Active OB stars: structure, evolution, mass loss, and critical limits
Proceedings IAU Symposium No. 272, 2010
C. Neiner, G. Wade, G. Meynet & G. Peters, eds.

doi:10.1017/S1743921311011124

The multiplicity of massive stars

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Abstract. Binaries are excellent astrophysical laboratories that provide us with direct measurements of fundamental stellar parameters. Compared to single isolated stars, multiplicity induces new processes, offering the opportunity to confront our understanding of a broad range of physics under the extreme conditions found in, and close to, astrophysical objects.

In this contribution, we will discuss the parameter space occupied by massive binaries, and the observational means to investigate it. We will review the multiplicity fraction of OB stars within each regime, and in different astrophysical environments. In particular we will compare the O star spectroscopic binary fraction in nearby open clusters and we will show that the current data are adequately described by an homogeneous fraction of $f \approx 0.44$.

We will also summarize our current understanding of the observed parameter distributions of O + OB spectroscopic binaries. We will show that the period distribution is overabundant in short period binaries and that it can be described by a bi-modal Öpik law with a break point around $P \approx 10$ d. The distribution of the mass-ratios shows no indication for a twin population of equal mass binaries and seems rather uniform in the range $0.2 \leqslant q = M_2/M_1 \leqslant 1.0$.

Keywords. binaries (including multiple): close, binaries: general, binaries: spectroscopic, binaries: visual, stars: early-type, open clusters and associations: individual (Col 228, IC1 805, IC 1848, IC 2944, NGC 330, NGC 346, NGC 2004, NGC 2244, NGC 6231, NGC 6611, N 11, Tr 14, Tr 16, West 1, 30 Dor)

1. Introduction

Massive stars have many fascinating aspects, which extend well beyond stellar physics alone. One of their most striking properties is conceptually very simple: their high-degree of multiplicity. Most O- and early B-type stars are found in binaries and multiple systems. Even single field stars are often believed to have been part of a multiple system in the past, then ejected by a supernova kick or by dynamical interaction. To ignore the multiplicity of early-type stars is equivalent to neglecting one of their most defining characteristics.

In this review we concern ourselves with the multiplicity of stars more massive than 8 $M_\odot$ on the zero-age main sequence, which have spectral types earlier than B3 V. Our approach is to focus on their observational properties, with the emphasis on O-type binaries, although early B-type binaries feature in some of the quoted works. Despite the importance of detailed studies of individual objects, our prime motivation here is to consider the broader results from the literature, in an attempt to lift the veil on some of the general properties of the binary population of early-type stars.

The distributions of the orbital parameters of massive binaries, as a population, are of fundamental importance to stellar evolution, yet remain poorly constrained. These distributions trace the products of star formation and the early dynamical evolution of the host systems, and are necessary ingredients to population synthesis studies. Only with an understanding of these distributions can we hope to recover accurate predictions for some of the exotic late stages of binary evolution.

This contribution is structured as follows. Section 2 describes some of the physical processes and observational biases that are present in multiple systems compared to single stars. Section 3 introduces the different parts of parameter space occupied by massive binaries, and the observational means to investigate them; Section 4 then reviews the multiplicity fraction of OB stars within each regime, and in different astrophysical environments. Section 5 attempts to summarize our current understanding of the parameter distributions of O + OB spectroscopic binaries. Finally, Section 6 provides a summary.

2. Physical processes and observational biases

Binaries are excellent astrophysical laboratories that provide us with direct measurements of fundamental parameters such as stellar masses and radii. Multiplicity induces new processes compared to isolated single stars, offering the opportunity to confront our understanding of a broad range of physics under the extreme conditions found in, and close to, astrophysical objects. Moreover, if one fails to take multiplicity into account, observations (and their analysis) can be significantly biased or misleading. Most critically, early-type binaries with orbital periods of up to 10 years follow significantly different evolutionary paths, an aspect that can also impact the outputs of population synthesis models (e.g., Vanbeveren 2009). By way of additional motivation to understand multiplicity in massive stars, some of the observational and evolutionary impacts include:

Different evolutionary paths: Binarity significantly affects the evolutionary path of the components of the systems compared to single stars. Tidal effects in close binaries modifies the evolution of stellar rotation rates, thus also the induced rotational-mixing of enriched material into their photospheres de Mink *et al.* (2009). Roche-lobe overflow will result in mass and angular momentum transfer, spinning up the secondary to its critical rotation rate Packet (1981); Langer *et al.* (2008). While the gaining star might be rejuvenated by the increase in mass Braun & Langer (1995), the primary will see a reduction in the life-time of its red supergiant phase Eldridge *et al.* (2008). A common-envelope phase and/or stellar mergers are other possible outcomes of binary evolution. The impacts on observed stellar populations are numerous, including modified surface abundances, modified enrichment of the interstellar medium, the rate of supernova and γ-ray burst explosions, and on the number of evolved systems such as Wolf-Rayet stars and high-mass X-ray binaries (e.g., Izzard *et al.* 2006; Brinchmann *et al.* 2008).

Wind collisions: In binaries, the powerful stellar wind from the stars may interact with one another or with the surface of the star with the weaker wind Usov (1992). The supersonic collision heats the gas to temperature up to several 10^7 K Stevens *et al.* (1992). In several cases, the wind-wind interaction is also to accelerate particles up to relativistic energies. The signature of the wind collision can be observed throughout the electromagnetic spectrum, through non-thermal radio (and possibly X- and γ-ray) emission De Becker (2007), through X-ray thermal emission Parkin & Pittard (2010) and via a contribution to the recombination lines in the optical and infrared Sana *et al.* (2001). In massive binaries containing evolved stars with very dense winds, the wind interaction region can act as a nucleation site for dust particles, creating structures such as the pinwheel nebulae Tuthill *et al.* (2008). These effects can provide indirect indiciations of multiplicity. However, if multiplicity is not considered, wind collision can lead to erroneous estimates of fundamental properties such as intrinsic X-ray luminosities Sana *et al.* (2006), spectral classifications, and stellar mass-loss rates (as measured from the strength of, e.g., the Hα line).

Struve-Sahade effect: In its most generalized form, the Struve-Sahade (S-S) effect can be described as the variation in the apparent strength of the spectrum of one or both components when the star is approaching/receding (for an example, see e.g. Sana *et al.* 2001). Various physical effects can induce a S-S signature: gaseous streams in the systems, ellipsoidal variations, surface streams, and changes in the local surface temperature due to, e.g., mutual illumination or heating from a wind-wind collision (e.g., Bagnuolo *et al.* 1999; Linder *et al.* 2007).

Cluster dynamical mass: Ignoring the contribution of binaries to the stellar velocity dispersion in clusters (in both integrated-light observations of distant systems and studies of resolved clusters), can lead to a significant overestimate of their dynamical mass Bosch *et al.* (2009); Gieles *et al.* (2010). For example, some of the disagreement in the mass-to-light ratio of young extragalactic clusters might arise from the binary properties of their red supergiant populations Gieles *et al.* (2010).

Supermassive stars: Unresolved multiple systems have often been confused with very high mass stars due to their large luminosity. Numerous objects have indeed seen their masses revised at the light of improvements of the observing facilities (e.g. the case of R136: Cassinelli *et al.* 1981; Weigelt & Baier 1985; Crowther *et al.* 2010).

3. The parameter space

Before discussing the multiplicity properties of populations of massive stars, we attempt to give the reader a feel for the typical parameter space that needs to be investigated. Our aim is to provide a qualitative overview of the orders of magnitude involved; the values and sketches should only be considered as indicative!

While many more parameters are involved, it is useful to restrain our discussion to a two-dimensional space. Indeed the detection efficiency of most of the observing techniques can be discussed in terms of the orbital separation (or, equivalently, of the orbital period) and of the mass- or flux-ratio of the components. For a given evolutionary stage, the mass-ratio can directly be related the flux ratio and we will therefore assume a direct equivalence between these two values. This simplified approach assumes that observations with sufficient time-sampling are available, and knowingly neglects the second-order effects of eccentricity and orbital inclination on the detection probabilities.

Mass-ratio ($q = M_2/M_1$): In principle, the range of possible mass-ratios spans equal-mass binaries ($q = 1.0$) to a system with a massive star with a light companion ($q << 1$). For example, an $O5 + M8$ system would have a mass ratio of only $q \sim 0.002$. Of course, a companion with such a low mass would be very hard to detect, but the absence of observational clues does not preclude their existence. There are other observational issues, such as the likelihood that low-mass companions are still in the pre-main sequence phase – observations at longer wavelengths could provide crucial information in this scenario. The range of flux-ratios that require scrutiny can reach up to 10^5, providing a significant observational challenge.

Separations (d): An estimate of the minimal separation can be adopted as the distance at which two main-sequence stars would enter a contact phase. For typical O- and early B-type primaries, this corresponds to rough separations of 20 $R_\odot$ or 0.1 AU, equating to periods of 1-2 days depending of the system mass. The outer separation boundary is more of a grey zone that depends on both the system environment and on the timescale involved. In this context, we consider two arguments. The first makes the distinction between *hard* and *soft* binary systems, i.e., between systems that have a large likelihood of surviving a three-body interaction, versus systems that will be easily disrupted. Heggie (1975) defined *hard* binaries as systems in which the binding energy (E_b) is larger than the kinetic energy (E_k) brought about by an encounter :

$$|E_b| > E_k(encounter) = \frac{<m><v^2>}{2}, \tag{3.1}$$

where $<m>$ and $<v^2>$ are the typical mass and velocity dispersions of stars in a given cluster. Following Portegies Zwart *et al.* (2010) and adopting an effective cluster radius of 1 pc and cluster masses in the range $2.5{\times}10^3$ to 10^5 $M_\odot$, one estimates the maximum separation of *hard* binaries to be in the range of 10^3 to several 10^4 A.U.

A second more qualitative argument emphasized by Maíz Apellániz (2010) points out that massive stars have short life-times. One could therefore limit the parameter space to orbital periods of 10^5 to 10^6 yr as only these systems would accomplish a significant number of orbits during their life-time. Following the third Kepler law, this also corresponds to typical separations of several 10^4 AU. Interestingly, this means that most of the massive binaries are hard binaries, that will be difficult to disrupt over their life-time. The observed maximum range of separations considered here is in line with the statement of Abt (1988) that the more massive stars can sustain companions up to several 10^4 AU or more.

Observational techniques: Investigating such a large parameter space requires a combination of techniques (Fig. 1), each characterized by their own sensitivities and observational biases. Short-period close binaries are probed efficiently through spectroscopy, while very wide binaries, with angular separations larger than a couple of arcseconds can be detected by classical, high-contrast imaging. Enhanced imaging techniques such as adaptive optics (AO) and lucky imaging can provide about an order of magnitude in terms of closer separation and can also reach large flux contrasts. In principle, the gap between the spectroscopic and imaging regimes can be bridged with speckle interferometry, and ground-based and space interferometry. Speckle interferometry has the potential for large surveys but, to date, its applications have been limited to flux ratios of about ten Mason *et al.* (2009). Space and ground-based interferometry can reach separations of milliarcsecond scales, at flux ratios of up to 100, but are much more costly to operate and no large survey has yet been attempted.

Combining these various methods allows us in principle to explore the full range of separations for massive binaries out to a distance of ≈ 5 kpc. In practise, these techniques are not equally sensitive and do not offer the same detection probability in their respective regions of parameter space. For example, spectroscopy is very efficient for short-period binaries, with periods of up to a couple of years. The detection probability however decreases dramatically for long-period systems (see, e.g., Fig. 2 of Evans *et al.* 2010), in part due to the reduced radial velocity (RV) signal and also due to the longer timescales involved. Moreover, eccentric systems are harder to detect due the narrower window (sometimes less than a tenth of the orbital cycle) during which the RV variations are concentrated. Imaging techniques (classical, lucky, or AO-corrected) share a common bias in which the achievable contrast varies as a function of the separation (see e.g., Fig. 2 of Maíz Apellániz 2010).

Detailed comprehension of the limitations of each technique and of their observational bias is of prime importance in order to retrieve the global multiplicity properties of massive star populations.

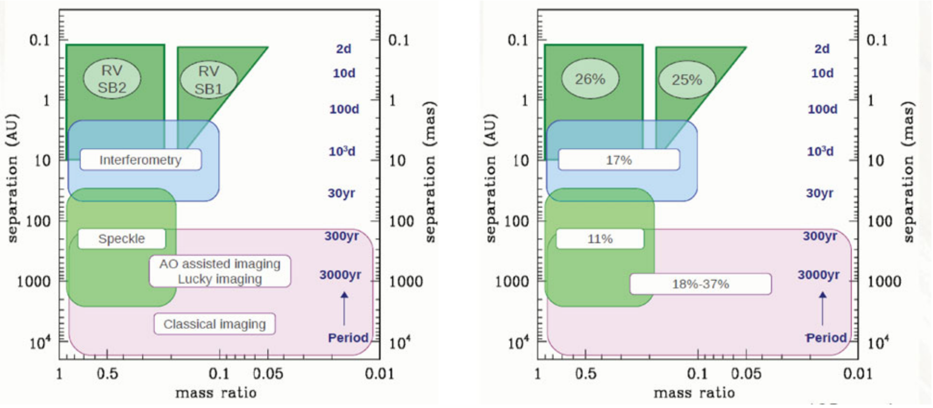

Figure 1. Left-hand panel: typical parameter space for massive binaries. A primary of 40 $M_\odot$ at a distance of 1 kpc has been assumed to construct this sketch. The relevant regions for various detection techniques have been overlaid. Right-hand panel: measured multiplicity in those parts of parameter space (see text for details).

4. The multiplicity fraction of O-type stars

4.1. *Spectroscopic binary fraction in various separation regimes*

The right-hand panel of Fig. 1 gives an overview of the results from recent surveys, including the minimum multiplicity fraction obtained in each part of parameter space from the relevant technique:

Spectroscopy: The most comprehensive overview of the spectroscopic binary (SB) fraction is provided by Mason *et al.* (2009). Based on a review of the literature covering more than 300 O-type objects, these authors found over half of the sample to be part of a SB system. The systems are separated, almost equally, into single- (SB1) and double-lined (SB2) systems.

Speckle interferometry: In the same paper, Mason *et al.* (2009) provide speckle observations of 385 O-type stars, thus covering almost all of the targets in the Galactic O star catalog Maíz-Apellániz *et al.* (2004). 11% of the objects in the Mason *et al.* (2009) sample are found to have speckle companions.

Enhanced imaging techniques: At larger separations, AO-corrected and lucky imaging surveys (respectively, Turner *et al.* (2008) – 138 O stars – and Maíz Apellániz (2010) – 128 O stars) found that 37% of the O stars are part of wide multiple systems. These two studies are mostly limited to the northern hemisphere and are thus missing some of the richer massive star clusters and associations in the southern sky. Part of this gap is filled by the AO campaigns of Duchêne *et al.* (2001) and Sana *et al.* (2010b) on, respectively, NGC 6611 and Tr 14. Both studies revealed a lower multiplicity fraction of 18% for their sample of OB stars. Yet, (part of) this difference results from the fact that these two regions are dense clusters. In these environments, disentangling the true pairs from chance alignment with stars in the same clusters becomes more challenging and only a smaller separation range can be investigated reliably. Interestingly, both Duchêne *et al.* (2001) and Sana *et al.* (2010b) concluded that OB stars have more companions than lower mass-stars.

Interferometry: As mentioned earlier, interferometry is less suitable for surveys. To the best of our knowledge, only one homogeneous survey has been attempted so far. Nelan *et al.* (2004) targeted a limited sample of 23 O-type stars in the Carina region with the *Hubble Space Telescope* fine guidance sensor, resolving close-by companions for four stars.

Table 1. Overview of the spectroscopic binary fraction in clusters.

Object	# O stars	Binary fraction^a	Ref	Object	# O stars	Binary fraction^a	Ref.
Nearby clusters				**Distant/extragalactic clusters**			
NGC 6611	9	0.44	1	West 1	20	0.30	9
NGC 6231	16	0.63	2	30 Dor	54	0.45	10
IC 2944	14	0.53	3	NGC346	19	0.21	11
Tr 16	24	0.48	4	N11	44	0.43	11
IC 1805	8	0.38	5	NGC2004	4	0.25	11
IC 1848	5	0.40	5	NGC 330	6	0.00	11
NGC 2244	6	0.17	6				
Tr 14	6	0.00	7	**Milky Way O star population**			
Col 228	15	0.33	8	Clusters & OB associations	305	0.57	12

Notes: ^{a} The quoted binary fraction is a lower limit as each new detection will increase it.
References: 1. Sana *et al.* (2009), 2. Sana *et al.* (2008), 3. Sana *et al.* (2010a), 4. Literature review, 5. Hillwig *et al.* (2006), 6. Mahy *et al.* (2009), 7. Penny *et al.* (1993), García *et al.* (1998), 8. Sana *et al.* (in prep.), 9. Ritchie *et al.* (2009), 10. Bosch *et al.* (2009), 11. Evans *et al.* (2006), 12. Mason *et al.* (2009)

Combining information from these various ranges, a minimum multiplicity fraction close to 70% for the population of Galactic O-type stars is reached Mason *et al.* (2009). Given the detection limits of these campaigns, there is ample scope for the true multiplicity fraction to be even larger.

Despite the quality of the observations collected so far, improvements are still needed in each of the ranges covered by the various observing techniques described above:

- Homogeneous AO and lucky imaging campaigns have been mostly limited to the northern sky. Extending such work to the rich and dense clusters and star-formation regions of the southern hemisphere is highly desirable,
- Higher flux contrasts are needed in the 10-100 mas separation regime. Techniques such as sparse-aperture masking coupled with AO could, in principle, bring some improvements,
- The separation range 5-100 AU remains almost unexplored,
- About half the known and suspected SBs lack an orbital solution. As a consequence, the distribution of the the orbital parameters remains largely uncertain (see also Section 5).

4.2. *Spectroscopic binary fraction in clusters*

Mason *et al.* (2009) investigated the dependence of the SB fraction on environment by comparing stars from clusters and associations with runaway and field stars, finding that the first category harbours many more binaries and multiple systems. This picture is mostly consistent with an ejection scenario for the field/runaway stars in which most of the multiple systems would be disrupted. In this section, we take a different approach and look for differences in the multiplicity fraction of various clusters. Several authors have indeed proposed the SB fraction to be related to the cluster density (e.g., Penny *et al.* 1993; García & Mermilliod 2001).

To support our discussion, Table 1 summarizes the SB fraction of O-star rich clusters (i.e., clusters with at least five O-type stars), with Fig. 2 giving a graphical comparison of the SB fractions in the various samples. Focusing on the qualitatively homogeneous sample formed by the nearby clusters, we calculate an average binary fraction of $f = 0.44 \pm 0.05$. While some deviations are observed around this average value, each can be explained by statistical fluctuations. Even the extreme case of Tr 14, with no known spectroscopic companions to its six O-type stars, is not statistically significant. For instance, the probability to have six single stars, drawn from an underlying binomial

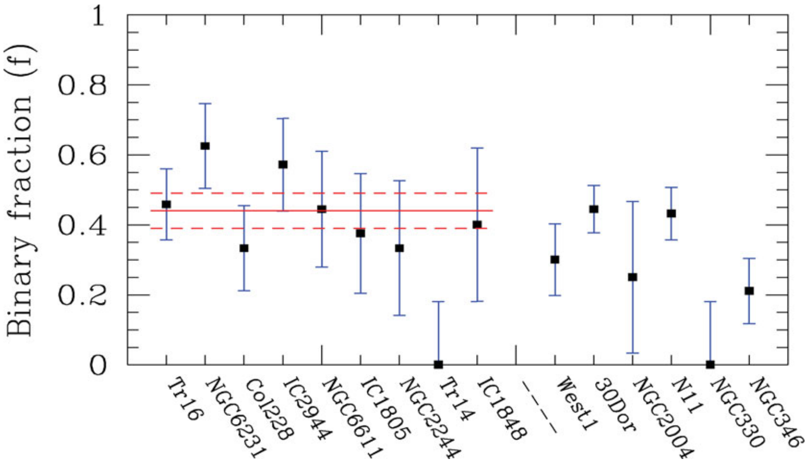

Figure 2. Spectroscopic binary fraction of nearby (left) and distant/extragalactic (right) clusters. The plain line and dashed lines indicate the average fraction and 1σ dispersion computed from the nearby cluster sample.

distribution with a multiplicity fraction of $f = 0.44$ is 3%. Assuming that parent population is the same, the chance of obtaining zero binaries in any one of our nine clusters (given the size of their respective O star population) is 13%, such that we cannot reject the null hypothesis. Of course, the fact that Tr 14 is the densest and possibly the youngest of the nine clusters in our sample is intriguing.

The multiplicity properties from distant and extragalactic clusters are less constrained and should be considered as lower limits, in part because some of these works have a limited baseline and/or a limited number of epochs. Aside from the case of NGC 330, there is again no fundamental disagreement with the results from the nearby cluster sample. With no companions seen for six O-type stars, the NGC 330 sample is similar, in terms of size and binary fraction, to Tr 14. Sample size effects could be invoked (as for Tr 14), but the fact that the much larger population of B-type stars in NGC 330 also show a depleted binary population Evans *et al.* (2006) is appealing. Interestingly, NGC 330 is an older region with a very low surface density, in strong contrast with the properties of Tr 14.

In summary, while some variations of the binary fraction might occur in peculiar situations, the null hypothesis of a common parent distribution cannot be rejected given the current data set. Adopting a uniform binary fraction of $f \approx 0.44$ is thus the most relevant description of the current data. As a direct consequence of this result, one can however reject with a very high confidence the null hypothesis that all O stars are spectroscopic binaries.

5. Distributions of the orbital parameters of spectroscopic binaries

This section provides an overview of our current knowledge of the orbital parameter distributions for O-type spectroscopic binaries. In doing so, it is useful to define two samples (Table 2):

- *The Galactic O-star sample:* mostly based on the sample of Mason *et al.* (2009). While Mason *et al.* (2009) only concentrate on the multiplicity aspect, we perform our own literature review to search for estimates of periods, mass-ratios and eccentricities. When no orbital solution was available, we estimated the mass-ratios of SB2 systems by

Table 2. Overview of the two O star samples used to derive the distributions of the orbital parameters. The first part of the table indicates the number of O stars, the number of O-type binaries and the binary fraction of the two samples. The second part of the table provides the number and the fraction of systems with constraints on their periods, mass-ratios and eccentricities.

	# Galactic O stars	**Nearby rich clusters**
# O stars	305	82
# binaries	173	38
Binary fraction	0.57	0.46
# periods	102 (59%)	33 (87%)
# mass-ratios	76 (44%)	29 (76%)
# eccentricities	86 (50%)	30 (79%)

Note: The sample of nearby clusters is formed by IC 1805, IC1848, IC 2944, NGC6231, NGC 6611 and Tr16.

adopting typical masses for the components as a function of their spectral classification Martins *et al.* (2005). Compared to the review of Mason *et al.* (2009), we also include information that became available in the last two years, as well as preliminary results from our work.

- *The nearby O-star rich clusters:* a subsample of the Galactic O-star sample, focusing on the O-star rich clusters within ≈ 3 kpc. These clusters have been more thoroughly studied so that the scope for observational biases is more limited.

The binary fraction of the two samples appear to be different, with the Galactic O-star sample displaying more binaries. A possible explanation for this is provided by García & Mermilliod (2001), who noted that the O stars in poor clusters (i.e., clusters with only one or two O-type stars) were almost all multiple. These clusters are not included in our second sample, which may pull the binary fraction to lower values.

While the Galactic O-star sample is the most comprehensive, only about 50% of the binaries have constraints on their orbital solution (Fig. 3), leaving a lot of room for observational biases. For example, the orbital solutions are more difficult to obtain for long-period high eccentricity systems. There might thus be an uneven representation of various parameter ranges in the observed distribution functions. The situation is much improved for the cluster sample, as almost 80% of the systems have proper orbital solutions and 87% have estimates of the orbital period. We therefore argue that the distributions derived from the cluster sample are much less affected by observational biases. In the following, we will compare the parameter distributions built from the two samples to one another and to analytical distributions commonly used to represent the properties of the massive star binary population.

Period: Fig. 3 provides an overview of the respective samples with the cumulative number distributions of the orbital periods. It shows that the period distribution function obtained from the cluster sample is almost fully constrained, but that uncertainties could still affect the Galactic sample. However, the cumulative distribution functions (CDFs) are mostly in agreement (Fig. 4, left-hand panel). Both CDFs show an overabundance of short periods, with 50 to 60% of the systems having a period shorter than 10 days. Consequently, the CDF of observed periods in the spectroscopic regime can not be represented by the traditional Öpik Law†. As already suggested by Sana *et al.* (2008), a much better representation of the period CDF is provided by a bi-uniform distribution

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† Öpik's Law states that the distribution of separations is flat in logarithmic space. The corresponding period distribution should be flat in $\log P$ as well.

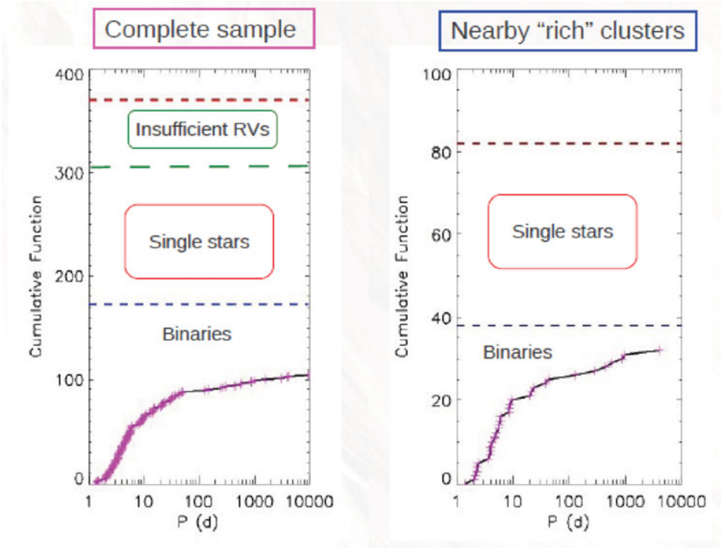

Figure 3. Cumulative number function of orbital periods for the complete sample (left) and for the nearby cluster sample (right). This plot aims to give a graphical impression of the potential biases affecting the two samples. Normalised cumulative distribution functions for systems with solutions are given in Fig. 4.

in $\log P$ (which one could consider a 'broken' Öpik Law) such that:

$$CDF(P) = \begin{cases} \dfrac{F_{\rm break}\left(\log P - \log P_{\rm min}\right)}{\log P_{\rm break} - \log P_{\rm min}}, & \text{for } \log P_{\rm min} \leqslant \log P \leqslant P_{\rm break} \\[2ex] F_{\rm break} + \dfrac{\left(1-F_{\rm break}\right)\left(\log P - \log P_{\rm break}\right)}{\log P_{\rm max} - \log P_{\rm break}}, & \text{for } P_{\rm break} < \log P \leqslant \log P_{\rm max} \end{cases} \tag{5.1}$$

where P is expressed in days. Adopting a break-point at $P_{\rm break} \approx 10$ d, with upper and lower limits of $\log P/{=}0.3$ and 3.5 d and considering that the binaries are evenly spread in the short and long period regimes (i.e., $F_{\rm break} \approx 0.5$), Eq. 5.1 becomes:

$$CDF(P) = \begin{cases} \frac{5}{7}\log P - \frac{10.5}{7}, & \text{for } 0.3 \leqslant \log P \leqslant 1.0 \\[2ex] \frac{1}{5}\log P - \frac{3}{10}, & \text{for } 1.0 < \log P \leqslant 3.5 \end{cases} \tag{5.2}$$

Eqs. 5.1 and 5.2 give an empirical description of the CDF of the observed periods. The latter should still be corrected for the detection probability (mostly affecting longer periods) and for the systems lacking orbital solutions (also more likely to affect the longer-period regime). The exact location of the lower and upper limits and of the 'break' still needs to be more tightly constrained. That said, the general behaviour and the overabundance of short-period spectroscopic binaries appear clear.

Mass-ratio: The CDFs of the mass-ratios (Fig. 4, middle panel) are well reproduced by a uniform distribution in the range $0.2 < q < 1.0$. The Galactic O-star sample shows slightly fewer systems with $q < 0.6$; this can be (partly) explained by observational biases as the detection of the secondary signature for systems with large mass differences (i.e., large flux contrasts) requires very high-quality data that are not always available for the Galactic sample. SB1 binaries represent about 20-25% of the cluster sample. For these stars, one cannot directly estimate the mass-ratio. However, we note that the fraction

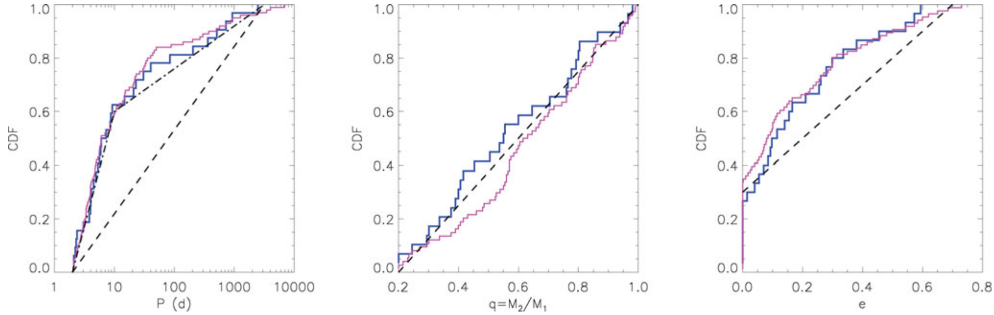

Figure 4. Cumulative distribution functions (CDFs) of the periods (P), mass-ratios (q) and eccentricities (e). The plain thin/magenta and thick/blue lines indicate the CDFs of, the Galactic O-star sample and the nearby cluster sample, respectively. Left-hand panel: the dashed line shows an Öpik Law over this range of periods, while the dot-dashed line indicates the alternative law given by Eq. 5.2. Middle panel: the dashed line indicates a uniform distribution in the considered range. Right-hand panel: the dashed line indicates a uniform distribution for $e > 0$.

of SB1 is roughly compatible with an extension of the uniform CDF towards $q < 0.2$; testing this statement will require detailed simulations.

As a direct consequence of a uniform mass-ratio CDF, the presence of a twin population with $q > 0.95$ proposed by Pinsonneault & Stanek (2006) can be rejected. Another implication resides in the fact that massive binaries cannot be formed by random pairing from a Salpeter/Kroupa IMF. Our results rather suggest the presence of a mechanism that favors the creation of $\mathrm{O+OB}$ binaries. Such a mechnaism could find part of its origin in the early dynamical evolution, where companion exchanges favor the capture of more and more massive secondaries. It could also trace a particular formation mechanism Zinnecker & Yorke (2007).

Eccentricity: The CDF of the eccentricities (Fig.4, right-hand panel) is characterized by an overabundance of circular and low eccentricity systems. Indeed, 25-30% of the systems displayed a circular orbit, while another 30% have $e < 0.2$. This behaviour contradicts the expected properties of a purely thermal binary population, which can be qualitatively explained by the large fraction of short-period systems for which tidal dissipation will tend to circularize the orbit.

An analytical description of the observed CDF for eccentric systems can be provided through $CDF(e > 0) \propto e^{0.5}$ in the range $0.0 < e < 0.8$. However, as 20% of the cluster sample and 50% of the Galactic sample are lacking robust eccentricities and as biases are most likely to affect larger eccentricities, we cannot consider this relation as definite. That said, one would expect that $CDF(e)$ will remain overabundant towards low eccentricity systems.

6. Summary

We have attempted to provide an overview of our current knowledge of the important multiplicity properties of massive stars. We described some of the physical processes and observational biases that lead to binaries behaving differently compared to single stars. We then briefly described the observational parameter space that one needs to explore to investigate massive binaries, and we discussed the challenges of probing it homogeneously. Despite these difficulties, it is now well established that the vast majority of O-type stars are part of a multiple system. The typical separation between the multiple components covers at least 4 order of magnitudes.

At least 45-55% of the O star population in clusters and OB associations is comprised by spectroscopic binaries, with a lower fraction found for field and runaway stars Mason *et al.* (2009). Here we have investigated possible variations of the multiplicity fraction among clusters with a rich O star population. While room for small variations remains due to our limited sample and due to the small O star population of some clusters, the binary fraction can mostly be considered as uniform with a value close to 44%. Given the current data set, one can hardly argue that the multiplicity fraction is significantly correlated with the cluster density (at least not in the range covered in our sample) . While density can still play a role, for example, to explain the difference observed between O-star rich and O-star poor clusters, its impact among rich clusters remain questionable in light of the current data. It is well accepted that most O-type stars are part of a multiple systems, but a similar statement does not hold when limiting ourselves to spectroscopic companions. Given the observed SB binary fraction and the sample sizes, it is unlikely that the underlying fraction of SBs is larger than 70-75%.

Finally, we have constructed CDFs for the periods, mass-ratios and eccentricities for two samples of massive binaries. The Galactic O-star sample is more extensive but has been studied less homogeneously. The second sample, based on the O star binary population in six rich nearby open clusters, is more homogeneous and is less susceptible to detection biases. There are some differences in the CDFs of the two samples (see Fig. 4), but two-sided Kolmogorov-Smirnoff tests do not reveal statistically significant deviations. These differences can be qualitatively understood in terms of different observational effects. Currently, the observed CDFs for P, q and e of spectroscopic O-type binaries can be analytically described by the following functions:

- *Periods:* a broken Öpik Law with a break point at $P \sim 10$ days,
- *Mass-ratios:* a uniform distribution down to $q = 0.2$, potentially extending in the SB1 domain (i.e., for $q < 0.2$),
- *Eccentricities:* 25-30% of the characterised systems have circular orbits. $CDF(e > 0)$ shows a square-root dependance with e, but detailed considerations of bias are lacking at present.

A quantitative analysis of the effects of the detection limit and of other observational biases would be highly desirable (although not trivial) in order to: (i) assess the completness and the exactness of the observed CDFs; (ii) retrieve the underlying distributions.

In conclusion, significant progress has been made in the past two decades but uncertainties on the exact multiplicity properties of massive stars remain numerous. In particular, an homogeneous exploration of the parameter space, the distribution function of the orbital parameters and the impact of the environment on the multiplicity properties are likely the areas in which observational progresses are the most crucially needed. Fortunately, numerous projects are currently underway which aim at improving our knowledge of these aspects. It is our hope to have drawn attention to the importance of a proper understanding of the detection limits and of the observational biases that affect each survey. These are necessary information to consider in order to glue all the pieces together toward a global view of the massive star properties across the full reach of parameter space and in different environements.

Acknowledgements

The authors warmly thank the organizers for their invitation and for their flexibility. The authors also wished to express their thanks to M. De Becker, A. de Koter, S. de Mink, M. Gieles, E. Gosset, P. Massey and S. Portegies Zwart for useful discussion in the preparation and redaction of this review.

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