

Massive Binary Mergers: A Unique Scenario for the sgB[e] Phenomenon?

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Abstract. At least 10 % of all massive stars are expected to merge with a binary companion during their evolution, producing an initially rapidly rotating merged object. These merger products are excellent candidates for B[e] supergiants. In this review we summarize the different types of mergers and show that the merger rate is compatible with the B[e] supergiant formation rate. We then apply the merger paradigm to various observed systems that have been suspected or proposed to be merged systems: the progenitor of SN 1987A, Sheridan 25, the B[e] supergiant R 4 and η Carinae.

1. Introduction

Binary mergers are one of the least studied phases of binary evolution. They occur as a consequence of common-envelope (CE) evolution where the CE cannot be ejected (see, e.g., Iben & Livio 1993; Podsiadlowski 2001). Despite their lack of attention, binary mergers are by no means rare events: estimates based on binary population synthesis studies (see, e.g., Podsiadlowski, Joss, & Hsu 1992; Han, Podsiadlowski, & Eggleton 1995) suggest that $\sim 10\%$ of *all stars* experience a complete merger with a companion star during their evolution.

The product of a merger event is an initially rapidly rotating single star, and at least some of these can be expected to appear as B[e] supergiants (sgB[e] stars). Indeed, considering the rapid rotation inferred for sgB[e] stars (Zickgraf 2006), which appears inconsistent with the evolution of single stars, this may be their main production channel. In this review, we first summarize the conditions for binary mergers and their different types, and then discuss various B[e] supergiants and related objects, such as the progenitor of SN 1987A, Sheridan 25, R 4 and η Carinae.

2. Common-Envelope Evolution and Binary Mergers

Common-envelope evolution involves the spiral-in of a companion star inside the envelope of the primary, often a (super)-giant, in a binary systems. It generally occurs when the mass-transfer rate in an interacting binary is larger than the rate at which the companion can accrete matter without filling its own Roche lobe. During the spiral-in phase, a fraction of the energy that is released by the

orbital decay is deposited in the envelope. If this energy is sufficient to eject the envelope, the system becomes a much closer binary consisting of the core of the primary and the companion (Paczynski 1976). If the energy is not sufficient, the two components merge completely to produce a single, rapidly rotating star.

In general, two types of mergers can be distinguished, depending on the merger timescale. The latter is determined mainly by the structure of the envelope of the primary, in particular its density profile, in the common-envelope phase since this determines the friction timescale and hence the spiral-in timescale during the spiral-in phase. This immediately implies that the merger types depend on whether the envelope is initially convective or radiative.

In the case of *radiative envelopes*, very little mass is contained in the outer low-density envelope (typically less than 1 % of the total mass in the outer 50 % or the radius of the star), but there is a fairly steep density gradient (see Fig. 2 of Podsiadlowski 2001). This implies that the frictional luminosity, which is proportional to the density, is initially very low, and that there is a long initial “contact” phase without significant spiral-in. This phase may last 100s to 1000s of years. Even a moderate shrinking of the orbit may release enough orbital energy to eject most of the mass surrounding the binary in a frictionally driven wind. If the mass ratio is sufficiently close to 1, this CE phase is likely to be temporary, and the system may survive as a semi-detached binary. However, once the immersed companion reaches the high-density layers of the envelope, the spiral-in accelerates and tends to run away, ultimately occurring on a dynamical timescale (because of the steep density gradient, envelope expansion can never lead to a self-regulated spiral-in as in the case of convective envelopes).

In contrast, in a *convective envelope* most of the mass of the envelope is contained in the outer parts of the envelope. Hence a convective envelope tends to have a much higher density in the outer parts, but a much shallower density gradient (see Fig. 2 of Podsiadlowski 2001). This implies that the initial spiral-in (after the loss of co-rotation) is much faster (because of the higher density), but once the envelope has expanded sufficiently the spiral-in can become self-regulated, where the frictional luminosity is low enough to be completely radiated away at the surface rather than drive further expansion of the envelope (Meyer & Meyer-Hofmeister 1979). The typical timescale for the spiral-in and merging phase in this case is 100s of years, and we refer to such mergers as *slow mergers* rather than *dynamical mergers*. A third type of merger can occur in dense clusters, where stars can collide directly to merge in *collisional mergers*, a case which may be important in dense clusters of young stars, but which we will not discuss further in this contribution.

3. Early Case B Mass Transfer and Dynamical Mergers

When a massive star starts to transfer mass to a companion while evolving across the Hertzsprung gap (so-called early case B mass transfer), mass transfer tends to be stable against dynamical mass transfer even for fairly large mass ratios ($q \simeq 3 - 4$). However, the evolution occurs on the thermal timescale of the massive donor, which leads to very high mass-transfer rates. Since the secondary may not be able to accrete all of the transferred mass, it may itself fill its Roche lobe, leading to a contact configuration. Detailed binary calculations

(Pols 1994; Wellstein, Langer, & Braun 2001) show that a contact phase can only be avoided if the mass ratio is close to 1 (typically $M_2/M_1 > 0.8$, where M_1 is the mass donor and M_2 the accreting component). Moreover, in cases where the two components merge completely, the subsequent evolution of the merger product will be dramatically altered; the star will spend most of its remaining evolution, in particular most of its helium core-burning phase, as a blue supergiant and never evolve to the red-supergiant region (Podsiadlowski & Joss 1989; Braun & Langer 1995), i.e. spend most of its evolution exactly in the part of the Hertzsprung-Russell diagram where B[e] supergiants lie. Moreover, at least initially these stars will be rapidly rotating. Since early case B mass transfer is one of the most common types of mass transfer, occurring over a wide range of initial orbital periods ($\sim 3\text{ d} - 3\text{ yr}$), some 20 % of all massive stars should experience this evolution. One can obtain a rough estimate of the number of potential B[e] supergiants by multiplying the birthrate of massive stars by the fraction of massive stars that merge and the lifetime of the post-main-sequence lifetime: e.g. for the LMC, setting the birthrate equal to the core-collapse supernova rate ($\sim 0.25 \times 10^{-2}\text{ yr}$; van den Bergh & Tammann 1991), taking a binary merger fraction of 10 % and a post-main-sequence lifetime of 10^6 yr , one obtains an estimate of 250 post-merger B supergiants. The number of these objects that appear as observable B[e] supergiants depends on how quickly the merger products spin down, which is the major uncertainty in this estimate. If this timescale is as short as 10^5 yr , one can still expect as many as 25 B[e] supergiants in the LMC (also see Zickgraf 2006).

4. Slow Mergers

Figure 1 shows the results of a typical slow spiral-in for a $15 M_\odot$ red supergiant merging with a $5 M_\odot$ companion (Ivanova & Podsiadlowski 2003). After the envelope has lost co-rotation with the envelope (after about 200 yr), there is a rapid initial spiral-in phase where all the orbital energy that is released by the orbital shrinkage is deposited in the envelope. Once the total orbital energy deposited in the envelope becomes comparable to the binding energy of the envelope, the envelope expands significantly. This causes a reduction of the envelope density and the frictional luminosity until a point is reached where all the frictional energy released by the orbital shrinkage can be transported by convection to the surface where it is radiated away. From this point on, the envelope no longer expands significantly and the spiral-in becomes self-regulated (Meyer & Meyer-Hofmeister 1979). Note that, even in this case, there is more than enough energy released by the orbital shrinkage in the subsequent slow spiral-in phase to eject the envelope, at least in principle. For compact companions, this self-regulation mechanisms always has to break down at some point, when the companion penetrates into the radiative region below the convective envelope which has a very steep density gradient, and this can lead to a *delayed dynamical ejection* of the common envelope.

In the case of a non-compact companion, the spiral-in phase ends when the embedded secondary fills its Roche lobe inside the supergiant envelope (at a typical separation of $10 R_\odot$ in the case shown in Fig. 1). At this point, the secondary starts to transfer mass to the core of the primary similar to normal

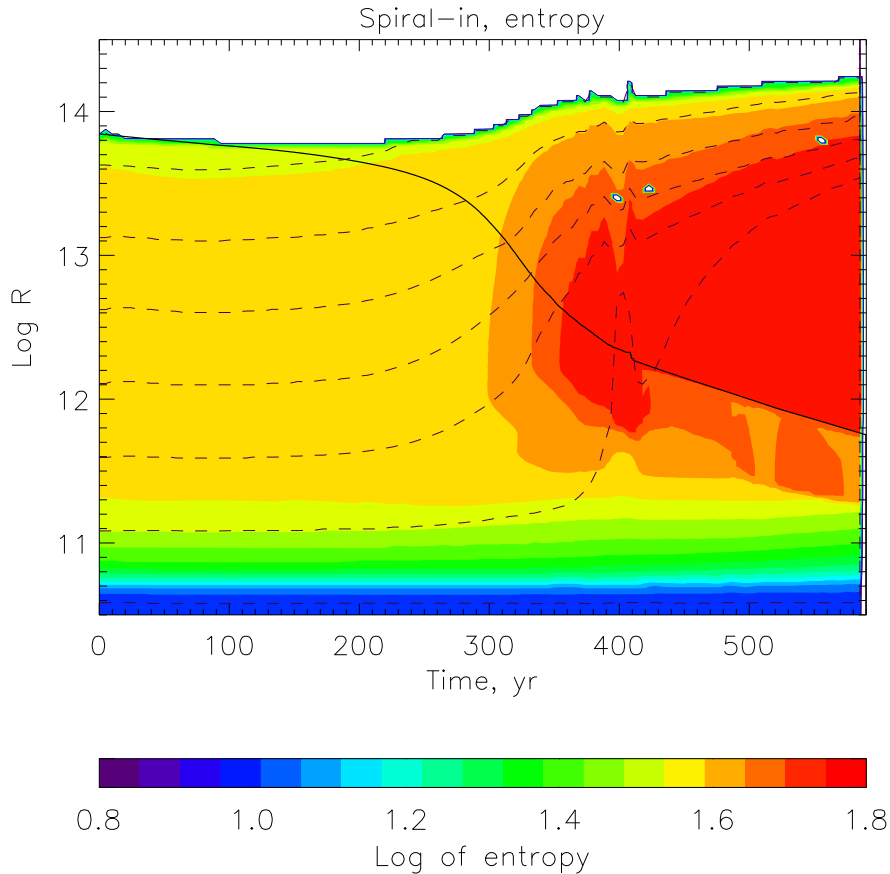


Figure 1. Spiral-in simulation for a $5 M_{\odot}$ star spiraling in inside the envelope of a $15 M_{\odot}$ red supergiant. The solid curve indicates the location of the companion star as a function of time since the beginning of the spiral-in.

Roche-lobe mass transfer, except that it occurs in an opaque, low-density envelope and that the mass transfer continues to be driven by the friction with the envelope on a characteristic timescale of ~ 100 yr.

The mass transfer phase ends when the flat-entropy core of the companion is exposed, which ultimately is expected to lead to its dynamical disruption and presumably the formation of a disk-like structure around the primary's core. The end product is a rapidly rotating single star, which because of the added mass in the envelope is likely to evolve to the blue-supergiant region and will spend most of its remaining evolution as a blue supergiant (Podsiadlowski, Joss, & Rappaport 1990), just as in the case of a dynamical merger, and will appear, at least initially, as a B[e] supergiant. This is the evolution that most likely explains the unusual properties of the progenitor of SN 1987A (Podsiadlowski & Ivanova 2003). Binary population synthesis simulations (Podsiadlowski, Joss, & Hsu 1992) suggest that this channel is much less important than the dynamical merger channel.

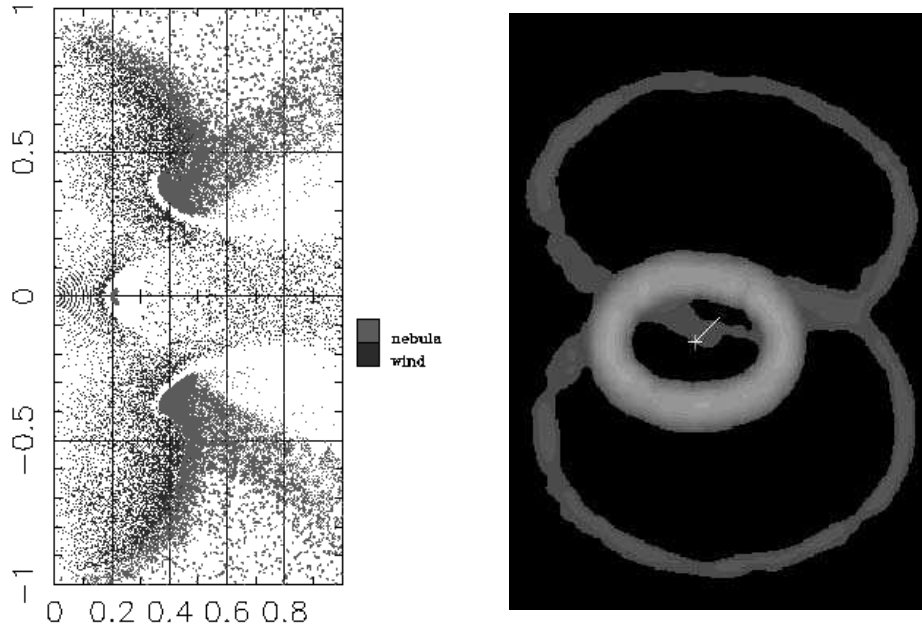


Figure 2. SPH simulations of the triple-ring nebula around SN 1987A in a merger scenario (Morris & Podsiadlowski 2006a,b). *Left*: Meridional projection of the final SPH particle distribution in the nebula at the time of the explosion. *Right*: Simulated emission model for the triple-ring nebula.

5. Applications

5.1. The Formation of the Triple-Ring Nebula around SN 1987A

Probably one of the most interesting cases of a binary merger is the progenitor of SN 1987A which is the most likely explanation for the unusual properties of this supernova (Podsiadlowski & Ivanova 2003). However, once two components in a binary have merged, apart from rapid rotation, there is little direct evidence that the newly formed object was once a binary system. Arguably the best evidence for the former binary nature of the progenitor of SN 1987A stems from the spectacular triple-ring nebula surrounding the supernova, first discovered with the NTT (Wampler et al. 1990) and best imaged with the HST (Burrows et al. 1995). All of the material in the ring nebula was ejected from the progenitor system some $\sim 20,000$ yr before the explosion and provides a unique fingerprint of the dramatic events that occurred at that time. Its almost axi-symmetric, but very non-spherical structure suggests rotation as an important physical ingredient, but elementary angular-momentum considerations imply that any single massive star that rotated rapidly on the main sequence could not possibly be rotating sufficiently rapidly as a red supergiant to produce the observed asymmetries. A source of angular momentum is required, most likely in the form of orbital angular momentum that was converted into spin angular momentum during a merger event some $\sim 20,000$ yr before the explosion.

The inner ring is very easy to understand in this picture. Since the merger product, initially a rapidly rotating red supergiant, has to shrink by a factor of

several 10s to attain its new equilibrium structure as a blue supergiant (Podsiadlowski et al. 1990), but has too much angular momentum (essentially most of the orbital angular momentum of the pre-merger binary) for a blue supergiant, it has to lose the excess angular momentum in the process, most likely by equatorial mass shedding at the beginning of the red-blue transition (see Heger & Langer 1998).

The two outer rings, almost parallel to the central ring plane but displaced above and below it, are most likely associated with matter lost from the common envelope at mid-latitudes during the initial rapid spiral-in phase which is subsequently swept up by the energetic wind in the final blue-supergiant phase.

To understand the origin of the triple-ring nebula, Morris & Podsiadlowski (2006a,b) have performed SPH simulations with the Gadget code (Springel, Yoshida, & White 2001). By injecting the energy that is released by the spiraling-in binary into a rotationally flattened envelope, where all of the initial orbital angular momentum is stored, one can show that for moderate energies (typically less than 1/2 the binding energy of the envelope), no mass loss occurs in the equatorial plane because of the larger mass concentration there. This has the consequence that matter that is initially accelerated equatorially by the high-entropy bubble generated by the spiraling-in binary is deflected by the overlying mass and is then mainly ejected at a latitude angle of about 45° . This is exactly the type of ejection profile one needs to understand the outer rings, since the blue-supergiant wind will subsequently sweep up these structures into two well-defined rings (see Fig. 2).

The slight asymmetries of the outer rings can also be well reproduced if the outer rings received a moderate kick (with a velocity of $\sim 2 \text{ km s}^{-1}$), perhaps due to a particular dynamical mode during the ejection process.

If this model is confirmed further (e.g. once the total mass distribution in the ring nebula has been mapped completely), it may provide the ultimate and conclusive proof for a merger history of the progenitor of SN 1987A, which at some point would also have appeared as a B[e] supergiant.

5.2. Sheridan 25

The B supergiant Sheridan 25 is surrounded by a nebula that in many respects resembles the triple-ring nebula around SN 1987A (Brandner et al. 1997): the star itself is at the center of a slightly offset ring-like component and there are two filled, ring-like structures displaced above and below the ring plane, marking the ends of a bipolar structure, where the rest of the bipolar structure is not filled in. The measured expansion velocities for the components of the nebula are somewhat larger than for SN 1987A, 30 km s^{-1} for the central ring and 70 km s^{-1} for the bipolar lobes, but the overall sizes of the two nebulae are comparable. This nebula may also have formed as a result of a merger some 6,500 yr ago (based on the dynamical age of the nebula). The larger expansion velocities suggest that this merger occurred when the primary was crossing the Hertzsprung gap, i.e. experienced early case B mass transfer. Therefore Sheridan 25 may provide an example for a dynamical merger. One significant difference to the SN 1987A nebula is the fact that the inner ring is slightly offset; this may imply that the inner ring formed during the merging phase rather than afterwards. The measured projected rotational velocity of the B super-

giant remnant is 65 km s^{-1} , not as large as inferred for a typical B[e] supergiant (see Zickgraf 2006). An important question therefore is whether it has already been spun down, which would affect the estimate of birthrates in Section 3, or whether it has not yet become a B[e] supergiant (e.g. the merged object could still be significantly oversized compared to its thermal equilibrium radius and hence have a significantly subcritical surface rotation rate).

5.3. The B[e] Supergiant R 4

The B[e] supergiant R 4 in the Small Magellanic Cloud provides perhaps the most convincing evidence that at least some B[e] supergiants are the results of binary mergers. The B[e] component has a luminosity of $L \simeq 10^5 L_\odot$ and effective temperature $T_{\text{eff}} \simeq 27,000 \text{ K}$, and its mass has been estimated to be $12 M_\odot$. The B[e] supergiant is a member of a binary system with an orbital period of 21.3 yr and the companion is an evolved A supergiant (Zickgraf et al. 1996). Moreover, NTT spectra show that the system is surrounded by a “cloverleaf” or double bi-polar nebula with a characteristic expansion velocity of $v \sim 100 \text{ km s}^{-1}$ and a size of 2.4 pc, giving the nebula a dynamical age of 10^4 yr (Pasquali et al. 2000). The composition of the nebula is also enriched in nitrogen, suggesting that CNO processed material has been ejected.

The most puzzling feature of the system is, however, the fact that the more evolved A supergiant is much less luminous (roughly by a factor of 10) than the B[e] supergiant, the opposite of what one would expect if the two stars formed at the same time and evolved in isolation. The likely resolution of this Algol-type paradox (Pasquali et al. 2000; Langer & Heger 1998) is that the system originally consisted of 3 stars, where the initially most massive component (now the A supergiant) evolved independently from the other two, but where the other two merged after the second most massive component evolved off the main sequence, producing a new object that is more massive and hence more luminous than the original primary, but is still less evolved. The “cloverleaf” nebula could be a combination of an equatorial outflow, associated with an outflow from one of the outer Lagrangian points during the binary contact phase, while the perpendicular structure is the result of a bipolar outflow ejected during the merger phase (plus any subsequent wind interaction).

5.4. Eta Carinae

One of the most spectacular nebulae in our Galaxy is the nebula around η Carinae, which was ejected between 1840 and 1860 in a giant outburst, during which the luminosity of the system reached a luminosity of almost $3 \times 10^7 L_\odot$. The mass ejected in the outburst has been estimated to be $\sim 10 M_\odot$. Combined with the measured expansion velocities, this gives the nebula a kinetic energy of $\sim 10^{50} \text{ erg}$ (Smith et al. 2003). This corresponds to about 10 % of the energy released in a typical core-collapse supernova, making this a truly remarkable event.

η Car appears to be a member of a relatively wide binary with an orbital period of 5.5 yr in a very eccentric orbit (with an eccentricity $e \gtrsim 0.6$), leading to periodic X-ray activity when the companion is near periastron. With this relatively long period, it seems unlikely that the binary companion is responsible

for the major outburst. There is also evidence for a latitude-dependent wind suggesting that η Car is rapidly rotating (Smith et al. 2003).

If it is indeed true that in the major outburst $\sim 10 M_{\odot}$ were ejected with an energy of $\sim 10^{50}$ erg, this would require a very dramatic, dynamical event. Considering that this energy is comparable to the binding energy of a massive early-type supergiant, it seems implausible that this could be caused by an envelope instability, which could at most release the binding energy of the outer envelope, which would be several orders of magnitude less than 10^{50} erg.

All of these facts combined again point in the direction of a merger, quite similar to the case of R 4, where two components in a triple system merged to produce the outburst in the mid-1800s. This could: (1) provide the energy for the mass ejection; in a dynamical merger, this is expected to be of the order of the orbital energy of the spiralling-in star near the point where it is disrupted. This could easily be as large as $\sim 10^{50}$ erg. (2) Cause the spin-up of the merger product. (3) Provide the excess thermal energy that needs to be radiated away after the merger, driving the post-eruption wind with an inferred wind mass-loss rate of $10^{-3} M_{\odot} \text{ yr}^{-1}$.

η Car may therefore provide us with a rare example of how the merger of two massive stars actually proceeds. This may have important other implications, e.g. for the idea that runaway mergers in globular clusters may produce super-massive stars and ultimately intermediate-mass black holes (e.g. Portegies Zwart et al. 2004; Rasio, Freitag, & Gürkan 2004). In particular, it demonstrates that mass loss, both dynamically during the merging phase as well as by a powerful stellar wind in the immediate post-merger phase, cannot be neglected and may ultimately limit the maximum mass of a star that can be produced by a runaway merger process.

6. Conclusions

The main conclusion of this review is that massive binary mergers occur and are relatively common. They plausibly lead to the formation of B[e] supergiants and may indeed be their main production channel. The merging process itself is likely to be a dramatic event, accompanied by a major outburst, perhaps similar to the great eruption of η Car, and will leave a complex nebula behind in its aftermath.

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