

The Triple-Ring Nebula: Fingerprint of a Binary Merger¹ (*or* Supernova 1987A: a Mystery Solved)

Supernova 1987A (SN 1987A), the first naked-eye supernova observed since Kepler's supernova in 1604, was an anomalous supernova that has confounded astronomers for many years. Its anomalies have long been attributed to the merger of two massive stars that occurred some 20,000 years before the explosion, but so far there has been no conclusive proof that this merger took place. In the present issue of *Science Magazine*, we present three-dimensional hydrodynamical simulations of the mass ejection associated with such a merger and the subsequent evolution of the ejecta, and we show that this accurately reproduces the properties of the triple-ring nebula surrounding the supernova in great detail. This proves beyond reasonable doubt the merger model for SN 1987A and brings to an end a 20-year old mystery.

Scientific credit: Prof. Philipp Podsiadlowski, Oxford University
Dr Thomas Morris, Oxford University and MPA, Munich
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1 Background

A supernova is caused by the explosion of a massive star at the end of its evolution. Supernova 1987A (SN 1987A) was the first supernova visible with the naked eye since Kepler's supernova in 1604. It occurred on February 23, 1987 in the Large Magellanic Cloud, a satellite galaxy of our own galaxy, the Milky Way, about 180,000 lightyears away². Since it was the first nearby supernova seen in almost 400 years, it has long been awaited by astronomers and therefore was one of the major astronomical events of the 80s. The observations of neutrinos from the supernova confirmed that supernovae are produced by the collapse of a massive star, leading to the formation of a neutron star³.

¹Background material to a report with the same title published in *Science Magazine* on February 23, 2007 by Thomas Morris and Philipp Podsiadlowski.

²This actually means that the supernova occurred some 180,000 years ago in the past, but it took light so long to reach the Earth before we could observe the event.

³Neutrinos are elementary particles that are produced when the core of a massive star collapses to form a neutron star. A neutron star is a small compact object, mainly composed of neutrons, somewhat more massive than the Sun, but only with a radius of 10 km.



Figure 1: SN 1987A in the Large Magellanic Cloud. *Right Panel:* AAT image of the region before the explosion. The arrow points at the blue supergiant star before the explosion. *Left Panel:* AAT image of the region after the explosion. The new bright source is the supernova, produced by the explosion of the blue supergiant.

2 The Mystery of the Progenitor Star

While SN 1987A confirmed some long-held beliefs about supernovae, the star that exploded defied expectations and provided a major mystery. Images of the region taken before the explosion (Fig. 1) showed that the star that exploded was a blue supergiant, a star about 20 times as massive as the Sun and about 40 times larger in radius. Theoretical models of the evolution of massive stars had predicted that these end their evolution as red supergiants with a radius at least 1,000 times the radius of the Sun⁴. In addition, the composition of the star that exploded was very unusual; most importantly, the outer layers of the star had an abundance of helium (as a fraction of the total composition) that was about a factor of 2 larger than the expected abundance, as if part of the material from the core, where helium has been produced during the previous evolution of the star, was mixed into the outer layers by some unexpected mixing process. Why was the star blue and not red and why were there these chemical anomalies? As with any major astronomical event, there was an initial scramble among theorists to explain the unusual properties of the progenitor, but as in any good mystery story, all of the early leads should turn out to be dead ends.

⁴For comparison, the distance of the Sun to the Earth is about 200 times the radius of the Sun. A red supergiant would therefore be larger than the orbit of Jupiter.

Figure 2

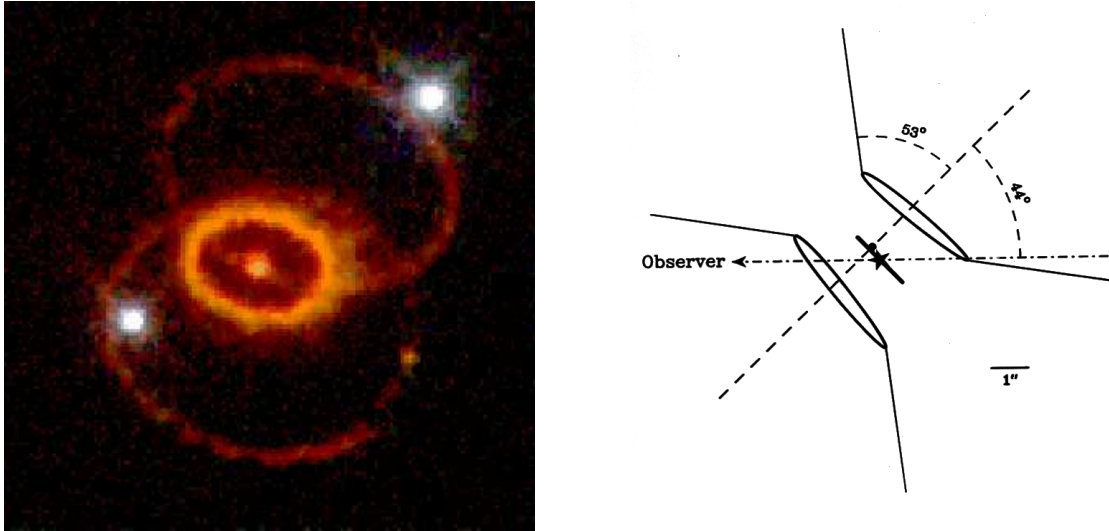


Figure 2: The triple-ring nebula around SN 1987A. *Left Panel:* Hubble Space Telescope image of the nebula. *Right Panel:* Three-dimensional geometry of the three rings. The supernova is at the center of the inner ring, the outer rings are displaced above and below the central ring plane. The rings are seen in projection by the observer (us) as indicated. All of the material in the rings was ejected some 20,000 years before the explosion.

3 The Triple-Ring Nebula

The key clue that showed that most of the early models could not work was the discovery of the triple-ring nebula around the supernova⁵.

The nebula is composed of three overlapping rings, seen in projection (see Fig. 2), and consists of material that was ejected from the progenitor star some 20,000 years before the explosion. The supernova occurred right at the center of the inner ring, while the outer rings lie in planes below and above the central ring plane. The whole nebula was flash-ionized by the supernova, and we are now seeing the afterglow of this flash. The nebula is almost axisymmetric. This generally suggests that rotation may have played an important role in the shaping of the nebula. However, any star that was rapidly rotating early in its evolution could not have been rapidly rotating as a supergiant⁶. This essentially ruled out that the progenitor

⁵The nebula was discovered by E. J. Wampler *et al.* (*Astrophys. J.* **362**, L13 [1990]) with a telescope operated by the European Southern Observatory (ESO) in Chile. The most spectacular images of the nebula have been taken with the Hubble Space Telescope (C. Burrows *et al.*, *Astrophys. J.* **452**, 680 [1995]); see Figure 2.

⁶This follows from the conservation of angular momentum. If a star expands by a large factor, its spin rate has to decrease, just as an ice-skater starts to spin more slowly when extending her arms at the end of a pirouette.

star could have been a *normal* single star and strongly suggested that the progenitor was a member of a binary system, where two stars orbit each other. In this case, it is possible to use some of the rotation stored in the binary motion to spin up one or both stars. Indeed, it is well established that the majority of massive stars are found in binary systems and are often close enough that the two stars interact directly; for example, mass can flow from one star to the other, transferring mass and spin in the process. One of the most dramatic types of binary interactions is the complete merger of two stars to form a *single, rapidly rotating* star. Such binary mergers are relatively common events. Theoretical models predict that about 10% of all massive stars will merge with a companion star at some point during their evolution⁷.

4 A Binary Merger Model for the Progenitor of SN 1987A

The idea that the anomalous properties of the progenitor of SN 1987A are the result of the merger of two stars about 20,000 years before the explosion has long been the leading model for the progenitor⁸. In this model, the system consisted initially of two massive stars, one with a mass of 15–20 times the mass of the Sun and a less massive companion with a mass of ~ 5 times the mass of the Sun. The two stars were orbiting each other with a period of at least 10 years (i.e. it took at least 10 years for one star to revolve around the other). With these parameters the stars would only interact late during the evolution of the more massive star, in fact about 20,000 years before the explosion⁹. When the more massive star starts to transfer mass to the less massive star, mass transfer is unstable, and the more massive star engulfs its less massive companion (see Fig. 3 for a schematic diagram). The less massive star then orbits the core of the more massive star inside the envelope of the more massive component. Because of friction with the envelope, the orbit decays, similar to the decay of the orbit of a satellite orbiting the Earth when entering into the Earth's atmosphere. Ultimately this leads to the complete merging of the two stars, spinning up the envelope in the process. While it is clear that such a model can qualitatively explain the main features of the supernova, the details of how the merger proceeds has only recently been studied in some detail. In her PhD thesis (Oxford 2003), Natasha Ivanova showed, using detailed stellar and hydrodynamical simulations (see Fig. 4) of the final merging of the companion with the core of the massive star that this leads to the erosion of part of the core and mixing of core material into the outer envelope, explaining both the chemical anomalies and the cause of the final red-blue transition.

⁷This estimate roughly applies to stars of all masses. This implies that there should be one merger event in our galaxy every ~ 10 years.

⁸A merger model to explain the blue color of the progenitor and its chemical anomalies were proposed initially independently by Ph. Podsiadlowski, P. C. Joss and S. Rappaport (*Astron. Astrophys.* **227**, L9 [1990]) and W. Hillebrandt and F. Meyer (*Astron. Astrophys.* **219**, L3 [1989]). The present best model is close to the revised version outlined in Ph. Podsiadlowski (*Publ. Astron. Soc. Pac.* **104**, 717 [1992]).

⁹For comparison, the overall lifetime of the star was $\sim 10^7$ years. The merging process itself took several 100 years.

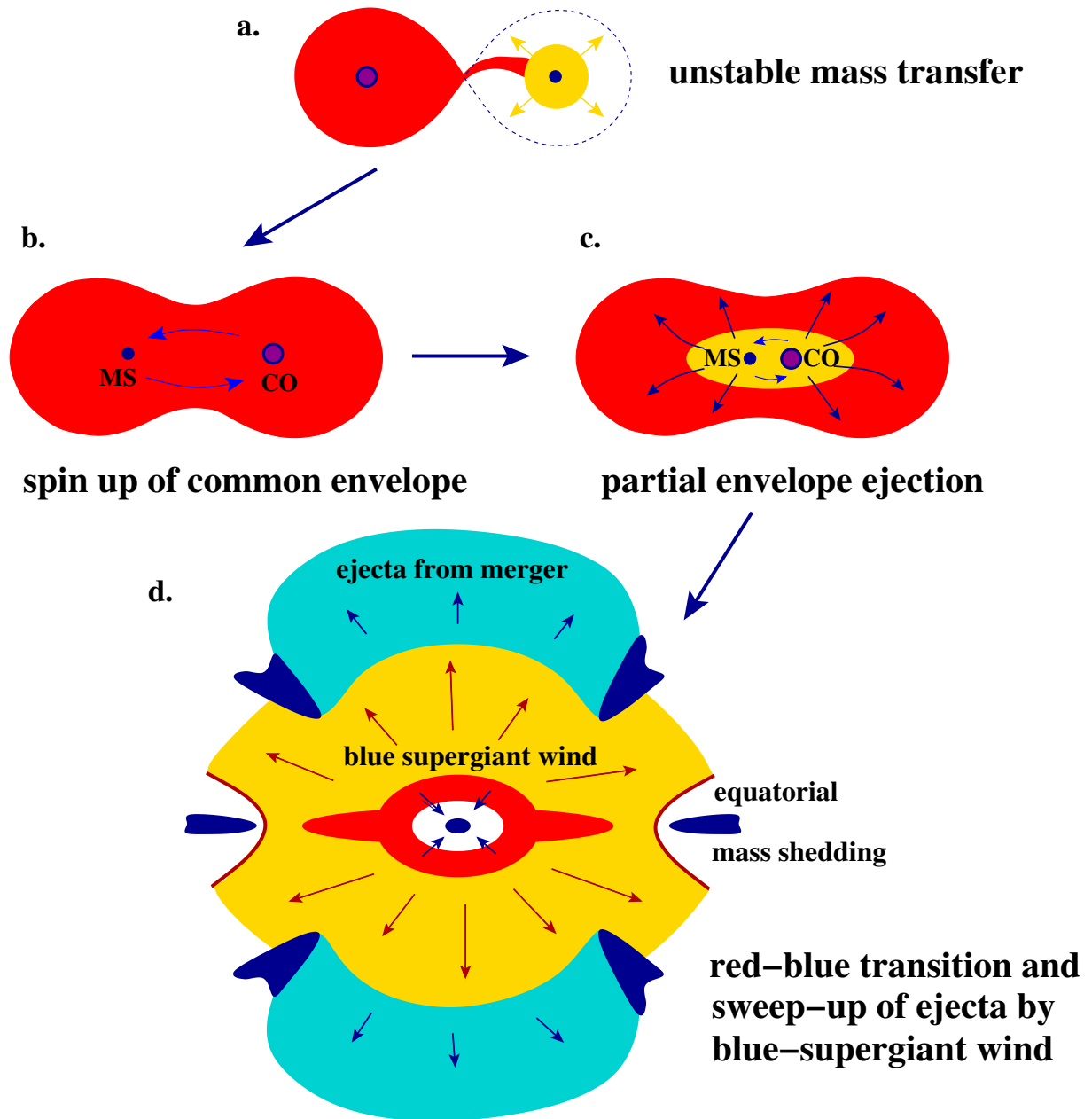


Figure 3: Schematic diagram illustrating the formation of the triple-ring nebula (taken from the *Science Report*).

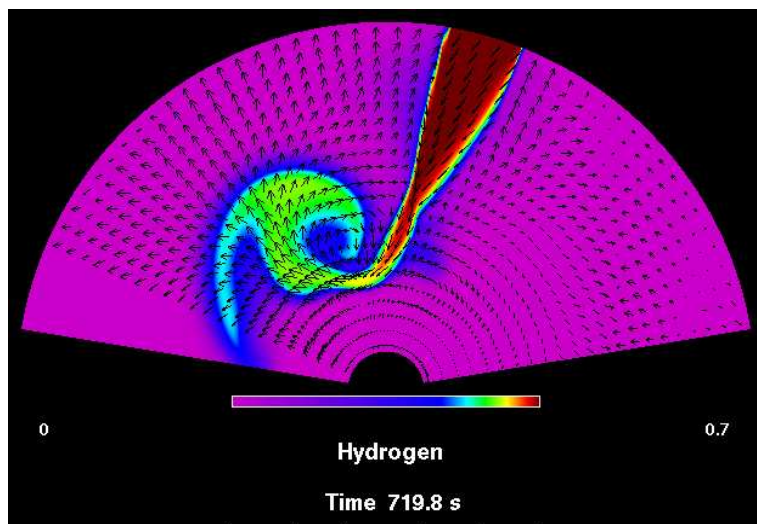


Figure 4: A two-dimensional hydrodynamical simulation showing how in the final merging phase, the stream from the immersed companion that is being dissolved impacts onto the core of the massive star, causing partial erosion of the core and mixing of core material into the outer envelope (from N. Ivanova, *DPhil Thesis*, Oxford 2003).

5 The Formation of the Triple-Ring Nebula

One of the remaining unsolved puzzles has been the formation of the triple-ring nebula. While there have been numerous suggestions in the past, none of these have been able to account for the geometry and the velocity structure of the nebula in a satisfactory manner. In his PhD thesis (Oxford 2006), Thomas Morris has modelled the mass ejection during the merging phase and the subsequent evolution of the ejecta and has been able to successfully reproduce all the major features of the nebula¹⁰. During the early spiral-in phase of the companion (see Fig. 5), the envelope is spun up to produce a disk-like geometry (Fig. 5a). As the companion spirals in, it heats up the envelope causing the ejection of part of the envelope (typically ejecting half a solar mass of material). Because of the disk-like structure of the envelope, matter is more easily ejected along the polar direction. Indeed in the best models, no mass is ejected in the plane of the disk; matter trying to escape in the direction of the disk is deflected by the disk mass towards higher latitude producing a high density concentration of ejected matter at an angle of roughly 45° (Fig. 5b,c). After the merger has been completed, the now single object shrinks to become a blue supergiant. In this transition as much as several solar masses are spun off in the equatorial direction producing a disk-like outflow. In the last 20,000 years before the star explodes, it is a blue supergiant. Such stars have strong stellar winds (i.e. eject parts of their envelopes just as the Sun expels matter in the solar wind). These winds then sweep up all the structures that have

¹⁰These simulations involve hydrodynamical simulations in three dimensions using the technique of smooth particle hydrodynamics, where the fluid is represented by typically 10^6 particles.

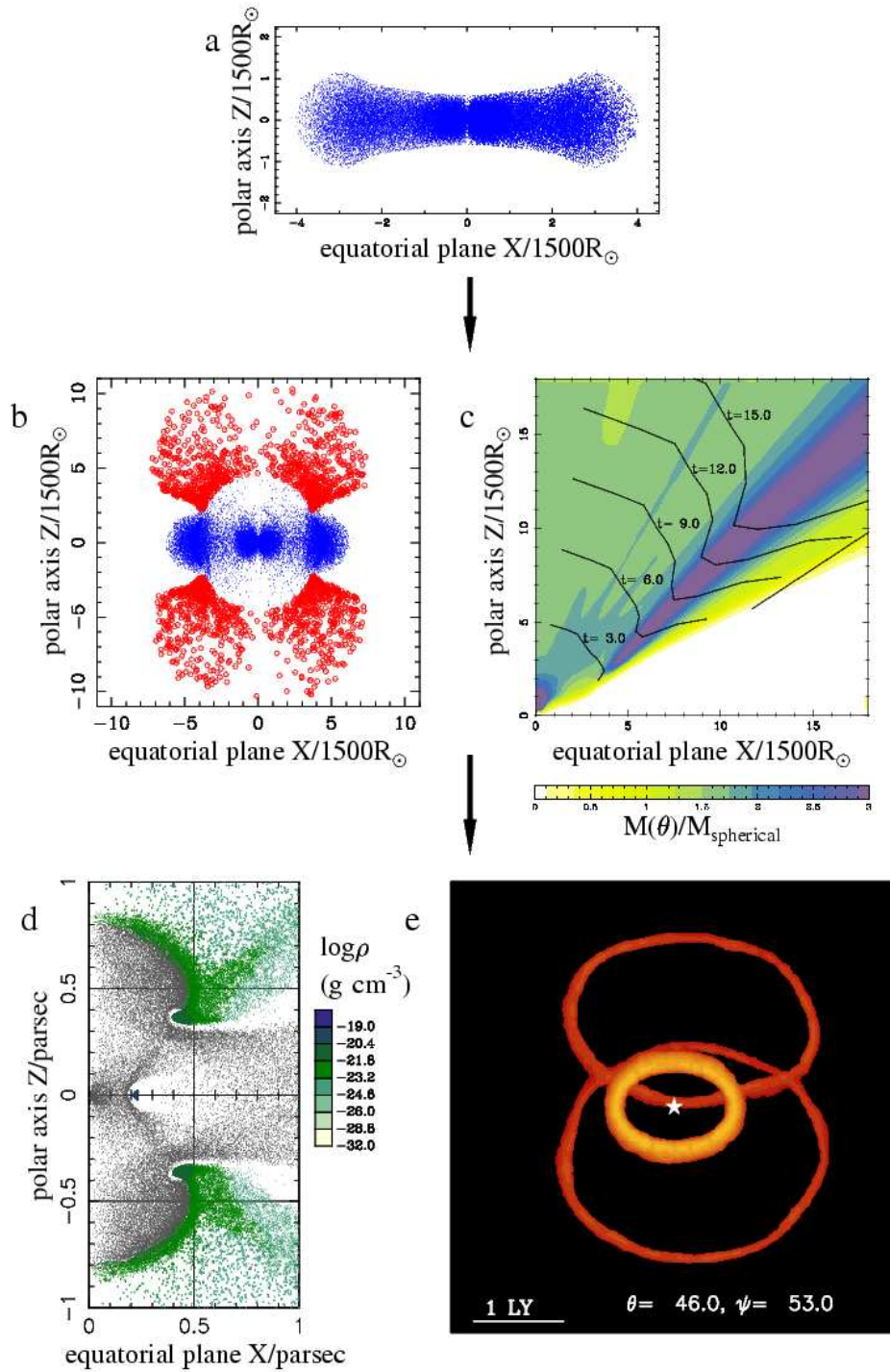


Figure 5: Three-dimensional hydrodynamical simulations illustrating the various phases of the formation of the triple-ring nebula (taken from the *Science Report*).

been produced previously to produce the observed triple-ring nebula.

It is important to note that this model now provides a complete physical picture to what happened to the progenitor of SN 1987A without requiring *ad hoc* assumptions or invoking unknown physics. Indeed had astrophysicists been clever enough and thought about the detailed physical processes involved in a binary merger, they could have predicted this before SN 1987A was observed.

Our latest simulations of the triple-ring nebula present a near-perfect fit to the observations of the nebula and have filled in the last major gap in our understanding of SN 1987A. This has now provided more-or-less conclusive proof of the merger model for the progenitor of SN 1987A, bringing to an end a 20-year old mystery.

6 Historical Notes

Prof. Podsiadlowski has worked on the problem of understanding the progenitor of SN 1987A for the last 20 years. In his PhD thesis (M.I.T. 1989), he examined different binary models for the progenitor and developed the basic merger model. Initially, the model was considered with some scepticism by the supernova community; this started to change with the discovery of the triple-ring nebula. Since about 1997 the merger model has been considered the most promising model for the progenitor of SN 1987A, but it required two more PhD thesis by Natasha Ivanova (Oxford, 2003) and Thomas Morris (Oxford, 2006) to fill in the gaps and provide the complete physical picture we now have.