Twenty Years of Supernova 1987A

Claes Fransson[1]
Roberto Gilmozzi[2]
Per Gröningsson[1]
Reinhard Hanuschik[2]
Karina Kjær[2]
Bruno Leibundgut[2]
Jason Spyromilio[2]

[1] Stockholm University
[2] ESO

The unique supernova SN 1987A has been a bonanza for astrophysicists. It provided several observational 'firsts', like the detection of neutrinos from the core collapse, the observation of the progenitor star on archival photographic plates, the signatures of a non-spherical explosion and mixing in the ejecta, the direct observation of supernova nucleosynthesis, including accurate masses of ^{56}Ni, ^{57}Ni and ^{44}Ti, observation of the formation of dust in the supernova, as well as the detection of circumstellar and interstellar material. Now, after 20 years, it continues to be an extremely exciting object as we will be able to observe the supernova shock interacting with the circumstellar ring in real time.

Entering with a bang

When the first signs of Supernova 1987A, the first supernova of the year 1987, were noticed early on 24 February 1987, it was clear that this would be an unusual event. It was discovered by naked eye and on a panoramic photographic plate taken with a 10-inch astrograph on Las Campanas in Chile by Oscar Duhalde and Ian Shelton, respectively. A few hours earlier, still on 23 February, two large underground proton-decay detectors registered the passage of high-energy neutrinos. Unlike the optical detections the localisation of the source was not so easy for the total of 20 neutrinos detected within about 13 seconds. Since SN 1987A exploded in the Large Magellanic Cloud (LMC), the detectors on the northern hemisphere measured the neutrinos after passage through the Earth. In recognition for this first detection of neutrinos from a celestial object other than the Sun, Masatoshi Koshiba was awarded the Nobel Prize in 2002 (shared with Riccardo Giacconi for X-ray astronomy and Raymond Davis Jr. for solar neutrinos).

The most important implication of the neutrinos was that it confirmed the hydrodynamic core collapse, releasing about 3×10^{53} ergs of gravitational energy, mainly in neutrinos of all kinds. This confirmed the predictions by Colgate, Arnett and others from the 1960s. Among many other results, the few neutrinos showed that the electron-neutrino mass has to be rather small ($m_{\nu_e} \leq$ 20 eV, superseded in the meantime by direct experiments) as no time-delay effects could be measured. Also, the fact that there is no structure in the neutrino burst indicates that they came from the collapse to the neutron star, but no further collapse to a black hole occurred. At the same time these neutrinos gave an unprecedented accuracy of better than a minute (the reason the accuracy is not better had to do with the time keeping at the neutrino detectors) for the time of explosion, which optical observations cannot provide, as the photons emerge from the shock breakout on the surface of the exploding star, which can occur several hours later. The neutrinos were the direct signal from the collapse of the core of Sanduleak -69° 202 to a neutron star.

A historical irony has it that this very star was on the target list of an ESO observing programme looking at blue supergiants in the LMC with the 3.6-m telescope in December 1986. Unfortunately, it was not observed and hence we do not have a high-resolution spectrum of it. Pre-explosion images show a rather unspectacular blue supergiant. The earliest optical observations of the supernova – some of them were pre-discovery plates – pieced together from observations in Australia and South America, showed a steep luminosity increase of about six magnitudes in less than half a day. Since the discovery was only made in the morning in Chile, the first spectrum of SN 1987A was obtained in South Africa. From then on, the supernova was on the observing programme of every major southern or active space observatory, in particular IUE. Ironically, it was too bright for the state-of-the-art 4-m telescopes and many of them had to be stopped down, e.g. by half-closed telescope covers. Some of the smaller telescopes took their chance. The 61-cm Bochum telescope on La Silla was used, on a nearly daily basis for more than a year, to measure optical spectroscopy with photometric accuracy. Since the LMC is circumpolar for most southern observatories, this also meant that we have an uninterrupted record of the photometry and spectroscopy; else we would have missed part of the peak phase, which lasted into May of 1987.

By July, the first conference on SN 1987A had already taken place at ESO in Garching (Danziger 1987) to be followed by several others during that year and following years. Among the many excellent reviews of different aspects of SN 1987A we note Arnett et al. (1989), Chevalier (1997), and McCray (1993, 2005).

An unusual supernova

The optical light curve of SN 1987A was rather different from the one of previously observed core-collapse supernovae. Progenitor stars were normally assumed to be red supergiants with extended envelopes, which would produce long plateau phases in the light curve. Not so SN 1987A, which started out as an extremely blue object only to turn into the reddest supernova ever observed. The reason for this was that the supernova was discovered so early that the early cooling phase, when the supernova ejecta cool down from the shock passage, could be observed. But SN 1987A did not become as luminous as expected. The compact nature of the blue supergiant meant that the adiabatic cooling was stronger, producing a fainter object than usual. About four weeks after the explosion, the supernova light curve was powered by the radioactive decay of freshly synthesised ^{56}Ni. Unlike any supernova before, it was possible to construct a bolometric light curve of SN 1987A, which was extremely useful for the physical interpretation of the event. The absence of a significant plateau phase was understood in the context of the nature of the progenitor star and the extent to which the ejecta of the supernova were mixed. It turned out that helium was mixed into the hydrogen layer and hydrogen further down into the ejecta. This was also apparent from the early appearance of X-rays, originating from the ^{56}Co decay. Further confirmation for the strong mixing of the layers in SN 1987A came from the line shapes of the infrared lines. The old models of spherical explosions had to be revised, and density inhomogeneities in the stellar structure were recognised as responsible for turbulent mixing when the shock moved across such boundaries.

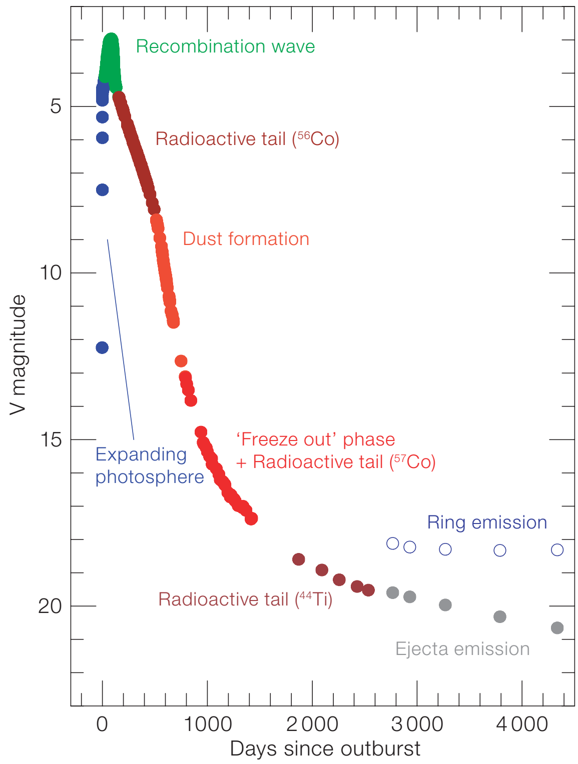


Figure 1: Light curve of SN 1987A over the first 12 years. The figure marks some of the most important events in the history of the supernova (from Leibundgut and Suntzeff 2003).

The next surprise was revealed by high-spatial resolution observations with speckle cameras at the AAT and the CTIO 4-m telescopes. They independently found a 'mystery' spot close to the supernova. The nature of this phenomenon remains unclear, but it was a strong indication of broken symmetry. The asymmetry was also detected in polarisation observations of SN 1987A.

The spectroscopic evolution provided further evidence for asymmetries in the explosion. The 'Bochum event' was a rapid change in the P Cygni profile of the Hα line observed with the Bochum telescope on La Silla (shown in Figure 2). It is the signature of a radioactive blob rising from the inner ejecta to the surface. The picture emerging from the observations of the first several weeks was certainly more complex than what had ever been assumed of supernovae before.

Once SN 1987A entered the radioactive decline, one could have expected that it would become less exciting. Far from it! IUE observations started to detect an increase in flux of several high-excitation lines, like N V, N IV], N III], C V, C III], He II, mirrored by similar behaviour of [O III] and Hα in the optical at about 80 days after explosion. These lines could not possibly come from the fast moving ejecta and were quickly recognised as originating from material outside the supernova, ionised by the soft X-rays from the shock breakout. From the high ionisation of these lines, a temperature of ~ 10^6 K at the shock breakout could be inferred.

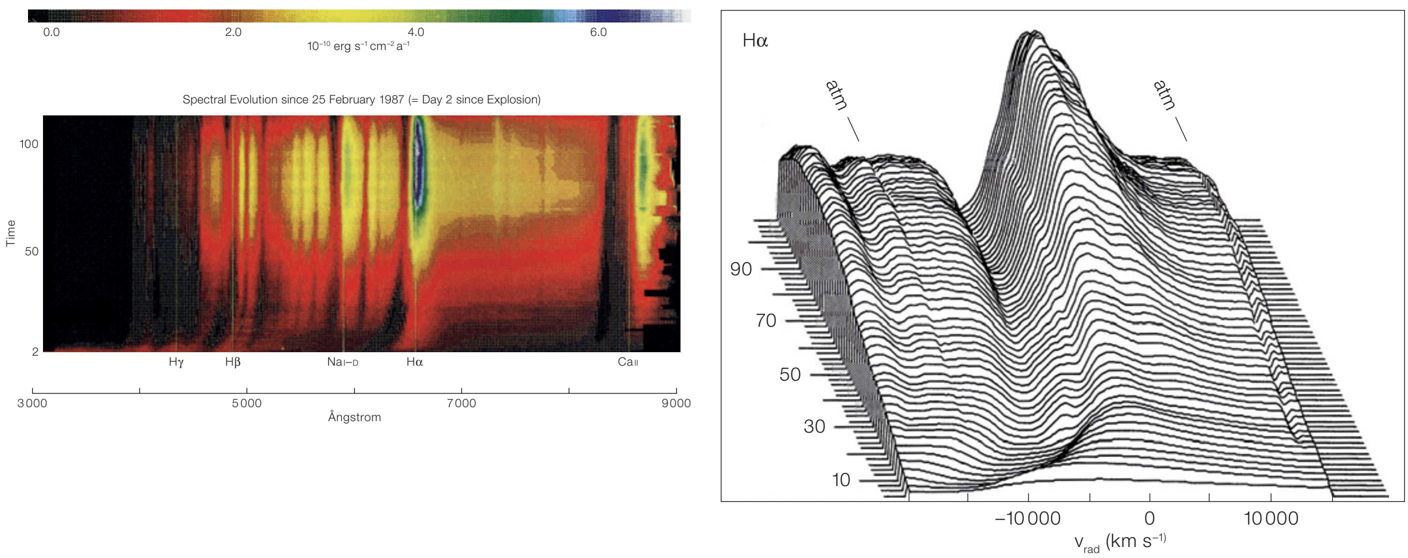


Figure 2: Spectral evolution of SN 1987A as observed with the Bochum telescope (Hanuschik and Thimm 1990). Important lines are marked at the bottom. The evolution covers the first 120 days and the redshifting of all lines is easily visible. The Bochum event is shown in the right panel displaying the Hα evolution as the blueshifted excess.

The circumstellar material had to be from the progenitor star itself due to the high N/C ratio, indicating CNO processing (Fransson et al. 1989). This was, of course, emission from the inner circumstellar ring around SN 1987A, which was first imaged with the NTT. Later HST images provided the linear dimensions of the ring. In combination with the rise time for the narrow circumstellar lines, this provided a purely geometric distance to SN 1987A (Panagia et al. 1991). With the LMC being the first rung in the distance ladder to determine the Hubble constant, SN 1987A provided a very solid stepping stone.

Of molecules, radioactivity and freeze-out

At just about the same time as the appearance of the UV lines, the supernova ejecta were presenting another surprise. Infrared spectroscopy about 100 days after explosion showed CO and SiO molecular signatures indicating substantial masses (about 10^{-3} $M_{\odot}$). The presence of the molecules within the ejecta was difficult to explain. The formation of molecules required that they be protected from the UV and X-rays in the harsh environment of the ejecta. This also contrasted with the observations of the characteristic γ-rays at 847 keV and 1.238 MeV from the ^{56}Co decay, observed with KVANT on MIR. The characteristic decay lines could be observed for the first time ever in a supernova, confirming the radioactive energy source. The X-rays are from Compton scattering of the γ-ray rays and their emission peaked after about 200 days and slowly declined thereafter as the number of ^{56}Co nuclei decayed away. The presence of molecules was a clear sign that there were regions in SN 1987A which could cool down significantly, while at the same time the radioactive material from the core had to be transported towards the surface to become observable.

Infrared wavelengths gained in importance as more and more radiation was emitted at longer wavelengths. The bolometric light curve very quickly started to become dominated by long-wavelength radiation and the inclusion of this spectral range became more and more important. ESO and CTIO collaborated for several years in providing this vital ingredient to measure the bolometric light curve. The decline of the light curve remained constant at the rate of decay of ^{56}Co and allowed the measurement of the mass of ^{56}Ni (0.07 $M_{\odot}$) produced in the explosion. The Ni→Co→Fe decay chain could be observed directly in the changing line ratios of the near-infrared Co and Fe lines. The bolometric light curve was also the first indicator that something else was happening about 500 days after explosion. The light curve started to drop below the expected decline rate due to dust formation in the ejecta. At the same time the near-infrared [Fe II] lines dropped dramatically as the ejecta cooled below the temperature to excite these lines, a signature of the infrared catastrophe predicted by modellers (Spyromilio and Graham 1992). Macroscopic dust grains which partially covered the ejecta, and hence blocked some of the light, had formed. The radiation was absorbed in the optical spectrum and shifted to the far infrared, where it was detected by the Kuiper airborne observatory. Line shifts towards shorter wavelengths of the infrared emission lines coming from the ejecta were a signature of the same phenomenon. Again, the explanation was that the distant part of the object is blocked by intervening dust (Lucy et al. 1992).

The light curve had one more unexpected deviation in store. After about 1200 days the decline started to slow down. First interpretations were that the slower decays of ^{57}Co were starting to dominate the light curve, but this would have required unreasonably high isotope ratios, which were inconsistent with the expected nucleosynthetic yields or the known abundances. This interpretation was also incompatible with the observed decline of the infrared Co lines compared to the Fe line, which allowed the amount of ^{57}Co to be deduced. The explanation here was that the time scale for recombination and cooling in the supernova envelope became comparable to the expansion time scale, i.e. some of the 'stored' energy was finally released. This was termed "freeze-out" as the ejecta were no longer in thermal equilibrium and detailed time-dependent calculations had to be performed. The light curve did flatten later because of the ^{57}Co (mass 0.001 $M_{\odot}$) and now is powered mostly by ^{44}Ti (~ 10^{-4} $M_{\odot}$) (Fransson and Kozma 2002). These three radioactive isotopes all formed during the first seconds of the explosion and the masses of these together contribute some very strong constraints on the explosion models. Besides the determination of the radioactive isotopes, the masses of the most abundant elements formed in the progenitor star and in the explosion could also be determined. These included such important elements as carbon, nitrogen, oxygen, manganese and silicon. For the first time one could determine reliable masses of these elements directly.

'Napoleon's hat' and other circumstellar matters

Narrowband imaging with the NTT about three years after the explosion revealed a circumstellar structure around SN 1987A which was supposed to resemble the triangular hat which Napoleon would have worn. Napoleon's hat gave the first opportunity for a three-dimensional view of SN 1987A. This image, together with the detection of extended narrow emission from the He I 1083 nm line and the IUE observations of the circumstellar gas, were the first indications that there was more to come with this supernova. HST revealed first the inner ring and then later confirmed the outer rings (Figure 3). The NTT was used to measure the density and other properties of the outer rings. The HST images also showed the fading supernova ejecta in the middle. The ring on the other hand had been fading extremely slowly and hence after about ten years it started to outshine the ejecta (cf. Figures 1 and 3). The circular ring is inclined by about 43° with the northern part closer to us. It is essentially stationary with an expansion velocity of about 10 km s^{-1}.

The existence of the ring presents an unsolved puzzle for SN 1987A. It is obviously the remnant of the stellar mass-loss history of the progenitor star, but how did it become concentrated into a ring and not be distributed spherically? With the two outer rings there appears to be an hour-glass-shaped structure enveloping the supernova itself. Even though it is not clear how to construct such a ring, it is likely that the progenitor system of SN 1987A had to be a binary (e.g., Morris

Figure 3: NTT image of the circumstellar environment of SN 1987A (left; Wampler et al. 1990) and the ring in 2003 as observed by HST (right).

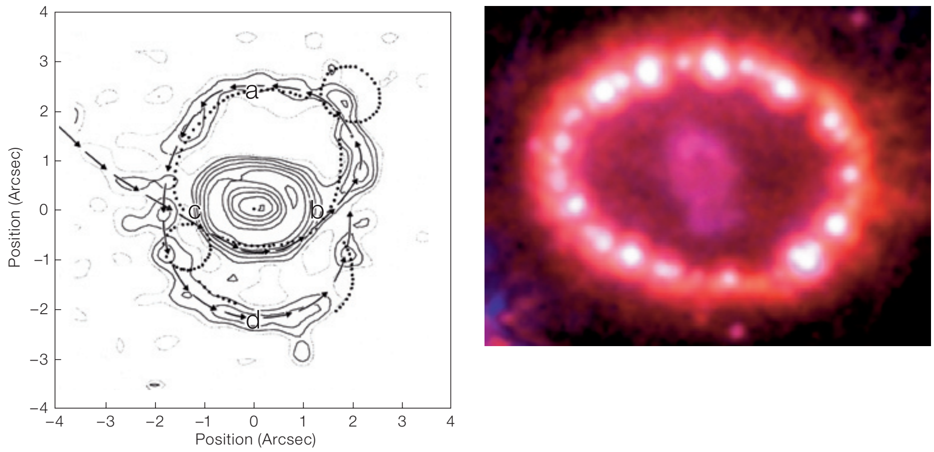
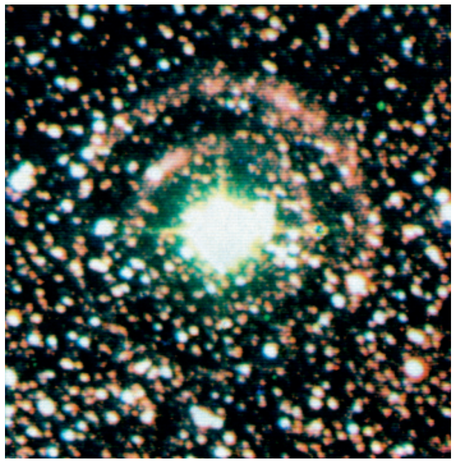


Figure 4: Expanding light echoes around SN 1987A. (ESO PR Photo 08d/07)



and Podsiadlowski 2005). What happened to the companion is unclear and no trace of it – other than the rings – has been detected. Some theories surmise that the progenitor of SN 1987A was a merger, a star that had swallowed its companion.

The prediction that the stationary ring would be reached by the supernova shock was made early on, but the exact date was debated. The radio flux of SN 1987A – after an initial short emission of a few weeks – started to increase again after about 1200 days (Manchester et al. 2002). This brightening has continued since then and was the first signal of the interaction of the supernova shock with the circumstellar environment.

Similarly, the X-ray flux started to increase, and has continued to increase almost exponentially (Park et al. 2006, Haberl et al. 2006). Finally, after 10 years, a spot of optical emission appeared toward the North-East of the ring. And again this was a surprise: rather than having the shock reach a smooth ring more or less simultaneously, the ring appears to be more like spokes on a wheel with inward intrusions. Also, the expansion of the supernova shock may not be uniform but faster in some directions than others. The asymmetries in the explosion could be reflected in this interaction as well. Over the past few years the ring has continued to be lit up in various places and now resembles a pearl necklace (Figure 3 right). The interaction is now observable at all wavelengths from the X-rays (Chandra and XMM), the optical and infrared (all major southern observatories VLT and Gemini, HST), as well as the far infrared (Spitzer) and radio (ATCA), and a rich data set is being assembled.

Several echoes, the integrated light from the peak phase reflected off interstellar sheets between the supernova and us, have been observed over the years around the supernova (see Figure 4). They have been monitored with several telescopes and have been used to map the interstellar material in the LMC near the supernova.

The supernova ejecta themselves are now difficult to observe due to their faintness and the increasing brightness of the inner ring, but it is becoming clear that they display an asymmetric shape. The details will have to be worked out from HST imaging and adaptive-optics observations from the ground.

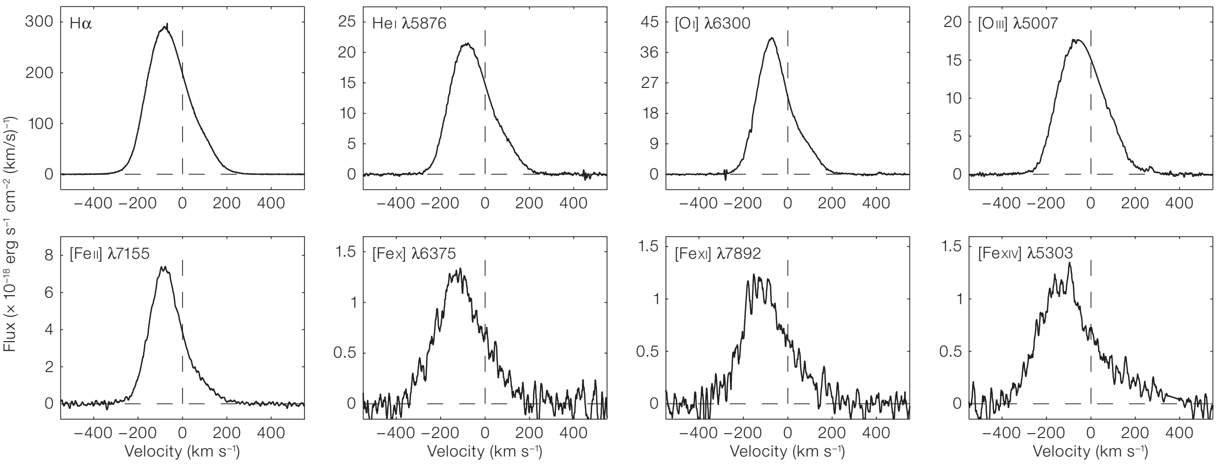
SN 1987A at twenty

Right now SN 1987A is undergoing another transition from the supernova emission to the supernova shock interaction with the circumstellar material. The 'three-ring circus' of SN 1987A has become an emblematic picture of modern astronomy. The supernova shock has now reached the inner ring and we can observe in real time how it will work its way through the ring.

At optical/near-IR wavelengths we can now distinguish five emission sites in SN 1987A: (1) the ejecta in the centre with a typical velocity structure of 3000 km s^{-1}; (2) the stationary extended ring with 10 km s^{-1} expansion; (3) the shocked material in the ring, visible in the hot spots and with velocities of about 300–500 km s^{-1}; (4) the reverse shock moving back into the supernova ejecta with a velocity of up to 15000 km s^{-1}. In addition, the X-rays show evidence of shocked gas with a temperature of $\geq 10^8$ K, which has not had time to cool down enough to be seen in the optical (Zhekov et al. 2006). We have observed these various components in the optical with high-resolution spectroscopy with UVES (Gröningsson et al. 2006) and in the near-IR with ISAAC and – spatially resolved – with SINFONI (Kjær et al., in preparation). The UVES spectra show asymmetric line shapes for several coronal lines, which are produced by the same shocked gas that is responsible for the soft X-rays (Figure 5). Our SINFONI data for the first time allow us to measure the velocity distribution around the ring, indicating how the shocks are accelerating ring material (Figure 6). At the same time, the X-ray observations show a rich line spectrum complementing the optical/IR observations. The radio light curve is increasing, reflecting the production of non-thermal electrons, and probably also cosmic rays, in the shock. Hot dust emission is seen by Spitzer, as well as by VISIR and Gemini (Bouchet et al. 2006).

The future

The coming years will provide exciting times (indeed!) and SN 1987A will remain the focus of observations with many telescopes. The destruction of the inner ring will take many years and maybe it will



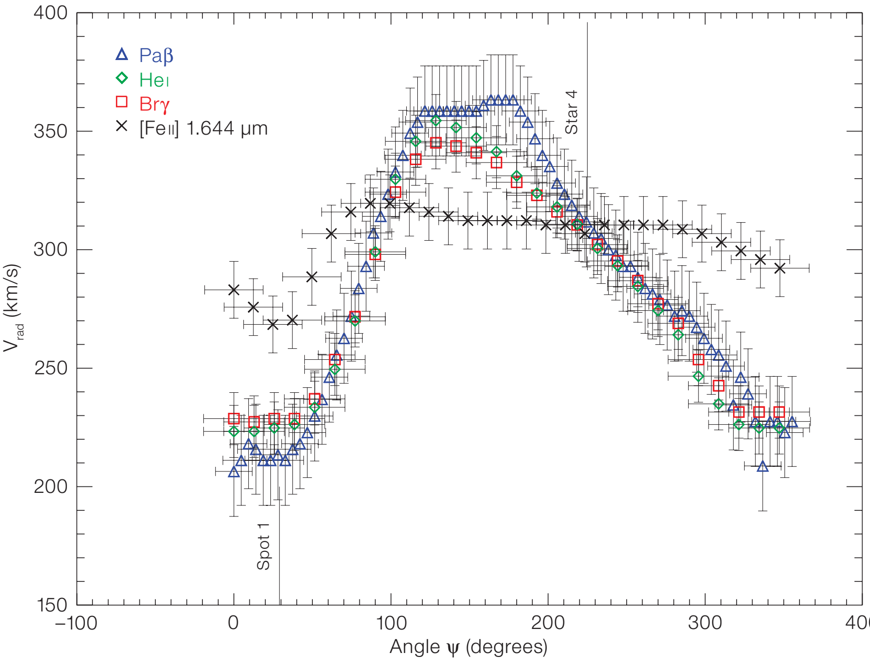


Figure 5 (above): Intermediate-velocity emission components from the cooling, shocked material from the inner ring, showing a range of ionisation stages, including highly ionised coronal lines from gas at ~ 2×10^6 K (from Gröningsson et al. 2006).

Figure 6 (left): The azimuthal velocity distribution of the inner ring is shown from different near-infrared emission lines (from Kjær et al., in prep.).

hold a clue to its origin. The X-rays may also help in illuminating any material outside the ionised ring which arises from a possible red supergiant stage. The circumstellar ring of SN 1987A will be a bright source at all wavelengths for several years.

The compact remnant in the centre has so far remained elusive. The neutrinos indicate that such a compact object should exist, but it remains deeply embedded in the ejecta. The very low limits to both the optical (Graves et al. 2005) and X-ray luminosity (Park et al. 2006) may be explained by either gas or dust absorption. In this case, however, the radiation should emerge in some waveband, possibly the far-IR. Other possibilities to explain the apparent absence of a neutron star include a weak magnetic field, slow rotation or that a black hole may have formed, possibly as a result of fall-back of material onto the newborn neutron star.

SN 1987A was full of surprises and it remains unique amongst the known supernovae. Not only was it the closest supernova for several centuries, it was also very peculiar, coming from a blue supergiant progenitor, with a circumstellar environment unlike any other supernova known. We will continue to monitor its evolution towards a supernova remnant.

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