1

The Zoo of Binary Stars

HENRI M. J. BOFFIN

1.1 Binaries Are Ubiquitous

Living on planet Earth in the Solar System, we are clearly in a very special place as, contrary to the majority of solarlike stars, the Sun has no stellar companion. This may be a good thing for us, but provides a severe bias in our understanding of binary stars in stellar evolution. Indeed, when looking away from the Sun, we can see that there are binaries everywhere!

Sirius, the brightest star in the night sky, is a binary, with a massive white dwarf companion in a 50-year orbit (Barstow et al., 2005). It was discovered, using astrometry, by Bessel (1844). Also, the closest star to our Sun, α Centauri, is a binary system (or even a triple, if Proxima Centauri is physically bound to α Cen AB). Distant 1.35 pc from the Sun, α Cen consists in a binary system with a 1.13 $M_{\odot}$ star orbiting a cooler 0.97 $M_{\odot}$ companion with a period of 79.91 years (Pourbaix and Boffin, 2016). As interesting, the closest brown dwarf to the Sun, Luhman 16AB, is also a binary system, composed of two brown dwarfs (Boffin et al., 2014b; Bedin et al., 2017) with a separation of about 3 au. A set of binary stars is also present around the visual pair Alcor and Mizar in the constellation of Ursa Major. If these two stars may not be physically linked, their aspect as visual binaries have had a profound cultural impact in Hindu and Japanese mythologies, and were also used as an eye test. However, more important for us, is that both Alcor and Mizar contain binaries. Alcor is thus a resolved binary, containing an A star with a low-mass companion, separated by 28 au (Mamajek et al., 2010), while Mizar is in fact a quadruple system: Mizar AB is a visual binary with a separation on sky of 14.4″, in which each component is itself a binary. Mizar A was apparently the first spectroscopic binary to be discovered, but was also resolved thanks to interferometry (Hummel et al., 1998), and contains two almost equal mass 2.4–2.5 $M_{\odot}$ stars with an orbital period of 20.5 days. Mizar B contains two stars in a 175.55-d orbit. Further out, and among younger stars, the Orion Trapezium stars also reveal a wealth of binaries and multiples. Two of the four Trapezium stars appear indeed binaries, while a third is a triple or even quadruple system. Thus the Trapezium is in fact composed of nine stars! Another famous binary star is Algol, the daemon. Now the prototype of a distinct type of variable stars, Algol, or β Persei, was found to be a variable star in 1667 by Geminiano Montanari. This eclipsing binary with a 2.86-d period is composed of a B8 V primary and a K2 IV secondary. Thus, the system presents the so-called Algol paradox as the most evolved of the two stars – the subgiant – is also the less massive of the two. Stellar evolution would have it the other way around, as a star evolves faster the more massive it is. The solution to this apparent paradox is mass transfer: the subgiant must have been the most massive of the two initially but then transferred most of its mass to its companion and the mass ratio was reversed.

A further dramatic example of a binary system is provided by η Carinae, which in the 1840s was the second brightest star in the night sky, and is still thought to be one of the most luminous stars in our Galaxy and perhaps also the next supernova that will explode in the Milky Way. The star itself is an extreme example of a Luminous Blue Variable (LBV) with an estimated mass of 120 $M_\odot$. The bright star, hidden in a thick nebula known as the Homunculus, belongs apparently to a binary system with a 30 $M_\odot$ companion in a 5.5-year orbit (Madura et al., 2012). At the other extreme, we have the close binary SDSS J010657.39-100003.3, which is a detached binary containing two white dwarfs (WDs) in a 39-minute orbit (Kilic et al., 2011) – due to gravitational wave radiation, it is thought that this system will merge within the next 37 Myr to become a subdwarf star. But if this wasn't extreme enough, there is also HM Cancri, which is another double system of white dwarfs, but interacting this time and with an orbital period of 5 minutes (Roelofs et al., 2010) and most likely the shortest period binary star known!

1.2 The Fraction of Binaries

The previous section showed how binaries are everywhere and come in a wide variety. However, are most stars indeed in binaries? Many works have been devoted to the study of the multiplicity of stars (e.g., Raghavan et al., 2010; Duchêne and Kraus, 2013; De Rosa et al., 2014), and they all reveal that the multiplicity of stars is a function of the mass of the primary[1] – the more massive stars being more often in binaries and multiple systems. The multiplicity of the most massive stars is well above 90%, while Raghavan et al. (2010) found that Sun-like stars have an overall observed fractions of single, double, triple and higher-order systems of 56%, 33%, 8% and 3%, respectively – thus, finding that, apparently, the majority of solartype stars are single. More recently, however, Fuhrmann et al. (2017) presented a multiplicity census for a volume-complete all-sky survey of 422 stars with distances less than 25 pc and found for the F- and G-type Population I stars that 58% are in binary or multiple systems, thus proving that the majority of solarlike stars are nonsingle. These authors also found a dependence on the mass of the primary. Moreover, these analyses also miss the important point that less massive stars will also be companions to more massive primaries. Boffin and Pourbaix (2018) found for example that also the

[1] The primary of a binary system is often defined as the more luminous component, with the companion being called the secondary. As the system evolves, a component that was initially the primary may become the secondary. Note that sometimes, primary is associated with the mass of the star – however, as there may be mass exchange in a binary system, this is not the best definition to use, as due to mass transfer, the less massive star may still be the more evolved, and thus the more luminous – e.g., in Algol.

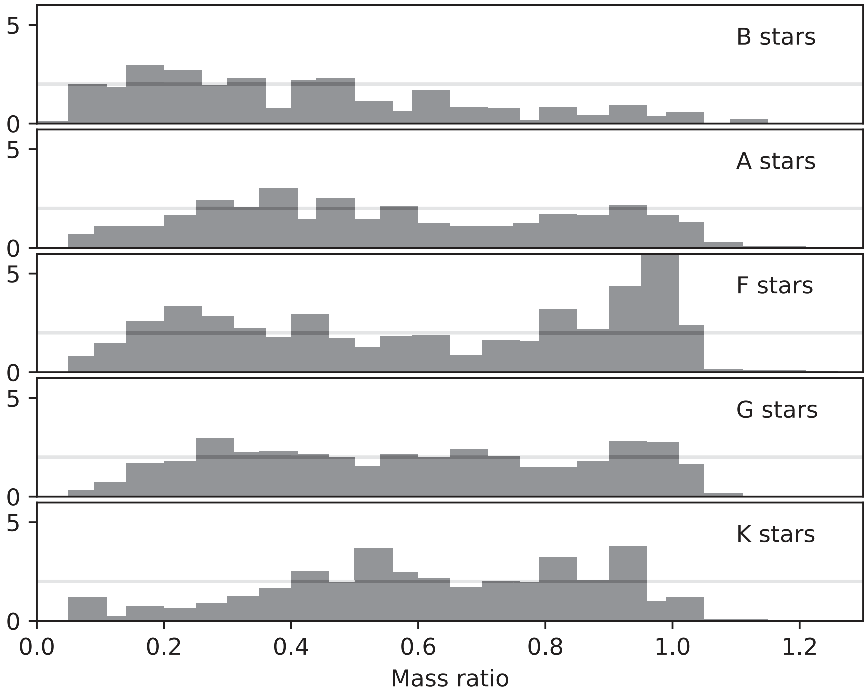

Figure 1.1 Mass-ratio distributions for the stars in the SB9 catalogue as a function of the spectral type of the primary. Adapted from Boffin and Pourbaix (2018).

mass ratio distribution (see Figure 1.1) depends on the primary mass: B stars will have more companions with smaller mass ratios than solarlike stars, and F stars seem to show an excess of twin systems, although overall, all stars seem to have a rather uniform mass-ratio distribution over a wide range of mass ratios. This means that there are many low-mass stars hidden in these binary systems and when accounted for, the multiplicity of G, K and M stars is increased, so that a majority of stars are in binary systems (see also Whitworth and Lomax, 2015).

The fraction of binaries is not the only important factor – one needs also to look at the distribution of separations or, alternatively, the distribution of orbital periods. Duchêne and Kraus (2013) show that this is also extremely dependent on the primary spectral type. Solarlike stars show a broad distribution centred around 30–50 au, while M stars are more centred around a few au, and OB stars are mostly seen in spectroscopic binaries with small separations and orbital periods below 100–1,000 days. This has also dramatic consequences on the fraction of stars that will interact during their life. This is particularly true for massive stars, as Sana et al. (2012) found that "more than 70% of all massive stars will exchange mass with a companion, leading to a binary merger in one-third of the cases," clearly

Cambridge University Press
978-1-108-42858-3 — The Impact of Binary Stars on Stellar Evolution
Edited by Giacomo Beccari , Henri M. J. Boffin
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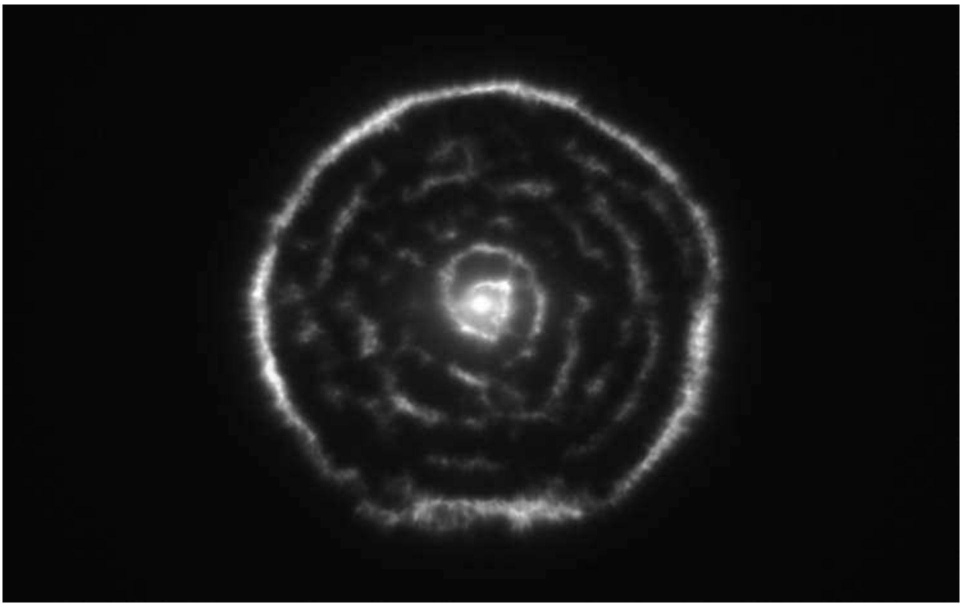

Figure 1.2 Observations using the Atacama Large Millimeter/submillimeter Array (ALMA) have revealed a spiral structure in the material around the AGB star R Sculptoris, probably caused by a hidden companion star. Credit: ALMA (ESO/NAOJ/NRAO)/M. Maercker et al. See Maercker et al. (2012).

indicating that binary interactions dominate the evolution of massive stars. For solarlike stars, the interaction will most likely happen when the star is evolving on the red giant and asymptotic giant branch (AGB), leading to many examples of interesting systems. It is not clear, however, what is the limit in orbital period for the interaction to be significant, as examples exist of systems with orbital periods as large as 350 years to show signs of interaction (see Figure 1.2; Maercker et al., 2012).

1.3 Interacting Binaries

Having seen that many stars will interact one way or another during their lives, when being part of a binary, one can now look at the kinds of interactions to expect. These come in four flavours:

- Tidal interaction
- Wind accretion
- Roche-lobe overflow
- Common-envelope evolution (CE)

Depending on the kind of interaction, as well as on the nature of the components of the binary system, the outcome will be a different type of outcome, many of which are discussed in this book. Here, we will quickly provide an overview of examples of mass transfer in binaries.

1.3.1 Wind Accretion

When the system is detached, i.e., none of the components are filling their Roche lobe, mass transfer can still happen though stellar wind. Massive stars as well as more evolved low- and intermediate-mass stars possess strong winds that have two effects: (i) they allow mass transfer between the two stars, and possibly, chemical pollution; and (ii) they induce angular momentum loss and thus a variation of the orbital elements. As shown by Theuns et al. (1996) and Nagae et al. (2004), the structure of the flow (see Figure 1.3) – and the resulting mass accretion rate – is extremely dependent on the ratio between the wind velocity and the orbital velocity, moving from an asymmetric Bondi–Hoyle kind of flow (as seen in, e.g., ζ Aur stars or massive OB stars) to a much complicated flow, where the wind is filling the Roche lobe of the primary, hence is now given the name wind Roche-lobe overflow. The latter is particularly relevant in systems where an AGB star transfers mass to a companion, as in this case, the wind velocity (5–10 km/s) is smaller or of the order of the orbital velocity (Theuns et al., 1996; Morris et al., 2006; Maercker et al., 2012). The angular momentum loss – and the subsequent evolution of the orbital elements – is also very dependent on the wind velocity and thus the respective effects of the orbital motion as shown by Hachisu et al. (1999) and Jahanara et al. (2005). Unfortunately, these effects have until now been ignored in binary evolution models, although it seems that this is starting to change (Saladino et al., 2018), which is most welcome given the current inability to provide a satisfactory answer to the origin of many systems that must have undergone such mass transfer. Indeed, the increased angular momentum loss that is seen in these simulations would imply that the orbit will shrink, instead of increase as

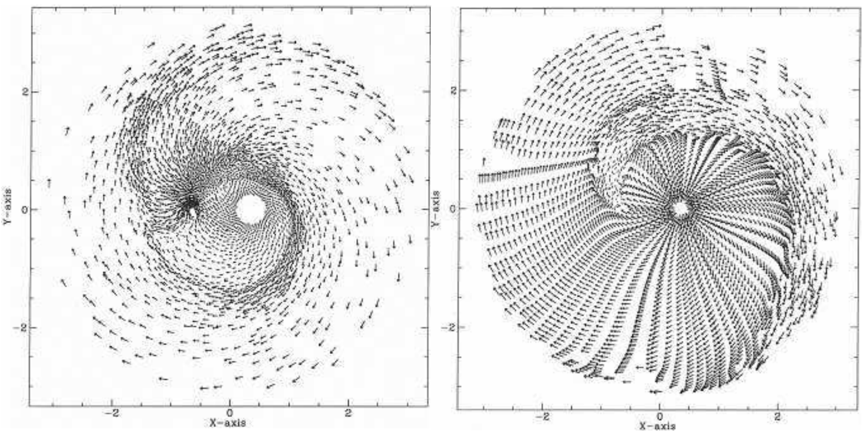

Figure 1.3 SPH simulation of mass transfer by wind in the case of an AGB star in a 3 au orbit with a companion, for two different values of the wind speed (Boffin, 1993, priv. comm.).

generally assumed, thereby providing a natural explanation for a whole class of post–mass transfer systems, including blue straggler stars, Barium stars, symbiotic stars, and post-AGB binaries. Barium stars (McClure and Woodsworth, 1990; Van der Swaelmen et al., 2017; Escorza et al., 2017) are chemically polluted (in carbon and s-process elements) stars, members of a binary system with a white dwarf companion. The material has been transferred to the barium star when the former primary, now a white dwarf, was an AGB star. Their orbital elements, similar to those seen for blue straggler stars in open clusters, for example (Geller et al., 2009), and especially their orbital periods and nonzero eccentricities, have until now resisted any tentative of explanations and therefore remain one of the most important problems in binary stellar evolution. In symbiotic stars, mass is also transferred between a red (or sometimes a yellow) giant and a hot companion that may be a WD or a main sequence star. Using interferometry, Boffin et al. (2014a) and Boffin et al. (2014c) showed that red giants in symbiotic systems are rather normal and the fact that they have larger mass-loss rates than single giants must be linked in some way to their binary nature, adding credence to the companion-reinforced attrition process mechanism (Tout and Eggleton, 1988) – a mechanism that is also not getting the attention it deserves in binary evolution models. A more detailed description of the wind mass transfer can be found in Boffin (2015).

1.3.2 Roche-Lobe Overflow

A star will fill its Roche lobe and transfer mass to its companion, if its radius is larger than the Roche-lobe radius, which in most cases can be approximated (Paczyński, 1971) by

$$R_L = a(0.38 + 0.2 \log q), \tag{1.1}$$

where a is the semimajor axis and q is the mass ratio. Thus, the ability to fill the Roche lobe will depend mostly on the separation (or equivalently, the orbital period) and the evolutionary stage of the star. For a solarlike star on the main sequence, the separation will have to be of the order of a few solar radii and the orbital period of a few hours. This is, for example, the case of cataclysmic variables. When the star evolves and moves on to the red giant branch, systems with orbital periods between a few days (e.g., Algol) and a few years (i.e., symbiotic stars) are concerned. This range of possibilities of when the Roche-lobe overflow (RLOF) will occur is at the origin of a whole zoo of binary systems. When the star fills its Roche lobe, matter is transferred to its companion and because this matter has some angular momentum, a disc may form around the accretor – for short period systems, this will be the case when the accretion is a WD (cataclysmic variable), a neutron star (low-mass X-ray binaries) or a black hole (high-mass X-ray binary), while if the system is wide, this may happen when the accretion is a main sequence star, for example in symbiotic stars. On the other hand, for binary systems with short orbital periods, when the accretion happens onto a main sequence star, no disc can form, and there will be direct impact onto the star (as in Algols).

1.3.3 Common Envelope Evolution

In some cases, the RLOF will be dynamically unstable, leading to the formation of a common envelope (CE) around the two components of the binary system (Paczyński, 1976). This will happen when the mass-losing star is a red giant with a deep convective envelope. In this case, the mass transfer leads to a runaway process where the star expands when losing mass, thereby continuously overfilling its Roche lobe. The mass transfer happens on a dynamical timescale, and the companion is unable to process this and will expand as well, until a common envelope forms. Once inside the envelope, dynamical friction will make the two cores spiral towards each others, while the envelope will eventually be ejected. This scenario would explain the formation of very close binary systems containing a WD with orbital periods below 1d – such as cataclysmic variables. and progenitors of Type Ia supernovae. It could also explain mergers and red transients (Ivanova et al., 2013b). Yet, despite its importance, the CE is still one of the least understood phases in the evolution of compact binaries (Ivanova et al., 2013a), although here also progress is being made in simulating it (e.g., Iaconi et al., 2018).

The CE phase also seems to play a very important role in the formation and evolution of planetary nebulae (PNe; Jones and Boffin, 2017). Indeed, it is now known that 80% of all PNe are nonspherical and many present jetlike structures. Moreover, there is now overwhelming evidence for a large fraction of post-CE systems lying at the heart of PNe[2]. Compelling evidence has been found for a clear correlation between the morphology of the nebula and the presence of a binary, as well as between chemical abundances in the nebula or the central stars and the binarity. It is therefore likely that PNe are for a large part the outcome of binary interactions. This clearly indicates that textbooks need to be rewritten (see Figure 1.4)!

1.4 Massive Star Interactions and Exploding Events

As shown earlier, the large fraction of OB stars that reside in relatively short period binary systems leads to the staggering fact that 70% of them will interact one way or another during the course of their lives. This leads to a variety of phenomena, many of which are further described in this book. Chief among them is perhaps the existence of Luminous Blue variable stars (LBVs). These are among the most luminous stars in the Milky Way and as described at the beginning of this chapter, the most extreme case, η Car, was quite a sight in the nineteenth century. It is now more and more thought that binaries have to be at the origin of this class of star (Smith and Tombleson, 2015; Smith et al., 2018). The discovery, based on interferometry, that another of these stars, HR Car, is also a binary, with an orbital period of about five to six years (Boffin et al., 2016) lends further credit to the binary hypothesis, which is further discussed in Chapter 11.

[2] An up-to-date list is available at http://drdjones.net/?q=bCSPN.

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978-1-108-42858-3 — The Impact of Binary Stars on Stellar Evolution
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Figure 1.4 With so many examples of the importance of binarity in the evolution of stars, it is clear that textbooks need to be rewritten! Photo: H. M. J. Boffin.

The mass transfer in these binaries will most likely lead to the formation of different kinds of supernovae as expected from single star evolution. Similarly, it is now well established that short gamma-ray bursts are due to the merging of neutron stars in binary systems. But evidence is now mounting that even long gamma-ray bursts may have a binary origin. As another class of exploding events, it is also well established that the origin of Type Ia supernovae are due to binary interactions, although the real channel – if there is only one – is still unknown: is it the accretion of mass onto a WD, is it a merger of two WDs or is it even some other mechanism? All these are discussed further in this book.

Without any doubt, one of the most extraordinary observations of recent years is the discovery of gravitational waves coming from the merging of two black holes or two neutron stars. These, again, are the outcome of binary interactions, and as always, the recent observations have shed new light on the possible mechanisms at play. A chapter is also devoted to this in this book.

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