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SUPERNOVA 1987A: CELEBRATING A SILVER JUBILEE

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Abstract. The story of the SN 1987A explosion is briefly reviewed. Although this supernova was somewhat peculiar, the study of SN 1987A has clarified quite a number of important aspects of the nature and the properties of supernovae, such as the confirmation of the core collapse of a massive star as the cause of the explosion, as well the confirmation that the decays ^{56}Ni–^{56}Co–^{56}Fe at early times and ^{44}Ti–^{44}Sc at late times, are the main sources of the energy radiated by the ejecta. Still we have not been able to ascertain whether the progenitor was a single star or a binary system, nor have we been able to detect the stellar remnant, a neutron star that should be produced in the core collapse process.

Keywords: supernovae: general, supernovae: 1987A, neutrinos, binaries: general, stars: neutron.

1. Introduction

Supernova 1987A was discovered on February 24, 1987 by Ian Shelton [29] in the Large Magellanic Cloud. Thanks to the modern instruments and telescopes available, it was possible to observe SN 1987 in great detail and and with high accuracy so that this event has been a *first* in many aspects (e.g. neutrino flux, progenitor identification, gamma ray flux) and definitely the *best* studied event ever.

The early evolution of SN 1987A has been highly unusual. It brightened much faster than any other known supernova: in about one day it jumped from 12th up to 5th magnitude at optical wavelengths (a factor of ~ 1000!). However, equally soon its rise leveled off and took a much slower pace, indicating that this supernova would have never reached such high peaks in luminosity as the astronomers were expecting. Similarly, in the ultraviolet, the flux initially was very high, even higher than in the optical. But since the very first observation, made with the International Ultraviolet Explorer (IUE in short) satellite less than fourteen hours after the discovery [28, 59], the ultraviolet flux declined very quickly, by almost a factor of ten per day for several days. It looked as if it was going to be a quite disappointing event but eventually it became apparent that SN 1987A has been the most valuable probe to test our ideas about the explosion of supernovae.

Reviews of both early and recent observations and their implications can be found in [3, 36, 37, 42]. The proceedings of the 2007 Aspen conference *Supernova 1987A, Twenty Years Later: Supernovae and Gamma-Ray Bursters*, (eds. S. Immler, R. McCray, K.W. Weiler, AIP, Conf. Proc. Vol. 937, 2007) provide an extensive update on all SN 1987A studies. Here, I summarize some of the early findings on SN 1987A and discuss some of the new results obtained in recent years.

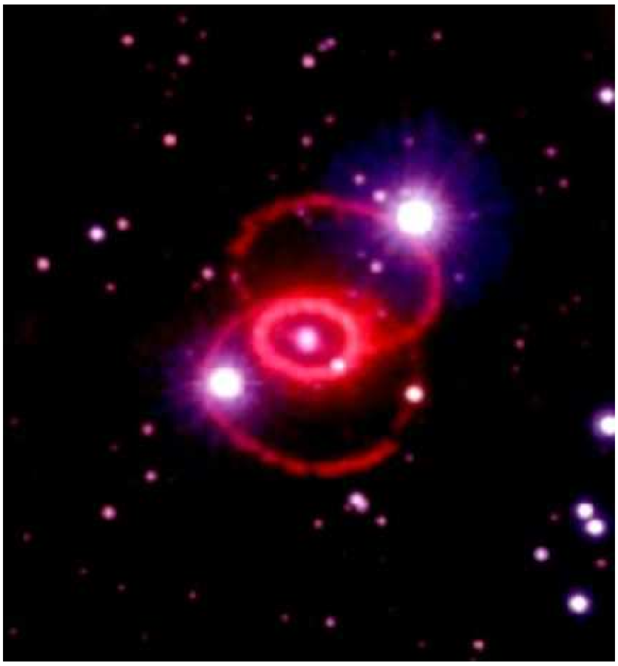

Figure 1. True color picture (*HST-WFPC2*) of SN 1987A, its companion stars, and the circumstellar rings [Credit: Peter Challis (Harvard)].

2. Neutrino Emission from SN 1987A

For the first time, particle emission from a supernova was directly measured from Earth: on February 23, around 7:36 Greenwich time, the neutrino telescope "Kamiokande II" recorded the arrival of 9 neutrinos within an interval of 2 seconds and 3 more 9 to 13 seconds after the first one. Simultaneously, the same event was revealed by the IMB detector and by the "Baksan" neutrino telescope which recorded 8 and 5 neutrinos, respectively, within a few seconds from each other. This makes a total of 25 neutrinos from an explosion that allegedly produces about 10^{58} of them! But two dozens neutrinos were enough to verify and confirm the theoretical predictions made for the core collapse of a massive star that becomes a neutron star (e.g. [3, and references therein]). This process was believed to be the cause of the explosion of massive stars at the end of their lives, and SN 1987A has provided the experimental proof that the theoretical model was sound and correct, promoting it from a nice theory to the description of the truth.

At the same time we cannot discard other evidence that may reveal puzzling aspects of this supernova explosion. In particular, about five hours before the Kamiokande event, the Mont Blanc neutrino detector recorded a series of five neutrinos grouped within 7 seconds from each other [1]. Such an event appeared to be highly significant (99.9 % significance) but was not revealed by the other detectors (possibly because of the different detection thresholds among the various experiments) and was not consistent with the timing of the light curve rise in the optical and in the UV. Barring an exceptionally high (and rare) fluctuation as discussed by Galeotti [19], the reality of this event would imply that the supernova progenitor underwent a double collapse, in which only the second one rebounded so as to generate the outward shock that, breaking out at the stellar surface, started the UV/optical burst (e.g. [14, 57]). A possible model of such phenomenon has been put forward by Imshennik and Ryazhskaya [22] who show that a rotating collapsar may be expected to explode in a two-stage collapse with a phase difference of ~ 5 hours. We are inclined to argue that this phenomenon is more likely to occur with a binary system progenitor because such a system would *naturally* provide the opportunity of having two merging stellar cores to collapse in a multi-step process.

3. SN 1987A progenitor star

From both the presence of hydrogen in the ejected matter and the conspicuous flux of neutrinos, it was clear that the star which had exploded was quite massive, about twenty times more massive than our Sun. And all of the peculiarities were due to the fact that just before the explosion the supernova progenitor was a blue supergiant star instead of being a red supergiant as expected. There is no doubt about this explanation because SN 1987A is exactly at the same position as that of a well known blue supergiant, Sk −69°202. And the IUE observations indicated that such a star was not shining any more after the explosion: the blue supergiant star unambiguously was the SN progenitor. This *heretic* possibility was first suggested in Panagia et al. [39] and confirmed by the more detailed analyses presented by Gilmozzi et al. [20] and Sonneborn, Altner & Kirshner [52].

On the other hand, the presence of narrow emission lines of highly ionized species, detected in the SN 1987A short wavelength spectrum since late May 1987, has provided evidence for the progenitor having been a red supergiant before coming back toward the blue side of the HR diagram [17]. Also, the detection of early radio emission that decayed in a few weeks [56] indicated that the ejecta were expanding within a circumstellar environment whose properties were a perfect match to the expected wind of a blue supergiant progenitor [9].

Such an evolution for a star with mass of $\sim 20\,M_\odot$ was not expected, and theorists have struggled quite a bit to find a plausible explanation for it. As summarized by Podsiadloswki [46], in order to explain all characteristics of SN 1987A, rotation has to play a crucial role, thus limiting the possibilities to models involving either a rapidly rotating single star [30], or a stellar merger in a massive binary system [46].

More recently, Podsiadlowski & Morris [47] pointed out that while SN 1987A anomalies have long been attributed to a merger between two massive stars that occurred some 20 000 years before the explosion, so far there has been no observational proof that this merger took place. However, their detailed 3-D hydrodynamical simulations of the mass ejection associated with such a merger has shown that such scenario not only could account for the unusual evolution of the massive progenitor but also it appears to accurately reproduce the properties of the triple-ring nebula surrounding the supernova.

4. Explosive Nucleosynthesis

The optical flux reached a maximum around mid-May, 1987, and declined at a quick pace until the end of June, 1987, when rather abruptly it slowed down, settling on a much more gentle decline of about 1 % a day [48]. Such a behaviour was followed for about two years quite regularly: a perfect constant decay with a characteristic time of 111 days, just the same as that of the radioactive isotope of cobalt, ^{56}Co, while transforming into iron. This is the best evidence for the occurrence of nucleosynthesis during the very explosion: ^{56}Co is in fact the product of ^{56}Ni decay and this latter can be formed at the high temperatures which occur after the core collapse of a massive star. Thus, not only are we sure that such a process is operating in a supernova explosion, but we can also determine the mass of ^{56}Ni produced in the explosion, slightly less than 8/100 of a solar mass or $\sim 1\,\%$ of the mass of the stellar core before the explosion. The detection of hard X-ray emission since July 1987, and the subsequent detection of gamma-ray emission have confirmed the reality of such a process and provided more detailed information on its distribution within the ejecta (e.g. [3, and references therein]). Eventually, the detection of CoII lines in the mid-infrared [4] confirmed the light curve result and provided the first *direct* evidence of the production of ^{56}Ni in supernova explosions.

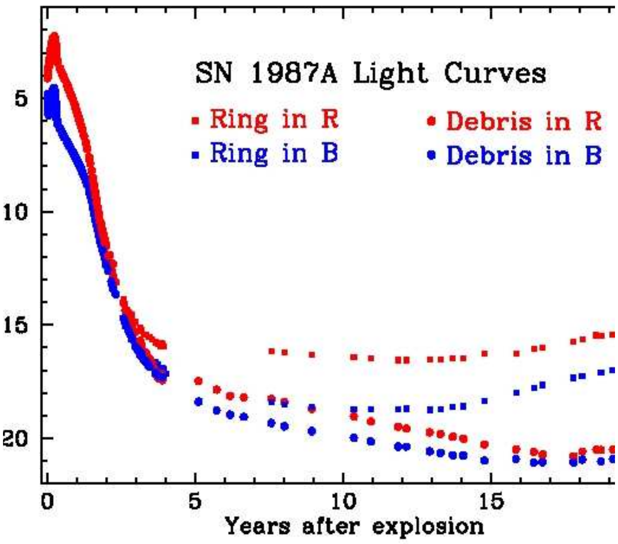

Figure 2. B and R band light curves of SN 1987A debris (dots) and the equatorial ring (squares) [Credit: SINS Team, and Peter Challis (Harvard)].

5. Energetics of the Emitted Radiation

SN 1987A ultraviolet spectra obtained with *IUE* over the period 1987 February 24 [day 1.6] through 1992 June 9 [day 1567]) [48] show that the UV flux plummeted during the earliest days of observations because of the drop in the photospheric temperature and the increase in opacity. However, after reaching a minimum of 0.04 % of the total UVOIR bolometric luminosity on day 44, the UV flux increased by about 200 times in its relative contribution to 7 % of the bolometric luminosity at day 800. A study of the UV colors reveals that the supernova started to get bluer in the UV around the time when dust started to form in the ejecta (about 500 days after the explosion; [12]). These results are consistent with the possibility that the condensed dust be metal-rich and of small size.

In the early '90s the SN light curve decay appears to slow down (see Fig. 2), decreasing at a rate that is consistent with the decay of ^{44}Ti into ^{44}Sc in an amount as expected by explosive nucleosynthesis [13, 27]. On the other hand, around 2001 the optical flux was observed to increase again mimicking the behaviour shown by the inner ring radiation. As discussed by Larsson et al. [31] this increase results from heat deposited by X-rays produced as the ejecta interact with the surrounding material.

6. HST Observations

The Hubble Space Telescope (*HST*) was not in operation when the supernova exploded, but it did not miss its opportunity in due time and its first images, taken with the *ESA-FOC* on August 23 and 24, 1990, revealed the inner circumstellar ring in all its "glory" and detail [23]. Subsequent observations made with the *FOC* allowed Jakobsen et al. [24, 25] to measure the angular expansion of the supernova ejecta. The results confirmed the validity of the expansion models put forward on the basis of spectroscopy. Additional observations, made with the *WFPC2* (Burrows et al. 2005) on the refurbished *HST* confirmed the early trend of the expansion and revealed the presence of structures that had never been seen before [26, 61].

HST-FOS spectroscopic observations of SN 1987A, made over the wavelength range 2000÷8000 Å on dates 1862 and 2210 days after the supernova outburst, indicate that at late times the spectrum is formed in a cold gas that is excited and ionized by energetic electrons from the radioactive debris of the supernova explosion [60]. The profiles are all asymmetric, showing redshifted extended tails with velocities up to 10 000 km s^{-1} in some strong lines. The blueshift of the line peaks is attributed to dust that condensed from the SN 1987A ejecta and is still distributed in dense opaque clumps.

7. The Circumstellar Rings

Important clues to the nature of SN 1987A are provided by the study of its circumstellar rings, i.e. an equatorial ring (the "inner ring") about 0.86″ in radius and inclined by about 45 degrees, plus two additional "outer rings" which are approximately but not exactly, symmetrically placed relative to the equatorial plane, approximately co-axial with the inner ring, and have sizes 2 ÷ 2.5 larger than the inner ring. The presence of the inner ring was originally revealed with the *IUE* detection of narrow emission lines [17]. Detailed studies of the rings, mostly based on spectroscopy and imaging done with *HST*, concluded that the rings display a strong N overabundance and a moderate He enhancement [17, 32, 40, 41, 53]. Most likely, they were ejected in two main episodes of paroxysmal mass loss which occurred approximately 10 000 (the inner ring) and 20 000 years (the outer rings) before the supernova explosion, respectively [34, 41].

8. Interaction of the ejecta with the equatorial ring

Since mid-1997 HST has observed the high-velocity material from the supernova explosion starting to overtake and crash into the slow-moving inner ring. Figure 3 shows dramatic evidence of these collisions. The circumstellar ring started to develop bright spots in 1997, and in late 2006 one can identify at least twenty bright spots. These bright spots are the result of the fast moving component of the ejecta (at a speed of about 15 000 km s^{-1}) colliding with the stationary equatorial ring (e.g. [38, 54]). Independent evidence for an interaction whose strength is quickly increasing with time is provided by both radio emission (e.g. [18, 55]) and X-ray emission (e.g. [2, 43–45]). Actually, Bouchet et al. [5, 6] emphasized that a comparison of their Gemini 11.7 μm image with Chandra X-ray images, HST UV-optical images, and ATCA radio

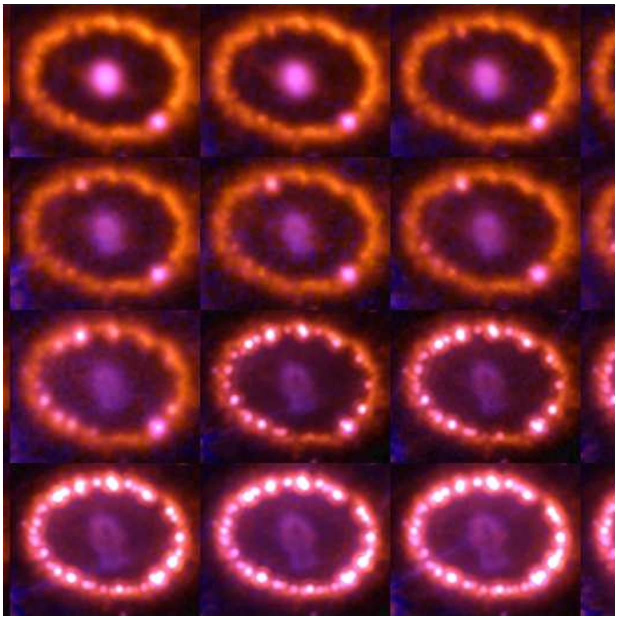

Figure 3. Images of SN 1987A and its inner ring obtained with *HST-WFPC2* over the years 1996–2006, during which time the ring has developed at least twenty hot spots. [Credit: SINS Team, Peter Challis (Harvard) and NASA]

synchrotron images shows generally good correlation across all wavelengths.

On the other hand, a good correlation does not necessarily imply a one-to-one correspondence. For example, Gaensler et al. [18] stressed that an asymmetric brightness distribution is seen in radio images at all ATCA epochs. The eastern and western rims have higher fluxes than the northern and southern regions, indicating that most of the radio emission comes from the equatorial plane of the system, where the progenitor star's circumstellar wind is thought to be densest. The eastern lobe is brighter than, and further away from the supernova site than the western lobe, suggesting an additional asymmetry in the initial distribution of supernova ejecta. Similar asymmetries are also found at X-ray wavelengths, but in the optical it is the West side that appears to become brighter at late times.

Right now, we are witnessing the transition of SN 1987A from a supernova proper, in which the energetics are dominated by the ejecta themselves, into a full-fledged supernova remnant where most of the energy is produced by the interaction of the ejecta with a surrounding medium. Over the next decades, as the bulk of the ejecta reach the ring, more spots will light up and the whole ring will shine as it did in the first several months after explosion (e.g. [37]). Eventually, the ejecta will completely sweep the ring up, clearing the circumstellar space of that beautiful remnant of the pre-supernova wind activity.

9. Dust associated with SN 1987A

Discussing the physical correlation between IR and X-ray emission, Bouchet et al. [6] pointed out that if the dust responsible for the IR emission resides in the diffuse X-ray-emitting gas then it is collisionally heated. In this case, the IR emission can be used to derive the plasma temperature and density, which they found to be in good agreement with those inferred from the X-rays. Alternatively, the dust could reside in the dense UV-optical knots and be heated by the radiative shocks that are propagating through the knots. Bouchet et al. [6] conclude that in either case the dust-to-gas mass ratio in the CSM around the supernova appears to be significantly lower than that in the general interstellar medium of the LMC, suggesting either a low condensation efficiency in the wind of the progenitor star or an efficient destruction of the dust by the SN blast wave.

Recent mid- and far-IR observations made with the Spitzer and the Herschel space telescopes have provided a wealth of new information about the properties and the nature of the dust associated with SN 1987A [15, Matsuura et al. 2011]. Spitzer observations in the mid-IR (3.6 to 24 µm) show a spectrum that peaks around 20 µm and whose luminosity indicates a mass of dust in the inner ring of about $1.2 \times 10^{-6} M_\odot$ (Dwek at al. 2011). Compared to the estimated total mass of the ring ($\sim 6 \times 10^{-2} M_\odot$ [35], such a dust mass implies a gas to dust ratio as high as 5×10^4, i.e. much higher than an average value of 300 appropriate for the LMC. On the other hand, the spectrum measured with Herschel peaks around 160 µm, suggesting dust temperatures around 20 K (Matsuura et al. 2011). The mass inferred from these data depends on assumptions about the nature of the grains, but all estimates range between 0.34 and $3.4 M_\odot$ and values around $0.5 M_\odot$ are deemed to be most reasonable according to the authors. This is a large amount even accepting the idea of Matsuura et al. 2011 that we are dealing with dust formed in the ejecta: considering that the total mass of the ejecta is estimated to be about $10 M_\odot$ even the lowest value of $0.34 M_\odot$ would require both a very high metal abundance in the progenitor's outher layers and a very high efficiency for dust formation during the expansion of the ejecta. Future observations in the FIR, hopefully made with high angular resolution telescopes (perhaps ALMA?) will be able to verify these claims and to clarify if SNe are actually efficient dust producers.

10. A missing neutron star?

HST observations both in spectroscopy (STIS, $1140 \div 10\,266$ Å) and in imaging (ACS $2900 \div 9650$ Å) have failed to detect any point source inside the SN 1987A remnant [21], implying an UVOIR luminosity below 8×10^{33} erg s^{-1}. The presence of bright young pulsars such as Kes 75 or the Crab pulsar is excluded by optical and X-ray limits on SN 1987A. While non-plerionic X-ray point sources have optical luminosities similar to the above limits, among all young pulsars known to be associated with SNRs, those with ages less than about 5000 years are much brighter in X-rays than the limits on SN 1987A.

Discussing theoretical models, Graves et al. [21] find that spherical accretion onto a neutron star is firmly ruled out and that spherical accretion onto a black hole is possible only if the dust absorption in the remnant is considerably higher than expected. In the case of thin-disk accretion, the flux limit requires a small disk ($< 10^{10}$ cm in size), with an accretion rate lower than 0.3 times the Eddington accretion rate. Possible ways to hide a surviving compact object include the removal of all surrounding material at early times by a photon-driven wind, a small accretion disk, or very high levels of dust absorption in the remnant. Graves et al. [21] conclude that it will not be easy to improve substantially on the present optical-UV limit for a point source in SN 1987A, although one can hope that a better understanding of the thermal infrared emission will provide a more complete picture of the possible energy sources at the center of SN 1987A.

11. Conclusions

It is clear that SN 1987A constitutes an ideal laboratory for the study of supernovae, and of explosive events, in general. As summarized above, a great deal of observations have been made and quite a number of aspects have been clarified and understood, such as confirming that the core collapse of a massive star was the cause of the explosion, as well ascertaining that the decays ^{56}Ni–^{56}Co–^{56}Fe and ^{44}Ti–^{44}Sc are the main sources of the energy radiated at early and at late times, respectively. On the other hand, there are still important points that need clarification and further study, as well as more observations. For example, the stellar remnant left behind by the explosion has eluded our detection so far and its nature remains a complete mystery. We still debate whether the SN progenitor was a single rotating star or a binary system. Also, the detection of an early interaction of the supernova ejecta with the inner circumstellar ring has opened a new chapter in the study of this supernova, which is expected to culminate in about ten years, when the colliding materials will become the brightest objects in the LMC, with a display of fireworks at X-ray, UV and optical wavelengths that defy our most vivid imagination.

Acknowledgements

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