SN1987A: The birth of a supernova remnant

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Supernova 1987A has been a prime target for the Hubble Space Telescope since its launch, and it will remain so throughout the lifetime of HST. Here I review the observations of SN1987A, paying particular attention to the rapidly developing impact of the blast wave with the circumstellar matter as observed by HST and the Chandra Observatory.

1. Introduction

If there was ever a match made in heaven, it is the combination of SN1987A and the Hubble Space Telescope. Although the HST was not available to witness the first three years after outburst, it has been the primary instrument to observe SN1987A since then.

SN1987A in the Large Magellanic Cloud is the brightest supernova to be observed since SN1604 (Kepler), the first to be observed in every band of the electromagnetic spectrum, and the first to be detected through its initial burst of neutrinos. Although the bolometric luminosity of SN1987A today is \( \approx 10^{-6} \) of its value at maximum light \( (L_{\text{max}} \approx 2.5 \times 10^{8} L_\odot) \), it will remain bright enough to be observed for many decades in the radio, infrared, optical, UV, and X-ray bands.

SN1987A is classified as a Type II supernova (SNeII) by virtue of the strong hydrogen lines in its spectrum. It was atypical of SNeII in that its light curve did not reach maximum until three months after outburst and its maximum luminosity was about 1/10 the mean maximum luminosity of SNeII. These differences can be attributed to the fact that the star that exploded was a blue giant, unlike the progenitors of most SNeII, which we believe to be red giants.

The burst of neutrinos observed from SN1987A proved beyond doubt that its explosion followed the collapse of the core of the star, but subsequent observations have shown no evidence of the neutron star or black hole that we expect to find at the center of the debris.

The expanding gaseous debris of SN1987A cooled rapidly after the explosion (McCray 1993). By 4 months, the debris had become transparent at optical and infrared wavelengths and its spectrum was dominated by emission lines. By 3 years, its temperature was less than 2,000 K throughout and the heavy elements had formed molecules and dust. With a present temperature < 100 K, the inner debris is perhaps the coldest optically emitting source known to astronomers. It is glowing because the atoms (primarily hydrogen) are excited by nonthermal electrons and positrons produced by the decay of radioactive elements, primarily \(^{44}\)Ti. HST images of SN1987A (Figure 1) show that this inner debris is slightly elongated in the NS direction, and that it is expanding with transverse velocity \( \sim 2,800 \text{ km s}^{-1} \). The irregular shape of the optical image is most likely a consequence of the irregular distribution of dust within the inner debris.

Perhaps the most outstanding mystery of SN1987A is the absence of any evidence (except the neutrino flash) of a compact object at its center. The central object must have a luminosity \( \lesssim 300 L_\odot \); otherwise we would have detected it by now.

The next most exciting mystery of SN1987A is the remarkable system of circumstellar rings shown in Figure 1. Evidently, they were ejected by the supernova progenitor some 20,000 years before it exploded. But how do we account for their morphology? At the
moment, there is no satisfactory explanation. But, as I shall describe in this chapter, events beginning now will give us a new window on the supernova's past.

The supernova blast wave is now beginning to strike the inner ring. This impact marks the birth of a supernova remnant, defined as the stage when the supernova light is dominated by the impact of the supernova debris with circumstellar matter. It will be a spectacular event. During the coming decade, the remnant SNR1987A will brighten by orders of magnitude at wavelengths ranging from radio to X-ray. HST will continue to be our most powerful tool to observe this unique event. But it will not be the only one. With the Chandra Observatory, we have already obtained our first images and spectra of the X-ray source. Large ground-based telescopes equipped with adaptive optics have already begun to provide excellent images and spectra at optical and near-infrared wavelengths. Future observatories, such as the Space Infrared Telescope Facility and the Atacama Large Millimeter Array, will provide data at other wavelength bands to complement the HST observations. The combination of these data will give us a unique opportunity to probe the rich range of physical phenomena associated with astrophysical shocks and to learn about the death throes of a supernova progenitor.
2. Energetics

Before describing the HST observations of SN1987A, it might be useful to review its energy sources. These are summarized in Table I.

As Table I shows, SN1987A has three different sources of energy, each of which emerges as a different kind of radiation and with a different timescale. The greatest is the collapse energy itself, which emerges as a neutrino burst lasting a few seconds. The energy provided by radioactive decay of newly synthesized elements is primarily responsible for the optical display. Most of this energy emerged within the first year after outburst, primarily in optical and infrared emission lines and continuum from relatively cool ($T \lesssim 5,000$ K) gas. Note that the radioactive energy is relatively small, $\sim 10^{-4}$ of the collapse energy.

The kinetic energy of the expanding debris can be inferred from observations of the spectrum during the first three months after explosion. Astronomers infer the density and velocity of gas crossing the photosphere from the strengths and widths of hydrogen lines in the photospheric spectrum. By tracking the development of the spectrum as the photosphere moved to the center of the debris, astronomers can measure the integral defining the kinetic energy. Doing so, they find that $\sim 10^{-2}$ of the collapse energy has been converted into kinetic energy of the expanding debris. Why this fraction is typically $10^{-2}$ and not, say, $10^{-1}$ or $10^{-3}$, is one of the unsolved problems of supernova theory.

This kinetic energy will be converted into radiation when the supernova debris strikes circumstellar matter. When this happens, two shocks always develop: the blast wave, which overtakes the circumstellar matter; and the reverse shock, which is driven inwards (in a Lagrangian sense) through the expanding debris. The gas trapped between these two shocks is typically raised to temperatures in the range $10^6$–$10^8$ K and will radiate most of its thermal energy as X-rays with a spectrum dominated by emission lines in the range 0.3–10 keV.

Most of the kinetic energy of the debris will not be converted into thermal energy of shocked gas until the blast wave has overtaken a circumstellar mass comparable to that of the debris itself, $\sim 10$–20 $M_\odot$. Typically, that takes many centuries, and as a result, most galactic supernova remnants (e.g., Cas A) reach their peak X-ray luminosities after a few centuries and fade thereafter.

As I discuss below, we believe that SN1987A is surrounded by a few $M_\odot$ of circumstellar matter within a distance of parsec or two. Thus, a significant fraction of the kinetic energy of the debris will be converted into thermal energy within a few decades as the supernova blast wave overtakes this matter.
3. The circumstellar rings

The first evidence for circumstellar matter around SN1987A appeared a few months after outburst in the form of narrow optical and ultraviolet emission lines seen with the *International Ultraviolet Explorer* (Fransson et al. 1989). Even before astronomers could image this matter, they could infer that:

- the gas was nearly stationary (from the linewidths);
- it was probably ejected by the supernova progenitor (because the abundance of nitrogen was elevated);
- it was ionized by soft X-rays from the supernova flash (from emission lines of NV λλ1239, 1243 and other highly ionized elements in the spectrum);
- it was located at a distance of about a light year from the supernova (from the rise time of the light curve of these lines); and
- the gas had atomic density $\sim 3 \times 10^3 - 3 \times 10^4$ cm$^{-3}$ (from the fading timescale of the narrow lines).

The triple ring system was first seen in images obtained by the ESO *NTT* telescope (Wampler et al. 1990), but the evidence of the outer loops was not compelling until astronomers obtained an image with the *HST* WFPC-2 (Burrows et al. 1995). By measuring the Doppler shifts of the emission lines, Crotts & Heathcote (1991) found that the inner ring is expanding with a radial velocity $\approx 10$ km s$^{-1}$. Dividing the radius of the inner ring (0.67 lt-year) by this velocity gives a kinematic timescale $\approx 20,000$ years since the gas in the ring was ejected, assuming constant velocity expansion. The more distant outer loops are expanding more rapidly, consistent with the notion that they were ejected at the same time as the inner ring.

The rings observed by *HST* may be only the tip of the iceberg. They are glowing by virtue of the ionization and heating caused by the flash of EUV and soft X-rays emitted by the supernova during the first few hours after outburst. But calculations (Ensmann & Burrows 1992) show that this flash was a feeble one. The glowing gas that we see in the triple ring system is probably only the ionized inner skin of a much greater mass of unseen gas that the supernova flash failed to ionize. For example, the inner ring has a glowing mass of only about $\sim 0.04$ M$_{\odot}$, just about what one would expect such a flash to produce.

In fact, ground-based observations of optical light echoes during the first few years after outburst provided clear evidence of a much greater mass of circumstellar gas within several light years of the supernova that did not become ionized (Wampler et al. 1990; Crotts, Kunkel, & Heathcote 1995). The echoes were caused by scattering of the optical light from the supernova by dust grains in this gas. They became invisible about five years after outburst.

What accounts for this circumstellar matter and the morphology of the rings? My hunch is that the supernova progenitor was originally a close binary system, and that the two stars merged some 20,000 years ago. The inner ring might be the inner rim of a circumstellar disk that was expelled during the merger, perhaps as a stream of gas that spiraled out from the outer Lagrangean (L2) point of the binary system. Then, during the subsequent 20,000 years before the supernova event, ionizing photons and stellar wind from the merged blue giant star eroded a huge hole in the disk. Finally, the supernova flash ionized the inner rim of the disk, creating the inner ring that we see today.

The binary hypothesis provides a natural explanation of the bipolar symmetry of the system, and may also explain why the progenitor of SN1987A was a blue giant rather than a red giant (Podsiadlowski 1992). But we still lack a satisfactory explanation for
the outer loops. If we could only see the invisible circumstellar matter that lies beyond the loops, we might have a chance of reconstructing the mass ejection episode.

Fortunately, SN1987A will give us another chance. When the supernova blast wave hits the inner ring, the ensuing radiation will cast a new light on the circumstellar matter. As I describe below, this event is now underway.

4. The crash begins

The first evidence that the supernova debris was beginning to interact with circumstellar matter came from radio and X-ray observations. As Figure 2 shows, SN1987A became a detectable source of radio and soft X-ray emission about 1200 days after the explosion and has been brightening steadily in both bands ever since. Shortly afterwards, astronomers imaged the radio source with the Australia Telescope Compact Array (ATCA) and found that the radio source was an elliptical annulus inside the inner circumstellar ring observed by HST (Figure 6). From subsequent observations, they found that the annulus was expanding with a velocity $\sim 3,500 \text{ km s}^{-1}$.

Chevalier (1992) recognized that the radio emission most likely arose from relativistic electrons accelerated by shocks formed inside the inner ring where the supernova debris struck relatively low density ($n \sim 100 \text{ cm}^{-3}$) circumstellar matter, and that the X-ray emission probably came from the shocked circumstellar matter and supernova debris. Subsequently, Chevalier & Dwarkadas (1995) suggested a model for the circumstellar matter, in which the inner circumstellar ring is the waist of an hourglass-shaped bipolar nebula. The low density circumstellar matter is a thick layer of photoionized gas that
lines the interior of the bipolar nebula. The inner boundary of this layer is determined by balance of the pressure of the hot bubble of shocked stellar wind gas and that of the photoionized layer. In the equatorial plane, the inner boundary of this layer is located at about half the radius of the inner ring. According to this model, the appearance of X-ray and radio emission at \( \sim 1200 \) days marks the time when the blast wave first enters the photoionized layer.

5. The reverse shock

Following Chevalier & Dwarkadas (1995), Borkowski, Blondin, & McCray (1997a) developed a more detailed model to account for the X-ray emission observed from SN1987A. They used a 2-D hydro code to simulate the impact of the outer atmosphere of the supernova with an idealized model for the photoionized layer. They found a good fit to the ROSAT observations with a model in which the thickness of the photoionized layer was about half the radius of the inner ring and the layer had atomic density \( n_0 \approx 150 \text{ cm}^{-3} \).

With the same model, we found to our delight that Ly\( \alpha \) and H\( \alpha \) emitted by hydrogen atoms crossing the reverse shock should be detectable with the STIS. Then, in May 1997, only three months after our predictions appeared in the ApJ (Borkowski et al. 1997a), the first STIS observations of SN1987A were made, and broad \((\Delta V \approx \pm 12,000 \text{ km s}^{-1})\) Ly\( \alpha \) emission lines were detected (Sonneborn et al. 1998). Within the observational uncertainties, the flux was exactly as predicted.

One might at first be surprised that such a theoretical prediction of the Ly\( \alpha \) flux would be on the mark, given that it was derived from a hydrodynamical model based on very uncertain assumptions about the density distribution of circumstellar gas. But, on further reflection it is not so surprising because the key parameter of the hydrodynamical model, the density of the circumstellar gas, was adjusted to fit the observed X-ray flux. Since the intensity of Ly\( \alpha \) is derived from the same hydrodynamical model, the ratio of Ly\( \alpha \) to the X-ray flux is determined by the ratio of cross sections for atomic processes, independent of the details of the hydrodynamics.

The broad Ly\( \alpha \) and H\( \alpha \) emission lines are not produced by recombination. (The emission measure of the shocked gas is far too low to produce detectable Ly\( \alpha \) and H\( \alpha \) by recombination.) Instead, the lines are produced by neutral hydrogen atoms in the supernova debris as they cross the reverse shock and are excited by collisions with electrons and protons in the shocked gas. Since the cross sections for excitation of the \( n \geq 2 \) levels of hydrogen are nearly equal to the cross sections for impact ionization, about one Ly\( \alpha \) photon is produced for each hydrogen atom that crosses the shock. Thus, the observed flux of broad Ly\( \alpha \) is a direct measure of the flux of hydrogen atoms that cross the shock. Moreover, since the outer supernova envelope is expected to be nearly neutral, the observed flux is a measure of the mass flux across the shock.

The fact that the Ly\( \alpha \) and H\( \alpha \) lines are produced by excitation at the reverse shock gives us a powerful tool to map this shock. Since any hydrogen in the supernova debris is freely expanding, its line-of-sight velocity, \( V_\parallel = z/t \), where \( z \) is its depth measured from the mid-plane of the debris and \( t \) is the time since the supernova explosion. Therefore, the Doppler shift of the Ly\( \alpha \) line will be directly proportional to the depth of the reverse shock: \( \Delta \lambda/\lambda_0 = z/ct \). Thus, by mapping the Ly\( \alpha \) or H\( \alpha \) emission with STIS, we can generate a 3-dimensional image of the reverse shock.

Figure 3 illustrates this procedure. Panel a shows the location of the slit superposed on an image of the inner circumstellar ring, with the near (N) side of the tilted ring on the lower left. Panel b shows the actual STIS spectrum of Ly\( \alpha \) from this observation. The slit is black due to geocoronal Ly\( \alpha \) emission. The bright blue-shifted streak of Ly\( \alpha \)
extending to the left of the lower end of the slit comes from hydrogen atoms crossing the near side of the reverse shock, while the fainter red-shifted streak at the upper end of the slit comes from the far side of the reverse shock.

From this and similar observations with other slit locations we have constructed a map of the reverse shock surface, shown in panel c. Note that the emitting surface is an annulus that lies inside the inner circumstellar ring. Presumably, the reverse shock in the polar directions lies at a greater distance from the supernova, where the flux of atoms in the supernova debris is too low to produce detectable emission. Panel d is a model of the STIS Lyα spectrum that would be expected from hydrogen atoms crossing the shock surface illustrated in panel c. By comparing such model spectra with the actual spectra (e.g. panel b), we may refine our model of the shock surface.

Note that the broad Lyα emission is much brighter on the near (blue-shifted) side of the debris than on the far side, and so is the reconstructed shock surface. There is one obvious reason why this should be so: the blue-shifted side of the reverse shock is nearer to us by several light-months, and so we see the emission from the near side as it was several months later than that from the far side. Since the flux of atoms across the reverse shock is increasing, the near side should be brighter. But this explanation fails quantitatively. The observed asymmetry is several times greater than can be explained by light-travel time delays, and must be attributed to real asymmetry in the supernova debris. As we shall see, observations at radio and X-ray wavelengths also provide compelling evidence for asymmetry of the supernova debris.

6. The hot spots

One can estimate the time that the blast wave should strike the inner circumstellar ring from Chevalier's (1982) self-similar solutions for the hydrodynamics of a freely expanding stellar atmosphere striking a circumstellar medium. Stellar atmosphere models give a good fit to the spectrum of SN1987A during the early photospheric phase with a stellar atmosphere having a power-law density law $\rho(r, t) = At^{-3}(r/t)^{-9}$ (Eastman & Kirshner 1989; Schütz et al. 1990). If this atmosphere strikes a circumstellar medium having a uniform density $n_0$, the blast wave will propagate according to the law $R_B(t) \propto A^{1/9}n_0^{-1/9}t^{2/3}$. For such a model, the time of impact can be estimated from the
equation $t \propto A^{-1/6} n_0^{1/6}$. The coefficient, $A$, of the supernova atmosphere density profile can determined from the fit to the photospheric spectrum, leaving the density, $n_0$, of the gas between the supernova and the circumstellar ring as the main source of uncertainty. With various assumptions about the density distribution of this gas, predictions of the time of first contact ranged from 2003 (Luo & McCray 1991) to 1999 ± 3 (Luo, McCray, & Slavin 1994) to 2005 ± 3 (Chevalier & Dwarkadas 1995).

In April 1997, Sonneborn et al. (1998) obtained the first STIS spectrum of SN1987A with the 2 × 2 arcsecond aperture. Images of the circumstellar ring were seen in several optical emission lines. No Doppler velocity spreading was evident in the ring images except at one point, located at $P.A. = 29^\circ$ (E of N), which we now call "Spot 1," where a Doppler-broadened streak was seen in Hα and other optical lines.

Figure 4 (Michael et al. 2000) shows a portion of a more recent (March 1998) STIS spectrum of Spot 1, where one can see vertical pairs of bright spots corresponding to emission from the stationary ring at Hα and [NII]λλ6548, 6584 (one also sees three more fainter spots at each wavelength where the outer loops cross the slit, and a broad horizontal streak at the center due to the Hα emission from the rapidly expanding inner debris). The emission lines are broadened (with FWHM $\approx 250$ km s$^{-1}$) and blue-shifted (with $\Delta V \approx -80$ km s$^{-1}$) at the location of Spot 1, which is located slightly inside the stationary ring.

Spot 1 evidently marks the location where the supernova blast wave first touches the dense circumstellar ring. When a blast wave propagating with velocity $V_r \approx 4,000$ km s$^{-1}$ through circumstellar matter with density $n_0 \approx 150$ cm$^{-3}$ encounters the ring, having density $n_r \approx 10^4$ cm$^{-3}$, one would expect the transmitted shock to propagate into the ring with $V_r \approx (n_0/n_r)^{1/2} V_b \approx 500$ km s$^{-1}$ if it enters at normal incidence, and more slowly if it enters at oblique incidence. Since Spot 1 is evidently a protrusion, a range of incidence angles, and hence of transmitted shock velocities and directions, can be expected. Obviously, the line profiles will be sensitive to the geometry of the protrusion. Since the protrusion is on the near side of the ring and is being crushed by the entering shocks, most of the emission will be blue-shifted, as is observed. But part of the emission is red-shifted because it comes from oblique shocks entering the far side of the protrusion.
Looking back to previous WFPC images, Garnavich et al. (2000) found that Spot 1 had begun to brighten as early as 1996. It has continued to brighten steadily, with a current doubling time scale of about one year. As of February 2000, Spot 1 had a flux \( \approx 7\% \) of the rest of the inner circumstellar ring.

Since the detection of Spot 1, several new spots have appeared, of which four (at P.A. \( \approx 91^\circ, 106^\circ, 123^\circ \) and \( 230^\circ \), are evident in Figure 5 (Garnavich et al. 2000; Lawrence et al. 2000). Clearly, the blast wave is beginning to overtake the inner circumstellar ring in several places.

The emission line spectrum of Spot 1 resembles that of a radiative shock, in which the shocked gas has had time to cool from its post-shock temperature \( T_1 \approx 1.6 \times 10^3 [V_r/(100 \text{ km s}^{-1})]^2 \) K to a final temperature \( T_f \approx 10^4 \) K or less. As the shocked gas cools, it is compressed by a density ratio \( n_f/n_r \approx (T_1/T_f)^{1/2} \), where \( T_f = (10^4 \text{ K}) \). We see evidence of this compression in the observed ratios of forbidden lines, such as [NII] \( \lambda \lambda 6548, 6584 \) and [SII] \( \lambda \lambda 6717, 6731 \), from which we infer electron densities in the range \( n_e \sim 10^6 \text{ cm}^{-3} \) using standard nebular diagnostics.

The fact that the shocked gas in Spot 1 was able to cool and form a radiative layer within a few years sets a lower limit, \( n_r \gtrsim 10^4 \text{ cm}^{-3} \), on the density of unshocked gas in the protrusion. Given that limit, we can estimate an upper limit on the emitting surface area of Spot 1, from which we infer that Spot 1 should have an actual size no greater than about one pixel on WFPC2. This result is consistent with the imaging observations.

The cooling timescale of shocked gas is sensitive to the postshock temperature, hence shock velocity. For \( n_r = 10^4 \text{ cm}^{-3} \), shocks faster than 250 km s\(^{-1}\) will not be able to radiate and form a cooling layer within a few years. It is quite possible that such fast non-radiative shocks are present in the protrusions but are invisible in optical and UV line emission. For example, I estimated above that a blast wave entering the protrusion at normal incidence might have velocity \( \sim 500 \text{ km s}^{-1} \). We would still see the line emission from the slower oblique shocks on the sides of the protrusion, however.

We have attempted to model the observed emission line spectrum of Spot 1 with a radiative shock code kindly provided by John Raymond. Up to now, our efforts have
met with only partial success. This is perhaps not surprising, given the complexity of the hydrodynamics. It is known, for example, that radiative shocks are subject to violent thermal instabilities (e.g. Innes, Giddings & Falle 1987), which we have not included in our initial attempts to model the shock emission.

7. The X-ray source

As I have already mentioned in §4, we believe that the X-ray emission from SNR1987A seen by ROSAT (Figure 2) comes from the hot shocked gas trapped between the supernova blast wave and the reverse shock. But, with its 10″ angular resolution, ROSAT was unable to image this emission; nor was ROSAT able to obtain a spectrum.

Very recently, Burrows et al. (2000) used the new Chandra Observatory to advance our knowledge of the image and spectrum of X-rays from SNR1987A. Figure 6 is a montage of images of SNR1987A, showing: the HST optical image (a); the ATCA radio image from the (b); and the X-ray images observed by Chandra on 6 October 1999 (c) and 17 January 2000 (d). The optical image (a) is replicated as contour lines on images (b), (c), and (d). We see immediately that the ATCA radio source (b) is an annulus that is somewhat smaller than the optical ring and is much brighter on the E side than on the W.
The two Chandra images appear different, but we are not sure whether this difference represents an actual change of the X-ray source or is an artifact of the limited photon statistics of the observations and the deconvolution procedure we used to achieve the maximum possible angular resolution. We can be sure, however, that the X-ray source, like the radio source, is an annulus that lies mostly within the optical ring, and that it is brighter on the E side than on the W.

The X-ray images of SNR1987A are consistent with the model by Borkowski et al. (1997a), except that they obviously do not have the cylindrical symmetry assumed in that model. The fact that the X-ray and radio images have roughly the same morphologies suggests that the relativistic electrons presumed responsible for the non-thermal radio emission have energy density proportional to that in the X-ray emitting gas and reside in roughly the same volume.

The fact that the X-ray and radio images are both brighter on the E side than on the W could be explained by a model in which either: (a) the circumstellar gas inside the inner ring had greater density toward the E; or (b) the outer supernova debris had greater density toward the E. But the fact that most of the hot spots are found on the E side favors the latter hypothesis. If the circumstellar gas had greater density toward the E side and the supernova debris were symmetric, the blast wave would have propagated further toward the W side, and the hot spots would have appeared there first.

This conclusion is also supported by observations of Hα and Lyα emission from the reverse shock (§5), which show that the flux of mass across the reverse shock is greater on the W side.

These observations highlight a new puzzle about SNR1987A: why was the explosion so asymmetric? We might explain a lack of spherical symmetry by rapid rotation of the progenitor, but how do we explain a lack of azimuthal symmetry?

With the grating spectrometer on Chandra, Burrows et al. (2000) also obtained a spectrum of the X-rays from SNR1987A, shown in Figure 7. It is dominated by emission lines from helium- and hydrogen-like ions of O, Ne, Mg, and Si, as well as a complex of Fe-L lines near 1 keV, as predicted by Borkowski et al. (1997a). The characteristic electron temperature inferred from the spectrum, $kT_e \sim 3$ keV, is much less than the proton temperature, $kT_p \sim 30$ keV for a blast wave propagating with $V_b \approx 4,000$ km s$^{-1}$. This result was expected because Coulomb collisions are too slow to raise the electron temperature to equilibrium with the ions.

The Chandra observations show that the current X-ray flux from SNR1987A is about twice the value that would be estimated by extrapolating the ROSAT light curve to January 2000 (Figure 2). The X-ray flux is expected to increase by another factor $\sim 10^2$ during the coming decade as the blast wave overtakes the inner circumstellar ring (Borkowski et al. 1997b). Are we already beginning to see the X-ray emission from the shocked ring? Further imaging (with Chandra) and spectroscopic (with XMM) observations will tell.

8. The future

SNR1987A has been tremendous fun so far, but the best is yet to come. During the next ten years, the blast wave will overtake the entire circumstellar ring. More hot spots will appear, brighten, and eventually merge until the entire ring is blazing brighter than Spot 1. We expect that the Hα flux from the entire ring will increase to $F_{\text{Hα}} \gtrsim 3 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$, or $\gtrsim 30$ times brighter than it is today and that the flux of ultraviolet lines will be even greater (Luo et al. 1994).
As we have already begun to see, observations at many wavelength bands are needed to tell the entire story of the birth of SNR1987A. Fortunately, powerful new telescopes and technologies are becoming available just in time to witness this event. Large ground-based telescopes equipped with adaptive optics will provide excellent optical and infrared spectra of the hot spots. We need to observe profiles of several emission lines at high resolution in order to unravel the complex hydrodynamics of the hot spots. These telescopes also offer the exciting possibility to image the source in infrared coronal lines of highly ionized elements (e.g. [Si IX] 2.58, 3.92 μm, [Si X] 1.43 μm) that may be too faint to see with HST. Observations in such lines will complement X-ray observations to measure the physical conditions in the very hot shocked gas.

The circumstellar rings of SN1987A almost certainly contain dust, and so does the envelope of SN1987A (McCray 1993). When dusty gas is shocked to temperatures $\gtrsim 10^6$ K, its emissivity at far infrared wavelengths ($\gtrsim 10 \mu$m) exceeds its X-ray emissivity by factors $\sim 10^2$–$10^3$ (Dwek & Arendt 1992). Therefore, we expect that SNR1987A will be brightest at far infrared wavelengths, with luminosity $\sim 10^2$–$10^3$ times its X-ray luminosity. This makes SNR1987A a prime target for SIRTF. Together with the Chandra and XMM observations of the X-ray spectra, the SIRTF observations will give us a unique opportunity to investigate the destruction of dust grains in shocked gas.

The observations with the ATCA have given us our first glimpse of shock acceleration of relativistic electrons in real time, but the angular resolution of ATCA is not quite good enough to allow a detailed correlation of the radio image with the optical and X-ray images. This will become possible several years from now when the Atacama Large Millimeter Array (ALMA) is completed. Such observations will give us a unique opportunity to test our theories of relativistic particle acceleration by shocks.
Finally, I’ll take this opportunity to do some shameless special pleading to continue intensive observations of SNR1987A with HST. Most likely, we won’t have a comparable opportunity to observe the birth of a supernova remnant during the lifetime of HST—indeed, during our lifetimes. The opportunities to observe SNR1987A with other new facilities do not challenge the preeminence of HST; they enhance it.

Of course, we should continue to map the emission of fast Lyα and Hα from the reverse shock with STIS. Such observations give us a three-dimensional image of the flow of the supernova debris across the reverse shock, providing the highest resolution map of the asymmetric supernova debris. We expect this emission to brighten rapidly, doubling on a timescale ~ 1 year. Most exciting, such observations will give us an opportunity to map the distribution of nucleosynthesis products in the supernova debris. We know that the debris has a heterogeneous composition. The early emergence of gamma rays from SN1987A showed that some of the newly synthesized $^{56}$Co (and probably also clumps of oxygen and other elements) were mixed fairly far out into the supernova envelope by instabilities following the explosion (McCray 1993). When such clumps cross the reverse shock, the fast Hα and Lyα lines will vanish at those locations, to be replaced by lines of other elements. If we keep watching with STIS, we should see this happen during the coming decade.

Likewise, we should continue to monitor the development of the hot spots with HST, using WFPC2 to observe images and STIS to observe spectra. Optical and infrared spectra obtained with ground-based telescopes will be of limited value unless they are complemented by HST observations to tell us which spots are producing which lines. Moreover, only HST can observe UV lines such as N iv $\lambda\lambda$ 1483, 1486 and N v $\lambda\lambda$ 1239, 1243, the ratio of which are sensitive functions of shock velocity. We need to measure these ratios as a function of Doppler shift to untangle the complex hydrodynamics of the shocks entering the spots. Spot 1 is now becoming bright enough to do that with HST.

The shocks in the hot spots are surely producing ionizing radiation, roughly half of which will propagate ahead of the shock and ionize heretofore invisible material in the rings. The effects of this precursor ionization will soon become evident in the form of narrow cores in the emission lines from the vicinity of the hot spots.

In §3 I pointed out that the circumstellar rings of SN1987A represent only the inner skin of a much greater mass of circumstellar matter, and that we obtained only a fleeting glimpse of this matter through ground-based observations of light echoes. The clues to the origin of the circumstellar ring system lie in the distribution and velocity of this matter, if only we could see it clearly. Fortunately, SNR1987A will give us another chance. Although it will take several decades before the blast wave reaches the outer rings, the impact with the inner ring will eventually produce enough ionizing radiation to cause the unseen matter to become an emission nebula. Luo et al. (1994) have estimated that the fluence of ionizing radiation from the impact will equal the initial ionizing flash of the supernova within a few years after the ring reaches maximum brightness. I expect that the circumstellar nebula of SNR1987A will be in full flower within a decade. In this way, SN1987A will be illuminating its own past.

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