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Supernova 1987A: Twenty Years After

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Abstract I briefly review the story of the SN 1987A explosion, with special emphasis on the most recent findings. It appears that 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 in general, 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 unambiguously 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.

Key words: supernovae: general — supernovae: 1987A — neutrinos — binaries: general — stars: neutron

1 INTRODUCTION

Supernova 1987A was discovered on February 24, 1987 by Ian Shelton (Kunkel & Madore 1987) in the Large Magellanic Cloud, and immediately became the "best hit" supernova despite the fact that it appeared to be more than hundred times fainter than its illustrious predecessors in the last millennium. Thanks to the modern instruments and telescopes available, it was possible to observe SN 1987 in such a detail and with such an accuracy as to make this event 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 and completely at variance with the *wisest* expectations. It brightened much faster than any other known supernova: in about one day it jumped from 12th up to 5th magnitude at optical wavelengths, corresponding to an increase of about a factor of thousand in luminosity. However, equally soon its rise leveled off and took a much slower pace indicating that this supernova would have never reached those 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 (Kirshner et al. 1987; Wamsteker et al. 1987), 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 and, for sure, quite peculiar, thus not suited to provide any useful information about *"normal"* supernova explosions. But, fortunately, this proved not to be the case and soon 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 Arnett et al. (1989), McCray (1993, 2003, 2005), Gilmozzi and Panagia (1999), and Panagia (2003, 2005). The proceedings of the recent Aspen conference *Supernova 1987A, Twenty Years Later: Supernovae and Gamma-Ray Bursters"*, (eds. S. Immler, R. McCray & K. W. Weiler, AIP, 2007, in press) provides the most complete

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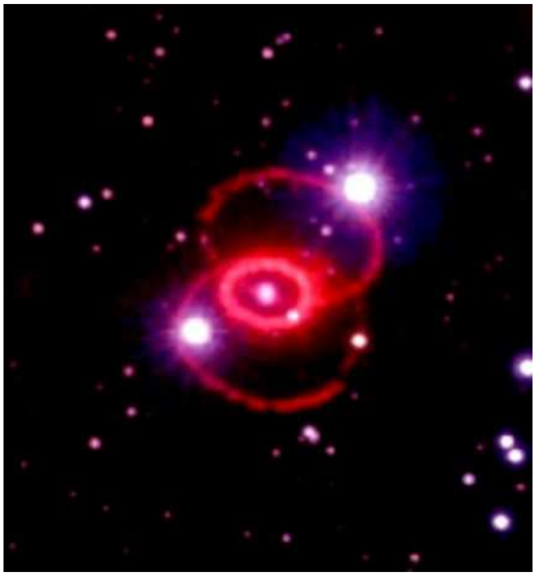

Fig. 1 True color picture (*HST-WFPC2*) of SN 1987A, its companion stars, and the circumstellar rings [Credit: Peter Challis (Harvard)].

update on all SN 1987A studies. Here, I briefly summarize some of the early findings on SN 1987A and consider in some more detail the new results obtained in recent years.

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" (a big cylindrical "tub" of water, 16 m in diameter and 17 m in height, containing about 3300 m^3 of water, located in the Kamioka mine in Japan, about 1000 m underground) 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 (located in the Morton-Thiokol salt mine near Faiport, Ohio) and by the "Baksan" neutrino telescope (located in the North Caucasus Mountains, under Mount Andyrchi) which recorded 8 and 5 neutrinos, respectively, within 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. Arnett et al. 1989 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 (Aglietta et al. 1987). Such an event appeared to be highly significant (the probability of dealing with a random fluctuation was estimated to be less than 10^{-4}) but was not noticed 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, 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. de Rujula 1987; Voskresensky et al. 1987). A possible model of such phenomenon has been put forward by Imshennik & Ryazhskaya (2004) who show that a rotating collapsar may be expected to explode in a two-stage collapse with a phase difference of $\sim$ 5 hours. On the other hand, it could also be that this phenomenon is more likely to occur with a binary system progenitor because such a system would *naturally* provide the possibility 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 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 common wisdom was predicting. 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. (1987) and subsequently confirmed by the more detailed analyses presented by Gilmozzi et al. (1987) and Sonneborn, Altner & Kirshner (1987).

On the other hand, the presence of narrow emission lines of highly ionized species, detected in 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 (Fransson et al. 1989). Also, the detection of early radio emission that decayed in a few weeks (Turtle et al. 1987) 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 (Chevalier & Dwarkadas 1995).

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 (1992), 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 (Langer 1991), or a stellar merger in a massive binary system (Podsiadlowski 1992).

More recently, Podsiadlowski & Morris (2007) 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 conclusive proof that this merger took place. Therefore, they embarked in detailed three-dimensional hydrodynamical simulations of the mass ejection associated with such a merger and the subsequent evolution of the ejecta, and were able to show that this accurately reproduces the properties of the triple-ring nebula surrounding the supernova.

On the other hand, at the Aspen conference Woosley (2007) showed that with a judicious selection of stellar parameters (main sequence mass $\sim 18\,M_\odot$, rotational velocity on the MS $\sim$220–240 km s^{-1}) models that include all the proper physics (e.g. magnetic torques, mass loss, modern opacities, etc.) are also able to reproduce most of the observational results, such as surface enhancements of He and N (see Section 8) due to rotational mixing, and ejection of rings induced by large centrifugal force in the final Blue Supergiant phase.

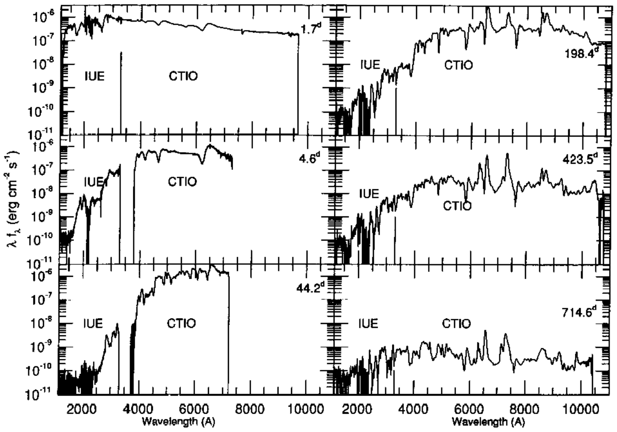

Fig. 2 Evolution of the UV and optical spectrum of SN 1987A (Pun et al. 1995).

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 (Pun et al. 1995). 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. Arnett et al. 1989 and references therein). Eventually, the detection of [CoII] lines in the mid-infrared (Bouchet & Danziger 1988) confirmed the light curve result and provided the first *direct* evidence of the production of ^{56}Ni in supernova explosions.

5 ENERGETICS OF THE EMITTED RADIATION

A catalog of SN 1987A ultraviolet spectra obtained with *IUE* (751 spectra over the period 1987 February 24 [day 1.6] through 1992 June 9 [day 1567]) have been presented by Pun et al. (1995). They show that the UV flux plummeted during the earliest days of observations (Fig. 3) because of the drop in the photospheric temperature and the increase in opacity. However, after reaching a minimum of 0.04% on day 44, the UV flux increased by 175 times in its relative contribution to 7% of the total UVOIR bolometric luminosity at day 800 (Fig. 3). 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; Danziger et al. 1989). These results are consistent with the possibility that the condensed dust may be metal-rich and of small size.

At later times the SN light curve appears to flatten out (see Fig. 4) at a level that is consistent with the decay of ^{44}Ti into ^{44}Sc in an amount as expected by explosive nucleosynthesis (e.g. Diehl & Timmes 1998).

6 THE UV ECHO OF SN 1987A: SPECTRUM OF THE EXPLOSION

Bright transient events such as nova and supernova outbursts can give rise to the phenomenon of a light echo. This is produced when light from the explosion illuminates nearby interstellar dust and is reflected in the direction of the observer. In the case of SN 1987A echoes were predicted by Chevalier (1986) and Schaefer (1987), and their discovery was first announced by Crotts (1988) and Rosa (1988). Since the UV light curve was already plummeting by the time of the first IUE observation, a UV echo is expected to be the reflection of the light emitted at the very time of the explosion (i.e. *before* the discovery of the supernova!). Indeed, ultraviolet light emitted by SN 1987A at the shock breakout was detected by means of IUE observations, made one year apart from each other, at a location a few arcseconds outside a bright portion of an optical echo (Gilmozzi & Panagia 1999). The spectrum of the echo shows a hot continuum and a wide P Cyg-like feature centered around 1500 Å (Fig. 4) which, if interpreted as CIV 1550 Å, implies an expansion velocity at the time of the shock breakout as high as 40 000 km s^{-1}. This is in agreement with the first “direct” IUE spectrum, taken 24 hours after the explosion, which showed a MgII line with a terminal velocity of about 35 000 km s^{-1}(Kirshner et al. 1987).

7 HST OBSERVATIONS - STRUCTURE AND EXPANSION OF THE EJECTA

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 (*cf.* Jakobsen et al. 1991), showing that, even with spherical aberration, *HST* was not a complete disaster, after all. More observations were made with the *FOC*, which allowed Jakobsen et al. (1993, 1994) 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* on the re-refurbished *HST* confirmed the early trend of

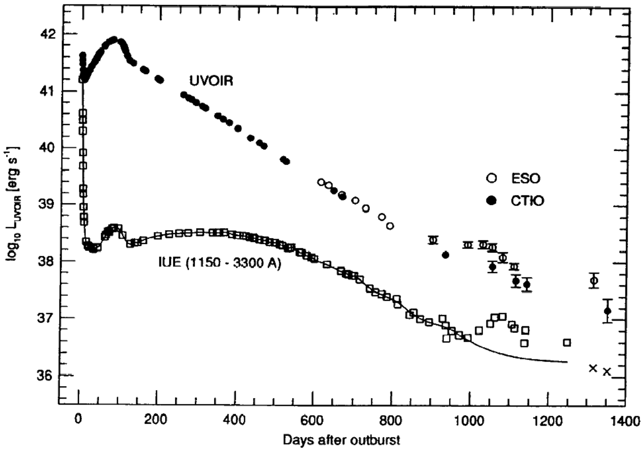

Fig. 3 UV and bolometric light curve of SN 1987A (Pun et al. 1995).

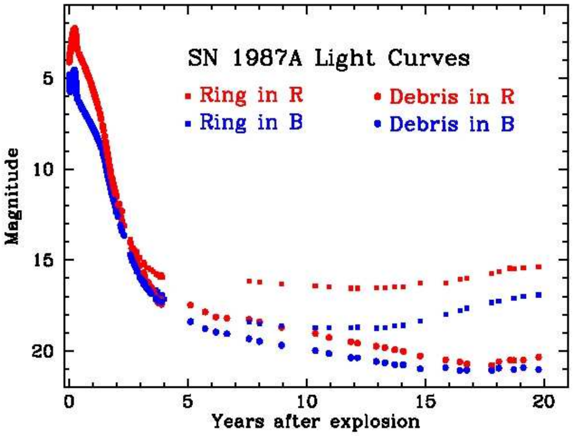

Fig. 4 B and R band light curves of SN 1987A debris (dots) and the equatorial ring (squares) [Credit: SINS Team, and Peter Challis (Harvard)].

the expansion and revealed the presence of structures that had never been seen before (Jansen & Jakobsen 2001; Wang et al. 2002).

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 (Wang et al. 1996). 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.

8 PROPERTIES AND NATURE OF 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

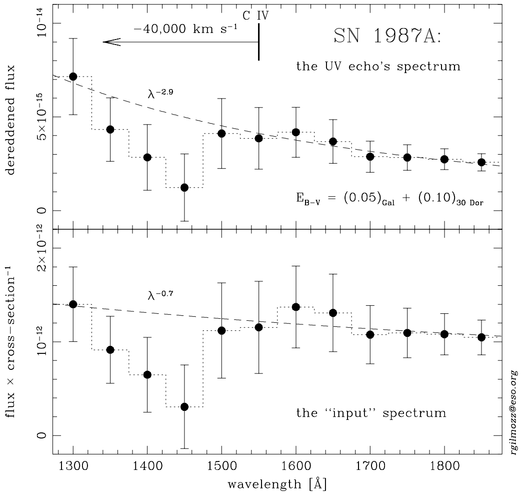

Fig. 5 The spectrum of the UV echo. **Upper panel:** dereddened observed data. **Lower panel:** an appropriate dust scattering correction has been applied to reveal the actual shape of the spectrum at the shock breakout [adapted from Gilmozzi & Panagia 1999].

of the inner ring was originally revealed with the *IUE* detection of narrow emission lines (Fransson et al. 1989). Heroic efforts done with ground based telescopes (Crotts et al. 1989; Wampler et al. 1990) provided early measurements of the shapes of the circumstellar rings. Subsequently the rings were superbly imaged by *HST* using both the *FOC* and *WFPC2* cameras (e.g. Jakobsen et al. 1991; Burrows et al. 1995). Detailed studies of the rings, mostly based on spectroscopy and imaging done with *HST*, have suggested that the rings, characterized by a strong N overabundance and a moderate He enhancement (Fransson et al. 1989, Panagia et al. 1991; Panagia et al. 1996; Lundqvist & Fransson 1996; Sonneborn et al. 1997), 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 (Panagia et al. 1996; Maran et al. 2000).

9 INTERACTION OF THE EJECTA WITH THE EQUATORIAL RING

Since mid-1997 Hubble has observed the high-velocity material from the supernova explosion starting to overtake and crash into the slow-moving inner ring. Figure 6 shows the dramatic evidence of these collisions. The circumstellar ring started to develop bright spots in 1997, and in November 2003 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. Sonneborn et al. 1998; Michael et al. 2003). Independent evidence for an interaction whose strength is quickly increasing with time is provided by both radio (e.g. Manchester et al. 2002, 2007; Gaensler et al. 2007) and X-ray (e.g. Park et al. 2002, 2006, 2007; Aschenbach 2007) emission (cf. Figure 7). Actually, Bouchet et al. (2004, 2006) emphasized that a comparison of their Gemini 11.7 μm image with Chandra X-ray images, HST UV-optical images, and ATCA radio 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. (2007) 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 (e.g. Figure 8), but in the optical it is the West side that appears to become brighter at late times (see Figure 6).

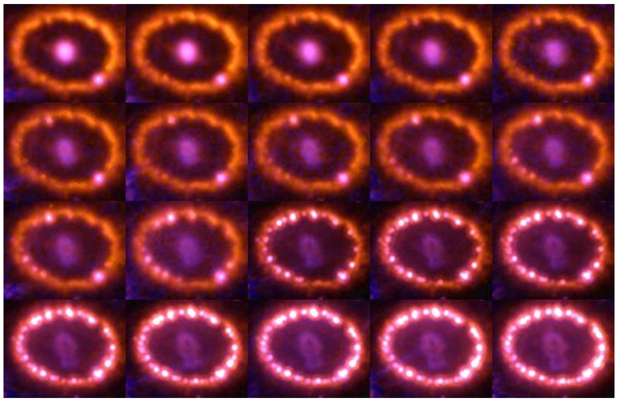

Fig. 6 Images of SN 1987A and its inner ring obtained with *HST-WFPC2* over the years 1996–2006, during which time the ring has developed at least twenty hot spots. [Credit: SINS Team, Peter Challis (Harvard) and NASA]

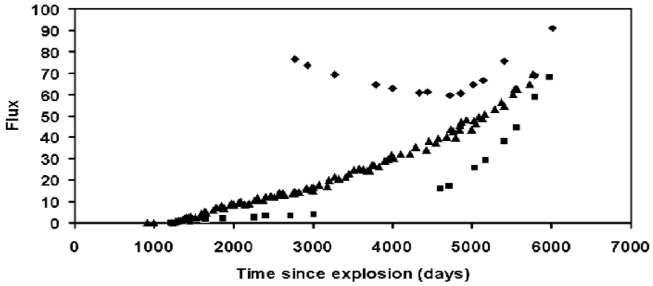

Fig. 7 The late evolution of the ring emission in the optical (diamonds), radio (triangles) and X-ray (squares) domains [adapted from McCray 2004].

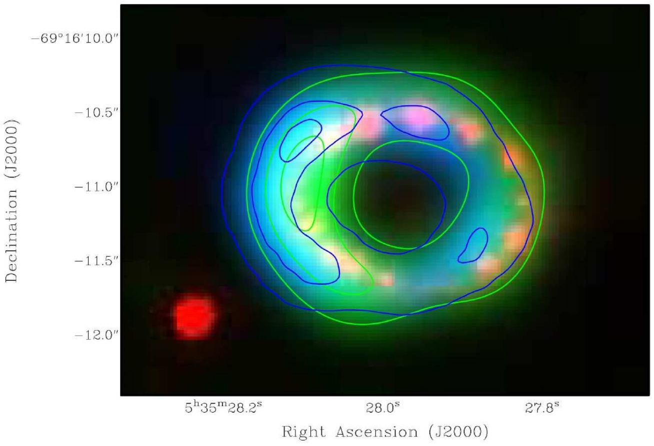

Fig. 8 Overlay of SN 1987A and its inner ring images obtained in the optical (Hα filter; red), radio (blue), and X-ray (green). Note the both radio and X-ray images show a remarkably stronger brightness on the East side whereas the optical displays brighter spots on the West side (Gaensler et al. 2007).

Discussing the physical correlation between IR and X-ray emission, Bouchet et al. (2006) 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. (2006) 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. Dwek & Arendt (2007) have also shown that the IR emission provides important complementary information on the interaction of the SN blast wave with the circumstellar equatorial ring that cannot be obtained at any other wavelength.

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. McCray 2004). Eventually, the ejecta will completely sweep the ring up, clearing the circumstellar space of that beautiful remnant of the pre-supernova wind activity.

10 STELLAR REMNANT: A MISSING NEUTRON STAR

As reported by Graves et al. (2005) supernova 1987A was observed with the Space Telescope Imaging Spectrograph (STIS) on the HST in 1999 September and again with the Advanced Camera for Surveys (ACS) on the HST in 2003 November. The spectroscopic observations cover UV and optical wavelengths from 1140 to 10266 Å, and the imaging observations cover UV and optical wavelengths from 2900 to 9650 Å. No point source was seen in the remnant. The derived limiting flux of $F_{\rm opt} < 1.6 \times 10^{-14}$ erg s^{-1} cm^{-3} in the wavelength range 2900–9650 Å corresponds to an intrinsic luminosity of $L_{\rm opt} < 8 \times 10^{33}$ erg s^{-1} after allowance of an expected 35% attenuation due to dust absorption. Graves et al. (2005) show that any survivor of a possible binary system must be less luminous than an F6V star. Bright young pulsars such as Kes 75 or the Crab pulsar are excluded by optical and X-ray limits on SN 1987A. Other non-plerionic X-ray point sources have optical luminosities similar to the limits on a point source in SN 1987A. On the other hand, of the young pulsars known to be associated with SNRs, those with ages less than about 5000 years are all too bright in X-rays to be compatible with the limits on SN 1987A.

Discussing theoretical models for an accreting compact object, Graves et al. (2005) find that spherical accretion onto a neutron star is firmly ruled out and that spherical accretion onto a black hole is possible only if dust absorption in the remnant is considerably higher than predicted. 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. (2005) 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 a 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, that 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.

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