Astronomy in Focus
XXXIInd IAU General Assembly, August 2024
Diana M. Worrall, ed.
doi:10.1017/S1743921324002369

Observational constraints on massive binaries

Tomer Shenar

Tel Aviv University, The School of Physics and Astronomy, Tel Aviv 6997801, Israel
email: tshenar@tau.ac.il

Abstract. Binary interactions are commonplace among massive stars, giving rise observed phenomena such as X-ray binaries, stripped stars & supernovae, and gravitational-wave sources. The multiplicity properties of massive stars thus represent a fundamental observable to calibrate, test, and benchmark models of single-star and binary evolution. In these proceedings, I provide a modern summary of the observed properties of massive binaries across various metallicities, and discuss open problems in the field.

Keywords. Massive stars, binaries

1. Introduction

Spectroscopic and interferometric studies of massive stars – stars initially more massive than $8\,M_\odot$ – have revealed beyond doubt that the majority of them evolve alongside nearby stellar companions (e.g., Abt 1983; Vanbeveren et al. 1998; Sana et al. 2012; Sana et al. 2013, 2014; Moe & Di Stefano 2017). With typical physical separations not exceeding a few au, the majority of massive stars will interact with their companion stars during their lifetime, typically during the rapid expansion phase that follows core hydrogen exhaustion (see, e.g., Marchant & Bodensteiner 2023, and references therein). These interactions lead to a plethora of observable counterparts that are unique products of binary interaction: post mass-transfer stipped stars and mass accretors (e.g., Paczyński 1967; Götberg et al. 2018; Shenar et al. 2020a; Bodensteiner et al. 2020a; Wang et al. 2020; Klement et al. 2022), single degenerate binaries and X-ray binaries (e.g., Corral-Santana et al. 2016; Shenar et al. 2022a; Mahy et al. 2022), magnetic stars (e.g. Ferrario et al. 2009; Schneider et al. 2018; Shenar et al. 2023) and gravitational-wave (GW) sources (e.g. de Mink & Mandel 2016; Mandel & Farmer 2022).

In these proceedings, I provide a brief outline of our current knowledge of the multiplicity statistics of massive stars across various key evolutionary phases and metallicity conditions. Extensive reviews of the subject can be readily found in recent literature (e.g., Marchant & Bodensteiner 2023; Moe & Di Stefano 2017; Offner et al. 2023).

2. Multiplicity statistics: pre-interaction

The pre-interaction phase is represented by populations of massive stars that are still on the main sequence, which typically appear spectroscopically as O and early B-type stars (B2 and earlier). Multi-epoch spectroscopic surveys of massive stars have thusfar been the most efficient way to study the multiplicity properties of OB binaries, which typically span the orbital period range $0 \lesssim \log P/[\mathrm{d}] \approx\lesssim 3$, for which spectroscopy is adequate. Spectroscopic surveys have systematically yielded high observed binary fractions of the order of 30-60% for O-type stars ($M \gtrsim 15\,M_\odot$), with some variance depending on the

© The Author(s), 2026. Published by Cambridge University Press on behalf of The International Astronomical Union. This is an Open Access article, distributed under the terms of the Creative Commons Attribution licence (https://creativecommons.org/licenses/by/4.0/), which permits unrestricted re-use, distribution and reproduction, provided the original article is properly cited.

https://doi.org/10.1017/S1743921324002369 Published online by Cambridge University Press

environment (e.g. Kobulnicky et al. 2014; Sana et al. 2012; Sana et al. 2013; Britavskiy et al. 2023), dropping to somewhat lower fractions of 20-50% for B-type stars (e.g. Abt et al. 1990; Banyard et al. 2022; Bodensteiner et al. 2021; Dunstall et al. 2015; Villaseñor et al. 2021). When correcting for biases, the intrinsic fractions however are found to be comparable and of the order of 50-70% for both populations.

The distributions of orbital periods P and mass ratios $q = M_2/M_1$ ($M_2 < M_1$) of pre-interaction binaries are typically assumed to follow a power-law distribution in the form $N \propto (\log P)^{\pi}\ q^{\kappa}$, where π and κ are the power-law indices of the period and mass-ratio distributions, respectively. Derived periods of OB-type binaries follow very closely a flat distribution on $\log P$ ($\pi = 0$), implying that the periods generally tend to be short. For example, after correcting for observational biases, Almeida et al. (2017) report an index of $\pi = -0.1$ for the power-law distribution in the form $(\log P)^{\pi}$. Similarly, the mass-ratio distribution is found to be very closely flat of q ($\kappa = 0$). For example, after correcting for biases, Shenar et al. (2022b) report $\kappa = 0.2 \pm 0.2$ for O-type stars in the LMC.

3. Dependence on metallicity

The dependence of multiplicity statistics on metallicity Z can inform models of star and binary formation, and help calibrate evolution models in different environments. Specifically, conditions of multiplicity statistics at sub-solar metallicity, present in galaxies such as the Large and Small Magellanic Clouds (LMC, SMC), are of pivotal importance for understanding electromagnetic and GW transients originating largely or elusively in low-metallicity environments (e.g. Woosley & Heger 2006; Quimby et al. 2011; Fryer et al. 2001; Modjaz et al. 2008; Mandel & Farmer 2022).

Data compiled in Offner et al. (2023) suggests that, for low-mass stars, a trend of increased binary fraction with decreasing metallicity exists. Assuming a linear model on $\log Z$ of the form $f_{\rm bin} = m\ \log Z + b$, the latter study suggests $m = -0.20 \pm 0.04$ for low-mass stars. For massive stars, obtaining such information is more challenging given the lack of high-quality data and statistics on the multiplicity of low-metallicity OB-type populations. One survey put forth to improve this situation is the Binarity at LOw Metallicity (BLOeM) survey, which will monitor ≈ 1000 massive stars in the SMC, at a metallicity content of $Z = 1/5\ Z_{\odot}$ (Shenar et al. 2024). By combining results from spectroscopic surveys of O-type stars in the Milky Way (Sana et al. 2012), LMC ($Z \approx 1/2 Z_{\odot}$, Sana et al. 2013), and early results from the BLOeM survey (Sana et al. submitted), no such trend is apparent for O-type stars. Formally, one finds $m = -0.07 \pm 0.15$ for the slope, which is consistent with being metallicity-independent. However, it is also consistent with the relation found by Offner et al. (2023) for low-mass stars, within 1σ. For B-type stars, combining results from Banyard et al. (2022), Dunstall et al. (2015), and early BLOeM results (Villaseñor et al. submitted to A&A), a regression yields $m = -0.32 \pm 0.14$, which is consistent with results published by Offner et al. (2023) for low-mass stars. This difference between O- and B-type stars may mark a different mode of binary formation for these mass ranges, although this cannot yet be claimed with high certainty given the current uncertainties on the binary fractions.

4. Multiplicity statistics: post-interaction

Unlike the pre-interaction phase, the post-interaction phase has a plethora of observable counterparts. In these proceedings, I addressed only a few important examples in this context.

Wolf-Rayet stars: After interaction, the mass donor typically loses substantial amounts of mass, exposing its helium-rich layers. At the upper-mass end, these stars tend to launch powerful radiatively-driven stellar winds and thus spectroscopically appear as Wolf-Ryaet

https://doi.org/10.1017/S1743921324002369 Published online by Cambridge University Press

(WR) stars. WR binaries thus offer an attractive laboratory to study the post-interaction phase at the upper-mass end, although they can also form as single stars via intrinsic wind stripping given the high mass of their progenitor stars (Meynet & Maeder 2005). Generally, the observed binary fraction of WR stars is found to be of the order of 40%, regardless of the environment (Foellmi et al. 2003; Schnurr et al. 2008; Neugent & Massey 2014; Shenar et al. 2020b; Dsilva et al. 2020, 2022, 2023; Schootemeijer et al. 2024). Correction for biases to obtain the intrinsic fractions is more challenging than for the pre-interaction case, since our knowledge of the period and mass-ratio distribution of WR binaries is heavily model-dependent (e.g., Langer et al. 2020). Regardless, there is growing evidence that roughly half of the WR stars do not have companions related to their formation. For example, Schootemeijer et al. (2024) conducted a modern high-resolution UVES/VLT spectroscopic monitoring of WR stars in the SMC, but did not reveal companions to any of the WR stars previously classified as single in the period range $P \lesssim 3$ yr and mass ratio range $0.1 \lesssim q \lesssim 1$. Similar results are reported by Massey et al. (2023) for a class of low-luminosity WR stars in the LMC. Additionally, Deshmukh et al. (2024) conducted an interferometric GRAVITY/VLTI survey of Galactic WR stars, finding similar results, but for wider separations and more extreme mass ratios. However, the formation of WR stars via wind stripping still poses a challenge for single-star models, and the question remains whether apparently-single WR stars are the products of binary evolution with the companions no longer present (e.g., mergers or disrupted systems).

Stripped stars: At lower masses, stars stripped off their outer layers retain a spectroscopic appearance similar to those of OB-type subdwarfs (sdBs, sdOs), since they lack the strong winds which give rise to the Wolf-Rayet phenomenon (Dionne & Robert 2006; Götberg et al. 2018; Shenar et al. 2020b; Sander & Vink 2020). Such objects are faint in the visual band and, lacking the strong emission lines charactaristic of WR stars, are much more difficult to spot, even though they should be more common than WR stars. Recently, the first sample of "intermediate mass stripped stars" was uncovered by Drout et al. (2023) and Götberg et al. (2023). Given the lower masses of their progenitor stars (initial masses $M_{\rm ini} \lesssim 20\,M_\odot$ in the Milky Way), it is likely that such objects form solely via binary stripping, and hence one may expect that the vast majority of them, if not all, will harbour binary companions. Analysis of follow-up spectroscopy of this sample is currently underway.

OBe stars: angular-momentum transfer during mass accretion is thought to efficiently spin up the mass accretors to near-critical rotation Packet (1981). A well-known class of rapidly-rotating stars are the OBe stars, which are OB-type stars with emission features associated with decretion disks. The last years have yielded overwhelming evidence that the majority, if not all, of OBe stars are the products of binary interaction. Virtually all OBe stars with confirmed companions are clear post-interaction systems, in which the companions are either compact objects or stripped stars of different types (e.g. Wang et al. 2018, 2020; Klement et al. 2022; Shenar et al. 2020a; Ramachandran et al. 2023). In contrast, no massive OBe star has a confirmed main sequence companion (Bodensteiner et al. 2020b). Taken together, this strongly points towards a binary origin of OBe stars. However, robust statistical information regarding the binary fraction and the nature of companions to OBe stars (e.g., fraction of black holes neutron stars, white dwarfs, and stripped stars) is still missing.

Single-degenerate binaries: after the first core-collapse, the binary system may be disrupted due to the combination of kicks and mass loss (e.g. Podsiadlowski et al. 2004). If the system survives this disruption, one may expect the formation of a single-degenerate binary comprising a massive OB star and a compact object (OB+co). Until recently, such objects were only known where the compact object would be close enough to accrete material from the donor OB star (e.g. Reig 2011; Corral-Santana et al. 2016). Such

https://doi.org/10.1017/S1743921324002369 Published online by Cambridge University Press

high-mass X-ray binaries (HMXBs) are relatively easy to find via X-ray surveys, but are physically rare compared to the general population of OB+co binaries. Only recently has the latter population of binaries, also referred as dormant single-degenerate binaries, started to be uncovered. Dormant single-denegerate binaries, especially in which the compact object is a black hole, offer a direct route to test and calibrate models involving supernova explosions and kicks (e.g. Vigna-Gómez et al. 2024). The Gaia mission should be able to uncovered tens, perhaps hundreds, of such systems in our Galaxy (Janssens et al. 2022, 2023), although highly stringent quality constraints on the binary solutions so far published by Gaia only allowed low-mass single-degenerate systems to be uncovered (El-Badry et al. 2023b,a; Shahaf et al. 2023; Gaia Collaboration et al. 2024). Spectroscopic monitoring of massive stars in the Milky Way and LMC revealed two systems with dormant black holes in them (Mahy et al. 2022; Shenar et al. 2022a). The combination of high-precision astrometry and continuous spectroscopic monitoring are expected to increase the sample size of dormant single degenerates by orders of magnitudes in the coming years.

References

Abt, H. A. 1983, ARA&A, 21, 343.
Abt, H. A., Gomez, A. E., & Levy, S. G. 1990, ApJS, 74, 551.
Almeida, L. A., Sana, H., Taylor, W., et al. 2017, A&A, 598, A84.
Banyard, G., Sana, H., Mahy, L., et al. 2022, A&A, 658, A69.
Bodensteiner, J., Sana, H., Wang, C., et al. 2021, A&A, 652, A70.
Bodensteiner, J., Shenar, T., Mahy, L., et al. 2020a, A&A, 641, A43.
Bodensteiner, J., Shenar, T., & Sana, H. 2020b, A&A, 641, A42.
Britavskiy, N., Simón-Díaz, S., Holgado, G., et al. 2023, A&A, 672, A22.
Corral-Santana, J. M., Casares, J., Muñoz-Darias, T., et al. 2016, A&A, 587, A61.
de Mink, S. E. & Mandel, I. 2016, MNRAS, 460, 3545.
Deshmukh, K., Sana, H., Mérand, A., et al. 2024, arXiv e-prints, arXiv:2409.15212.
Dionne, D. & Robert, C. 2006, ApJ, 641, 252.
Drout, M. R., Götberg, Y., Ludwig, B. A., et al. 2023, Science, 382, 1287.
Dsilva, K., Shenar, T., Sana, H., & Marchant, P. 2020, A&A, 641, A26.
Dsilva, K., Shenar, T., Sana, H., & Marchant, P. 2022, A&A, 664, A93.
Dsilva, K., Shenar, T., Sana, H., & Marchant, P. 2023, A&A, 674, A88.
Dunstall, P. R., Dufton, P. L., Sana, H., et al. 2015, A&A, 580, A93.
El-Badry, K., Rix, H.-W., Cendes, Y., et al. 2023a, MNRAS, 521, 4323.
El-Badry, K., Rix, H.-W., Quataert, E., et al. 2023b, MNRAS, 518, 1057.
Ferrario, L., Pringle, J. E., Tout, C. A., & Wickramasinghe, D. T. 2009, MNRAS, 400, L71.
Foellmi, C., Moffat, A. F. J., & Guerrero, M. A. 2003, MNRAS, 338, 360.
Fryer, C. L., Woosley, S. E., & Heger, A. 2001, ApJ, 550, 372.
Gaia Collaboration, Panuzzo, P., Mazeh, T., et al. 2024, A&A, 686, L2.
Götberg, Y., de Mink, S. E., Groh, J. H., et al. 2018, A&A, 615, A78.
Götberg, Y., Drout, M. R., Ji, A. P., et al. 2023, ApJ, 959, 125.
Janssens, S., Shenar, T., Sana, H., et al. 2022, A&A, 658, A129.
Janssens, S., Shenar, T., Sana, H., & Marchant, P. 2023, A&A, 670, A79.
Klement, R., Schaefer, G. H., Gies, D. R., et al. 2022, ApJ, 926, 213.
Kobulnicky, H. A., Kiminki, D. C., Lundquist, M. J., et al. 2014, ApJS, 213, 34.
Langer, N., Baade, D., Bodensteiner, J., et al. 2020, A&A, 633, A40.
Mahy, L., Sana, H., Shenar, T., et al. 2022, A&A, 664, A159.
Mandel, I. & Farmer, A. 2022, Phys. Rep., 955, 1.
Marchant, P. & Bodensteiner, J. 2023, arXiv e-prints, arXiv:2311.01865.
Massey, P., Neugent, K. F., & Morrell, N. I. 2023, ApJ, 947, 77.
Meynet, G. & Maeder, A. 2005, A&A, 429, 581.
Modjaz, M., Kewley, L., Kirshner, R. P., et al. 2008, AJ, 135, 1136.

https://doi.org/10.1017/S1743921324002369 Published online by Cambridge University Press

Moe, M. & Di Stefano, R. 2017, ApJS, 230, 15.
Neugent, K. F. & Massey, P. 2014, ApJ, 789, 10.
Offner, S. S. R., Moe, M., Kratter, K. M., et al. 2023, in Astronomical Society of the Pacific Conference Series, Vol. 534, Protostars and Planets VII, ed. S. Inutsuka, Y. Aikawa, T. Muto, K. Tomida, & M. Tamura, 275.
Packet, W. 1981, A&A, 102, 17.
Paczyński, B. 1967, Acta Astron., 17, 355.
Podsiadlowski, P., Langer, N., Poelarends, A. J. T., et al. 2004, ApJ, 612, 1044.
Quimby, R. M., Kulkarni, S. R., Kasliwal, M. M., et al. 2011, Nature, 474, 487.
Ramachandran, V., Klencki, J., Sander, A. A. C., et al. 2023, A&A, 674, L12.
Reig, P. 2011, Ap&SS, 332, 1.
Sana, H., de Mink, S. E., de Koter, A., et al. 2012, Science, 337, 444.
Sana, H., Le Bouquin, J. B., Lacour, S., et al. 2014, ApJS, 215, 15.
Sana, H., van Boeckel, T., Tramper, F., et al. 2013, MNRAS, 432, L26.
Sander, A. A. C. & Vink, J. S. 2020, MNRAS, 499, 873.
Schneider, F. R. N., Ramírez-Agudelo, O. H., Tramper, F., et al. 2018, A&A, 618, A73.
Schnurr, O., Casoli, J., Chené, A. N., Moffat, A. F. J., & St-Louis, N. 2008, MNRAS, 389, L38.
Schootemeijer, A., Shenar, T., Langer, N., et al. 2024, arXiv e-prints, arXiv:2406.01420.
Shahaf, S., Bashi, D., Mazeh, T., et al. 2023, MNRAS, 518, 2991.
Shenar, T., Bodensteiner, J., Abdul-Masih, M., et al. 2020a, A&A, 639, L6.
Shenar, T., Bodensteiner, J., Sana, H., et al. 2024, arXiv e-prints, arXiv:2407.14593.
Shenar, T., Gilkis, A., Vink, J. S., Sana, H., & Sander, A. A. C. 2020b, A&A, 634, A79.
Shenar, T., Sana, H., Mahy, L., et al. 2022a, Nature Astronomy, 6, 1085.
Shenar, T., Sana, H., Mahy, L., et al. 2022b, A&A, 665, A148.
Shenar, T., Wade, G. A., Marchant, P., et al. 2023, Science, 381, 761.
Vanbeveren, D., De Loore, C., & Van Rensbergen, W. 1998, A&A Rev., 9, 63.
Vigna-Gómez, A., Willcox, R., Tamborra, I., et al. 2024, Phys. Rev. Lett., 132, 191403.
Villaseñor, J. I., Taylor, W. D., Evans, C. J., et al. 2021, MNRAS, 507, 5348.
Wang, C., Langer, N., Schootemeijer, A., et al. 2020, ApJ, 888, L12.
Wang, L., Gies, D. R., & Peters, G. J. 2018, ApJ, 853, 156.
Woosley, S. E. & Heger, A. 2006, ApJ, 637, 914.

https://doi.org/10.1017/S1743921324002369 Published online by Cambridge University Press