Supernova 1987A at Age 20

Richard McCray

JILA, University of Colorado, Boulder, CO 80309-0440

Abstract. At this conference, we celebrated the 20th anniversary of the discovery of SN1987A. What have we learned from this wonderful event? What questions remain outstanding? What can we expect to learn during the coming decades? Here, I briefly review these questions and set a context for some of the topics that are discussed in more detail in this volume.

Keywords: supernovae; supernova remnants
PACS: 95.30.Dr; 98.38.Am; 98.38.Mz

INTRODUCTION

Figure 1 shows SN1987A at age 20. The faint homunculus in the center is all that remains visible of the supernova itself. It has faded by a factor $\sim 10^{-7}$ since maximum light. Surrounding SN1987A is the remarkable system of three circumstellar rings. The inner ring is encircled by rapidly brightening "hot spots", caused by the impact of the supernova blast wave. Beyond the inner ring, we can barely make out the two faint outer loops.

As I shall describe, this image tells only part of the story. From images and spectra taken at wavelengths ranging from radio to X-ray, our community has developed a fairly coherent story of how SN1987A has evolved up to today. But the story has significant gaps and many mysteries remain – for example:

- What is the composition and distribution of newly synthesized elements in the supernova debris?
- What is the nature of the compact object at the center and why haven't we seen it?
- What processes account for the triple ring system and the circumstellar matter beyond these rings?
- What accounts for the hot spots?
- How were the relativistic particles responsible for the radio emission accelerated?

In this chapter, I will briefly address these questions and introduce a number of related topics, of which the reader will find more detailed discussions in other chapters of this volume.

LIGHT CURVE AND EXPLOSION DEBRIS

Victor Utrobin [1] describes how one can infer the progenitor mass ($\sim 20M_{\odot}$), radius ($\sim 35R_{\odot}$) and explosion energy ($\sim 1.5 \times 10^{51}$ ergs) from fits to the light curve and Hα line during the photospheric phase. The light curve during the photospheric phase is

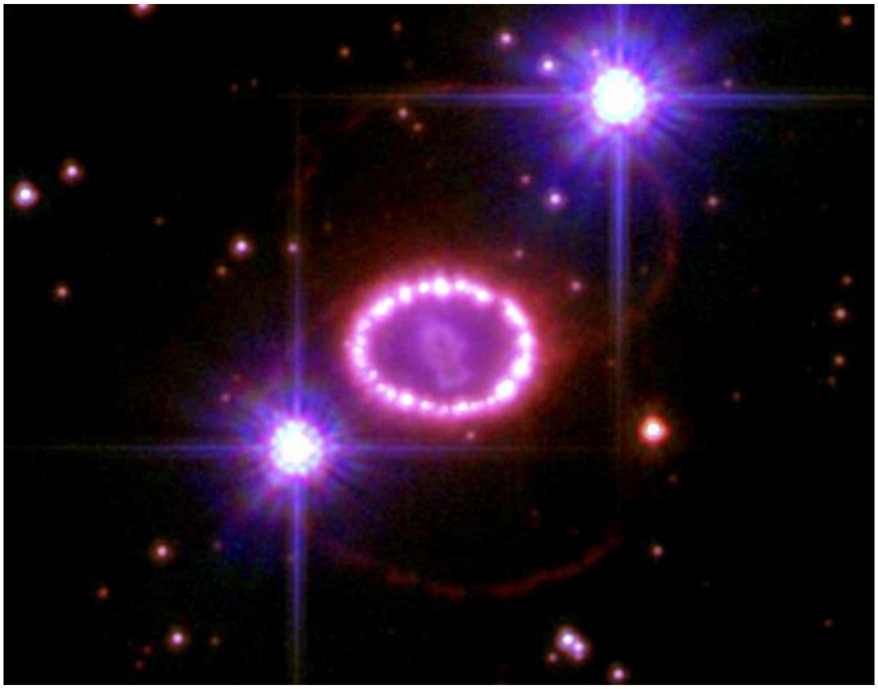

FIGURE 1. Supernova 1987A at Age 20 (December 2006). Courtesy of Bob Kirshner and the Space Telescope Science Institute

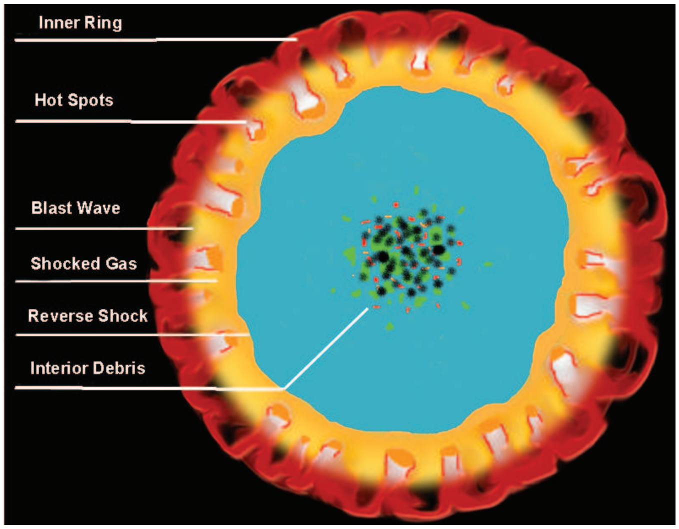

FIGURE 2. Schematic of SN1987A

dominated by energy input from $0.075M_\odot$ of newly synthesized ^{56}Ni, which decays to ^{56}Co and thence to ^{56}Fe.

The products of nucleosynthesis, both those produced in the late stages of stellar burning (such as O, Ne, Si) and the radioactive elements synthesized during the explosion, were mixed throughout the volume contained within the surface co-moving at radial ve-

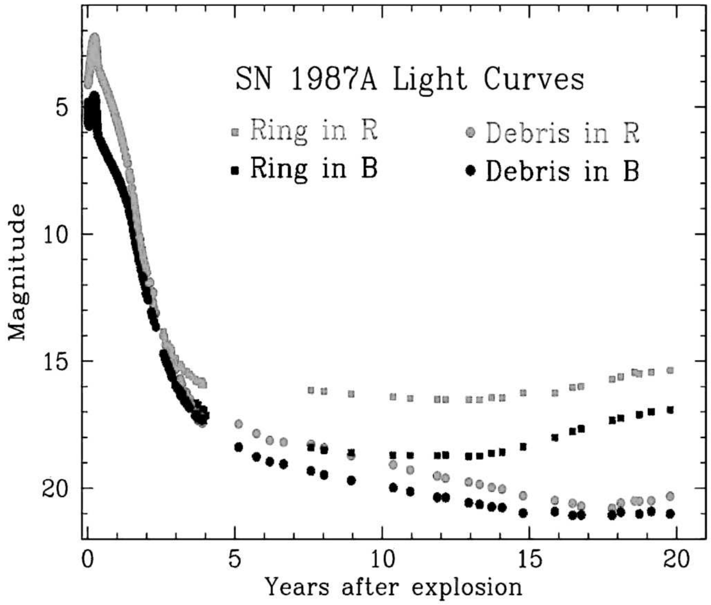

FIGURE 3. Light curves of SN1987A (courtesy of Bob Kirshner and Peter Challis)

locity $v \sim 3000$ km s^{-1} as a result of instabilities during the explosion. This mixing was macroscopic, not microscopic, so that this inner debris contained chunks having distinct elemental compositions (Fig. 2).

Figure 3 shows the light curve of the supernova debris. After the photosphere moved to the center ($t \approx 120$ d), the light curve decayed exponentially following the radioactive decay of ^{56}Co ($t_{1/2} = 77.3$ d). At $t \sim 400$ d, the optical light began to drop more rapidly, while the infrared emission increased so that the net luminosity continued to track the ^{56}Co decay [2]. At the same time the profiles of the optical and near infrared emission lines changed dramatically. The red wings nearly vanished, while the blue wings suffered much less obscuration. These events provide compelling evidence that dust formed in the supernova interior (Fig. 2). The obscuration was nearly independent of wavelength, indicating that the interior dust clouds had high optical depth.

The decay rate of the light began to slow down at $t \sim 3$ years, owing to radioactive heating by the longer-lived isotope ^{57}Co ($t_{1/2} = 271.8$ d) and to delayed recombination of the inner debris [3]. Today, the light curve is almost flat, and is dominated by heating due to the long-lived isotope ^{44}Ti ($t_{1/2} = 63$ yr). With a magnitude $R \sim 21$, the supernova is fainter than it was at maximum ($R \sim 3$) by a factor $\sim 10^{-7}$!

But we can still see it! As Bob Kirshner discusses [4], the inner debris is a faint irregular homunculus that now extends more than halfway to the inner circumstellar ring (Fig. 1). The shape of this glowing blob is determined, not only by the distribution of radioactively heated inner debris, but also by the distribution of interior dust clouds, which obscure more than half of the actual optical and near-infrared emission, especially that from the far side of the debris.

This homunculus may be the coldest optically emitting object known to astronomy. It is glowing by virtue of radioactive (primarily β^+) energy deposition by ^{44}Ti ($t_{1/2} = 63$ yr), but it has cooled dramatically. Wang et al. [5] showed that, six years after the explosion, the hydrogen gas in the inner debris had temperature $T < 400$ K, and this gas would have cooled significantly since then by adiabatic expansion ($T \propto t^{-2}$). The lumps of heavy elements probably have even lower temperature because their atoms and molecules can radiate far more efficiently than gas composed mainly of hydrogen and helium.

Despite considerable success in detailed modeling the observed spectrum of this inner debris during the nebular phase [2], we still do not have very good measures of the abundances of many of the elements in the inner debris. The reason is that the strengths of many of the observed emission lines are far more sensitive to temperature than they are to abundances. The most notable exceptions are the abundances of the radioactive isotopes driving the light curves: ^{56}Co ($0.075 M_\odot$), ^{57}Co ($3.3 \times 10^{-3} M_\odot$), and ^{44}Ti ($[0.5 - 2.0] \times 10^{-4} M_\odot$) [3].

THE MISSING COMPACT OBJECT

Underground detectors in Japan and Ohio registered a burst of neutrinos a few hours before the optical flash of the supernova was noticed. The inferred energy ($\sim 3 \times 10^{53}$ ergs), temperature (~ 4 MeV) and decay time (~ 4 s) of the burst were just what would be expected from the production of a neutron star through core collapse.

But since then, despite intensive searches in every wavelength band, we see no indication of a compact object at the center of SN1987A. Figure 4 shows the upper limits (ranging from infrared to gamma rays) to the observed luminosity of a point source at the center, and Dick Manchester [6] discusses the upper limits for a radio or optical pulsar.

The upper limit to a point source at optical wavelengths (in Nov. 2003) was $\approx 1.0 L_\odot$ [7]. It's possible to attribute this very low limit to absorption by internal dust. Figure 5 shows my estimates of the optical depths of the debris of SN1987A in various wavelength bands. In the optical band, the estimated range is $0.5 < \tau_O < 50$. The lower value is an estimate by Graves et al. [7], which I regard as optimistic, while upper value is a more pessimistic estimate, which I made by assuming that the newly synthesized silicon and carbon formed dust in the inner debris with high efficiency. In fact, the HST image (Fig. 1) [4] shows a dark spot right at the center of the glowing debris. That may be the culprit – an opaque dust cloud that just happens to lie in front of the compact object.

The optical depth at infrared wavelengths will be substantially less than that at optical wavelengths [11]. I estimate a range $10^{-2} < \tau_{18.6\mu m} < 1$ (Fig. 5). Thus, even in the pessimistic scenario, present observations (Fig. 4) can rule out an infrared point source with intrinsic luminosity $L_{18.6\mu m} \geq 100 L_\odot$.

As Figure 5 shows, the debris should be transparent at 3 keV, but is probably still opaque at 1 keV. The observed upper limit for a point source at 1 keV is interesting, as it is already less than the thermal radiation spectrum expected from a cooling neutron star with no accretion [12]. We might hope to observe such a source in the near future, since the X-ray optical depth should decrease $\propto t^{-2}$; but nature may thwart us. The impact of the supernova blast wave with its circumstellar matter is already producing a ring of

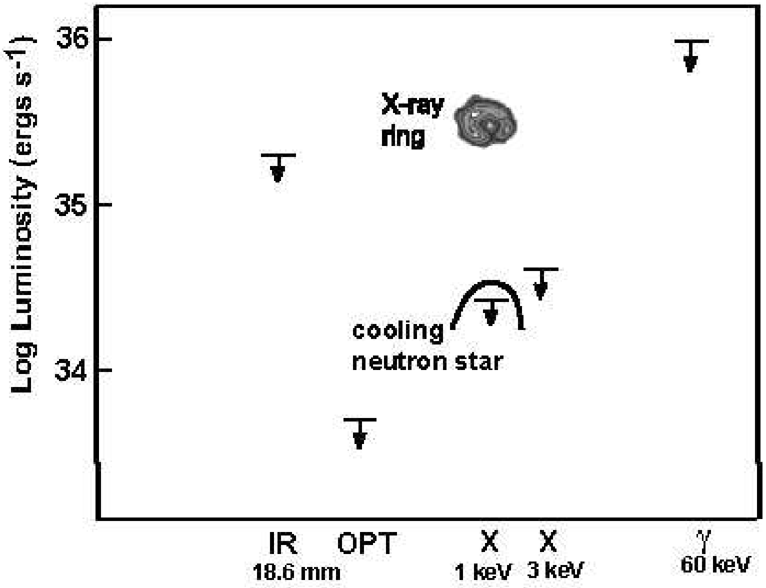

FIGURE 4. Observed limits to luminosity around a point source in SN1987A. IR [8]; OPT [7]; X [9]; Gamma [10].

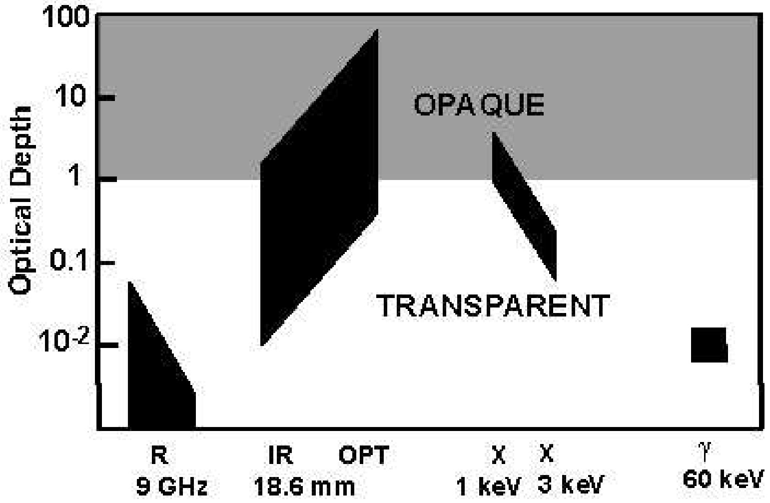

FIGURE 5. Optical depth estimates. The dark parallelograms indicate the estimated range of possible optical depths at 20 years. The dominant opacity mechanisms are: R – free-free; IR – dust; OPT – dust; X – photoelectric; Gamma – Compton scattering.

X-rays with luminosity ~ 20 times greater than the upper limit for the point source, and this ring is brightening rapidly (see below). Consequently, it will become increasingly difficult to detect a faint point source, and we may not be able to detect or rule out a cooling neutron star for the foreseeable future.

With current observations, we can probably rule out a compact object of any type with luminosity $> 100L_{\odot}$, but a less luminous neutron star or black hole might have escaped detection.

CIRCUMSTELLAR MATTER

What is the significance of the triple ring system surrounding SN1987A? Nobody expected that! This system provides a unique window on the evolution of the progenitor star, but we have a long way to go before we can unravel the story that is embedded in these rings and their surrounding circumstellar matter.

We do know some basic facts about these rings, as Peter Lundqvist [14], and Jason Pun [15] describe. From the early light curves of narrow emission lines observed in the spectrum of SN1987A, we know that these rings were ionized by a flash of radiation that accompanied the emergence of the supernova blast from the photosphere of the progenitor From the fading rate of various ultraviolet and optical emission lines, we know that the rings are composed of circumstellar gas having densities ranging from 3×10^3 cm$^3 \leq n \leq 3 \times 10^4$ cm^{-3} [15]. During the first few years the emission from the inner ring was dominated by the higher density gas, but that gas cooled and recombined more rapidly, so now the emission is dominated by the lower density gas. The nitrogen abundance in the ring is enriched by a factor ~ 10 over the LMC abundances [16], as would be expected if the gas in the ring was subjected to CNO processing in the progenitor star and then ejected.

We see that the inner ring is expanding with radial velocity ~ 10.3 km s^{-1}. Dividing its radius by its radial velocity gives us an estimate of $\Delta t \approx 20,000$ years since this ring was ejected. One arrives at the same estimate from the outer loops, which are roughly three times as far from the supernova and expanding roughly three times as fast as the inner ring.

The gas that we see in the inner ring has total mass $\sim 0.07 M_\odot$, but this glowing gas is only the inner skin of the actual mass that was ejected by the supernova progenitor. Its mass is limited by the initial flash of ionizing photons, which lasted about a day [17].

We saw clear evidence for substantially more circumstellar gas beyond the triple ring system from echoes of the supernova light scattered by dust grains in this gas, as described by Arlin Crotts [18]. Unfortunately, Arlin and his collaborators weren't provided enough telescope time to follow the development of these echoes as closely as we would like, so one can reconstruct the distribution of circumstellar matter only by making assumptions about its symmetry to fill in the gaps. By assuming cylindrical and reflection symmetry, Sugerman et al. [19] developed a wonderful (and complex) model for the distribution of this circumstellar matter, which extends from the rings to ~ 10 pc.

Sugerman et al. also estimated that the circumstellar matter responsible for the echoes had a net mass $\sim 1.7 M_\odot$. Their estimate was based on an assumed LMC dust/gas ratio ~ 0.1 times that of interstellar gas in the Milky Way. But, as Eli Dwek describes [13] (see below), the dust/gas ratio in the shocked circumstellar gas is $< 10^{-2}$ that of the Milky Way. If that ratio holds true for all the circumstellar matter responsible for the light echoes, its mass could be $> 10 M_\odot$.

How was this complex distribution of circumstellar matter formed? Ten years ago, in La Serena, Phillip Podsiadlowski argued that the progenitor of SN1987A was a massive binary, and that triple ring system was probably ejected during a merger of the two stars, and here [20] he describes progress since then. In particular, Morris & Podsiadlowski [21] have developed the binary merger model further with hydrodynamic simulations that appear to reproduce the morphology of the rings. Although I'm not sure that this model is correct in all its details, I think the binary scenario is the most likely explanation for the triple ring system. The acid test will be to see whether it can also account for the circumstellar matter seen in the light echoes.

CRASH!

Given that the photosphere of SN1987A was seen to expand at velocities $v \sim c/20$ and that the inner ring had a radius ≈ 0.6 light years, it doesn't take a rocket scientist to estimate that there would be a crash in a decade or so after outburst. The actual crash would be delayed somewhat because low density circumstellar gas inside the inner ring would decelerate the blast wave. Estimates of the year of first impact ranged from 1993 [22] to 1999 [23].

Actually, the first evidence of an impending crash was the nearly simultaneous appearance of soft X-ray and nonthermal radio emission $\sim 1200 - 1400$ days after outburst, as described by Bernd Aschenbach [24] and Lister Staveley-Smith [25]. That event was interpreted by Chevalier & Dwarkadas [26] as the consequence of the supernova blast wave overtaking a density discontinuity between the shocked stellar wind of the progenitor and gas photoevaporated from the inner ring and its environs.

Shortly after the 10 year anniversary celebration of SN1987A at La Serena, Pun et al. [27] reported the detection of a rapidly brightening "Spot 1" at P.A. 29° on the inner circumstellar ring. Actually Spot 1 was evident in HST images as early as March 1995 [28], although it wasn't noticed until April 1997. We soon recognized that Spot 1 was the result of the supernova blast wave overtaking a finger of relatively dense gas protruding inwards from the inner ring [29]. But we were all puzzled by the lack of evidence of interaction anywhere else on the ring until early 2002, when more spots began to appear.

Today, this crash is fully underway. The radiation in every band (except gamma rays) is dominated by the crash rather than the interior glow (Fig. 3). By this measure we can say that SN1987A has made the transition from supernova to supernova remnant. The montage in Figure 6 shows the evolution of SNR1987A in spectral bands ranging from radio to X-ray. The HST optical images show that the inner ring is fully encircled by hotspots. Claes Fransson [30], Karina Kjaer [31], and Nathan Smith [32] describe the evolving optical and infrared spectra of these hotspots.

The Chandra images of the rapidly brightening X-ray source have morphology similar to the HST images, allowing for the lower angular resolution of the Chandra telescope. On the other hand, the radio images from the ATCA [33] have a different morphology, suggesting that the relativistic particles responsible for this emission are not coming from the same location as the X-rays and optical emission. The 11.7 μm image shown in Figure 6 has a morphology very similar to the HST and Chandra images, suggesting that the infrared radiation, like the X-rays, is coming from the same location as the optical hotspots.

Sangwook Park [9] and Bernd Aschenbach [24] describe the X-ray light curve and spectrum of SNR1987A, while Lister Staveley-Smith [25] describes the radio light

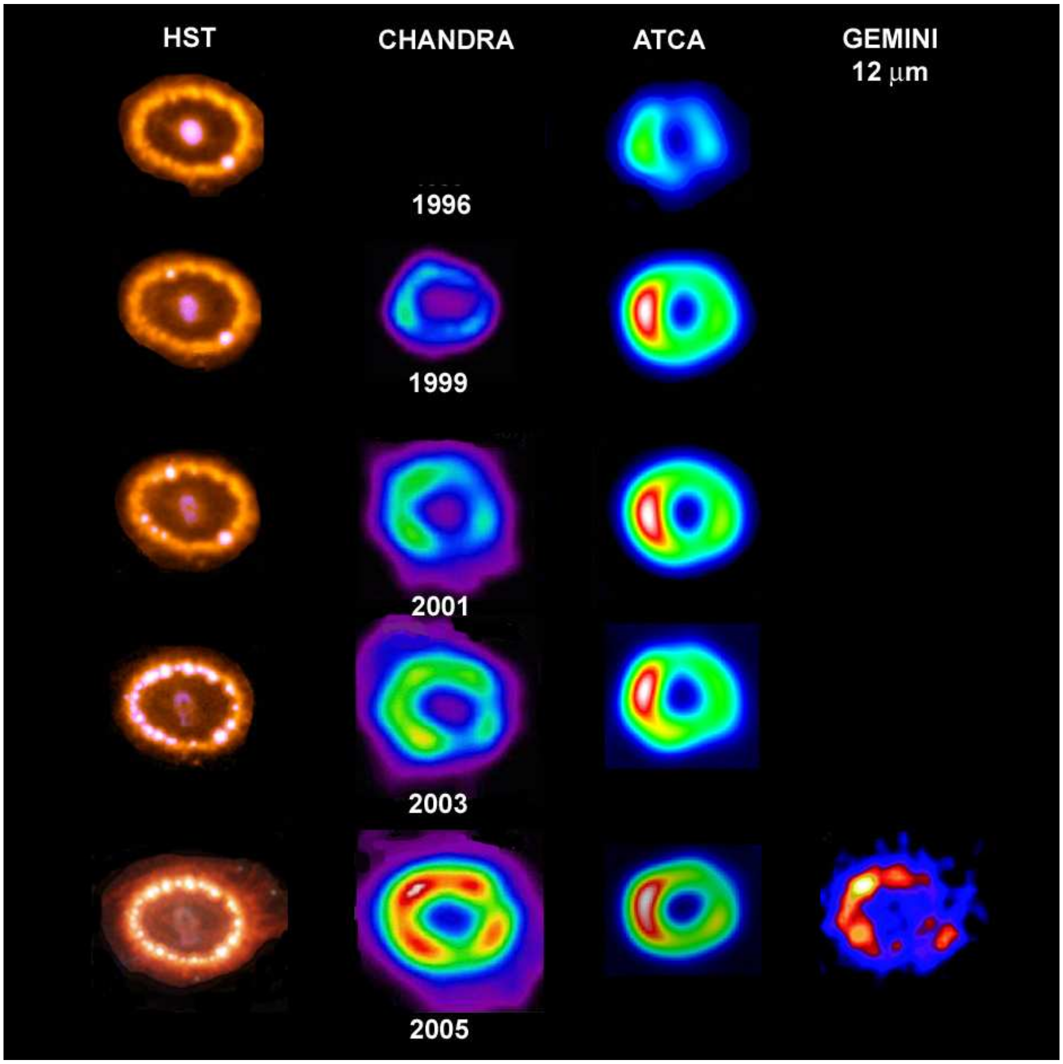

FIGURE 6. Development of SNR 1987A at several wavelength bands. HST –optical images, courtesy of P. Challis and R. Kirshner. Chandra – 0.5 - 3 keV X-ray images, courtesy of S. Park; ATCA – 9 GHz images from Australia Compact Telescope Array, courtesy of Bryan Gaensler; Gemini – 11.7 μm image, from [8].

curve. The radio and X-ray light curves tracked each other very well until about 1999 ([9], Fig. 4); but thereafter, the soft X-rays brightened much faster than the radio and hard X-rays. The fact that this brightening was roughly coincident with the appearance of the optical hotspots supports the idea that the soft X-rays are dominated by the hotspots, while the radio and harder X-rays are coming mainly from a region interior to the hotspots.

Figure 2 illustrates my notion of the hydrodynamics of SNR1987A. Going from inside outwards, the blue zone represents the freely expanding outer envelope of SN1987A, which is composed mainly of cold neutral hydrogen and helium. This gas is decelerated and heated to temperatures $\geq$ 10 keV at a reverse shock (the blue-yellow boundary).

The shocked supernova debris drives a blast wave, which propagates with velocity $\sim 3000-4000$ km s^{-1} through the relatively low density ($n \sim 100$ cm^{-3}) circumstellar gas inside the ring. The blast wave is now overtaking fingers of relatively dense gas extending inwards from the inner circumstellar ring (shown in red). When it hits the dense ($n \sim 10^4$ cm^{-3}) fingers, it is suddenly decelerated to ~ 700 km s^{-1} or less, depending on the density of the fingers and the angle of incidence.

In this picture, most of the soft X-ray emission comes from relatively fast ($v \sim 500-700$ km s^{-1}) shocks, while the optical emission comes from gas that has been compressed by relatively slow ($v \sim 150-300$ km s^{-1}) shocks. Only gas that has had time to cool by radiation will emit significant optical radiation, and this criterion puts an upper limit on the velocity that we see in the optical line profiles [34]. The difference in velocity can be attributed in part to angle of incidence: for example the head-on shocks that enter the tips of the hotspots (shown in orange) will be faster than the oblique shocks that enter the sides of the hotspots (shown in red). Also, irrespective of angle of incidence, the transmitted shocks will have a considerable range in velocities owing to the range of gas densities in the inner ring.

To this date, we have no good explanation for the morphology of the hotspots. The fingers must have been there before the blast wave hit them. The hotspots are still mostly unresolved at the angular resolution of the Hubble Space Telescope. Spot 1 has not merged with its neighbors even after more than 10 years, which implies that the finger responsible for Spot 1 must have a length $> 5 \times 10^{16}$ cm, assuming that the blast wave is overtaking the finger with radial velocity ~ 1500 km s^{-1}. The apparent radial expansion velocity of both the optical [4] and X-ray [9] images, ~ 1500 km s^{-1}, is substantially greater than the actual physical velocity measured from the respective linewidths ($\Delta v_{opt} \sim 150$ km s^{-1}, ($\Delta v_X \sim 500$ km s^{-1}).

The fingers responsible for the hotspots were probably formed by the action of the stellar wind of the progenitor on the inner circumstellar ring, which I suspect is actually the inner rim of a disk that was expelled during the merger of a binary progenitor. The fact that the hotspots seem to have a regular spacing, which is roughly equal to the thickness of the inner ring, may be an important clue to the instability that produced the fingers.

The harder X-rays probably come from the hotter gas between the blast wave and the reverse shock. I also suspect that the relativistic particles responsible for the non-thermal radio emission are accelerated at the reverse shock surface, but the current radio images do not have sufficient angular resolution to confirm this conjecture.

As Kevin Heng describes [35], we can measure the flux of hydrogen atoms through the reverse shock through spectroscopic observations of high velocity ($v \sim 12000$ km s^{-1}) Hα and Lyα emission. The gas flowing through the reverse shock is the piston that drives the hydrodynamics of the interaction. Heng et al [36] show that this flux is increasing, so we can be certain that the SNR1987A will continue to brighten in all wavelength bands for several more years at least.

In addition to the emission that we see coming from the reverse shock surface, Heng et al. also see high velocity Hα and Lyα emission that appears to come from the supernova debris inside the reverse shock. A likely explanation for this emission is illumination of the outer supernova debris by X-rays from the crash. Indeed, the external X-ray illumination may also account for the slight brightening of the inner debris during the past few years (Fig. 3 and in part for the apparent expansion of the internal debris.

Recent infrared observations from both ground-based telescopes and the Spitzer Observatory are giving us a wonderful opportunity to observe the properties of dust grains in the shocked gas. As Eli Dwek describes [13], [8], dust grains are heated by collisions with electrons and ions in the X-ray emitting gas. The temperature of the grains is insensitive to the grain size and the gas temperature but it does depend on the gas density. Dwek and Arendt show that the grain temperature ($T_{dust} \approx 180 \pm 15$ K) inferred from the Spitzer observations implies that the grains are embedded in gas of density $n_0 \sim 800$ cm^{-3}.

The infrared/X-ray luminosity ratio of the shocked gas gives a measure of the dust/gas density ratio. Dwek and Arendt show that this ratio in SN1987A is $\sim 10^{-2}$ of that for typical interstellar gas in the Milky Way, implying that dust formation was inefficient during the ejection episode that produced the inner circumstellar ring. As we have already mentioned, this result also implies that the mass of circumstellar gas inferred from the observed light echoes may have been underestimated substantially.

Finally, the fact that the observed infrared luminosity increased by a factor ~ 2 from December 2003 to September 2006 while the X-ray luminosity increased by a factor ~ 3 is evidence that dust grains are being destroyed by sputtering in the X-ray emitting gas [13].

THE NEXT 20 YEARS

We had a great time at the 10th anniversary celebration in La Serena. As we have seen, SN1987A has changed dramatically since then and it is still changing rapidly at this moment. One of the reasons SN1987A is so much fun to study is that we can forecast its future behavior, and we don't have to wait too long to see whether we guessed right. So here, I'll make a few more predictions.

The first prediction, and the one I can make with greatest confidence, is that there will be plenty of reasons to hold another SN1987A celebration in 2017. SN1987A continues to brighten with doubling timescales of a few years at radio, infrared, optical, and X-ray wavelengths. I expect that this brightening will continue for the next decade. The hotspots should merge. The X-ray and optical emission from the ring will be ~ 10 times brighter than they are today. The ionizing radiation from the crash will illuminate the freely expanding interior debris. We should therefore see this debris continue to brighten, and this brightening will give us a new look at its spatial distribution and elemental composition.

The ionizing radiation will also illuminate the external circumstellar matter, and so we should see a gradual brightening of narrow line emission from gas beyond the inner ring, giving us our first opportunity to see the distribution of this gas since the light echoes vanished. Such observations may give us the clues that we need to reconstruct the complex hydrodynamics that took place some 20,000 years before the supernova explosion.

Ten years from now, we will be observing SN1987A with powerful new telescopes now under construction. We have already begun to see that ground-based telescopes equipped with adaptive optics, such as VLT and Gemini-S, can produce infrared images and spectra with angular resolution rivaling the Hubble Space Telescope, and we have much to learn from more such observations. The James Webb Space Telescope will provide infrared images and spectra having even greater sensitivity and angular resolution, especially at far infrared wavelengths where we might hope to see evidence for a compact object.

Perhaps the most exciting new prospect for observing SN1987A is the Atacama Large Millimeter Array (ALMA). As Lister Staveley-Smith points out [25], this array will provide images of SN1987A at millimeter wavelengths having angular resolution comparable to or better than HST. Observations with ALMA will enable us to look much deeper for radio emission from a compact object. Possibly even more exciting, the ALMA images of nonthermal radiation from SN1987A will enable us, for the first time, to see relativistic particle acceleration taking place in real time and to identify this acceleration with the hydrodynamics that we can measure from observations at other wavelength bands.

How about the 2027 celebration? Now the crystal ball becomes a bit more cloudy, but I can still make some reasonably well-informed predictions. First, the crash will continue. The optical and X-ray light curves probably will have leveled off by then but they will not diminish [37]. By 2027, the newly synthesized elements in the inner debris will begin to cross the reverse shock, and so we should begin to see dramatic changes in the X-ray and optical spectra that will give us quantitative measures of supernova nucleosynthesis in unprecedented detail.

SN1987A has been tremendous fun for the past 20 years. I have no doubt that it will continue to provide new thrills for the rest of our lives, not only for me but also for the youngest participants in this conference.

REFERENCES

1. V. Utrobin *these proceedings*, – (2007).
2. R. McCray, *Annual Reviews Astronomy & Astrophysics* **31**, 175–216 (1993).
3. C. Fransson, & C. Kozma, *New Astron. Rev.* **46**, 487–92 (2002).
4. R. Kirshner, *these proceedings*, ... – ... (2007).
5. L. Wang, et al., *Astrophysical Journal* **466**, 998–1010 (1996).
6. R. Manchester, *these proceedings*, ... – ... (2007).
7. G. J. M. Graves et al., *Astrophysical Journal* **629**, 944 - 59 (2005).
8. P. Bouchet, et al., *Astrophysical Journal* **650**, 212–27 (2006).
9. S. Park, *these proceedings*, ... – ... (2007).
10. P. E. Shtykovskiy, A. A. Lutovinov, M. R. Gilfanov, & R. A. Sunyaev, *Astronomy Letters* **31**, 258–62 (2005).
11. B. Draine, 2003, *Annual Reviews Astronomy & Astrophysics* **41**, 241–89 (2003).
12. S. Tsuruta, M. A. Teter, T. Takatsuka, T. Tatsumi, & R. Tamagaki, *Astrophysical Journal* **571**, L143–46 (2002).
13. E. Dwek & R. G. Arendt *these proceedings*, ... – ... (2007).
14. P. Lundqvist *these proceedings*, ... – ... (2007).
15. C.J.S. Pun *these proceedings*, ... – ... (2007).
16. P. Lundqvist & C. Fransson, *Astrophysical Journal* **464**, 924–42 (1996).
17. L. Ensman & A. Burrows, *Astrophysical Journal* **393**, 742–55 (1992).
18. A. Crotts, *these proceedings*, ... – ... (2007).
19. B. E. K. Sugerman, et al. 2005, *Astrophysical Journal Suppl.* **159**, 60–99 (2005).
20. P. Podsiadlowski, *these proceedings*, ... – ... (2007).

21. T. Morris & P. Podsiadlowski, *Science* **315**, 1103–6 (2007).
22. D. Luo & R. McCray, *Astrophysical Journal* **372**, 194–8 (1991).
23. D. Luo, R. McCray, & J. Slavin, *Astrophysical Journal* **430**, 264–76 (1994).
24. B. Aschenbach, *these proceedings*, ... – ... (2007).
25. L. Staveley-Smith, *these proceedings*, ... – ... (2007).
26. R. A. Chevalier, & V. Dwarkadas, *Astrophysical Journal* **452**, L45–48 (1995).
27. C.J.S. Pun, et al., *IAU Circ.* **No. 6665** (1997).
28. S. S. Lawrence et al., *Astrophysical Journal* **537**, L123–6 (2000).
29. G. Sonneborn, et al., *Astrophysical Journal* **492**, L139–42 (1998).
30. C. Fransson, *these proceedings*, ... – ... (2007).
31. K. Kjaer, *these proceedings*, ... – ... (2007).
32. N. Smith, *these proceedings*, ... – ... (2007).
33. B. Gaensler, *these proceedings*, ... – ... (2007).
34. C.J.S. Pun, et al., *Astrophysical Journal* **572**, 906–931 (2002).
35. K. Heng, *these proceedings*, ... – ... (2007).
36. K. Heng et al., *Astrophysical Journal* **644**, 959–970 (2006).
37. K. Borkowski, et al., *Astrophysical Journal* **477**, 281–93 (1997).