The Progenitor of SN 1987A

Philipp Podsiadlowski

Abstract

Supernova 1987A in the Large Magellanic Cloud was the first naked-eye supernova since Kepler's supernova in 1604. Neutrino detections from the event dramatically confirmed the long-held belief that this type of supernova is triggered by the final collapse of the core of a massive star, but in many other respects it was a very unusual, even anomalous event. The progenitor was a blue supergiant instead of a red supergiant, as had been predicted theoretically, and the system was surrounded by a spectacular triple-ring nebula that consists of material that was ejected only 20,000 years before the explosion. This chapter will discuss the mystery of the supernova progenitor and how all the evidence points toward a dramatic event that occurred some 20,000 years ago, the merger of two massive stars and how future observations will further help to prove or refute the current picture.

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1 Introduction

Supernova 1987A (SN 87A) was first detected on February 23, 1987. It was the first naked-eye supernova since Kepler's supernova in 1604, an event astronomers had long been waiting for. It occurred in the Large Magellanic Cloud (LMC), a satellite galaxy of the Milky Way in the outskirts of the Tarantula Nebula (30 Doradus), a very active region of massive star formation, in fact the closest mini-starburst we know of. At its peak, it reached a visual magnitude of 3 and could clearly be seen with the naked eye from the Southern hemisphere. The discovery of neutrinos from the supernova confirmed in a spectacular way that supernovae of this type are caused by the collapse of a massive star to a neutron star, as was first speculated by Fritz Zwicky and his colleagues in the 1930s. While this has been one of the major successes in modern theoretical astrophysics, in many other respects the supernova was quite different from what had been expected. While stellar evolution theory firmly predicted that massive hydrogen-rich stars explode as red supergiants, the progenitor, which in this case could be identified on old plates taken before the supernova, was a blue supergiant (the arrow in Fig. 1 points to), a star that did not appear to be even close to the end of its life. Why this star exploded as a blue

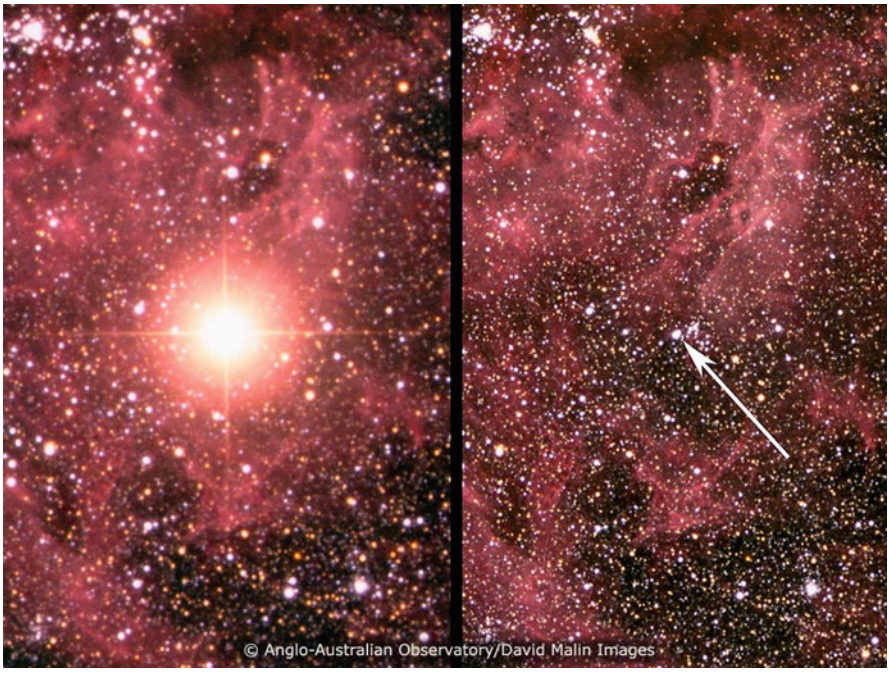


Fig. 1 Before (*right*) and after (*left*) images, taken with the AAT, of the region where SN 1987A occurred. The *arrow* in the *left panel* points at SK $-69^{\circ}202$, a system of stars that contained the progenitor of the supernova, a *blue supergiant*

supergiant has remained one of the most enduring puzzles of this spectacular event and will be the topic of this chapter. As in any good mystery story, there have been many false leads and unexpected turns, but a consistent picture has emerged over the years that can describe the unusual evolution of the progenitor up to its final surprising demise.

Detailed reviews on all aspects of SN 1987A can be found in Arnett et al. (1989), McCray (1993), and McCray and Fransson (2016), reviews specifically on the question of the progenitor (including all relevant references) in Podsiadlowski (1992) and Podsiadlowski et al. (2007). In this chapter, I will start by discussing the importance of the supernova neutrino burst (Sect. 2) and explain the mystery of the progenitor (Sect. 3). In Sect. 4, I will summarize the key observational clues that were essential for helping to unravel the mystery and strongly point to a binary origin for the progenitor, followed by a general discussion of binary evolution effects in Sect. 5 that are important for understanding the diversity of observed supernova events. In Sect. 6 I will discuss in detail the presently best model that can explain all the aspects of this event and in Sect. 7 possible alternative ideas as far as they exist. In Sect. 8 I will look at how future observations should be able to ultimately either prove or refute our working model and discuss some unresolved open questions, followed with some brief conclusions in Sect. 9.

2 The Neutrino Burst

The discovery of neutrinos from the supernova proved to be one of the most spectacular successes of modern theoretical astrophysics. The two main neutrino detectors that were operating at the time discovered a total of 18 neutrinos, 11 from the Kamiokande II detector in Japan and 7 from the IMB detector in Ohio. The two detectors were two huge water detectors that discovered most of the neutrinos by the Cherenkov radiation caused by the recoil of positrons produced in the absorption of electron anti-neutrinos on the free protons in the water molecules (for more details, see Arnett et al. 1989). The neutrinos, with a typical energy of about 4 Mev, reached the detectors some 3 h before the first light could have been seen from the supernova. The reason for the delay is that, because of the weak interactions of neutrinos with matter, they can travel essentially unimpededly from outside the core to the observer, while it took some 3 h for the supernova shock triggered by the collapse to reach the surface of the progenitor, which initiates the observable supernova display.

Even though there were only 18 neutrinos discovered, their cross sections with matter are sufficiently well known that it allowed astronomers to estimate the energy in the neutrino burst: assuming that there are 3 light neutrino species, the energy has been estimated to be $E_\nu = 2.5 \pm 1.5 \times 10^{46}$ J, an energy that is remarkably close to the gravitational binding energy of a neutron star, roughly 10 % of its rest mass for a 1.4 $M_\odot$ neutron star. This proved that indeed most of the energy released in the collapse of the progenitor's core escaped in the form of neutrinos, and it remains one of the lasting theoretical problems how a fraction of this neutrino energy can be trapped by the infalling envelope to eject the rest of the star and drive an explosion,

i.e., produce an observable supernova. Moreover, the neutrinos were observed over a period of 12 s, much longer than the actual collapse phase (<1s). This showed that the compact remnant was dense enough that neutrinos were initially trapped in the core and had to diffuse out over a period of 12 s. In fact, this neutrino diffusion phase can be perfectly modeled by the cooling of a proto-neutron star, providing irrefutable evidence that a neutron star was formed in the SN 87A collapse – at least initially. However, even after 30 years no evidence for such a neutron star has been detected in the remnant, one of the remaining puzzles of the supernova (see Sect. 8.2).

3 The Mystery of the Progenitor

Because the supernova occurred so close to the Galaxy, just some 50 kpc away, it made it possible for the first time to identify the progenitor star that actually exploded. There was, however, quite a bit of confusion in the early days. Pre-supernova images clearly showed a stellar object at the position of the supernova, Sk −69°202, the two-hundred-second object at a declination of -69 deg. It had been classified as a B3I supergiant, a fairly normal star that did not show any evidence that it was approaching the end of its life. Closer inspection of pre-supernova plates showed that the image was extended, implying that it was caused by the superposition of at least two bright stars, not very surprising for a crowded field like 30 Doradus. The real surprise came when the supernova had faded enough in the ultraviolet, and there were still two blue stars at the location of the supernova, and for a while it seemed that Sk −69°202 was still there. It took a few weeks before further detailed comparisons of pre- and post-supernova plates revealed that the initial image actually contained three blue stars, of which the brightest (now referred to as star 1) had disappeared after the supernova and therefore was – in all probability – the progenitor of the supernova. It was a blue star with a temperature of 16,000 ± 1500 K and a luminosity of $1.1 \pm 0.3 \times 10^5\, L_\odot$. The inferred compact radius of $45 \pm 15\, R_\odot$ was much less than the $\sim 1000\, R_\odot$ that had been predicted for the red-supergiant progenitor of a massive hydrogen-rich star.

The observed lightcurve of the supernova provided independent confirmation that the star that exploded was a more compact blue supergiant. Figure 2 compares the lightcurve of a typical Type II-P (plateau) supernova, whose progenitors are believed to be red supergiants, with the lightcurve of SN 87A. Even though the explosion energy in both supernovae was probably comparable ($\sim 10^{44}$ J), a larger fraction of this energy goes into adiabatic expansion of the more compact envelope of the blue supergiant, making the initial lightcurve much fainter than in a typical SN II-P and causing a double-peaked lightcurve rather than a long plateau phase at higher luminosity. The first peak in the lightcurve of SN 87A is caused by the cooling of the energy that had been deposited by the supernova shock as it passed through the envelope, while the main peak is powered by the diffusion of the radioactive energy deposited in the envelope by the decay of ^{56}Ni, first to ^{56}Co and finally to ^{56}Fe. The amount of radioactive ^{56}Ni that was produced in the explosion itself

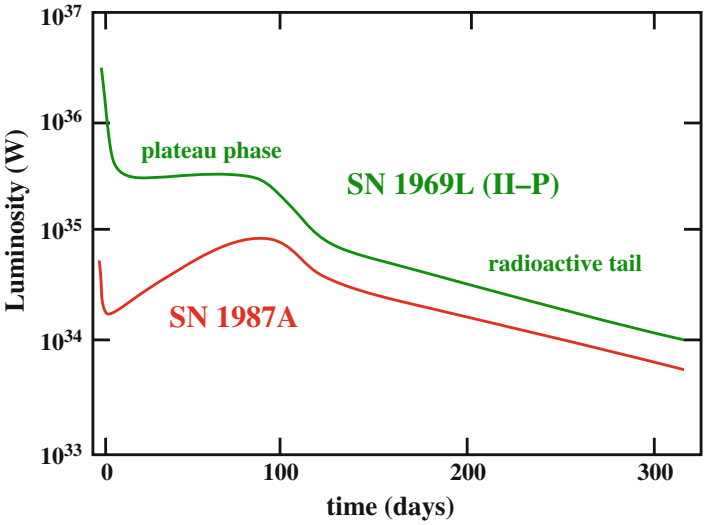


Fig. 2 Comparison of the lightcurves of a typical Type II-P supernova with the lightcurve of SN 87A. Both supernova types involve exploding stars with massive hydrogen-rich envelopes, *red* supergiants (with radii larger than $\sim$1000 $R_\odot$) for SNe II-P, and a more compact *blue* supergiant (with a radius of $\sim$ 45 $R_\odot$) for SN 87A

could be measured quite accurately in this case as $M_{\rm Ni} = 0.075\,M_\odot$ from the late, exponential lightcurve tail which exactly followed the exponential decay time for the decay of ^{56}Co (111 d).

Early Progenitor Models

It did not take long for theorists to offer various explanations for this unusual progenitor (see the review by Podsiadlowski 1992), proving the old adage that theorists are always wiser after the fact. As in any good mystery story, however, none of the early ideas stood the test of time.

Stellar evolution theory predicts that massive stars (up to about 40 $M_\odot$) become red supergiants where they are expected to explode unless they lose almost all of their hydrogen-rich envelopes and then become compact Wolf-Rayet stars. Therefore it is conceivable that, in such an *extreme mass-loss model*, the progenitor just passed through the blue-supergiant region at the time of the explosion. However, such models would predict a very low-mass hydrogen-rich envelope at the time of the explosion that is not compatible with the broad second lightcurve peak of SN 87A which requires at least $\sim$ 5 $M_\odot$ of hydrogen-rich material.

Another early suggestion identified the lower metallicity of the LMC compared to the galaxy as a potential culprit (*low-metallicity model*). Stellar evolution calculations suggest that, at sufficiently low metallicity, massive stars avoid a red-

supergiant phase immediately after the main-sequence phase and spend all of their helium core-burning phase as blue supergiants where they even might explode. However, this predicts that there should be no red supergiants in the LMC which is completely inconsistent with the distribution of massive stars in the Hertzsprung-Russell diagram of the LMC. Furthermore, more recent calculations suggest that the metallicity at which a red-supergiant phase is avoided is less than about 1/10 the solar metallicity ($Z_\odot$), much lower than the typical metallicity of a massive star in the LMC ($\sim 1/2\, Z_\odot$).

More complicated *hybrid models* employed a combination of factors (such as low metallicity, changes in the treatment of convection, and an unusually low helium abundance) to find evolutionary tracks where the star becomes a blue supergiant just before the explosion (i.e., experiences a so-called late blue loop). While there are still enough uncertainties in our understanding of stellar evolution theory to not be able to rule out such a fine-tuned model completely, such a model is very unlikely to explain some of the other anomalies discussed in the next section.

Rapid rotation could be another factor to explain an unusual progenitor, though rotation generally produces larger hydrogen-exhausted cores which tend to favor red-supergiant structures (unless the rotation is so large that the star evolves more or less homogeneously and directly becomes a Wolf-Rayet star).

Some early numerical experiments showed that, if some helium was mixed from the core into the envelope in a late evolutionary phase, this could trigger the transition from a red supergiant to a blue supergiant. Indeed, in the presently most favored model (see Sect. 6), such helium dredge-up plays an important role in explaining the chemical anomalies. However, on its own, such a *helium-enrichment model* lacks a mechanism that can cause the dredge-up of a significant fraction of the helium core.

A radical alternative early idea involved a binary model in which it was not the blue supergiant but a fainter red-supergiant companion that exploded. While it is possible to construct such models, involving mass transfer between the binary components, where the primary star explodes first but is fainter (i.e., involving a classical Algol paradox), they predict much smaller envelope masses than are compatible with the supernova lightcurve. Moreover, the blue supergiant should have reappeared once the supernova had faded sufficiently; as this did not happen, such *binary companion models* can also be firmly ruled out.

4 The Triple-Ring Nebula and the Chemical Anomalies

A real game changer in understanding the SN 87A progenitor was the discovery of the complex triple-ring nebula that surrounded the supernova progenitor and, based on its dynamical age, involved material that was ejected from the progenitor system just ~20,000 years before the explosion. That there was slowly expanding material around the supernova had already been deduced from UV observations with the IUE satellite soon after the explosion. The first direct imaging of it was achieved with the ESO New Technology Telescope (NTT; Fig. 3a), but its structure can be

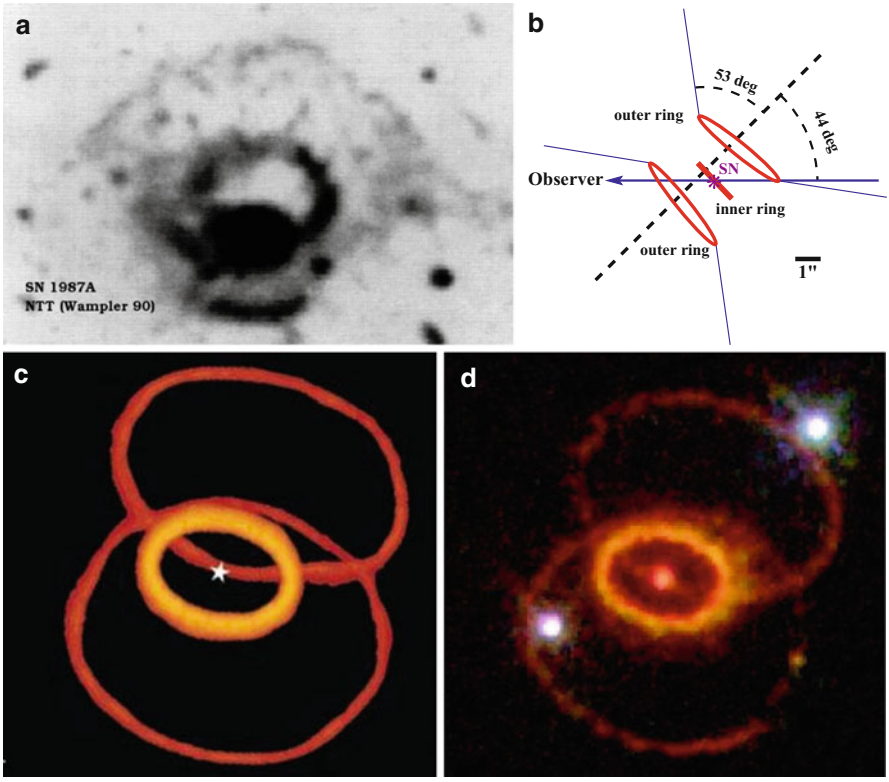


Fig. 3 The triple-ring nebula around SN 87A. *Panel a*: discovery image taken with the ESO NTT, also showing a larger structure referred to as *Napoleon's Hat*. *Panel b*: detailed geometrical model for the triple-ring nebula (*side view*). *Panels c and d*: comparison of a theoretical model for the triple-ring nebula (*left*, see Sect. 6) to an HST image (*right*)

most clearly studied with images taken with the Hubble Space Telescope (HST; Fig. 3d). The observed radiation is caused by the recombination of hydrogen that was ionized by the initial UV flash when the supernova shock emerged from the photosphere of the supernova progenitor. While the NTT image has occasionally been interpreted as showing a limb-brightened hourglass nebula, the HST images clearly proved that in reality the three rings form three physically distinct rings in space (see Fig. 3b for a geometrical model): the supernova lies at the geometrical center of the inner ring, while the two outer rings are displaced to the south and the north but are in approximate alignment with the symmetry axis of the inner ring. This geometry implies an approximately axi-symmetric but highly non-spherical structure of the pre-supernova mass loss, a key feature any successful progenitor model has to explain. The axi-symmetry strongly suggests that rotation must have played an important role in the shaping of the nebula. However, since any single star would only be slowly rotating as a red supergiant when this material was ejected

(based on the low expansion velocity of the ring material), this gave one of the strongest hints that the progenitor most likely involved a binary interaction where the angular momentum stored in the orbital motion provided an important source of angular momentum in the late evolutionary phase of the progenitor.

Besides the blue-supergiant puzzle and the triple-ring nebula mystery, there were also a number of major *chemical anomalies* that needed explaining. Detailed analysis of the chemical composition of the inner ring showed that it was not only highly enriched in CNO-processed material (with $N/C \sim 5$ and $N/O \sim 1$, where the ratios are by number), but also had a helium abundance that was almost twice solar (with $He/H \sim 0.25$), something that is not expected in the evolution of a single massive star (with the possible exception of a model involving very rapid rotation).

In summary, the key properties any successful model for the progenitor of SN 87A has to explain are:

- *The blue-supergiant progenitor* and the fact that it was a red supergiant in the not-too-distant past
- *The triple-ring nebula,* composed of material that was ejected only $\sim$20,000 years before the explosion
- *The dredge-up of a large amount of helium and CNO-processed material*

All of these anomalies directly point to an unusual event that occurred just $\sim$20,000 years before the explosion, most likely involving a binary interaction.

5 The Importance of Binary Interactions

It has long been known that massive stars are most commonly found in binary systems, often with components of similar mass. While many of the systems will be sufficiently wide so that the two stars evolve independently just like single stars, recent observations have shown that perhaps 50–70 % of all massive stars are in binaries that are close enough that mass transfer will take place between the two components at some point during their evolution, thereby drastically altering the further evolution and final appearance of the stars. As supernova explosions probe the final structure of the progenitors, it is almost certain that binary interactions are responsible for the large diversity of supernova types and sub-types that is being observed.

In the simplest type of binary interaction, *stable mass transfer*, mass is transferred from a Roche-lobe-filling component to its companion, affecting the structure of both stars: one by *mass loss*, one by *mass accretion*. If the mass-losing component has a hydrogen-rich envelope, the most likely outcome is that it loses all/most of its hydrogen-rich envelope and becomes a helium (or Wolf-Rayet) star, a progenitor for a Type Ib/c supernova. If some hydrogen-rich material is left over, producing a stripped star with a small hydrogen-rich envelope, the resulting supernova may appear as a hybrid SN IIb. How the structure of the mass-accreting star is changed depends on the evolutionary phase of the accretor. If it is still on the main sequence,

the star will be *rejuvenated* and subsequently behave like a more massive single star (at least up to the point where it might fill its own Roche lobe). On the other hand, if accretion takes place after the accretor has left the main sequence, this will increase its total mass relative to its core mass. Detailed binary evolution calculations show that such stars are much more likely to burn helium as blue supergiants, avoiding a red-supergiant phase altogether and may explode as blue supergiants just like SN 87A.

The most dramatic type of binary interaction involves the actual merger of the two components. The further evolution will also depend on the evolutionary stage of the two components when the merger occurs. If it is on the main sequence, the resulting merger product will be a rejuvenated star whose further evolution will resemble that of a single more massive star. If the primary has already left the main sequence and the merger occurs in the Hertzsprung gap, the subsequent evolution again is likely to avoid a red-supergiant phase and ultimately produce a blue-supergiant supernova progenitor. This is statistically the most likely phase for a star to merge and may be the fate of 5–10 % of all massive stars.

A binary merger is at the present time the best model to explain SN 87A. However, the dynamical age of the triple-ring nebula, which is most likely linked with the merger event, shows that the merger must have occurred very late in the evolution of the primary, in fact after helium core burning had been completed, as will be discussed in detail in the next section.

6 The Merger Model for SN 1987A

The idea that the progenitor of SN 87A involved the merger of two stars in a binary was first suggested by Chevalier and Soker (1989) who noted that the observed polarization of supernova light required a flattened structure of the progenitor's envelope which was not consistent with that of a single star. Hillebrandt and Meyer (1989) and Podsiadlowski et al. (1990) independently showed that a merger would also help to explain a blue-supergiant progenitor. The initial merger idea has evolved significantly since those early days, and I will discuss its latest version in the following (further details can be found in Podsiadlowski et al. 2007).

Figure 4 presents a cartoon that illustrates the merger event that leads to the formation of the triple-ring nebula. The binary started out as a garden-variety binary with two stars of $\sim$15–20 $M_\odot$ and $\sim$5 $M_\odot$, respectively (although the precise masses are presently not very well constrained). The system was wide enough (with an orbital period $>$10 years) so that the primary only filled its Roche lobe after it had completed helium burning in the core (leading to so-called Case C mass transfer). Because of the large mass ratio, mass transfer is unstable, and the expanding envelope of the primary engulfs the companion leading to a common-envelope phase, where the core of the primary and the companion star are embedded in the envelope of the red-supergiant primary. Because of friction between the immersed binary and the envelope, the orbit of the binary will shrink. This has two important consequences: first, the orbital angular momentum of the binary is

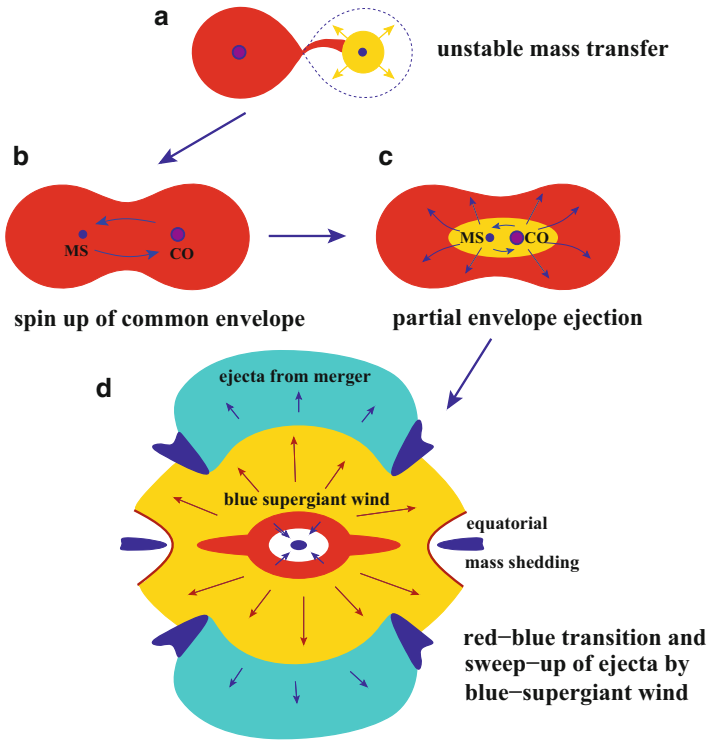


Fig. 4 Schematic diagram showing the formation of the triple-ring nebula in the Case C merger model (From Morris and Podsiadlowski 2007)

transferred to the envelope, spinning it up and producing a flattened, even disc-like envelope structure. Second, as the initial spiral-in is quite rapid, a significant fraction of the orbital energy that is released in the initial rapid spiral-in is deposited in the envelope causing its partial ejection (this will be essential for understanding the formation of the outer rings). Once enough energy has been deposited in the envelope, the envelope will have expanded sufficiently to slow down the spiral-in process. The system now enters into a slow spiral-in phase, probably lasting several 100 years, where all the further energy that is released in the spiral-in is transported by convection to the surface where it is radiated away. This phase ends when the companion starts to fill its own Roche lobe and starts to transfer mass to the core of the initial primary inside the common envelope. Detailed simulations of this phase show that, because of its low entropy, the hydrogen-rich stream emanating from the secondary can penetrate deep into the outer parts of the primary's helium core, dredging up a significant fraction of the helium core in the process. As this material is mixed with the rest of the envelope, this provides a natural explanation for the chemical anomalies observed in the progenitor and its nebula. Ultimately, the companion will have been completely eroded and the now merged single star

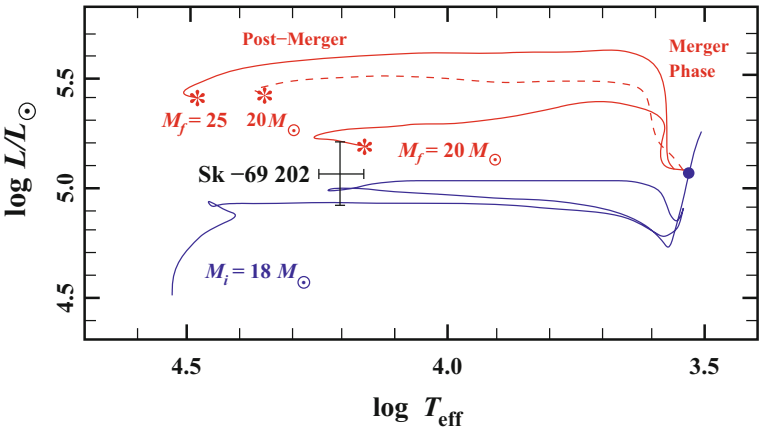


Fig. 5 HR diagram illustrating the merger of a star with an initial mass of 18 $M_\odot$ with a 10 $M_\odot$ companion after helium core burning has been completed for different amounts of helium dredge-up. The final masses are indicated

will have some unusual properties: (a) it will be rapidly rotating (at least initially), (b) have anomalous chemical abundances in the envelope, and (c), because of the reduction in core mass and the increase of the helium mass fraction in the envelope, is likely to become a blue supergiant.

Figure 5 shows several representative merger calculations that simulate the merger of a 18 $M_\odot$ star merging with a 10 $M_\odot$ for different assumptions about the mass loss and the amount of dredge-up from the core (see Podsiadlowski et al. 2007 for further details).

The Formation of the Triple-Ring Nebula

In the merger model, the outer rings form from material that is ejected in the initial rapid spiral-in phase where the impulsive injection of energy in the envelope causes the ejection of a small fraction of the envelope (10^{-2}–10^{-1} $M_\odot$). Because of the flattened envelope structure, material cannot be ejected in the equatorial direction but only in the polar direction, producing a bipolar shell-like outflow. After the merger has been completed and after the star has become a blue supergiant, the fast wind from the blue supergiant will sweep up all the slowly expanding structures that had been ejected previously and produce two dense physical rings at the end of two bipolar caps (see Fig. 4).

The inner ring is most likely produced at the beginning of the transition from the red- to the blue-supergiant phase when the merged object has to lose all its excess angular momentum: there is much more angular momentum in the original orbit than a blue supergiant can stably store in its spin. This causes equatorial mass shedding (which may contain 1 $M_\odot$ of material or more) and a slowly

expanding ring-like structure. Detailed hydrodynamical simulations show that this can perfectly reproduce the triple-ring nebula. Figure 3c shows the result of such a simulation that can produce both the geometrical and the kinematical structure of the nebula as well as the Hα emission observed with the HST.

7 Alternative Ideas

While the merger model described in the previous section is probably the best current model, one needs to ask whether there might be alternative ideas to explain the anomalies of the progenitor. Since there are still significant gaps in our modeling of massive stars, it is possible that, for some combination of physical parameters, even some single stars return from the red-supergiant region to the blue just before the explosion, but this would only explain one of the anomalies. If such a star was also very rapidly rotating initially, some of that angular momentum might still be left in the red-supergiant phase which in the transition to the blue (when the density structure changes to a centrally concentrated profile) can become concentrated in a small surface layer which can even be spun up to critical rotation. However, it follows from simple angular-momentum-conservation considerations that this could not involve more than a few percent of a solar mass, probably orders of magnitude less than will likely be found in the triple-ring nebula. Magnetic fields are sometimes invoked to produce bipolar structures. However, to apply this to SN 87A, it would require magnetic fields that are dynamically important in the outflowing material, much larger than one can reasonably expect from a single star. Indeed, this would probably require a powerful magnetic field in the red-supergiant phase, which in turn would require a powerful dynamo which can only be driven by a large amount of (differential) rotation and which most likely could only be achieved in a binary merger scenario. More promising alternatives to such single-star ideas probably involve other types of binary interactions; for example, an accretion scenario where the companion (the initial primary of the system) has already become a compact object (neutron star or black hole) and is now difficult to detect; such a scenario could potentially also explain the major supernova anomalies.

8 Future Tests and Unsolved Mysteries

8.1 The Complex Outer Circumstellar Nebula

The circumstellar nebula around SN 87A does not only involve the triple-ring nebula. In addition, to the "Napoleon's Hat" feature (Fig. 3a), light echo studies show other complex structures further out, some of which are clearly caused by the interaction with material that was ejected in the red-supergiant phase. Figure 6 shows some of the expected structures in the merger scenario if the red-supergiant mass loss is taken into account. While these simulations appear broadly consistent with the observed light echos, there are a number of modeling uncertainties.

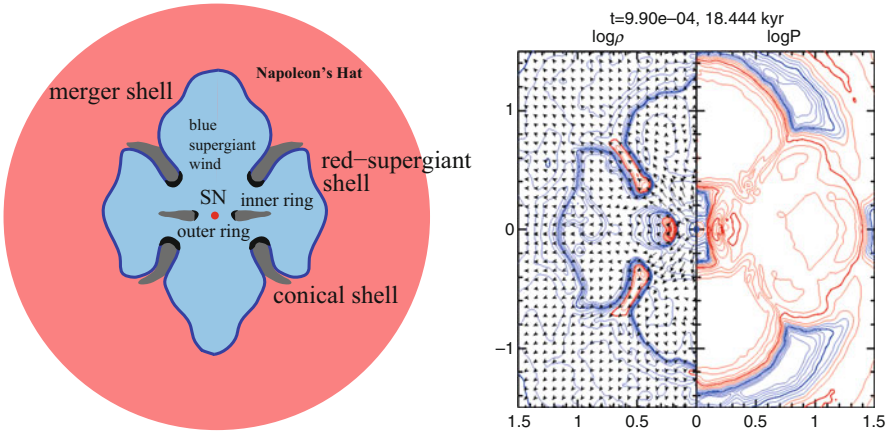


Fig. 6 The predicted outer CSM around SN 87A including red-supergiant mass loss. *Left panel*: cartoon illustrating the main expected structures. *Right panel*: hydrodynamical simulations showing density and pressure contours

Fortunately, future observations of the interaction of the supernova ejecta with the nebula will remove all remaining uncertainties. This interaction which has already started will in the long run destroy all the intricate structures produced by the progenitor. This will allow us to exactly determine how much mass is in the circumstellar medium (CSM) and its exact three-dimensional geometry and therefore directly test the merger predictions. But even before the ejecta have reached the outer nebula, the high-energy radiation produced by the interaction of the ejecta with the dense material (e.g., in the inner ring) may partially re-ionize the nebula, making presently invisible structure visible (again) and potentially give us a completely new view of the whole nebula.

8.2 The Missing Compact Remnant

One major puzzle is the question of the missing remnant. While it is clear from the neutrino burst (Sect. 2) that a neutron star was initially formed, even 30 years after the explosion there is no evidence for a pulsar or any central energy source. A pulsar could in principle either be seen directly if it is beamed toward us or indirectly by providing an energy source to the supernova remnant. Present constraints rule out even a rather faint pulsar. This has led some people to argue that the neutron star has, since its formation, collapsed to a black hole. On the other hand, we now know that not all neutron stars are born as powerful pulsars like the Crab pulsar. For example, the neutron star detected by the Chandra X-ray satellite in Cas A, a young supernova remnant, would be far too faint to be detectable at the distance of the LMC. Therefore it is still too early to rule out a neutron star remnant.

9 Conclusions

SN 87A has been a spectacular event that proved that Type II supernovae are caused by the collapse of massive stars. The question of the progenitor has been a long-lasting puzzle, but there have been enough clues (in particular from the triple-ring nebula) that a complex but pretty much complete picture has finally emerged that links all the observed anomalies to the merger of two stars some 20,000 years before the explosion. While the model may still not have convinced the last skeptic, it makes a number of specific predictions that will ultimately be tested by the interaction of the supernova ejecta with the outer nebula, a process that will take place over the next few decades. While SN 87A has provided us already with a wealth of new understanding of massive stars and supernovae, we can look forward for this to continue for the foreseeable future.

Cross-References

- ▸ Explosion Physics of Core-Collapse Supernovae
- ▸ Neutrino Driven Explosions
- ▸ Neutrino Emission from Supernovae
- ▸ The Physics of Supernova 1987A
- ▸ The Supernova – Supernova Remnant Connection

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