SN 1987A - Exciting Physics

Bruno Leibundgut

ESO, Karl-Schwarzschild-Straße 2, 85748 Garching, Germany

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Observing the evolution of a supernova over several decades is unique. SN 1987A is the only object where this has been possible in great detail and it has shown us some physics, which we never had expected. Even now – after 10000 days – does SN 1987A provide new surprises on its way to become a supernova remnant. We present here an overview of the current status of the observations of SN 1987A with a focus on the evolution of the emission from the circumstellar ring. SN 1987A can be detected at all electromagnetic wavelengths, which gives us a complete picture of the energy sources and some of the radiation transfer. There are several emission sites present in SN 1987A and we will present them in this overview.

1 The first two decades of SN 1987A

As the only celestial source other than the Sun from which so far neutrinos have been observed, SN 1987A has been an observational bonanza across the electromagnetic spectrum. It has provided insights in the many different astrophysical topics including stellar evolution, core collapse, nucleosynthesis, explosion physics and the interaction with surrounding material. The early phases of SN 1987A have been summarised in several reviews [1, 2, 3, 4]. The most important features are the evidence for the core collapse from the neutrino emission, the peculiar progenitor star as a blue supergiant (observed *before* the explosion), the evidence for mixing of elements within the explosion bringing some radioactive material to the surface very early on and the interaction with circumstellar material, which quickly was identified as being non-spherically distributed. In the following, the evidence for radioactive powering of the light curve and energy input from long-lived isotopes like ^{57}Co and ^{44}Ti could be found. Molecule formation could be observed directly through the emission of vibrational bands of CO and SiO and dust formation in the inner ejecta could be observed through an increased decline of the UV-optical-near-infrared (UVOIR) light curve and showed that the inner parts of the explosion had cooled down dramatically. The circumstellar environment of SN 1987A could be imaged and the surrounding torus identified. An outer ring system was also seen in narrow emission lines and light echoes from interstellar dust sheets in the Large Magellanic Cloud became obvious after some months. Over the years the supernova shock reaching the equatorial torus could be observed through the increased luminosity of individual knots in the ring.

A particular feature of SN 1987A was its observability from the ground. Its position in the Large Magellanic Cloud is close enough to the celestial south pole that it could be observed all year from many southern observatories. Hence the supernova light curve is without major gaps. If the SN would have been placed only a few degrees further north, we would have lost the maximum phase and also several of the other interesting details of the supernova. Its proximity is, of course, the other characteristic which allows us to observe the supernova until today throughout the electromagnetic spectrum. This is one of the reason that we could learn so much from this single object.

The early light curve (see [4] for a figure which labels the various phases) displays all the characteristics of a core-collapse supernova and some more. The shock breakout can be inferred in the UV and the bluest bands as a decrease during the adiabatic expansion phase. The bolometric light curve then rose to a peak within several weeks and ended in a 'plateau' phase, which was extremely short due to the compact progenitor star. This is also the reason why SN 1987A did not reach a peak luminosity comparable to other core-collapse supernovae. After maximum the light curve settled into a steady decline, which followed the ^{56}Co decay time as all the energy generated in this radioactive decay was thermalised in the ejecta. After about 400 days the light curve started to decline faster because some optical light was blocked by dust and re-emitted in the mid-infrared ($> 20\mu$m) and was not observed from the ground. Only after about 1000 days did the light curve settle onto a slower decline again as the emission was powered by ^{57}Co with a longer lifetime. After some 2000 days the light curve decline was slowed even more due to the thermalisation of γ-rays from ^{44}Ti. After about 2500 days the emission from the ring was dominating over the ejecta by about a factor 10 in luminosity. This ratio has steadily increased over the years due to the supernova ejecta interacting with the stationary, dense equatorial torus. The supernova-ring interaction has been studied at many wavelengths and has led to a steady increase in flux in all wavebands. It certainly has been the dominating feature during the second decade of SN 1987A.

The second and third decade of SN 1987A are reviewed in [5]. Over the years five emission sites from SN 1987A could be distinguished. The inner ejecta (sometimes referred to as 'debris'), the stationary material in the circumstellar torus/ring, the shocked material in the torus, a reverse shock between the inner ejecta and the torus, and light echoes from scattered supernova light off interstellar dust sheets between SN 1987A and us. While the inner ejecta are powered by the radioactive decays of elements synthesised in the explosion, the ring glowed originally due recombination of stationary material ionised by the supernova shock breakout. The optical ring emission started to dominate over the ejecta about 5 years after the explosion as it was fading much more slowly than the ejecta. After 8 years a first 'hot spot' on the ring was detected [6, 7] and over the following years the ring brightness increased due to the outer supernova ejecta colliding with inward protrusions of ring material, which was observed as a series of bright knots (sometimes referred to as a 'pearl necklace'). The full ring evolution over the two decades from 1994 to 2014 is shown in [8]. The ring brightening could also be observed in the radio [9] and at X-ray energies [10] as the shocks from the fast-moving supernova ejecta and the nearly stationary ring material built up. The X-ray emission had started to increase already earlier as the shock was making its way through the dense material of an HII region created by the blue supergiant inside the ring [11].

2 The inner ejecta

Theoretical models of core-collapse supernova predict non-symmetric explosions. The reason are several hydrodynamic instabilities which are important for the neutrino-driven explosions (e.g. [12]). However, it has been so far impossible to observe the geometry of supernova ejecta directly. SN 1987A provided the possibility to obtain spatially resolved images of the inner ejecta with the VLT and HST. Integral-field observations in the near-infrared showed that the extension of the inner ejecta as measured through the 1.64 μm line, which is probably a mixture of [Si I] and [Fe II], was at an unexpected angle [13]. If the ring indeed is equatorial to the progenitor star of SN 1987A, then in some models the explosion was expected to be along the stellar poles and hence should be elongated orthogonal to the ring. The VLT SINFONI observations showed that the ejecta lie mostly within the plane of the ring, i.e. inclined nearly 42 degrees [13]. Further studies confirmed this geometry, but also indicated a slight misalignment of the two lobes relative to the centre [14]. The appearance in the Hα emission line at 10000 days after explosion is markedly different from the one in [Si I]. The Hα image shows a shell-like structure with an emission hole near the centre, while the [Si I] image displays a filled, centrally located emission.

The inner ejecta had been fading for many years as the energy input from the radioactive decays was dwindling. However, [15] found that around 5500 days after explosion the ejecta started to increase in brightness at optical wavelengths again. This is a rather unexpected development as an extra energy source is needed. Radioactivity only provides diminishing energy with time and radiation effects, e.g. changes in the opacity, are not expected at such a late phase. It had to be external energy input and the X-ray radiation from the supernova shock with the circumstellar ring was identified as the culprit. The X-rays penetrate back into the inner ejecta and ionise the hydrogen creating the shell-like appearance. The silicon on the other hand is still powered by the radioactive decay of ^{44}Ti [15, 8].

Mid- and far-infrared measurements of SN 1987A were only enabled by the Spitzer and Herschel satellites around 9000 days after explosion. These are typically combined with millimetre wavelength observations from the ground. A large dust mass (up to half a solar mass) was inferred from these late observations [16], which needs to be compared to the dust measurement at 1150 days after the explosion ($3 \cdot 10^{-3} M_{\odot}$; [17]). Over the 22 years between these observations the refractory material must have formed the dust we observe today. Since ALMA became operational, it observed he dust continuum emission [18] and vibrational transitions of carbon monoxide (CO) and silicon oxide (SiO) [19]. The inner ejecta must be filled with cold (<50 K) dust. Another molecule found in the inner ejecta is H_2, which was observed after 6500 days [20]. It was predicted to be formed with CO and SiO, but was only recently detected in the near infrared. It is concentrated towards the core of the ejecta similar to the [Si I]/[Fe II] emission and most probably is heated by the radioactive decays.

The evolution of the inner ejecta is unclear. The X-rays will penetrate further into the ejecta and the radioactive input will decrease continuously, although with a long (^{44}Ti has a 60 year half-life) decay time. It will also expand in size and eventually will reach the circumstellar ring.

3 The equatorial ring

SN 1987A is surrounded by a circumstellar ring, whose origin remains unclear. It could be the remnant of a stellar merger shortly before explosion, but the details of such a scenario are not resolved (e.g. [5]). It is clear from the mottled appearance with many individual hot spots that the ring is not uniform. It rather seems that it is broken up into clumps and inward protrusions due to some dynamic instability during the formation process. We can distinguish shocked and unshocked gas in the ring. The emission from unshocked is coming from essentially stationary material moving with $\sim$10 km s^{-1} and ionised through the soft X-rays from the shock. The shocked gas has been ionised and accelerated to about >300 km s^{-1} by the supernova forward shock [21, 22, 23]. Some of the ionisation is so high that coronal lines, e.g. of [Fe XIV] are observed. High-resolution spectroscopy, even if the ring cannot be not spatially resolved, hence allows us to separate the different emission sites based on the observed velocities. In the near-infrared integral-field spectroscopy has yielded both spatial and spectral information. In this case the orientation of the ring could be determined by tracing the expanding ring on the sky [24]. This confirmed the previous geometry derived from HST imaging [25, 26]. The ring is inclined by 43 degrees with the northern part closer to us and a rotation out of the sky of 9 degrees with the eastern part slightly closer than the western ring. The systemic velocity of the ring is 286.5 km s^{-1}, which can be compared to the systemic velocity of the Large Magellanic Cloud of 278 km s^{-1} [27].

The first ring region reached by the supernova shock was to the north-east at around 4000 days after explosion. The ring then brightened through the north and the east wrapping around finally to the western part of the ring. This process took about 5 years [8]. The ring emission was maximum shortly after 8000 days (in B and R filters) and started to decline thereafter. This evolution is nicely traced by emission lines from the shocked gas, mostly Hα, [O III] 5007Å, and coronal lines like [Fe XIV] 5303Å. The narrower lines from the unshocked gas, Hα, [O III] and [N II] 6583Å, declined already after 7000 days. The peak is reached later with increasing wavelength when observing into the infrared [28]. The fading of the ring is an indication that the shock has now overrun most of the ring material and is moving beyond the ring. Based on the fading of the individual emission lines the ring will become unobservable by around 2020 [8].

The optical peak brightness was reached at different times with the NE peaking around 6800 days and the SW only after 8500 days following roughly the time lag of the first appearance of the spots. The brightest parts now are in the west and the spots in this region have on average also reached a higher flux peak. Until today the ring emission is not been fully closed [14].

The ring is also observed in synchrotron emission at radio wavelengths. Here the shocks accelerate the electrons in the magnetic field. The shocks can be directly seen in X-rays, where the ring is resolved in Chandra observations [10]. Contrary to the optical the X-rays have not peaked yet, which is an indication that the shock is still running through lower density material, which does not radiate in the optical.

Recent HST observations have revealed new emission sites outside the equatorial ring [8]. The supernova forward shock has overrun the ring in several places and starts to interact with clouds outside the ring. Projection effects also have to be taken into account as the ring is inclined and we may see the shock outside the ring plane starting to interact with material above (or below) the ring plane. Since the shock has been decelerated in the ring, parts in other directions have now reached further out and eventually will start to interact with any material in its way. In particular, we should be able to distinguish whether there is a continuous connection between the inner and the outer rings and the shock should encounter such material. It will reveal the gas distribution in the wider surroundings of the supernovae.

4 The reverse shock

A reverse shock has built up between the forward shock moving through the equatorial ring and the inner ejecta. This is the outer ejecta catching up with the slowed down forward material encountering the dense equatorial ring and other material in the predicted HII region [11]. The reverse shock is characterised through high velocity (>10000 km s^{-1}) hydrogen lines (Lyα, Hα, Hβ), which emerge from the ionised ejecta flowing into the shock region, where material has been decelerated behind the forward shock. SN 1987A has developed a strong reverse shock around 1997 [6, 29] and its flux has increased continuously until 2009 (more than 9000 days after explosion; [31, 32, 33]). A detailed description of the reverse shock in SN 1987A has been provided in [30] for the location and by [33] describing the temporal evolution of the spectral appearance. The direct imaging has provided evidence that the reverse shock emission has been observed outside the equatorial ring plane towards the outer rings [30], which is an indication that the SN shock has expanded into the hourglass shaped region connecting the outer rings with the equatorial ring. This is further supported by the large observed velocity, which indicates that there has to be flux outside the equatorial ring [8]. The outer ejecta appear to be heated by X-rays coming from the shocks and display a very high ratio of Lyman-α to Balmer-α emission, which leads to an increased Lyman-α flux. The flux evolution follows nearly exactly the soft X-ray increase, which is a clear indication that the heating of the reverse shock material is done through X-rays. An early prediction that the Hα emission from the reverse shock will disappear by around 2014 due to the full ionisation of hydrogen before it reaches the shock region [31] has not been confirmed, but there appears to be a flattening of the flux coming from the reverse shock. This could mean that the reverse shock in the equatorial plane has reached the intrusions from the inner ring [33]. The emission outside the equatorial ring will increase in the coming years outlining the material distribution outside the equatorial plane and mapping the mass loss history of the progenitor star of SN 1987A. Future observations will map the evolution of the reverse shock in SN 1987A and hence the circumstellar matter distribution around the supernova explosion.

5 The compact object

The neutrino signal from SN 1987A indicated the core collapse to a neutron star. However, no signature of the neutron star or a possible black hole, if the neutron star due to fallback of material not expelled in the explosion became unstable and collapsed further, has so far been detected. A young neutron star is expected to rapidly lose energy as it spins down within a magnetic field. A resulting pulsar wind nebula, similar to the one observed in the Crab nebula should be expected, although the observed upper limits on the luminosity of a compact object in SN 1987A is already below the one observed in the Crab.

The distance of SN 1987A makes it difficult to isolate a central compact object in X-rays and at radio wavelengths from the ejecta, reverse shock and the ring interaction. The X-rays would be the most promising wavelength region for the detection of the plasma ionised by the pulsar wind. So far, no detection has been reported. Also, the synchrotron radiation could be detected at radio frequencies. No central point source has been seen to date (e.g. [34, 35]). Emission at optical wavelengths is difficult to detect as the dust, which formed in the inner ejecta (e.g. [18]) could block the line of site towards the centre. An attempt to detect UV continuum emission between the many emission lines has been done some 10 years ago [36] setting the currently strongest limits of less than 1.3 $L_{\odot}$. The lack of a detection of the compact source means that the magnetic field of the neutron star is fairly weak as a Crab-like plerion should have been detected already.

6 The future

SN 1987A continues its evolution towards a supernova remnant. The recent years have shown surprises, like the formation of massive dust in the ejecta, the additional heating of the hydrogen layers in the inner ejecta from the X-rays created in the shocks and the lack of emission from the central compact object, which must have formed in the collapse. Several predictions on how SN 1987A would evolve have been confirmed. Among them are the continued interaction with the equatorial ring, the emission coming from outside the ring and the strengthening of the reverse shock over the years. These also set the expectations on what the future will bring. Foremost the ring will be overrun by the shock in a few years and its emission will start to drop. The structure of the inner ejecta will be revealed further through the emission evolution due to the different heating mechanisms. The reverse shock will start to weaken when it approaches the ring in the equatorial plane, but will continue to map out the circumstellar structure outside that plane. It will be interesting to see whether more dust is forming in the inner ejecta and when the cold dust shell between the forward and reverse shocks will become detectable. The search for the central compact object will continue and it will hopefully become observable in the coming years.

There is still a lot in store for observers of SN 1987A. Eventually, this supernova will be joined by other objects detected through their neutrino emission. The prospects are excellent that we may be witnessing such an event in the not too distant future.

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