Binary Evolution and the Progenitor of SN 1987A

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Abstract. Since the majority of massive stars are members of binary systems, an understanding of the intricacies of binary interactions is essential for understanding the large variety of supernova types and subtypes. I therefore briefly review the basic elements of binary evolution theory and discuss how binary interactions affect the presupernova structure of massive stars and the resulting supernovae.

SN 1987A was a highly anomalous supernova, almost certainly because of a previous binary interaction. The most likely scenario at present is that the progenitor was a member of a massive close binary that experienced dynamical mass transfer during its second red-supergiant phase and merged completely with its companion as a consequence. This can naturally explain the three main anomalies of SN 1987A: the blue color of the progenitor, the chemical anomalies and the complex triple-ring nebula.

1. Introduction

In the last few years, it has become increasingly clear that SN 1987A in the Large Magellanic Cloud (LMC) was a remarkable, but highly unusual event. One of the major surprises of SN 1987A was the fact that the star that exploded was a blue supergiant rather than a red supergiant as had been predicted. While there have been many attempts in the early years to explain the blue-supergiant progenitor within the framework of single stellar evolution theory (e.g., Woosley, Pinto & Ensmann 1988; for a review see Podsiadlowski 1992), these models are no longer viable with the best, up-to-date input physics (Woosley 1997). In particular, the recent large increase in stellar opacities (Rogers & Iglesias 1992) had as an immediate consequence that there are no longer any plausible parameters for which a massive star first becomes a red supergiant and then experiences a late blue loop after helium core burning (Woosley 1997). Of course, even if such models could be constructed, they still would not be promising models for the progenitor of SN 1987A, since they still could not explain any of the other major anomalies of this event: the complex triple-ring nebula surrounding the progenitor and the various chemical anomalies (see Podsiadlowski 1992 and section 3). It is now almost certain that these anomalies are somehow connected to binary evolution. In section 2, I therefore first review some of the main, relevant principles of binary stellar evolution theory and, in section 3, summarize the observational constraints any model for the progenitor has to fulfill. In
section 4, I present in detail an updated version of a merger scenario that at present provides the only framework in which not only some, but all of these anomalies can be understood. Throughout this review, I emphasize the still substantial theoretical uncertainties in this model and indicate how observations may help to conclusively verify it in all its details.

2. Binary interactions

As is not very widely known in the supernova community, most stars in the sky are actually members of binary (or multiple) systems. To zeroth order, all stars are members of binaries (see, e.g., the references in Podsiadlowski, Joss & Hsu 1991 [PJH] and Ghez 1996). Of course to have its presupernova structure altered, a star has to be in a close, interacting binary where at least one star fills its Roche lobe during its evolution. The fraction of massive stars in interacting binaries can be estimated to be in the range of 30−50%. For example, Garmany, Conti & Massey (1980) found that 36% of massive stars are spectroscopic binaries with massive companions with periods less than \( \sim 1 \) yr. This estimate would imply a true interacting-binary frequency of around 50%. It is worth noting that Roche-lobe overflow occurs more frequently in evolved phases simply because the radius of a star expands only by a factor of \( \sim 2 \) during the main sequence, while it expands by a factor of \( \sim 100 \) subsequently. This means that, for any plausible orbital-period distribution, a star is much more likely to encounter mass transfer after its main-sequence phase. Since stars spend the largest fraction of their lives on the main sequence, most stars observed in the sky have not (yet) experienced a binary interaction. On the other hand, supernovae probe the very final stage in the evolution of a star. Therefore a large fraction of all supernova progenitors are affected by a previous binary interaction. This is, at least in part, responsible for the large variety of observed supernova types.

In general, two qualitatively very different modes of mass transfer can be distinguished: more-or-less conservative mass transfer and dynamically unstable mass transfer.

*(Quasi-)*conservative mass transfer usually occurs when the mass donor has a radiative envelope and the mass ratio of the mass-accreting to the mass-losing component is not too small (e.g., de Loore & de Grève 1992). Then, a large fraction (\( \geq 0.5 \)) of the mass lost from the primary is accreted by the secondary. Thus in this case, both components of the binary are affected, one by losing mass, the other by accreting it. During mainly conservative mass transfer, the orbital period tends to increase.

Dynamical mass transfer usually takes place when the secondary is a giant star with a deep convective envelope. In this case, mass transfer is dynamically unstable and leads to the formation of a common envelope surrounding the core of the giant and the secondary (Paczynski 1976). Due to friction between this immersed binary with the common envelope, the orbit of the binary starts to shrink. Dependent on how much energy is released in the orbital decay of the binary and is deposited in the envelope, two different outcomes are possible. If the deposited energy exceeds the binding energy of the envelope, the common envelope can be ejected, leaving a very close binary consisting of a helium star
(or Wolf-Rayet star) and a normal companion star (which is hardly affected by the common-envelope phase). If the energy is not sufficient to unbind the envelope, the less dense component of the immersed binary will ultimately be tidally destroyed and the two components merge completely to form a single, but rapidly rotating giant (see section 4.2).

In a typical binary scenario, a binary system may experience several different phases of mass transfer, which is the reason for the large variety of possible binary scenarios. In the following, I will concentrate on the main consequences of the various mass-transfer types for the structure of the immediate supernova progenitors (for a more detailed discussion see PJH and Hsu et al. 1996).

2.1. Mass loss

Some 30–50% of all massive stars experience Roche-lobe overflow and mass loss at some point during their evolution. In most cases, they lose all of their hydrogen-rich envelopes and become helium stars or Wolf-Rayet stars, which are excellent candidates for type Ib/Ic supernovae. In some cases, however, it is possible for the primary to retain part of its hydrogen-rich envelope, in particular when mass transfer occurs very late during the evolution of the primary and when the initial mass ratio is very close to one. However, even in this case, at most a few solar masses can be retained in the envelope. The immediate supernova progenitor will be a *stripped supergiant* with a small envelope mass (Joss et al. 1988). It is interesting to note that the outer appearance of this star will be very similar to that of a star that has lost no mass at all, since the radius and the luminosity of the star are almost independent of the envelope mass (PJH). The resulting supernova will, however, be quite different. The light curve will show no extended plateau phase but resemble a type II-L or, in the most extreme case, a type IIb supernova (Nomoto et al. 1993; Podsiadlowski et al. 1993; Woosley et al. 1994; Hsu et al. 1996).

2.2. Mass accretion

Just as the structure and appearance of the mass-losing star can be strongly affected, the structure and further evolution of the accreting companion can also be dramatically altered by mass transfer. This depends, however, strongly on the evolutionary stage of the accreting secondary at the beginning of the mass-transfer phase.

*Secondary on the main sequence*

If the secondary is still on the main sequence at the beginning of the mass-transfer phase, the secondary is usually *rejuvenated* and will behave subsequently (after the mass-transfer phase) like a single, but now more massive star (Hellings 1983; PJH). However, as was shown by Braun & Langer (1995), this need not be the case if accretion occurs very late on the main sequence and if semi-convection is very slow (combined with the Ledoux criterion for convective instability), since the convective core will then not grow significantly as a result of accretion. The subsequent evolution will resemble the evolution of a star that accreted after the main-sequence phase (see below); in particular, the star may never become a red supergiant and spend the whole post-main-sequence phase in the blue-supergiant region of the Hertzsprung-Russell (H-R) diagram.
Secondary has completed hydrogen core burning

If the secondary has already left the main sequence before the beginning of the mass-transfer phase, the subsequent evolution will generally differ quite substantially from the evolution of a normal single star. Since the mass of the helium core will not grow as a result of mass accretion, the main effect of post-main-sequence accretion is to increase the envelope mass relative to the core mass. As was first shown by Podsiadlowski & Joss (1989) (see also De Loore & Vanbeveren 1992; PJH), this has the consequence that the star will now not become a red supergiant or, if it was a red supergiant at the time of the accretion phase, leave the red-supergiant region and spend its remaining lifetime as a blue supergiant (see also Barkat & Wheeler 1989 for a related scenario). The final location of the star in the H-R diagram at the time of the supernova depends on how much mass has been accreted in the accretion phase. The star will be the bluer, the more mass it has accreted. The final supernova will be of the SN 1987A variety (type II[blue]). Since a star has to accrete only a few percent of its own mass from a binary companion to be spun up to critical rotation, the progenitor is expected to pass through a phase where it is rapidly rotating. Rapid rotation may also induce large-scale mixing in the accreting star (even across chemical gradients). However, whether this happens depends critically on the angular-momentum transport inside and the structure of the accreting star.

2.3. Binary mergers

The most dramatic type of binary interaction is dynamical mass transfer leading to a common-envelope and spiral-in phase. If the orbital energy released during the spiral-in is sufficient to eject the common envelope, the end product is a short-period binary consisting of a Wolf-Rayet primary and a normal stellar companion. The primary will eventually explode as a type Ib/Ic supernova. If the system remains bound, the secondary is also likely to experience mass loss in the future leading to a second mass-transfer phase, just as in the mass-accretion scenarios discussed in the previous subsection.

If the common envelope is not ejected, the two components will merge completely to produce a more massive and rapidly rotating single star. This end product resembles in many ways the outcome of the post-main-sequence accretion models in section 2.2. In particular, it may end its evolution as a blue supergiant rather than as a red supergiant either because of the added mass in the envelope (Podsiadlowski, Joss & Rappaport 1990) or because of the dredge-up of helium (Hillebrandt & Meyer 1989) or both. The resulting supernova may again be of the SN 1987A variety. Podsiadlowski et al. (1991) have estimated that the combined frequency for a blue-supergiant progenitor in either an accretion or a merger scenario is about 5% of all core-collapse supernovae with an uncertainty of about a factor of two.

Complications. In this section, I only discussed the main types of interactions. However, many binaries experience more than one phase of mass transfer. For example, low-mass helium stars, produced in a first mass-transfer phase, will expand again after core helium burning to become helium giants and may fill their Roche lobes for a second time (so-called case BB mass transfer; De Grève & De Loore 1977; Delgado & Thomas 1981). This still does not exhaust the whole variety of multiple mass-transfer scenarios. Nomoto et al. (1994) summarized
various scenarios to produce bare CO cores as progenitors of type Ic supernovae, which involve up to three mass-transfer phases.

3. Observational Constraints on the Progenitor of SN 1987A

3.1. The blue-supergiant progenitor

One of the major early surprises of SN 1987A was the fact that its known progenitor, SK $^{-69\circ202}$, was a blue supergiant rather than a red supergiant, the normally expected supernova progenitor. Moreover, from the dynamical age of the surrounding low-velocity nebula ($\sim 30000 \text{ yr}$) one can infer that it was a red supergiant just a few $10^4 \text{ yr}$ ago. Any model of the progenitor has to explain this recent transition and be consistent with the general behaviour of massive stars in the LMC in the H-R diagram. Many of the early models already failed this obvious test (see Podsiadlowski 1992).

3.2. The triple-ring nebula

One of the most spectacular features of SN 1987A is the complex, but very axisymmetric nebula surrounding the supernova, which was formed out of material that was ejected from the progenitor in the not-too-distant past. The main geometry of the nebula consists of three rings, an inner ring centered on the supernova (Wampler et al. 1990; Jacobson et al. 1991) and two rings displaced to the South and the North, but in approximate alignment with the symmetry axis of the inner ring (Wampler et al. 1990; Burrows et al. 1995). This geometry implies an axisymmetric, but highly non-spherical structure of the envelope of the progenitor and/or its winds. The origin of this non-sphericity provides a severe constraint for models of the progenitor. A plausible mechanism to produce the required asymmetry is the flattening of the progenitor’s envelope caused by rapid rotation (Chevalier & Soker 1989). However, straightforward angular-momentum considerations show that a single star which was rapidly rotating on the main sequence would be a slow rotator in any subsequent supergiant phase and could not possibly be significantly flattened at the time of the supernova explosion. Recent HST observations (Pun 1997) which show that the supernova ejecta themselves are elongated along the symmetry axis of the nebula provide further evidence for a rapidly rotating, flattened (oblate) progenitor, since in this case the supernova shock will propagate faster in the polar directions, thereby generating a prolate structure of the ejecta.

3.3. The chemical anomalies

The third major surprise of the supernova involves a number of chemical anomalies in the progenitor’s hydrogen-rich envelope and in the presupernova ejecta.

The inner ring: the helium anomaly

As is now firmly established, the composition of the inner ring shows that significant amounts of CNO-processed material have been dredged up to the surface (with $N/C \sim 5$, $N/O \sim 1$ [all ratios are by number]) and that, most importantly, the helium abundance in the inner ring is about twice solar ($\text{He}/\text{H} \sim 0.25$;
The outer rings: two dredge-up phases?

Recently, Panagia et al. (1996) found that the chemical composition of the outer rings is significantly different from the composition of the inner ring, indicating a smaller amount of dredge-up of CNO-processed material (N/C $\sim 2$; N/O $\sim 0.6$). This, if confirmed, might suggest that there were two dredge-up phases, the first associated with the normal convective dredge-up when a star becomes a red-supergiant and develops a deep convective envelope and the second, a few $10^4$ yr ago, connected with the event that produced all the other anomalies as well. Determination of the helium abundance of the outer rings could shed more light on the details of this process.

The barium anomaly

The third chemical anomaly, most people had hoped would go away, is the enhancement of barium (by a factor of 5–10) and other s-process elements in the progenitor's envelope (Williams 1987; Höflich 1988; Mazzali, Lucy & Butler 1992; Mazzali & Chugai 1995). This suggests the simultaneous occurrence of hydrogen and some helium-burning reactions (in particular, $^{13}\text{C} + \alpha$) in the outer parts of the core, similar to the process that produces these elements in S stars on the asymptotic-giant branch (Sanders 1967).

All of these anomalies together suggest that there was a single, dramatic event a few $10^4$ yr ago that is responsible for them. Several of these show clear fingerprints of binary interactions. Just as in any good mystery story, there are plenty of traces and clues, and it is just up to us to decipher their meanings and to reconstruct what really happened to the progenitor of SN 1987A.

4. The Progenitor of SN 1987A: a Binary Merger

Over the last ten years, numerous binary models have been suggested (for a review, see Podsiadlowski 1992; see also Rathnasree 1993; Braun & Langer 1995). Both accretion and merger models (see section 2) can explain a rapidly rotating blue-supergiant progenitor. However, since in the former class of models it is the secondary that accretes from a more evolved star and since all of this should have occurred in the very recent past, this would require the masses of the stars to have been extremely close initially. This implies enormous fine-tuning of the binary parameters and therefore is no longer a favoured model. It now appears most likely that the progenitor was a binary that merged with its companion in the recent past (as originally proposed independently by Hillebrandt & Meyer [1989] and Podsiadlowski et al. [1990]; also see Chevalier & Soker [1988] for an earlier suggestion).

In this section, I will present an updated version of the merger scenario outlined in Podsiadlowski (1992) and schematically illustrated in Figure 1 (details will be published in Podsiadlowski 1997). The calculations use the chemical abundances for massive LMC stars determined by Russell & Bessell (1989) and Russell & Dopita (1990) (with $Z = 0.01$ but an uncertain carbon abundance), updated opacities by Rogers & Iglesias (1992) and Alexander (1994), as provided by Eggleton (1997).
The Merger Scenario for SN 1987A

massive, wide binary

dynamical mass-transfer and complete merging after core helium burning:
formation of a single, rapidly rotating supergiant

rotationally forced disk outflow in red-blue transition

blue-supergiant wind sweeps up previous structures:
formation of the triple-ring nebula

Figure 1
Figure 2. Representative merger calculations for a star with an initial mass of $18 \, M_\odot$ merging with a $10 \, M_\odot$ star after helium core burning for different amounts of helium dredge-up (solid and dashed curves) and final masses as indicated.

Initially, the progenitor was a member of a very typical binary, consisting of a primary of $\sim 15 \, M_\odot$ and a significantly less massive secondary ($5 - 10 \, M_\odot$) in a fairly wide orbit (with an orbital period of $\sim 10 \, yr$), so that the primary started to fill its Roche lobe only on the asymptotic-giant branch (i.e., on its second ascent of the red-supergiant branch after helium core burning). The mass of the companion is not well determined by the model at the present time. Indeed, a relatively low-mass companion could be sufficient. The system then experienced dynamical mass transfer, leading to the complete merger of the two stars. The end product of this evolution is a single, but very rapidly rotating red supergiant, which has been thoroughly stirred up during the merging process (explaining the main chemical anomalies, provided that this environment allows for s-processing). The star will now want to shrink to become a blue supergiant, producing a rotationally forced disk-like outflow in the process. In the subsequent blue-supergiant phase, the energetic blue-supergiant wind sweeps up all the structures generated previously and produces the triple-ring nebula (for a model of the outer rings in a merger scenario, see Podsialowski, Fabian & Stevens 1991; Lloyd, O’Brien & Kahn 1995; Podsialowski & Cumming 1995).

Figure 2 shows several representative merger calculations based on an analytic theory for the merger process (Podsiadlowski 1997; and Podsiadlowski & Spruit 1997), for a primary with an initial mass of $18 \, M_\odot$ merging with a $10 \, M_\odot$ companion. In the calculations represented by solid curves, $1.2 \, M_\odot$ of the helium core is dredged-up during the merger and the final masses of the merged stars are 20 and $25 \, M_\odot$, respectively (as indicated). Both stars have surface abundances of helium and the CNO elements that are in excellent agreement with the observational constraints (section 3.3). In the model shown as a dashed curve, the merger is even more dramatic and the final object would chemically be classified as a barium star, though this particular model is somewhat too hot and too luminous for the progenitor of SN 1987A.
4.1. Formation of the inner ring

The production of the inner ring requires a disk-like outflow in the red-supergiant phase. It has been suggested that gravitational focusing by a non-interacting companion (similar to what may happen in some planetary nebulae, e.g., Morris 1981) could provide such a focusing mechanism. However, the constraints on any distant companion after the supernova are quite stringent, and its mass could not be larger than $\sim 2 M_\odot$ (e.g., Plait et al. 1995). It is easy to show, using a Bondi-Hoyle-type wind theory, that the fraction of the red-supergiant wind that is gravitationally affected by the companion is of order $(v_{\text{orb}}/v_{\text{wind}})[M_2/(M_1 + M_2)]^2$, where $v_{\text{orb}}$ and $v_{\text{wind}}$ are the orbital velocity of the secondary and the wind velocity, respectively, while $M_1$ and $M_2$ are the masses of the primary and the secondary, respectively. For plausible parameters for the SN 1987A progenitor, this fraction cannot exceed $\sim 5\%$, which is completely insufficient to explain the large observed asymmetry.

On the other hand in a merger scenario, the problem is not a lack of rotation but an excess thereof (Podsiadlowski 1992; Chen & Colgate 1995), since all the orbital angular momentum in the pre-merger binary will be deposited in the envelope of the progenitor, spinning it up in the process. Indeed, for the parameters of the model shown in Figure 2, the total orbital angular momentum ($\sim 9 \times 10^{54}$ erg s) substantially exceeds the maximum angular momentum of a dynamically stable blue supergiant ($\sim 4 \times 10^{54}$ erg s). This immediately implies that the merged system will pass through a phase of critical surface rotation in the final red-blue transition, leading to rotationally enforced, equatorial mass loss. One can obtain a rough estimate for the minimum amount of mass that needs to be shed in this process by dividing the excess angular momentum by the specific orbital angular momentum of the initial binary. This yields

$$\Delta M \sim \frac{\Delta L}{\sqrt{GM_D}} \sim 4 M_\odot \left(\frac{D}{10 \text{AU}}\right)^{-1/2},$$

where $D$ is the characteristic co-rotation radius associated with the mass loss (assumed here to be of order the initial binary separation).

This estimate implies that one expects at least several solar masses to be lost after the merger. How this mass loss took place in detail is not so clear at the moment. It may involve a rotationally focused wind, as in the standard model for Be-star disks by Bjorkman & Cassinelli (1993), or dynamical instabilities in a critically rotating object (e.g., Durisen et al. 1986; Livio & Soker 1988; Taam & Bodenheimer 1991; Chen & Colgate 1995). In both cases, one would expect the formation of a disk-like, equatorial structure with a small radial velocity (as required to explain the low expansion velocity of 10 km s$^{-1}$ of the inner ring).

In this context it is worth noting that there is an observed system that seems to have merged in the very recent past and that shows some similarities to the SN 1987A progenitor: V Hydrae is a carbon-star giant rotating near break-up (Barnbaum, Morris & Kahane 1995). The system also shows evidence for a disk-like equatorial and a biconical polar outflow. Barnbaum et al. (1995) even suggested that the carbon-star characteristics of V Hyd may by a direct consequence of the dredge-up of carbon caused by the merging process. While this system is not entirely comparable to the progenitor of SN 1987A, one may
hope to learn more about this relatively unexplored, but not at all uncommon (~5%–10%) phase of binary evolution from V Hyd and, of course, SN 1987A.

4.2. The merger phase

One of the least studied aspects of the merger scenario involves the details of the final merging of the two binary components, the secondary and the helium core of the red supergiant, inside the common envelope. We (Podsiadlowski & Spruit 1997) have started to look at this process in some detail (also see Meyer & Meyer-Hofmeister 1979; Taam & Bodenheimer 1989, 1991; Terman, Taam & Hernquist 1994).

The spiral-in phase ends when the embedded secondary starts to fill its own Roche lobe (at a separation of \( \sim 10 R_\odot \)). It then begins to transfer mass to the helium core. This mass-transfer process resembles in many respects the “normal” mass transfer in interacting binaries, except that it occurs inside a low-density, opaque envelope. The mass-transfer rate is determined by the frictional drag the orbiting binary experiences with the common envelope. The timescale for the final destruction of the secondary is uncertain. Rough guesses range from a few days (assuming that the envelope does not expand as a result of the spiral-in) to hundreds of years (assuming that the frictional luminosity is self-regulated at the Eddington limit; e.g., Meyer & Meyer-Hofmeister [1979]). In the calculations presented earlier, I adopted, somewhat arbitrarily, a timescale of 1 yr. Because of the relatively large size of the helium core, the stream emanating from the Roche-lobe filling secondary does not self-intersect and form an accretion disk but rather impacts with the core and penetrates it. In other words, it drills a hole into the core and starts to erode it, causing the dredge-up of helium-rich material. The penetration depth can be estimated from the condition that the ram pressure in the stream must be of the order of the ambient pressure in the helium core. One major uncertainty in this estimate is how much energy is dissipated inside the stream by internal shocks (which must occur because of the pressure focusing of the stream and angular-momentum constraints). The characteristic temperature of the shock-heated material in the stream-impact region is \( T \sim 2 \times 10^8 \) K. Since this material is hydrogen-rich, but the temperature more typical of helium burning, one can expect some unusual nucleosynthesis in this region, possibly responsible for the more exotic chemical anomalies of SN 1987A like the barium anomaly.

Preliminary calculations using extended nuclear-reaction networks show that significant s-processing (with neutron exposures of \( \sim 10^{27} \) cm\(^{-2}\) with C\(^{13}\)+\(\alpha\) as neutron source) is possible in this environment. This requires that the dredge-up region of the core is continually mixed with some of the hydrogen-rich envelope that serves as a proton reservoir for an extended period of time (of order the merger timescale). Unfortunately, some of the key reaction rates are very temperature sensitive, while the burning conditions are not sufficiently well determined by the present analytic model to allow very firm conclusions. In addition, these calculations suggest that the abundances of the rare nitrogen and oxygen isotopes N\(^{15}\) and O\(^{17}\) may be overabundant by a large factor. This could provide a potentially sensitive tracer for the burning conditions in this environment.
5. Concluding Remarks

As I have shown in this review, binary interactions are almost certainly responsible for some of the large variety of observed supernova types in general and therefore cannot be ignored. As far as SN 1987A is concerned, a merger scenario provides at present the only model for the progenitor that can explain all the major features of this remarkable event. There are still many theoretical uncertainties, in particular involving the details of the merging process and the associated nucleosynthesis. Observations of abundances in different parts of the nebula may be particularly useful in helping to reconstruct the detailed merger history (for example, the helium abundance in the outer rings). In addition, there may be other chemical anomalies (overabundances of $\text{N}^{15}$ and $\text{O}^{17}$) that may be used as direct tracers of the unusual burning conditions that occur during the final merging process.

While a lot has been learned about the progenitor of SN 1987A in the last ten years, there still remains much more to be done, both theoretically and observationally. Ultimately, when the supernova blast wave reaches the inner ring, at least the structure of the whole nebula will be finally revealed and confirm or refute some of the aspects of the merger scenario.

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