stars with initially high rotational velocities maintain this property over most of their main-sequence lifetime. Assuming instead a past binary interaction, Britavskiy et al. (2024) showed that during a conservative mass transfer, the orbit widens and the orbital periods of post-RLOF systems are thus much longer than those observed. If the mass transfer is assumed non-conservative, the orbit shrinks, but an extreme mass-ratio configuration (as observed) is not expected in such cases as these systems would merge. Hierarchical triple systems could in principle lead to a fast rotator (resulting from the merger of the inner binary) coupled to a lower mass companion (the tertiary component of the initial triple system). However, the properties of the systems studied by Nazé et al. (2023) are such that these triple systems would likely be dynamically unstable. Britavskiy et al. (2024) thus conclude that the rapid rotation of these stars is primordial.

Another striking case of asynchronous rotation that is not due to a mass transfer is provided by the O7.5 Vz + O7.5 Vz binary HD 93343 ($P_{\rm orb} = 50.4$ days, $e = 0.398$, Putkuri et al., 2018). Both stars of this system have essentially identical masses ($M_{\rm s}/M_{\rm p} = 0.97 \pm 0.01$, $M_{\rm p}\,\sin^3 i = 22.8\,M_{\odot}$), but differ strongly by their projected rotational velocities (Rauw et al., 2009; Putkuri et al., 2018): $v_p\,\sin i = 65\,{\rm km\,s^{-1}}$ and $v_s\,\sin i = 325\,{\rm km\,s^{-1}}$ for the narrow line and broad line components, respectively (see Fig. 1). Whilst such a difference could arise from a past RLOF episode (see the case of Plaskett's Star in Sect. 3.4 hereafter), the stars in HD 93343 are very young unevolved objects (as indicated by the 'z' tag in their spectral classification; Putkuri et al., 2018), and mass exchange has not yet played any role. Hence, the difference in rotation must reflect either a misalignment of the rotation axes or stems from the formation mechanism of this young eccentric binary system.

2.2. Chemical enrichment

Enhanced N and He as well as depleted C and O abundances are expected at the surface of massive stars either as the result of rotational mixing or following the removal of the outer layers either by the action of a stellar wind or by binary interactions. Late O-type stars with unusually strong nitrogen lines in their spectra are classified as ON stars. Martins et al. (2015) studied the properties of 12 ON stars which are not members of SB2 binaries. All of these stars are He-rich and display N/C ratios between 0.5 and 1.0 dex higher than in normal O-stars. Though ON stars rotate faster on average than normal O-stars, evolution of single rotating stars cannot account

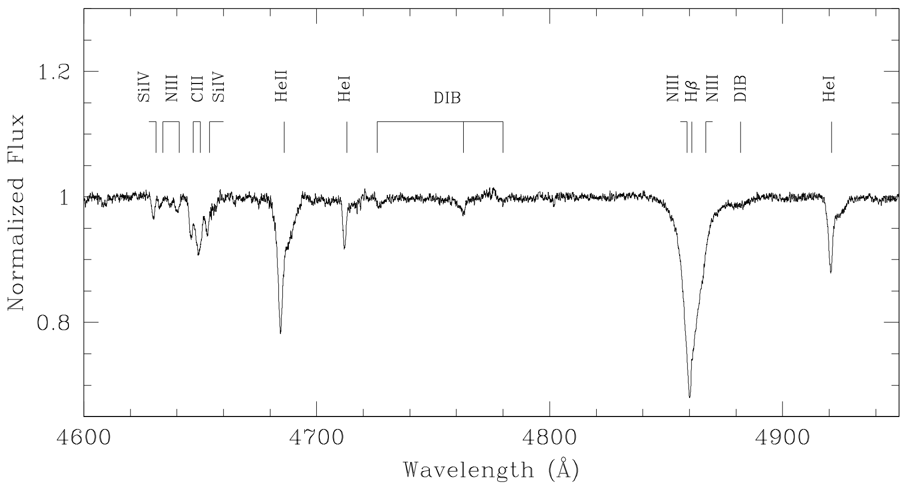

Figure 1: Blue spectrum of HD 93343 obtained with the FEROS spectrograph at the 2.2 m telescope of the ESO La Silla observatory in Chile on 25 May 2003. The blend between the narrow absorptions of the primary and the much broader absorptions of the secondary is best seen in the He I $\lambda\lambda$ 4713, 4922, He II λ 4686 and Hβ spectral lines.

for this enrichment as it is observed even for stars which are still on the main-sequence (Martins et al., 2015). Moreover, not all fast rotators display ON spectral characteristics. Some of the stars in the sample are likely members of SB1 binaries, suggesting that the ON stars would be the former mass gainers of these binaries. This is remarkable since in two post-RLOF SB2 systems that host ON stars (LZ Cep and HD 149404, see Sect. 3) the ON component is the mass donor instead.

Cazorla et al. (2017a,b) investigated the chemical composition and multiplicity of 40 O4 - B0.5 stars with $v \sin i \geq 200\,\mathrm{km\,s^{-1}}$ excluding SB2 binaries and Oe/Be stars. Out of 33 stars for which multi-epoch RV information could be derived, five were found to be SB1 binaries and another nine were classified as RV-variables (Cazorla et al., 2017a). Comparing the properties of these fast rotators with both single star and binary evolution models, Cazorla et al. (2017b) concluded that the properties of about 50% of the stars could be explained by single star evolution. The properties of the other stars were likely affected by binary interaction. Cazorla et al. (2017b) pointed out that most stars appeared more He-enriched than expected from their N/O ratio. This property is hard to explain both with either single or binary evolution models.

Martins et al. (2017) investigated the chemical composition of six eclipsing SB2 O-star binaries. In five out of the six systems, the surface abundances were found to be only mildly affected by stellar evolution or mixing and did not differ from those of single stars. The majority of these systems were detached pre-interaction binaries, and Martins et al. (2017) concluded that the effects of tides on the chemical evolution are limited. Moreover, the contact binary V382 Cyg (O6.5 V((f)) + O6 V((f)), $P_{\mathrm{orb}} = 1.886$ days) also did not display chemical enrichment. The only star showing a significant enrichment in their sample was the secondary of XZ Cep (O9.5 V + B1 III, $P_{\mathrm{orb}} = 5.097$ days). In this context, it is also interesting to note that the primary of XZ Cep rotates supersynchronously, whilst the opposite situation holds for the

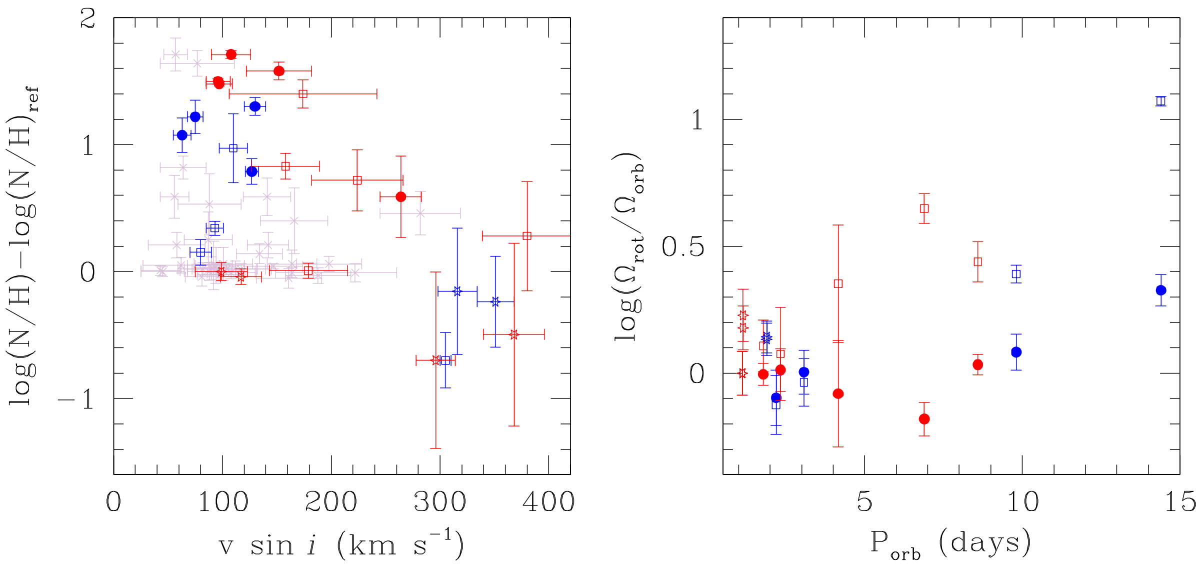

Figure 2: *Left:* N/H abundance ratio with respect to the reference abundance ($N/H = 0.60 \times 10^{-4}$ for Milky Way stars and $N/H = 0.79 \times 10^{-5}$ for LMC objects) as a function of $v sini$. The grey crosses stand for detached pre-interaction binary systems in the LMC (Mahy et al., 2020b). Blue and red symbols indicate interacting or post-interacting binaries respectively in our Galaxy and in the LMC. Filled dots stand for mass donors, whilst open squares represent accretors. Contact binaries are shown by stars. *Right:* ratio between rotational and orbital angular velocity for interacting or post-interacting binaries as a function of orbital period. The rotational axes are assumed to be perpendicular to the orbital plane. The symbols have the same meaning as in the left panel. Synchronisation due to tidal forces is clearly seen for $P_{\text{orb}} \leq 4$ days.

secondary.

Mahy et al. (2020b) investigated the atmospheric parameters of the components of 31 SB2 systems in the Tarantula region of the LMC. In agreement with Martins et al. (2017), they also concluded that tides play a minor role in the chemical enrichment of stars in detached pre-interaction binaries. Conversely, chemical enrichment was found in the spectra of mass donors of semi-detached systems, which were found to be mostly slow rotators. The mass gainers, some of which are rapid rotators spun up by transfer of angular momentum, showed only limited nitrogen enrichment. Mahy et al. (2020b) accordingly concluded that the outcome of binary interaction can explain the existence of slowly rotating N-rich O-stars as well as the existence of rapidly rotating non-enriched stars (see Fig. 2). Both categories of objects are hard to understand in single star evolution scenarios.

2.3. Magnetic fields

As outlined in Sect. 1, stellar mergers could lead to the formation of magnetic massive stars. According to this scenario, there should be no magnetic stars in close binary systems.

This prediction agrees with the apparent dearth of magnetic stars in close binaries as found in dedicated surveys (Neiner et al., 2015). Still, there are a few short period binaries hosting magnetic stars. The most emblematic cases are the double magnetic system ε Lupi (= HD 136504, B3 IV + B3: V, $P_{\rm orb} = 4.56$ days, $e = 0.277$, Shultz et al., 2015) and the rapidly rotating magnetic secondary star of Plaskett's Star (Linder et al., 2008; Grunhut et al., 2013, see also Sect. 3.4). The latter star has been interpreted as the mass gainer of a recent RLOF event. This opens up the possibility of a dynamo mechanism generated by differential rotation triggered by mass and angular momentum transfer (Vanbeveren et al., 2018). To observationally investigate the impact of past mass-transfer events on the generation of magnetic fields of massive stars, Nazé et al. (2017) analysed spectropolarimetry of a sample of 15 interacting or post-interaction massive binaries. No magnetic field was detected in any of them. This suggests that mass transfer events in massive binaries do not systematically trigger a stable strong magnetic field (Nazé et al., 2017). A radically different picture was drawn by Hubrig et al. (2023). These authors searched for Zeeman signatures in spectropolarimetry of 36 binary systems containing at least one O-type star. The systems in the sample had different evolutionary stages and covered a wide range of orbital separations. Hubrig et al. (2023) reported apparent detections for 22 systems, thus suggesting that binarity would play a key role in the generation of magnetic fields. However, the systems detected by Hubrig et al. (2023) include a number of binaries previously investigated by other groups who did not detect magnetic fields. The link between magnetic fields and past binary interactions is thus currently unclear and requires further studies.

Frost et al. (2024) considered the origin of the magnetic field of the Of?p star HD 148937. This is a wide binary consisting of a mid- and a late-type O-star in a 26-year eccentric ($e \simeq 0.78$) orbit. A magnetic field was detected only for the hotter star. Despite the low amplitude of the RV variations, Frost et al. (2024) reconstructed the spectra of the two stars via spectral disentangling. Both stars appear to be nitrogen-rich, although a quantitative assessment was only possible for the non-magnetic component. Frost et al. (2024) compared the location of the stars in a Hertzsprung–Russell diagram to single star evolution models and found that the magnetic primary is apparently younger than the secondary star, although the exact age difference depends on whether or not the N enrichment is taken into account. The primary star seems thus to be rejuvenated. Frost et al. (2024) argue that this cannot be the result of a past RLOF episode because the donor star would then still be near filling its Roche lobe and the eccentricity should be low. They instead favour a merger scenario and argue that this could explain the extreme N abundance of the nebula which is more in line with a WN composition than with the photospheric abundances of the stars (Mahy et al., 2017; Lim et al., 2024). According to this scenario, HD 148937 was originally a triple system with a close inner binary that underwent a merger event during which the magnetic field was produced and the nebula was ejected.

2.4. Overluminosities

Figure 3 compares the mass-luminosity relation of the components of interacting or post-interaction binaries (right panel) with that of core-hydrogen burning massive stars in detached eclipsing binaries (left panel). To compare with theoretical models of single stars, we use the

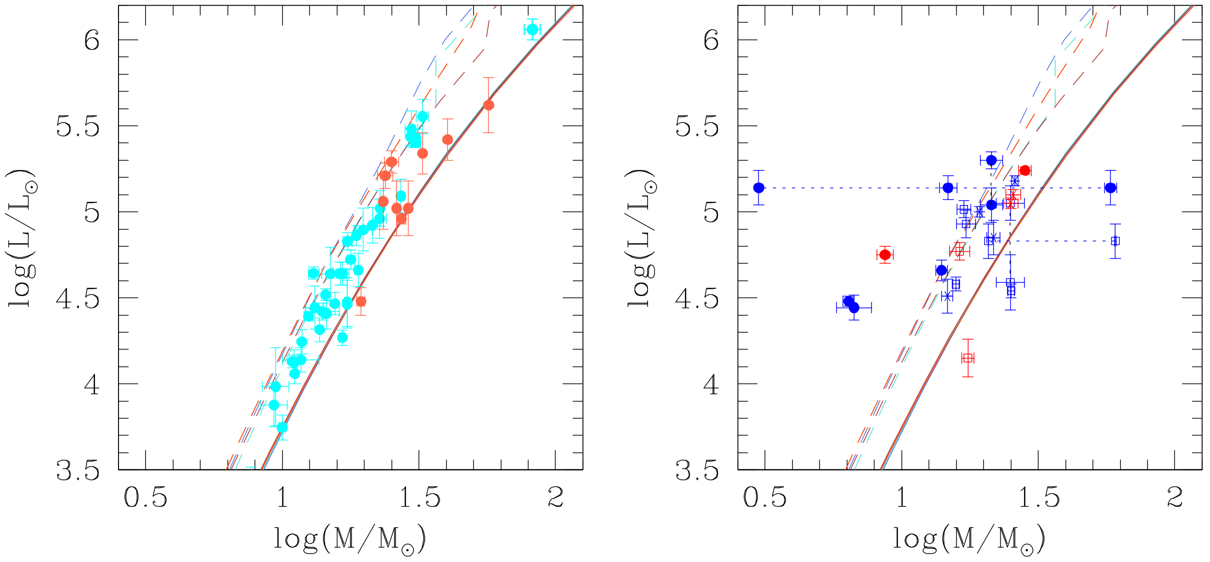

Figure 3: *Left:* mass-luminosity relation for the components of detached pre-interaction eclipsing massive binaries. The cyan and red symbols correspond to binary systems in our Galaxy and in the LMC. Theoretical mass-luminosity relations are illustrated at the onset (solid lines) and end (dashed lines) of the core hydrogen burning phase. The different lines correspond to models with metallicity $Z = 0.014$ without rotation (turquoise) and with initial rotation of 40% critical (blue), as well as with $Z = 0.006$ without rotation (dark red) and 40% critical rotation (orange). *Right:* mass-luminosity relation for the components of contact binaries (stars) as well as for the mass donors (filled circles) and accretors (open boxes) of semi-detached or post-RLOF systems. Blue (resp. red) symbols indicate binaries in our Galaxy (resp. the LMC). The same theoretical relations are shown by the lines. The dotted horizontal lines connect the possible locations of the components of Plaskett's Star (see Sect. 3.4). The dotted vertical lines indicate the possible solutions for the 29 CMa system.

mass-luminosity relation of single rotating main-sequence stars at the onset and at the end of the core-hydrogen burning phase. These relations are taken from the Geneva models for solar and LMC metallicities (Ekström et al., 2012; Eggenberger et al., 2021). Regarding observational data, we assembled a sample of detached, pre-interaction eclipsing massive binaries in our Galaxy and in the LMC. The main bibliographic sources are the compilation of Eker et al. (2014, and references therein) complemented by several additional studies (Freyhammer et al., 2001; Rauw et al., 2001; Massey et al., 2002; Rauw et al., 2005; Mahy et al., 2020a; Rosu et al., 2020, 2022a,b). The left panel of Fig. 3 shows that the components of detached, unevolved massive binaries nicely follow the theoretical relation. The situation is more complicated when we consider evolved systems (right panel). Here we focus on systems with relatively well determined parameters: LZ Cep (Mahy et al., 2011b); V382 Cyg, V448 Cyg, and XZ Cep (Harries et al., 1997); VFTS 061, VFTS 176 and VFTS 352 (Mahy et al., 2020a); and TU Mus (Linder et al., 2007). We further include two systems with larger uncertainties: Plaskett's Star (see Sect. 3.4) and 29 CMa (see Sect. 3). On average, the mass donors appear overluminous compared to main-sequence stars of same mass. However, whilst this overluminosity can reach values of 1 dex or more, not all mass donors display an overluminosity. The mass gainers display large dispersions in luminosity, with some of them being underluminous. Finally, the components of contact systems in Fig. 3 do not exhibit systematic over- or underluminosities. This latter result is at odds with the conclusion of Abdul-Masih et al. (2021) who found systematic overluminosities in three contact binaries. These discrepant conclusions probably reflect the huge uncertainties and biases that affect our knowledge of the properties of these objects (see Sect. 3).

3. How Well do we Know Evolved Massive Binaries?

From the examples presented in Sect. 2, we conclude that whilst binary interactions impact the properties of massive stars populations, none of the observational diagnostics taken individually can be unambiguously attributed to the sole effect of previous binary interaction phases. In this section, we thus review a handful of massive binaries that are considered good examples of post-RLOF systems, and we critically ask ourselves how well we know and understand these systems.

Modern observational studies of massive binaries usually rely on different types of data (photometry, spectroscopy, (spectro)polarimetry, interferometry, etc.). Spectral disentangling is applied to phase-resolved spectroscopy to reconstruct the individual spectra of the components and to infer their epoch-dependent RVs. Whilst the RVs are used to build the orbital solution of the system, the reconstructed spectra are analysed with non-LTE stellar model atmosphere codes to infer the stellar properties and the surface chemical compositions of the stars. In parallel, high-precision space-borne photometry, collected with missions such as *CoRoT*, *Kepler*, *BRITE* or *TESS*, is adjusted with sophisticated binary light curve models. The stellar parameters obtained this way can then be compared to the predictions of theoretical models.

3.1. Contact binaries

TU Mus (HD 100213) is an O-star eclipsing binary with a period of 1.387 d. Using optical spectra, Linder et al. (2007) classified the system as O7.5 V + O9.5 V, whereas Penny et al. (2008) assigned earlier O7 V + O8 V spectral types based on *IUE* UV spectra. Analyses of the *Hipparcos* light curve of this system indicate a contact configuration (Linder et al., 2007; Penny et al., 2008). The current mass ratio is about $M_{\rm s}/M_{\rm p} = 0.69$ according to Linder et al. (2007) or 0.63 according to Penny et al. (2008). The system is thought to experience a slow Case A RLOF where the mass gainer (the currently more massive star) also fills its Roche lobe due to its increase in mass and the rejuvenation of its interior (Penny et al., 2008). Both stars appear to be rotating nearly synchronously with the orbital motion (Penny et al., 2008), as expected for a situation where the orbital period is short and the tidal forces are strong (see right panel of Fig. 2). A remarkable feature of TU Mus is that different optical spectral lines yield different

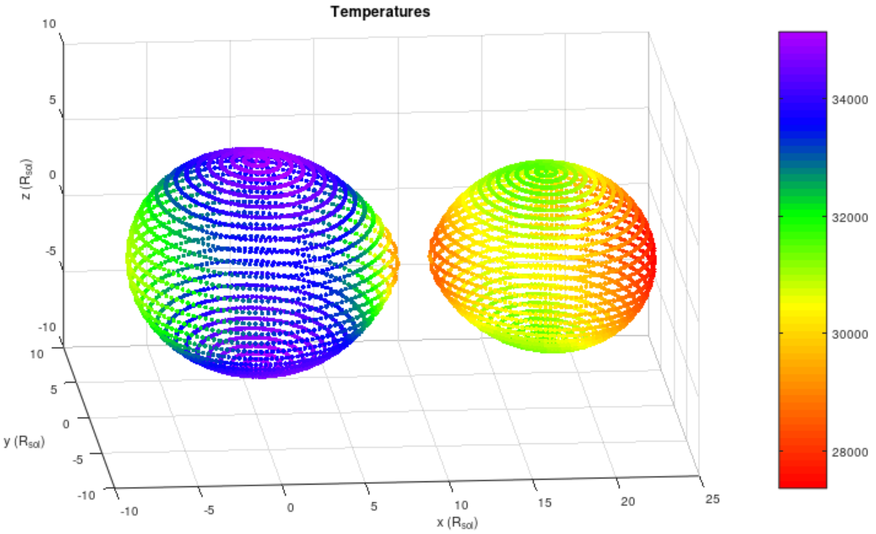

Figure 4: Simulated surface temperature distribution of the TU Mus system computed with the CoMBiSpeC code (Palate and Rauw, 2012; Palate et al., 2013). The calculations account for the effect of mutual heating and radiation pressure.

amplitudes of the RV curves (Linder et al., 2007) and that UV spectra yield RV amplitudes (K_p and K_s) that are significantly lower than those obtained from optical spectra (Penny et al., 2008). For instance, the He I λ 5876 line displays a K_p value that is 30 km s^{-1} (i.e. 12%) larger than the corresponding value of the He II λ 5412 line. A very similar 10% discrepancy holds for the RV amplitude of the secondary. Compared with UV spectra, the differences are even higher. This situation reflects the highly non-uniform surface temperature distributions due to the impact of gravity darkening of the highly distorted stars in this contact binary and mutual heating effects (Palate et al., 2013; see also Fig. 4). The result is a shift of the centres of light of different lines with respect to the centre of gravity of the stars. Such a situation has a severe negative impact on our knowledge of the masses of the stars. Indeed, the masses (16.7 and 10.4 $M_\odot$) inferred by Penny et al. (2008) are about 30% lower than the values (21.7 and 14.7 $M_\odot$) found by Linder et al. (2007) from the mean of their optical RV curves. This is a huge and unfortunate uncertainty when it comes to comparison with theoretical models. Moreover, the fact that different lines follow different RV curves hampers our possibility to apply spectral disentangling to this system, and thereby prevents us from studying the chemical compositions of the stars.

29 CMa (= HD 57060, $P_\mathrm{orb} = 4.39$ days) is another evolved O-star binary system which is thought to be in a contact or semi-detached configuration (Bagnuolo et al., 1994; Antokhina et al., 2011). The primary is an O8.5 I supergiant with a relatively powerful stellar wind as indicated by the rather strong N III $\lambda\lambda$ 4634-40 and He II λ 4686 emission lines. The secondary spectral signature is very weak. Based on optical spectra, Linder (2008) derived an O9.7 V spectral type for the secondary, a mass ratio of $M_\mathrm{s}/M_\mathrm{p} = 1.16$, and an optical brightness ratio $l_\mathrm{s}/l_\mathrm{p} = 0.21 \pm 0.08$. This latter value is at odds with the contact configuration inferred from the *Hipparcos* light curve of the system (Linder, 2008; Antokhina et al., 2011), which yields

$l_s/l_p = 1.08$ for a mass ratio of 1.16. Whilst the disentangled spectra of Linder (2008) clearly point at a nitrogen enrichment of the primary star, the huge uncertainty about the brightness ratio prevented a quantitative assessment of this effect. This is because the brightness ratio is a key parameter for assessing the dilution correction of the line strength in the normalized disentangled spectra. Similar issues have been encountered for several other evolved massive binaries. Solving this problem requires a revision of the spectroscopic and photometric analyses. The effects of the primary stellar wind might play a key role here, and could eventually change our interpretation of the photometric light curve. The existence of a strong stellar wind and the nitrogen enrichment suggest that the primary is about to become a WR star.

Abdul-Masih et al. (2021) investigated three overcontact binaries: V382 Cyg (=HD 228854, $P_{\rm orb} = 1.886$ days) in the Milky Way, VFTS 352 ($P_{\rm orb} = 1.124$ days) in the LMC, and OGLE SMC-SC10 108086 ($P_{\rm orb} = 0.883$ days) in the Small Magellanic Cloud (SMC). They found that both components of these systems are highly overluminous, but they observed no evidence for altered He and CNO surface abundances, confirming a result previously found for V382 Cyg by Martins et al. (2017). Moreover, in unequal-mass systems, they noted that the temperature of the less massive component is shifted towards that of the more massive star, and exceeds the temperature expected for the mass of the star. Abdul-Masih et al. (2021) proposed that this could result from irradiation by the primary, efficient heat exchanges through the common envelope, or efficient internal mixing. Only the latter mechanism can account for the global overluminosity (i.e., of both the primary and the secondary stars—see, however, Fig. 3 which does not reveal a systematic overluminosity). However, it is at odds with the lack of chemical enrichment. Abdul-Masih et al. (2021) argue that this could be an indication of a non-conservative mass loss. While this could explain why the mass gainer does not show enrichment (lack of pollution by the material of the mass donor), this explanation appears less convincing regarding the mass donor whose envelope would be stripped off. For V382 Cyg and OGLE SMC-SC10 108086, Abdul-Masih et al. (2021) found that spectral lines are broader than expected for stars which would be in synchronous rotation. However, no such effect was reported by Martins et al. (2017) for V382 Cyg.

Another interesting system in this context is LSS 3074 (= V889 Cen). The components of this binary are classified as O4.5 If$^+$ + O6.5-7 If, and the orbital period is $P_{\rm orb} = 2.185$ days (Raucq et al., 2017, and references therein). The photometric light curve displays ellipsoidal variations with a depth of 0.2 mag, but lacks clear photometric eclipses. Conventional binary light curve models can only fit this light curve assuming a contact or overcontact configuration (Raucq et al., 2017). The best-fit orbital inclination ($i = 54.5°$) then implies surprisingly low masses for the two stars ($M_p = (14.8 \pm 1.1)\,M_\odot$ and $M_s = (17.2 \pm 1.4)\,M_\odot$). Both stars would thus be hotter and more luminous than expected for their masses. Both stars display a strong N enrichment in their spectrum. The O4.5 primary also displays an enhanced He surface abundance. The analysis of the light curve implies an optical brightness ratio of $l_p/l_s = 1.09$. As for 29 CMa, this value is clearly at odds with the spectroscopic brightness ratio of 2.50 ± 0.43. This latter value indeed requires a semi-detached or detached configuration. Comparing the properties of LSS 3074 with binary evolutionary tracks, Raucq et al. (2017) suggested that the system is probably undergoing a highly non-conservative slow Case B mass transfer.

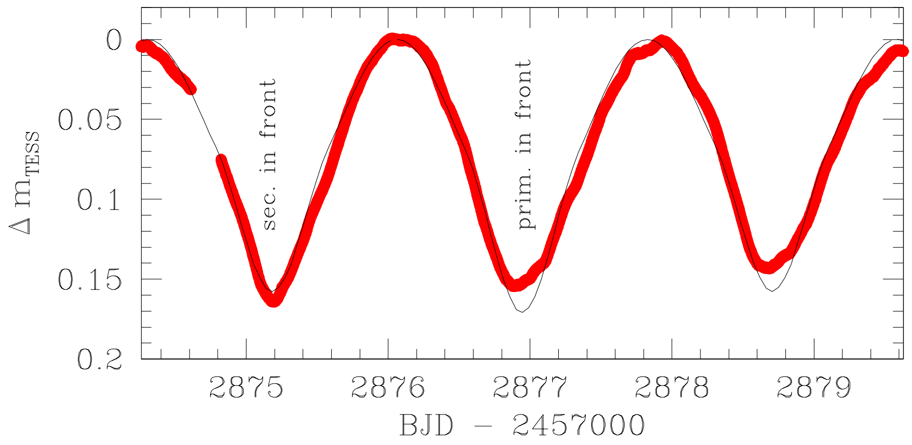

Figure 5: Light curve of AO Cas from *TESS* sector 57. Observed magnitudes are shown by red dots, whilst the black solid line yields a preliminary best-fit curve adjusted to the subset of observations taken between BJD 2459874.26 and 2459879.6. The fitted light curve leads to an inclination of $i = 55.7°$. The primary fills its Roche lobe, whilst the secondary has a filling factor of 0.97.

Rickard and Pauli (2023) analysed the ON3 If* + O5.5 V((f)) binary system NGC 346 SSN 7 ($P_{\rm orb} = 3.07$) in the SMC. From the orbital solution, they showed that the secondary star is the more massive object ($M_{\rm s}/M_{\rm p} = 1.47$). The dynamical minimum masses of the stars are low, suggesting a low inclination. Using a model atmosphere code, Rickard and Pauli (2023) inferred spectroscopic masses of 32 and 55 $M_\odot$ for the primary and secondary, respectively. This analysis further revealed that the primary's atmosphere is N-rich and depleted in O, as expected from the ON spectral classification. The chemical compositions and the mass ratio greater than 1.0 suggest a past mass-exchange episode. Rickard and Pauli (2023) conclude that the system is in a contact configuration undergoing a slow Case A mass exchange.

3.2. Semi-detached binaries

AO Cas (= HD 1337) has an orbital period of 3.52 days. Based on disentangling of optical spectra, Linder (2008) derived a spectral classification O9.5 III for the primary and O9 V for the secondary. The secondary is currently 1.6 times more massive than the primary star, but would be about four times fainter in the optical than the primary. Linder (2008) analysed *Hipparcos* photometry of AO Cas and found a solution with an inclination $i = 65.7°$. This solution yields rather low masses for both stars ($M_{\rm p} = 9.6 M_\odot$ and $M_{\rm s} = 15.6 M_\odot$). The photometric brightness ratio of the *Hipparcos* solution of Linder (2008) agrees with the spectroscopic value, and the best-fit model of the light curve consists of ellipsoidal variations and grazing eclipses. However, the observations display substantial scatter around the model. The *TESS* light curve of AO Cas seems to tell a different story though (see Fig. 5). It is dominated by ellipsoidal variations with no indication of grazing eclipses. The light curve further exhibits additional variations with amplitudes up to 0.02 mag. These variations affect the determination of the stellar parameters. Nonetheless, a preliminary analysis of the light curve indicates that the ellipsoidal variations are best explained if the more massive secondary also fills a significant fraction of its Roche lobe. Whilst the lower inclination obtained from the *TESS* data leads to larger masses (12.9 and 20.9 $M_{\odot}$), it now implies a tension between the spectroscopic optical brightness ratio and the photometric value. Indeed, the new photometric value is equal to $l_{\rm s}/l_{\rm p} = 1.62$, which differs significantly from the spectroscopic value ($l_{\rm s}/l_{\rm p} = 0.26 \pm 0.16$, Linder, 2008).

LZ Cep (= HD 209481) is an O9 III + ON9.7 V binary with an orbital period of 3.07 days (Mahy et al., 2011b, and references therein). The ON spectral type of the secondary hints at a strong N enrichment which was confirmed, along with a strong He enrichment and a C depletion, by the quantitative analysis of Mahy et al. (2011b). LZ Cep is in a semi-detached configuration as indicated by the analysis of the ellipsoidal variations seen in the *Hipparcos* light curve, and it is most likely the secondary star that fills-up its Roche lobe. The O9 III primary star has a mass of 16 $M_{\odot}$, whilst the ON secondary has a mass of only 6.5 $M_{\odot}$. Mahy et al. (2011b) therefore suggest that the secondary is a core He-burning object which has retained some parts of its envelope and has a comparatively weak wind. Given the lack of strong chemical enrichment of the primary star, these authors conclude that the mass transfer must have been quite inefficient. In view of the orbital period, tidal interactions are expected to be strong, and both stars are indeed found to have nearly synchronized rotational and orbital periods (see Fig. 2).

3.3. Detached systems

Some detached massive binary systems display clear hints of past RLOF episodes. Raucq et al. (2016) analysed the disentangled spectra of the O7.5 If + ON9.7 I system HD 149404 ($P_{\rm orb} = 9.81$ days, $M_{\rm s}/M_{\rm p} = 0.63$). As suggested by the ON spectral type of the secondary, this star presents a strong nitrogen enrichment and carbon depletion. Its [N/C] ratio was found to be 150 times solar, whilst that of the (currently) more massive primary was only five times solar. This hints at a system which has undergone a past Case A RLOF episode although *BRITE* photometry suggests that the secondary star is still close to filling its Roche lobe (Rauw et al., 2019). There are some caveats though. Indeed, the N enrichment of the donor star should go along with an increase of the He abundance, which was not observed (Raucq et al., 2016). Moreover, the observed enrichment would be more typical of Case B mass transfer whilst the properties of the system suggest a Case A event. Last but not least, the uncertainties on the orbital inclination (21–31°, Rauw et al., 2019) imply uncomfortably large uncertainties on the masses. Nonetheless, at least the secondary star appears to be overluminous for its mass.

Another candidate detached post-RLOF system is the eclipsing binary AzV 476 in the SMC (O4 IV-III((f))p + O9.5:Vn, $P_{\rm orb} = 9.37$ days, $e = 0.24$; Pauli et al., 2022). The spectrum of the O4 IV-III primary star displays a significant N enrichment. Moreover, with a mass of only about 20 $M_{\odot}$, it appears clearly too hot for its mass. The secondary has a mass of 18 $M_{\odot}$ which is well in line with its spectral type, but displays a very high projected rotational velocity ($v_s \sin i = 425\,{\rm km\,s^{-1}}$; Pauli et al., 2022). Comparing the properties of this system with binary evolutionary models, Pauli et al. (2022) concluded that AzV 476 must have experienced a Case B RLOF in the past, and that the primary is likely a core He burning object which has lost about half of its initial mass.

Finally, another interesting example of a post-RLOF system could be the WN6o + O9.5-9.7 V-III binary WR 138 (= HD 193077, $P_{\rm orb} = 1559$ days, $e = 0.16$; Rauw et al., 2023). The mass ratio $M_{\rm WN6o}/M_{\rm OB} = 0.53 \pm 0.09$ and the highly asynchronous rotation of the OB star ($v_{\rm OB}\,\sin i = (350 \pm 10)\,{\rm km\,s^{-1}}$ suggest that this system evolved through a Case B mass and angular momentum exchange episode in a way similar to the scenario of Vanbeveren et al. (2018). WR 138 has a significantly longer orbital period than the systems studied by Shara et al. (2017, 2020) which had periods ranging between 1.9 and 78.5 days. Hence, WR 138 provides a more extreme example of a binary system where tidal interactions are unable to explain the lower than critical rotation rate of the OB star.

3.4. Revisiting Plaskett's Star

HD 47129 (aka. Plaskett's Star) has been considered as a kind of textbook example of the outcome of Case A mass transfer, apparently ticking nearly all the boxes regarding evidence of a past RLOF episode (Linder et al., 2008, and references therein). This system consists of an O8 III/I star with narrow spectral lines (hereafter the primary star) and an O7.5 III companion (the secondary) displaying significantly broader lines. The primary lines describe a well documented circular orbital motion with a period of 14.396 days and a mass function of $12.3\,M_{\odot}$. Due to its rapid rotation and line profile variability, the RVs of the secondary star are much more difficult to measure. Linder et al. (2008) used a spectral disentangling method to measure the RVs of both components and derived a mass ratio $M_{\rm s}/M_{\rm p} = 1.05$, which results in both stars having minimum current masses around $45\,M_{\odot}$. The lines of the primary component clearly exhibit the signature of a N overabundance (by a factor 16.6 ± 5.0 with respect to solar; Linder et al., 2008). These properties were interpreted as the outcome of a recent Case A (or Case B, according to Vanbeveren et al. (2018)) mass and angular momentum transfer with the primary being the partially stripped mass donor and the secondary being the mass gainer that was spun-up by accretion.

Analysing the *CoRoT* light curve of HD 47129, Mahy et al. (2011a) discovered photometric variations related to the orbital cycle as well as a modulation with a $0.82\,{\rm d}^{-1}$ frequency along with six harmonic frequencies. The orbital light curve was interpreted as ellipsoidal variations altered by a bright spot on the primary facing the secondary and resulting from the wind-wind collision. The $0.82\,{\rm d}^{-1}$ frequency, which was subsequently also detected in spectroscopy (Palate and Rauw, 2014), and its harmonics were tentatively associated with non-radial pulsations (Mahy et al., 2011a). Using high-resolution spectropolarimetry, Grunhut et al. (2013) subsequently discovered a strong (2.8 kG) magnetic field associated with the secondary star. These authors suggested that the $0.82\,{\rm d}^{-1}$ frequency would be the rotation frequency of the secondary star.

Grunhut et al. (2022) confirmed the connection of the $0.82\,{\rm d}^{-1}$ frequency to the strength variations of the Hα, Hβ, Hγ and He II λ 4686 emission components which were shown to arise in the magnetosphere of the secondary star. Therefore, this frequency corresponds indeed to the rotational frequency of the magnetic secondary star. This star is thus the first example of an O-star hosting a rigidly rotating centrifugal magnetosphere. Most importantly, Grunhut et al. (2022) used Zeeman Doppler Imaging to map the magnetosphere of the secondary star of HD 47129. The results of such a reconstruction depend on the secondary's RVs. Grunhut et al. (2022) found that adopting the secondary RV amplitude from Linder et al. (2008) led to a rather poor adjustment of the Stokes V spectra and a complex magnetic field morphology. Instead, the formally best-fitting RV amplitude of the secondary found in the Zeeman Doppler Imaging was about $30\,\mathrm{km\,s^{-1}}$, roughly one sixth of the value found by Linder et al. (2008).

If confirmed, this reduced RV amplitude leads to a major shift in our interpretation of this system. Let us briefly consider the implications of this result. Adopting the $30\,\mathrm{km\,s^{-1}}$ RV amplitude for the secondary found by Grunhut et al. (2022) implies a mass ratio $M_{\mathrm{s}}/M_{\mathrm{p}} = 6.7$. Together with the primary's mass function, established by Linder et al. (2008), we obtain $M_{\mathrm{s}} \sin^3 i = (16.2 \pm 0.7)\,M_{\odot}$. For the formally best fit orbital inclination of 67° obtained by Mahy et al. (2011a), the absolute masses of the components become $M_{\mathrm{p}} \simeq 3\,M_{\odot}$ and $M_{\mathrm{s}} = 20.8\,M_{\odot}$, and the orbital separation amounts to $a = 71.8\,R_{\odot}$. If we adopt the distance (1283^{+127}_{-118} pc) from the third *Gaia* data release (Bailer-Jones et al., 2021) and the spectroscopic optical brightness ratio of $l_{\mathrm{p}}/l_{\mathrm{s}} = 1.9 \pm 0.1$, we can estimate absolute magnitudes of $M_{\mathrm{V},p} = -4.98 \pm 0.23$ and $M_{\mathrm{V},s} = -4.28 \pm 0.23$. With the bolometric corrections from Martins and Plez (2006) and the effective temperatures inferred by Linder et al. (2008), we then derive radii of $R_p = 11.0\,R_{\odot}$ and $R_s = 8.0\,R_{\odot}$. With the projected rotational velocities ($v_p \sin i \simeq 75\,\mathrm{km\,s^{-1}}$ and $v_s \sin i \simeq 305\,\mathrm{km\,s^{-1}}$; Linder et al., 2008) and assuming $i = 67°$ (Mahy et al., 2011a), the rotational periods of the primary and secondary star become 6.80 and 1.22 days, respectively. The latter value perfectly matches the $0.82\,\mathrm{d^{-1}}$ frequency.

Assuming that the mass ratio estimated by Grunhut et al. (2022) is confirmed by future studies, the revised picture of Plaskett's Star would be as follows: the primary star was the initially more massive star and has transferred considerable amounts of mass and angular momentum to its companion during a Case A RLOF phase. The companion was spun up significantly during this process. The reversal of the mass ratio led to an expansion of the orbit, thereby ending the mass transfer episode. Both stars are now well within their Roche lobes. The stripped primary star is now the object that we need to understand! Indeed, this star would be highly overluminous for its mass. Such overluminosities are expected for stripped massive stars, but the primary star of HD 47129 does not yet look like a genuine Wolf–Rayet star. However, with a luminosity of $\log \frac{L_{\mathrm{bol},p}}{L_{\odot}} = 5.13 \pm 0.09$, an effective temperature near 33500 K, and a mass of $\sim 3\,M_{\odot}$, its properties (especially its mass over radius ratio) strongly differ from those of normal O-type stars. Moreover, given its radius, one could expect the primary to appear as a bloated stripped star, which is not the case either. Indeed, beside the observed temperature which would be quite high for such an object, one important discrepancy concerns the value of $\log g$ which would be ~ 2.8 with the above mass and radius, whilst the model atmosphere fit presented by Linder et al. (2008) led to 3.5 ± 0.1 instead. Another puzzle to solve would be to find out how the primary star acquired its apparently super-synchronous rotation.

4. Conclusions

Various observational properties of massive binaries are best explained by ongoing or past binary interaction phases. The most prominent smoking guns are rapid rotation, enhanced nitrogen and helium abundances, and luminosities that do not match the stellar mass. However, taken individually, at least some of these properties might also be the outcome of single star evolution. Hence, detecting only one of these properties is not sufficient to draw conclusions about past mass exchange episodes. At first glance, observational investigations of specific binaries are in broad agreement with the predictions of binary evolution models. However, the devil often lies in the details! In-depth multi-technique investigations of such systems frequently lead to surprising or even conflicting results, implying significant uncertainties in our knowledge of their fundamental properties. Whilst some of these problems hint at some missing physics in the binary evolution models, the majority probably reflect deficiencies in the current analyses of observational data. In some systems, even such fundamental parameters as the stellar masses are subject to uncomfortably large uncertainties. It is thus highly desirable to continue investigating those systems in the coming years. In some cases, existing analysis tools might not be sufficient to achieve a full understanding and more sophisticated approaches will probably have to be developed to account for the specificities of these systems.

Further Information

Author's ORCID identifier

0000-0003-4715-9871 (Gregor RAUW)

Conflicts of interest

The author declares that there is no conflict of interest.

References

Abdul-Masih, M., Sana, H., Hawcroft, C., Almeida, L. A., Brands, S. A., de Mink, S. E., Justham, S., Langer, N., Mahy, L., Marchant, P., Menon, A., Puls, J., and Sundqvist, J. (2021) Constraining the overcontact phase in massive binary evolution. I. Mixing in V382 Cyg, VFTS 352, and OGLE SMC-SC10 108086. *A&A*, **651**, A96. https://doi.org/10.1051/0004-6361/202040195.

Antokhina, E. A., Srinivasa Rao, M., and Parthasarathy, M. (2011) Light curve analysis of Hipparcos data for the massive O-type eclipsing binary UW CMa. *NewA*, **16**(3), 177–182. https://doi.org/10.1016/j.newast.2010.09.008.

Bagnuolo, W. G., Jr., Gies, D. R., Hahula, M. E., Wiemker, R., and Wiggs, M. S. (1994) Tomographic separation of composite spectra. II. The components of 29 UW Canis Majoris. *ApJ*, **423**, 446–455. https://doi.org/10.1086/173822.

Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., and Andrae, R. (2021) Estimating distances from parallaxes. V. Geometric and photogeometric distances to 1.47 billion stars in Gaia Early Data Release 3. *AJ*, **161**(3), 147. https://doi.org/10.3847/1538-3881/abd806.

Britavskiy, N., Renzo, M., Nazé, Y., Rauw, G., and Vynatheya, P. (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.

Britavskiy, N., Simón-Díaz, S., Holgado, G., Burssens, S., Maíz Apellániz, J., Eldridge, J. J., Nazé, Y., Pantaleoni González, M., and Herrero, A. (2023) The IACOB project. VIII. Searching for empirical signatures of binarity in fast-rotating O-type stars. *A&A*, **672**, A22. https://doi.org/10.1051/0004-6361/202245145.

Cazorla, C., Morel, T., Nazé, Y., Rauw, G., Semaan, T., Daflon, S., and Oey, M. S. (2017a) Chemical abundances of fast-rotating massive stars. I. Description of the methods and individual results. *A&A*, **603**, A56. https://doi.org/10.1051/0004-6361/201629841.

Cazorla, C., Nazé, Y., Morel, T., Georgy, C., Godart, M., and Langer, N. (2017b) Chemical abundances of fast-rotating massive stars . II. ınterpretation and comparison with evolutionary models. *A&A*, **604**, A123. https://doi.org/10.1051/0004-6361/201730680.

Chen, X., Liu, Z., and Han, Z. (2024) Binary stars in the new millennium. *Progress in Particle and Nuclear Physics*, **134**, 104083. https://doi.org/10.1016/j.ppnp.2023.104083.

De Loore, C. and Vanbeveren, D. (1994) Massive close binary evolution in the Galaxy and in the Magellanic Clouds. *A&A*, **292**(2), 463–470. https://ui.adsabs.harvard.edu/abs/1994A&A...292..463D.

de Mink, S. E., Langer, N., Izzard, R. G., Sana, H., and de Koter, A. (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.

de Mink, S. E., Sana, H., Langer, N., Izzard, R. G., and Schneider, F. R. N. (2014) The incidence of stellar mergers and mass gainers among massive stars. *ApJ*, **782**(1), 7. https://doi.org/10.1088/0004-637X/782/1/7.

Dufton, P. L., Langer, N., Dunstall, P. R., Evans, C. J., Brott, I., de Mink, S. E., Howarth, I. D., Kennedy, M., McEvoy, C., Potter, A. T., Ramírez-Agudelo, O. H., Sana, H., Simón-Díaz, S., Taylor, W., and Vink, J. S. (2013) The VLT-FLAMES Tarantula Survey. X. Evidence for a bimodal distribution of rotational velocities for the single early B-type stars. *A&A*, **550**, A109. https://doi.org/10.1051/0004-6361/201220273.

Eggenberger, P., Ekström, S., Georgy, C., Martinet, S., Pezzotti, C., Nandal, D., Meynet, G., Buldgen, G., Salmon, S., Haemmerlé, L., Maeder, A., Hirschi, R., Yusof, N., Groh, J., Farrell, E., Murphy, L., and Choplin, A. (2021) Grids of stellar models with rotation. VI. Models from 0.8 to 120 $M_\odot$ at a metallicity $Z = 0.006$. *A&A*, **652**, A137. https://doi.org/10.1051/0004-6361/202141222.

Eker, Z., Bilir, S., Soydugan, F., Gökçe, E. Y., Soydugan, E., Tüysüz, M., Şenyüz, T., and Demircan, O. (2014) The catalogue of stellar parameters from the detached double–lined eclipsing binaries in the Milky Way. *PASA*, **31**, e024. https://doi.org/10.1017/pasa.2014.17.

Ekström, S., Georgy, C., Eggenberger, P., Meynet, G., Mowlavi, N., Wyttenbach, A., Granada, A., Decressin, T., Hirschi, R., Frischknecht, U., Charbonnel, C., and Maeder, A. (2012) Grids of stellar models with rotation. I. Models from 0.8 to 120 $M_\odot$ at solar metallicity ($Z = 0.014$). *A&A*, **537**, A146. https://doi.org/10.1051/0004-6361/201117751.

Ekström, S., Georgy, C., Meynet, G., Maeder, A., and Granada, A. (2011) Massive stellar models: rotational evolution, metallicity effects. *Proceedings of the International Astronomical Union*, **6**(S272), 62–72. https://doi.org/10.1017/S1743921311009987.

El-Badry, K., Conroy, C., Quataert, E., Rix, H.-W., Labadie-Bartz, J., Jayasinghe, T., Thompson, T., Cargile, P., Stassun, K. G., and Ilyin, I. (2022) Birth of a Be star: an APOGEE search for Be stars forming through binary mass transfer. *MNRAS*, **516**(3), 3602–3630. https://doi.org/10.1093/mnras/stac2422.

Freyhammer, L. M., Clausen, J. V., Arentoft, T., and Sterken, C. (2001) On the eclipsing nature of CPD–59°2628. *A&A*, **369**(2), 561–573. https://doi.org/10.1051/0004-6361:20010194.

Frost, A. J., Sana, H., Mahy, L., Wade, G., Barron, J., Le Bouquin, J.-B., Mérand, A., Schneider, F. R. N., Shenar, T., Barbá, R. H., Bowman, D. M., Fabry, M., Farhang, A., Marchant, P., Morrell, N. I., and Smoker, J. V. (2024) A magnetic massive star has experienced a stellar merger. *Sci*, **384**, 214–217. https://doi.org/10.1126/science.adg7700.

Gies, D. R., Shepard, K., Wysocki, P., and Klement, R. (2022) The transformative journey of HD 93521. *AJ*, **163**(2), 100. https://doi.org/10.3847/1538-3881/ac43be.

Götberg, Y., de Mink, S. E., Groh, J. H., Kupfer, T., Crowther, P. A., Zapartas, E., and Renzo, M. (2018) Spectral models for binary products: Unifying subdwarfs and Wolf–Rayet stars as a sequence of stripped–envelope stars. *A&A*, **615**, A78. https://doi.org/10.1051/0004-6361/201732274.

Grunhut, J. H., Wade, G. A., Folsom, C. P., Neiner, C., Kochukhov, O., Alecian, E., Shultz, M., and Petit, V. (2022) The magnetic field and magnetosphere of Plaskett's star: a fundamental shift in our understanding of the system. *MNRAS*, **512**(2), 1944–1966. https://doi.org/10.1093/mnras/stab3320.

Grunhut, J. H., Wade, G. A., Leutenegger, M., Petit, V., Rauw, G., Neiner, C., Martins, F., Cohen, D. H., Gagne, M., Ignace, R., Mathis, S., de Mink, S. E., Moffat, A. F. J., Owocki, S., Shultz, M., Sundqvist, J., and the MiMeS Collaboration (2013) Discovery of a magnetic field in the rapidly rotating O-type secondary of the colliding-wind binary HD 47129 (Plaskett's star). *MNRAS*, **428**(2), 1686–1695. https://doi.org/10.1093/mnras/sts153.

Harries, T. J., Hilditch, R. W., and Hill, G. (1997) Interacting O-star binaries: V382 Cyg, V448 Cyg and XZ Cep. *MNRAS*, **285**(2), 277–287. https://doi.org/10.1093/mnras/285.2.277.

Holgado, G., Simón-Díaz, S., Herrero, A., and Barbá, R. H. (2022) The IACOB project. VII. The rotational properties of Galactic massive O-type stars revisited. *A&A*, **665**, A150. https://doi.org/10.1051/0004-6361/202243851.

Hubrig, S., Järvinen, S. P., Ilyin, I., Schöller, M., and Jayaraman, R. (2023) Are magnetic fields universal in O-type multiple systems? *MNRAS*, **521**(4), 6228–6246. https://doi.org/10.1093/mnras/stad730.

Kippenhahn, R. and Weigert, A. (1967) Entwicklung in engen Doppelsternsystemen. I. Masseaustausch vor und nach Beendigung des zentralen Wasserstoff–Brennens. *ZA*, **65**, 251–273. https://ui.adsabs.harvard.edu/abs/1967ZA.....65..251K.

Langer, N., Schürmann, C., Stoll, K., Marchant, P., Lennon, D. J., Mahy, L., de Mink, S. E., Quast, M., Riedel, W., Sana, H., Schneider, P., Schootemeijer, A., Wang, C., Almeida, L. A., Bestenlehner, J. M., Bodensteiner, J., Castro, N., Clark, S., Crowther, P. A., Dufton, P., Evans, C. J., Fossati, L., Gräfener, G., Grassitelli, L., Grin, N., Hastings, B., Herrero, A., de Koter, A., Menon, A., Patrick, L., Puls, J., Renzo, M., Sander, A. A. C., Schneider, F. R. N., Sen, K., Shenar, T., Simón-Días, S., Tauris, T. M., Tramper, F., Vink, J. S., and Xu, X.-T. (2020) Properties of OB star–black hole systems derived from detailed binary evolution models. *A&A*, **638**, A39. https://doi.org/10.1051/0004-6361/201937375.

Lim, B., Nazé, Y., Chang, S.-J., and Hutsemékers, D. (2024) A morphokinematic study of the enigmatic emission nebula NGC 6164/5 surrounding the magnetic O-type star HD 148937. *ApJ*, **961**(1), 72. https://doi.org/10.3847/1538-4357/ad12c4.

Linder, N. (2008) *A Multi-Wavelength Study of Interactions in O + O Binary Systems*. Ph.D. thesis, University of Liège, Liège (BE).

Linder, N., Rauw, G., Martins, F., Sana, H., De Becker, M., and Gosset, E. (2008) High-resolution optical spectroscopy of Plaskett's star. *A&A*, **489**(2), 713–723. https://doi.org/10.1051/0004-6361:200810003.

Linder, N., Rauw, G., Sana, H., De Becker, M., and Gosset, E. (2007) The Struve–Sahade effect in the optical spectra of O-type binaries. I. Main-sequence systems. *A&A*, **474**(1), 193–204. https://doi.org/10.1051/0004-6361:20077902.

Mahy, L., Almeida, L. A., Sana, H., Clark, J. S., de Koter, A., de Mink, S. E., Evans, C. J., Grin, N. J., Langer, N., Moffat, A. F. J., Schneider, F. R. N., Shenar, T., and Tramper, F. (2020a) The Tarantula Massive Binary Monitoring. IV. Double–lined photometric binaries. *A&A*, **634**, A119. https://doi.org/10.1051/0004-6361/201936152.

Mahy, L., Gosset, E., Baudin, F., Rauw, G., Godart, M., Morel, T., Degroote, P., Aerts, C., Blomme, R., Cuypers, J., Noels, A., Michel, E., Baglin, A., Auvergne, M., Catala, C., and

Samadi, R. (2011a) Plaskett's star: analysis of the CoRoT photometric data. *A&A*, **525**, A101. https://doi.org/10.1051/0004-6361/201014777.

Mahy, L., Hutsemékers, D., Nazé, Y., Royer, P., Lebouteiller, V., and Waelkens, C. (2017) Evolutionary status of the Of?p star HD 148937 and of its surrounding nebula NGC 6164/5. *A&A*, **599**, A61. https://doi.org/10.1051/0004-6361/201629585.

Mahy, L., Martins, F., Machado, C., Donati, J.-F., and Bouret, J.-C. (2011b) The two components of the evolved massive binary LZ Cephei: Testing the effects of binarity on stellar evolution. *A&A*, **533**, A9. https://doi.org/10.1051/0004-6361/201116993.

Mahy, L., Sana, H., Abdul-Masih, M., Almeida, L. A., Langer, N., Shenar, T., de Koter, A., de Mink, S. E., de Wit, S., Grin, N. J., Evans, C. J., Moffat, A. F. J., Schneider, F. R. N., Barbá, R., Clark, J. S., Crowther, P., Gräfener, G., Lennon, D. J., Tramper, F., and Vink, J. S. (2020b) The Tarantula Massive Binary Monitoring. III. Atmosphere analysis of double–lined spectroscopic systems. *A&A*, **634**, A118. https://doi.org/10.1051/0004-6361/201936151.

Marchant, P. and Bodensteiner, J. (2024) The evolution of massive binary stars. *ARA&A*, **62**, 21–61. https://doi.org/10.1146/annurev-astro-052722-105936.

Martins, F., Mahy, L., and Hervé, A. (2017) Properties of six short-period massive binaries: A study of the effects of binarity on surface chemical abundances. *A&A*, **607**, A82. https://doi.org/10.1051/0004-6361/201731593.

Martins, F. and Palacios, A. (2013) A comparison of evolutionary tracks for single Galactic massive stars. *A&A*, **560**, A16. https://doi.org/10.1051/0004-6361/201322480.

Martins, F. and Plez, B. (2006) UBVJHK synthetic photometry of Galactic O stars. *A&A*, **457**(2), 637–644. https://doi.org/10.1051/0004-6361:20065753.

Martins, F., Simón-Díaz, S., Palacios, A., Howarth, I., Georgy, C., Walborn, N. R., Bouret, J.-C., and Barbá, R. (2015) Surface abundances of ON stars. *A&A*, **578**, A109. https://doi.org/10.1051/0004-6361/201526130.

Massey, P., Penny, L. R., and Vukovich, J. (2002) Orbits of four very massive binaries in the R136 cluster. *ApJ*, **565**(2), 982–993. https://doi.org/10.1086/324783.

Nazé, Y., Britavskiy, N., Rauw, G., Labadie-Bartz, J., and Simón-Díaz, S. (2023) Extreme mass ratios and fast rotation in three massive binaries. *MNRAS*, **525**(2), 1641–1656. https://doi.org/10.1093/mnras/stad2280.

Nazé, Y., Neiner, C., Grunhut, J., Bagnulo, S., Alecian, E., Rauw, G., and Wade, G. A. (2017) How unique is Plaskett's star? A search for organized magnetic fields in short period, interacting or post-interaction massive binary systems. *MNRAS*, page stx194. https://doi.org/10.1093/mnras/stx194.

Neiner, C., Mathis, S., Alecian, E., Emeriau, C., and Grunhut, J. (2015) The origin of magnetic fields in hot stars. *Proceedings of the International Astronomical Union*, **10**(S305), 61–66. https://doi.org/10.1017/S1743921315004524.

Packet, W. (1981) On the spin-up of the mass accreting component in a close binary system. *A&A*, **102**(1), 17–19. https://ui.adsabs.harvard.edu/abs/1981A&A...102...17P.

Palate, M. and Rauw, G. (2012) Spectral modelling of circular massive binary systems. Towards an understanding of the Struve–Sahade effect? *A&A*, **537**, A119. https://doi.org/10.1051/0004-6361/201117520.

Palate, M. and Rauw, G. (2014) Short-term spectroscopic variability of Plaskett's star. *A&A*, **572**, A16. https://doi.org/10.1051/0004-6361/201423608.

Palate, M., Rauw, G., Koenigsberger, G., and Moreno, E. (2013) Spectral modelling of massive binary systems. *A&A*, **552**, A39. https://doi.org/10.1051/0004-6361/201219754.

Pauli, D., Oskinova, L. M., Hamann, W.-R., Ramachandran, V., Todt, H., Sander, A. A. C., Shenar, T., Rickard, M., Maíz Apellániz, J., and Prinja, R. (2022) The earliest O-type eclipsing binary in the Small Magellanic Cloud, AzV 476: A comprehensive analysis reveals surprisingly low stellar masses. *A&A*, **659**, A9. https://doi.org/10.1051/0004-6361/202141738.

Penny, L. R., Ouzts, C., and Gies, D. R. (2008) Tomographic separation of composite spectra. XI. The physical properties of the massive close binary HD 100213 (TU Muscae). *ApJ*, **681**(1), 554–561. https://doi.org/10.1086/587509.

Podsiadlowski, Ph., Joss, P. C., and Hsu, J. J. L. (1992) Presupernova evolution in massive interacting binaries. *ApJ*, **391**, 246. https://doi.org/10.1086/171341.

Putkuri, C., Gamen, R., Morrell, N. I., Simón-Díaz, S., Barbá, R. H., Ferrero, G. A., Arias, J. I., and Solivella, G. (2018) Non-synchronous rotations in massive binary systems. HD 93343 revisited. *A&A*, **618**, A174. https://doi.org/10.1051/0004-6361/201833574.

Ramírez-Agudelo, O. H., Simón-Díaz, S., Sana, H., de Koter, A., Sabín-Sanjulían, C., de Mink, S. E., Dufton, P. L., Gräfener, G., Evans, C. J., Herrero, A., Langer, N., Lennon, D. J., Maíz Apellániz, J., Markova, N., Najarro, F., Puls, J., Taylor, W. D., and Vink, J. S. (2013) The VLT-FLAMES Tarantula Survey: XII. Rotational velocities of the single O-type stars. *A&A*, **560**, A29. https://doi.org/10.1051/0004-6361/201321986.

Raucq, F., Gosset, E., Rauw, G., Manfroid, J., Mahy, L., Mennekens, N., and Vanbeveren, D. (2017) Observational signatures of past mass-exchange episodes in massive binaries: the case of LSS 3074. *A&A*, **601**, A133. https://doi.org/10.1051/0004-6361/201630330.

Raucq, F., Rauw, G., Gosset, E., Nazé, Y., Mahy, L., Hervé, A., and Martins, F. (2016) Observational signatures of past mass-exchange episodes in massive binaries: The case of HD 149 404. *A&A*, **588**, A10. https://doi.org/10.1051/0004-6361/201527543.

Rauw, G., Crowther, P. A., De Becker, M., Gosset, E., Nazé, Y., Sana, H., van der Hucht, K. A., Vreux, J.-M., and Williams, P. M. (2005) The spectrum of the very massive binary system WR 20a (WN6ha + WN6ha): Fundamental parameters and wind interactions. *A&A*, **432**(3), 985–998. https://doi.org/10.1051/0004-6361:20042136.

Rauw, G., Nazé, Y., Fernández Lajús, E., Lanotte, A. A., Solivella, G. R., Sana, H., and Gosset, E. (2009) Optical spectroscopy of X-Mega targets in the Carina nebula – VII. On the multiplicity of Tr 16-112, HD 93343 and HD 93250. *MNRAS*, **398**(3), 1582–1592. https://doi.org/10.1111/j.1365-2966.2009.15226.x.

Rauw, G., Nazé, Y., and Gosset, E. (2023) Revisiting the orbital motion of WR 138. *NewA*, **104**, 102062. https://doi.org/10.1016/j.newast.2023.102062.

Rauw, G., Pigulski, A., Nazé, Y., David-Uraz, A., Handler, G., Raucq, F., Gosset, E., Moffat, A. F. J., Neiner, C., Pablo, H., Popowicz, A., Rucinski, S. M., Wade, G. A., Weiss, W., and Zwintz, K. (2019) BRITE photometry of the massive post-RLOF system HD149 404. *A&A*, **621**, A15. https://doi.org/10.1051/0004-6361/201833594.

Rauw, G., Sana, H., Antokhin, I. I., Morrell, N. I., Niemela, V. S., Albacete Colombo, J. F., Gosset, E., and Vreux, J.-M. (2001) Optical spectroscopy of XMEGA targets in the Carina Nebula – III. The multiple system Tr 16-104 ($\equiv$CPD -59° 2603). *MNRAS*, **326**(3), 1149–1160. https://doi.org/10.1046/j.1365-8711.2001.04681.x.

Renzo, M. and Götberg, Y. (2021) Evolution of accretor stars in massive binaries: Broader implications from modeling ζ Ophiuchi. *ApJ*, **923**(2), 277. https://doi.org/10.3847/1538-4357/ac29c5.

Rickard, M. J. and Pauli, D. (2023) A low-metallicity massive contact binary undergoing slow Case A mass transfer: A detailed spectroscopic and orbital analysis of SSN 7 in NGC 346 in the SMC. *A&A*, **674**, A56. https://doi.org/10.1051/0004-6361/202346055.

Rosu, S., Rauw, G., Conroy, K. E., Gosset, E., Manfroid, J., and Royer, P. (2020) Apsidal motion in the massive binary HD 152248. *A&A*, **635**, A145. https://doi.org/10.1051/0004-6361/201937285.

Rosu, S., Rauw, G., Farnir, M., Dupret, M.-A., and Noels, A. (2022a) Apsidal motion in massive eccentric binaries in NGC 6231: The case of HD 152219. *A&A*, **660**, A120. https://doi.org/10.1051/0004-6361/202141304.

Rosu, S., Rauw, G., Nazé, Y., Gosset, E., and Sterken, C. (2022b) Apsidal motion in massive eccentric binaries: The case of CPD-41° 7742, and HD 152218 revisited. *A&A*, **664**, A98. https://doi.org/10.1051/0004-6361/202243707.

Sana, H., de Mink, S. E., de Koter, A., Langer, N., Evans, C. J., Gieles, M., Gosset, E., Izzard, R. G., Le Bouquin, J.-B., and Schneider, F. R. N. (2012) Binary interaction dominates the evolution of massive stars. *Sci*, **337**, 444–446. https://doi.org/10.1126/science.1223344.

Schneider, F. R. N., Ohlmann, S. T., Podsiadlowski, Ph., Röpke, F. K., Balbus, S. A., Pakmor, R., and Springel, V. (2019) Stellar mergers as the origin of magnetic massive stars. *Natur*, **574**, 211–214. https://doi.org/10.1038/s41586-019-1621-5.

Schneider, F. R. N., Podsiadlowski, Ph., Langer, N., Castro, N., and Fossati, L. (2016) Rejuvenation of stellar mergers and the origin of magnetic fields in massive stars. *MNRAS*, **457**(3), 2355–2365. https://doi.org/10.1093/mnras/stw148.

Sen, K., Langer, N., Marchant, P., Menon, A., de Mink, S. E., Schootemeijer, A., Schürmann, C., Mahy, L., Hastings, B., Nathaniel, K., Sana, H., Wang, C., and Xu, X. T. (2022) Detailed models of interacting short-period massive binary stars. *A&A*, **659**, A98. https://doi.org/10.1051/0004-6361/202142574.

Sen, K., Langer, N., Pauli, D., Gräfener, G., Schootemeijer, A., Sana, H., Shenar, T., Mahy, L., and Wang, C. (2023) Reverse Algols and hydrogen-rich Wolf–Rayet stars from very massive binaries. *A&A*, **672**, A198. https://doi.org/10.1051/0004-6361/202245378.

Shao, Y. and Li, X.-D. (2021) Population synthesis of Galactic Be-star binaries with a helium-star companion. *ApJ*, **908**(1), 67. https://doi.org/10.3847/1538-4357/abd2b4.

Shara, M. M., Crawford, S. M., Vanbeveren, D., Moffat, A. F. J., Zurek, D., and Crause, L. (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, M. M., Crawford, S. M., Vanbeveren, D., Moffat, A. F. J., Zurek, D., and Crause, L. (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.

Shultz, M., Wade, G. A., Alecian, E., and the BinaMIcS Collaboration (2015) Detection of magnetic fields in both B-type components of the ε Lupi system: a new constraint on the origin of fossil fields? *MNRAS*, **454**(1), L1–L5. https://doi.org/10.1093/mnrasl/slv096.

Ud-Doula, A., Owocki, S. P., and Townsend, R. H. D. (2009) Dynamical simulations of magnetically channelled line–driven stellar winds – III. Angular momentum loss and rotational spin-down. *MNRAS*, **392**(3), 1022–1033. https://doi.org/10.1111/j.1365-2966.2008.14134.x.

van Bever, J. and 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. https://ui.adsabs.harvard.edu/abs/1997A&A...322..116V.

Vanbeveren, D. (1991) The evolution of massive close binaries revised. *A&A*, **252**(1), 159–171. https://ui.adsabs.harvard.edu/abs/1991A&A...252..159V.

Vanbeveren, D. and De Loore, C. (1994) The evolution of the mass gainer in massive close binaries. *A&A*, **290**, 129–132. https://ui.adsabs.harvard.edu/abs/1994A&A...290..129V.

Vanbeveren, D., De Loore, C., and Van Rensbergen, W. (1998) Massive stars. *A&ARv*, **9**(1-2), 63–152. https://doi.org/10.1007/s001590050015.

Vanbeveren, D., Mennekens, N., Shara, M. M., and Moffat, A. F. J. (2018) Spin rates and spin evolution of O components in WR+O binaries. *A&A*, **615**, A65. https://doi.org/10.1051/0004-6361/201732212.

Wang, L., Gies, D. R., Peters, G. J., Götberg, Y., Chojnowski, S. D., Lester, K. V., and Howell, S. B. (2021) The detection and characterization of Be+sdO binaries from HST/STIS FUV spectroscopy. *AJ*, **161**(5), 248. https://doi.org/10.3847/1538-3881/abf144.

Wang, L., Gies, D. R., Peters, G. J., and Han, Z. (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.

Yungelson, L., Kuranov, A., Postnov, K., Kuranova, M., Oskinova, L. M., and Hamann, W.-R. (2024) Elusive hot stripped helium stars in the Galaxy. I. Evolutionary stellar models in the gap between subdwarfs and Wolf–Rayet stars. *A&A*, **683**, A37. https://doi.org/10.1051/0004-6361/202347806.