Supernova 1987A

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Abstract. First, I summarize the main points that we have learned about the interior of SN1987A. Then, I describe in greater detail the rapidly developing impact of SN1987A with its inner circumstellar ring.

1 Introduction

As I write this Chapter, we are observing SN1987A approximately 15 years after its initial outburst. During the first 10 years, the radiation from SN1987A was dominated by energy deposited in the interior by the decay of newly synthesized radioisotopes. From observations of this radiation at many wavelengths, we learned a great deal about the dynamics and thermodynamics of the expanding debris. With the Hubble Space Telescope, we have also observed a remarkable system of three circumstellar rings, the origin of which remains a mystery today.

About 6 years ago, the blast wave from the supernova began to strike the inner circumstellar ring, resulting in the appearance of a rapidly brightening “hot spot” on the ring. Today, many more hot spots have appeared, and the radio, infrared, optical, and X-ray radiation from of the supernova is now dominated by the impact of the supernova debris with its circumstellar matter. This impact marks the birth of a supernova remnant, SNR1987A.

In this Chapter, I will first summarize what we have learned about the interior structure of SN1987A and the dynamics and thermodynamics of the debris. Then I will discuss what we know about the circumstellar matter and rings, and what we are learning from observations of the interaction of the supernova debris with the circumstellar matter. Finally, I will hazard a few guesses about what we can expect to learn from SNR1987A during the next few decades.

2 Energetics

Before going into detail, it might be useful to summarize the main energy sources of SN1987A. These are listed in Table 1.
Table 1: SN1987A Energetics

<table>
<thead>
<tr>
<th>Source</th>
<th>Collapse</th>
<th>Radioactivity</th>
<th>Expansion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Definition</td>
<td>$\sim \frac{GM_e^2}{R_{N*}}$</td>
<td>$^{56}\text{Ni} \rightarrow ^{56}\text{Co} \rightarrow ^{56}\text{Fe}$</td>
<td>$0.07M_\odot$</td>
</tr>
<tr>
<td>Emerges as: Neutrinos</td>
<td>O, IR</td>
<td>X-rays</td>
<td>(+ R, IR, O, UV)</td>
</tr>
<tr>
<td>$(kT \sim 4\text{MeV})$</td>
<td>($+ X, \gamma$)</td>
<td>$(10^{49})$</td>
<td>$(10^{47})$</td>
</tr>
<tr>
<td>Energy [ergs]</td>
<td>$10^{50}$</td>
<td>$10^{49}$</td>
<td>$10^{47}$</td>
</tr>
<tr>
<td>Timescale</td>
<td>$\sim 10$ seconds</td>
<td>$\sim 1$ year</td>
<td>$\sim 10 - 1000$ years</td>
</tr>
</tbody>
</table>

As Table 1 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, we 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 [1]. 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 Lagrangean 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, $\sim 10 - 20M_\odot$. Typically, this 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 shall describe, 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 Compact Object

The flash of $19 \pm 1$ neutrinos that was detected a few hours before the optical brightening of SN1987A provided compelling evidence that its core had collapsed to form a compact object [2]. The inferred energy ($\sim 3 \times 10^{53}$ ergs), temperature (kT $\sim 4$ MeV), and decay timescale ($\sim 4$ s) of the flash were in remarkably good agreement with models in which a degenerate iron core collapsed to form a neutron star. But since then, and despite great effort, astronomers have been disappointed to find no firm evidence of a compact object near the center of the expanding debris of the supernova. Why?

One thing is clear: if a compact object exists at the center of SN1987A, it must have bolometric luminosity $L_c \lesssim \text{few} \times 100L_\odot$. The bolometric (mostly far infrared) luminosity of the entire envelope is now $L_{env} \lesssim 1000L_\odot$, and a brighter compact object at the center of the debris could not have escaped detection. Note that $L_c \lesssim 10^{-2}$ times that of the 948 year old pulsar in the Crab Nebula. If it is a neutron star, it must be very faint — perhaps because it has an anomalously low magnetic field and/or spin rate. But that is not enough to escape detection. It also must not be radiating thermally above the detection limit, and it must accrete $\lesssim 10^{-11}M_\odot\text{yr}^{-1}$. The neutron star would probably cool fast enough so that its thermal radiation would barely escape detection [3]. Likewise, radiation pressure on the infalling matter could suppress accretion if $L_c \gtrsim L_E'$, where $L_E' \approx \text{few} \times 100L_\odot$ is a “modified Eddington limit” that takes into account the opacity due to resonance line scattering in addition to the electron scattering opacity [4].

Although the duration of the neutrino flash indicates that a neutron star formed during the supernova explosion, it is possible that enough matter fell back in the subsequent hours or days to cause it to collapse into a black hole [5]. The accretion rate need not be limited to the value $M_E \approx 3 \times 10^{-8}M_\odot\text{yr}^{-1}$ if the flow is dense and hot enough so that neutrinos can carry off the accretion luminosity. When it collapses initially, the iron core is expected to have a mass at the Chandrasekhar limit, $M_c \approx 1.4M_\odot$. After it forms, such a neutron star would have to accrete another $\Delta M_c \gtrsim 0.4M_\odot$ in order to collapse. Although we can’t rule out this possibility, I regard it as unlikely, especially as I see no compelling argument to rule out a neutron star within the envelope of SN1987A today.

How might we detect a compact object in the debris of SN1987A if its bolometric luminosity is much less than that of the radioactive debris? There is little chance of doing so with radio ($\gtrsim 1$ cm), ultraviolet, or X-ray observations, since the envelope will probably remain opaque in these bands for decades. Thus, our hopes turn to the submillimeter, infrared, optical, and hard X-ray and gamma ray bands.

We do see optical emission lines from the interior of SN1987A, but we also see dear evidence of extinction by dust in the debris. In fact, the dust appears to occult $\sim 50\%$ of the emission from the far hemisphere of the supernova debris, so there is a good chance that a foreground dust cloud might completely obscure the compact object at optical wavelengths. Such obscuration could account for
the absence of evidence of a central compact optical point source and the failure to confirm the purported detection [6] of a 2.1 ms optical pulsar.

We might detect the presence of a faint compact object in the envelope of SN1987A by observing optical or infrared emission lines from gas ionized by a central X-ray source [7]. The spectrum of the X-ray photoionized gas would display emission lines from atoms ionized twice or more and the emission lines would have widths $FWHM \lesssim 1000 \text{ km s}^{-1}$. It should be easy to distinguish such a spectrum from that of the radioactive-illuminated debris, which displays only broad ($FWHM \sim 3000 \text{ km s}^{-1}$) emission lines from neutral and once-ionized species. But this potentially sensitive method of detecting the compact object might be also confounded if the central X-ray nebula happens to be occulted by a foreground dust cloud in the debris.

4 The Debris

Most of us believe that supernovae make the heavy elements in the universe, and this notion gains impressive support from theoretical calculations of supernova nucleosynthesis (e.g., [8]). Remarkably, this notion has little empirical support from observations of supernova spectra [9]. What have we learned about the debris of SN1987A from analysis of its spectrum?

4.1 Radioactivity

Certainly, the most important result has been the confirmation that the light of SN1987A comes from the radioactive decays of $^{56}\text{Co}$ and $^{57}\text{Co}$, which were probably produced originally as $^{56}\text{Ni}$ and $^{57}\text{Ni}$. To account for the bolometric light curve, we know that these isotopes must be present with masses $M(\text{$^{56}\text{Co}$}) = 0.07M_\odot$ and $M(\text{$^{57}\text{Co}$}) = 0.003M_\odot$, respectively, and this result is confirmed by direct observations of gamma ray and infrared emission lines from these isotopes [10]. Today the bolometric luminosity of SN1987A is dominated by recombination of hydrogen that was ionized at an earlier epoch [11] and heating by positrons from $\sim 2 \times 10^{-4}M_\odot$ of $^{44}\text{Ti}$ [12].

4.2 Clumps and Voids

Another major result concerns the role of instabilities in mixing the debris of the explosion. The unexpectedly early emergence of X-rays and gamma rays showed that a fraction of the newly synthesized $^{56}\text{Ni}$ was expanding with radial velocities up to $\sim 4000 \text{ km s}^{-1}$, far greater than would be possible in spherically symmetric explosion models in which the newly synthesized elements remain in concentric spherical layers. Moreover, the emission lines of hydrogen, helium, oxygen, and other elements did not have the flat-topped profiles that would be expected if these elements were excluded from the central regions of the envelope.

The mixing implied by these observations must be due to Rayleigh-Taylor instabilities that occur in the decelerating gas behind the blast wave. But the theory still has trouble in accounting quantitatively for the highest velocity clumps
of $^{56}$Co, even allowing for the fact that such clumps would be expected to penetrate further than indicated by 2-D simulations [13]. Since the Rayleigh-Taylor instabilities depend on the deceleration following the passage of the initial blast wave, they only have a few e-folding timescales to grow. Therefore, they cannot account for the observed clumping unless substantial ($\sim 5 - 10\%$) perturbations already exist in the envelope before the explosion. Such perturbations are the natural consequence of the violent convection that occurs in the envelope of the progenitor.

The dynamical evolution of the envelope does not end when the Rayleigh-Taylor instabilities cease to grow. There is still one more mechanism that can alter the texture of the envelope: the radioactive energy released by the decay of $^{56}$Ni. Since the $^{56}$Ni clumps are opaque to gamma rays for several times the 8.8d mean lifetime of $^{56}$Ni, they will become hotter than their surrounding substrate and will swell up during the first few weeks. As a result, the supernova debris develops a “foamy” texture, in which the iron group elements occupy $\gtrsim 30\%$ of the emitting volume, even though they comprise only $\sim 1\%$ of the mass. This scenario is confirmed by analysis of the light curves of emission lines from the iron group elements [14].

4.3 Thermal Evolution

The envelope of SN1987A cooled fast. By $t = 1$ year after explosion, the emitting hydrogen had cooled to $T_H(1\text{yr}) \approx 4000$ K and was only about 1% ionized. Shortly thereafter, strong CO and SiO emission bands appeared in the infrared spectrum, indicating that the oxygen-rich gas containing these molecules had a temperature $T_{CO}(1\text{yr}) \approx 1000$ K [15]. On the other hand, the strength of the [OI] $\lambda 6300$ lines indicates that $T_O(1\text{yr}) \approx 3000$ K, implying that the [OI] emission is coming from a warmer zone of oxygen that lacks CO (probably because it contains metastable He*, which attacks CO $\rightarrow$ [16]). The infrared emission lines of Fe/Co/Ni indicate that these elements cooled from $T_{Fe}(1\text{yr}) \approx 4000$ K to $T_{Fe}(3\text{yr}) \approx 200$ K. Evidently, the emission line spectrum is a composite coming from regions of distinct chemical composition, which have very different temperature histories owing to differences in radiative cooling efficiency. Because their line profiles are similar, we know that clumps having different compositions must share roughly the same volume. The fact that these clumps have different temperature evolution proves that the line-emitting region of SN1987A is mixed macroscopically but not microscopically.

Today, SN1987A is perhaps the coolest optical emission source known to astronomy. Even the hydrogen gas has cooled to $T \lesssim 350$ K [17]; [18]. In fact, after $t \approx 2$ years, most of the envelope was too cool to emit optically and the emission line spectrum was dominated by lines excited by nonthermal electrons resulting from radioactive energy deposition. The hydrogen-rich gas has ionized fraction $\sim 10^{-3}$. Since the hydrogen recombination timescale is greater than the age of the supernova, the recombination lines reflect the ionization rate at earlier times and are insensitive to the present-day radioactive energy deposition.
The fact that the emission line spectrum at late times is produced primarily by nonthermal excitation offers the hope to infer the nucleosynthesis yields of elements from the observed line strengths. The idea is simple: at late times the emitting region is optically thin to gamma rays, so that all elements there are illuminated by a roughly uniform flux of gamma rays. Since the opacity to gamma rays is nearly independent of composition, the radioactive luminosity that is deposited (as nonthermal electrons) in regions of a given composition is nearly proportional to the net mass of gas having that composition. Kozma & Fransson [19] have calculated the nonthermal energy deposition fractions that appear in various emission lines. Therefore, it should be straightforward to infer the ratios of different element groups from the line ratios. Unfortunately, we have failed so far to realize the fruits of this idea. Kozma & Fransson [20][21] find that the theory under-predicts the strength of [OII]A6300,6364 doublet by nearly an order of magnitude if the oxygen-rich gas has a mass \( \sim 2M_\odot \). Evidently, the theory is still missing some crucial physical ingredient.

### 4.4 Internal Dust

Dust formed in the debris of SN1987A after \( t \sim 450 \text{ days} \) [10]. The dust clouds evidently obscure about half of the far side of the supernova envelope and absorb roughly half of the luminosity emitted by the envelope, re-radiating it at far-infrared (\( \gtrsim 5\mu\text{m} \)) wavelengths. The red wings of near-infrared lines are absorbed almost as effectively as those of the optical lines, indicating that the dust clouds, where present, are very opaque.

What is this dust? Since the far infrared spectrum shows no spectral features, we can only make theoretical conjectures. Element abundances do not constrain the possible composition; even primordial gas of LMC composition contains enough mass in refractory elements to make dust clouds of sufficient opacity if such elements could condense. Two conditions must be met for dust to condense: (1) the gas must be cold enough (\( \lesssim 1200 \text{ K} \) for FeO, \( \lesssim 1300 \text{ K} \) for MgSiO\(_3\), and \( \lesssim 1800 \text{ K} \) for graphite); and (2) dense enough [22][23].

### 4.5 Lessons from the Emission Line Spectrum

Besides what we have learned about SN1987A itself, our efforts to interpret its emission line spectrum [10][24] have taught us some important lessons about interpreting the spectra of supernovae in general:

- **Infrared spectra are more useful than optical spectra.** Our most reliable information about the physical conditions in the envelope of SN1987A comes from its infrared spectrum. The main reason is simple. The luminosities of thermally excited forbidden lines from some ion \( X \) are proportional to

\[
L_X \propto M_X \exp(-h\nu/kT),
\]

where \( M_X \) is the net mass of ion \( X \). For optical lines, \( h\nu/k \gtrsim 20,000 \text{ K} \). But, as we have seen, the supernova envelope has temperatures \( T \lesssim 3000 \text{ K} \). Since
optical lines are so sensitive to temperature, they are very good thermometers but very poor indicators of anything else. Moreover, if the gas temperature is not uniform, optical line emission from cooler gas can be completely masked by that from hotter gas. In contrast, the Boltzmann factor for infrared lines is far less sensitive to temperature. Moreover, the infrared spectrum of SN1987A contains many spectral features that have been most revealing of the conditions in the envelope — for example, the CO bands and the $\text{[Co]}_{\lambda_{10.2\mu m}}$ line.

- **Be careful about inferring element abundances from emission line strengths.**
  We learned this lesson from CaII [25]. CaII $\lambda\lambda 7293, 7324$ is prominent in the spectrum of SN1987A (and many other supernovae), not because calcium is particularly abundant but because this line happens to be the most effective channel for hydrogen- and helium-rich gas in supernova envelopes to radiate thermal energy. As long as this is true, the strength of CaII $\lambda\lambda 7293, 7324$ will be almost independent of the calcium abundance. If it is less than cosmic, the temperature of the hydrogen must rise enough so that the line will get rid of the thermal energy that is deposited there by gamma rays. Indeed, the CaII $\lambda\lambda 7293, 7324$ line emission from primordial calcium in the hydrogen- and helium-rich gas completely masks the emission from a much greater mass of calcium that is probably present in Si/Ca-rich clumps in the envelope. The situation is similar for the near-infrared emission lines of Fe/Co/Ni. For example, for $t \lesssim 2$ years, the FeII $1.26\mu m$ line comes mainly from newly synthesized iron. But thereafter, the iron-rich gas becomes too cool to emit this line, which then comes mainly from a much smaller mass of iron in the hydrogen- and helium-rich gas.

- **Internal extinction is a problem.** Even though we can see through the envelope of SN1987A at optical and near-infrared wavelengths, a good fraction of the envelope, especially the far side, is obscured by internal dust clouds. It’s quite possible that clumps of some compositions are more likely to be obscured than others. Therefore, although we can construct models for the emission line spectrum evolution that conform fairly well to our preconceived notions of supernova nucleosynthesis, we may go astray if we use observations taken after the dust forms.

5 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* [26]. 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 $\lambda\lambda 1239, 1243$ 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 $\sim 3 \times 10^3 - 3 \times 10^4 \text{ cm}^{-3}$ (from the fading timescale of the narrow lines)[27].

Figure 1 shows an image of the circumstellar rings of SN1987A taken with the WFPC on the Hubble Space Telescope [28]. Dividing the radius of the inner ring (0.67 lt-year) by the radial expansion velocity of the inner ring ($\approx 10 \text{ km s}^{-1}$) [29] 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 [30] 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 [31][32]. The echoes were caused by scattering of the optical light from the supernova by dust grains in this gas. They became invisible a few 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 [33]. 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.

### 6 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 7). From subsequent observations, they found that the annulus was expanding with a velocity $\sim 3,500 \, \text{km s}^{-1}$ [34].
Fig. 2. Radio (upper) and X-ray (lower) light curves.

The radio emission most likely comes 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 the X-ray emission comes from the shocked circumstellar matter and supernova debris [35]. Subsequently, Chevalier & Dwarkadas [36] 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.

7 The Reverse Shock

Following Chevalier & Dwarkadas [36], Borkowski et al. [37] 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 $n_0 \approx 150 \text{ cm}^{-3}$.

![Diagram](image)

**Fig. 3.** Hydrodynamic simulation of the interaction of SN1987A debris with circumstellar matter [40]. The supernova center is at the lower right corner and the grey scale indicates density. The figure is cylindrically symmetric about the right boundary, and the the photoionized layer is assumed to be a thick torus (labeled HII region). A blast wave enters the photoionized layer (HII region), while a reverse shock arrests the free expansion of the supernova debris. Between the blast wave and the reverse shock are layers of shocked HII region and shocked supernova debris, separated by an unstable contact discontinuity.

The same model predicted 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 these predictions were published, 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 [38]. Within the observational uncertainties, the flux was exactly as predicted [39].

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 Lyα 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 Lyα and Hα emission lines are not produced by recombination. (The emission measure of the shocked gas is far too low to produce detectable Lyα and Hα 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 Lyα photon is produced for each hydrogen atom that crosses the shock. Thus, the observed flux of broad Lyα 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 Lyα and Hα 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, $V_l = z/t$, 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 Lyα line will be directly proportional to the depth of the reverse shock: $\Delta \lambda / \lambda_0 = z/ct$. Thus, by mapping the Lyα or Hα emission with STIS, we can generate a 3-dimensional image of the reverse shock.

![Fig. 4. STIS spectrum of Lyα emission from the reverse shock [39]](image)

Figure 4 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 Lyα from this observation. The slit is black due to geocoronal Lyα emission.
The bright blue-shifted streak of Lyα 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, as would be expected from a hydrodynamic model such as that illustrated in Figure 3. 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 [40].

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 might 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. Moreover, the asymmetry is much greater in Lyα than it is in Hα. Recently, Michael et al. [40] have proposed that most of the asymmetry in Lyα can be attributed to resonant scattering of Lyα in the un-shocked supernova debris, which tends to reflect the Lyα emission in the radially outward direction. However, the Hα emission line from the reverse shock is not susceptible to resonant scattering, so the (~30%) asymmetry in Hα and must be attributed in part 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.

8 The Hot Spots

One can estimate the time that the blast wave should strike the inner circumstellar ring from self-similar solutions for the hydrodynamics of a freely expanding stellar atmosphere striking a circumstellar medium [41]. 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 $\rho(r, t) = At^{-3}(r/t)^{-1/2}$ [42][43]. If this atmosphere strikes a circumstellar medium having a uniform density $n_0$, the blast wave will propagate according to the law $R_B(t) \propto A^{1/3} n_0^{-1/3} t^{2/3}$. 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 1996 to 2005 [44] [45][36].

In April 1997, Sonneborn et al. [38] 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° (E of N), which we now call “Spot 1,” where a Doppler-broadened streak was seen in Hα and other optical lines.

![Diagram](image)

**Fig. 5.** Spectrum of Spot 1. (a) Slit orientation on image of SN1987A’s triple ring system; (b) Section of STIS G750M spectrum.

Figure 5 [46] 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 broad Hα from the reverse shock is invisible at this dispersion.) The emission lines are broadened (with FWHM ≈ 250 km s⁻¹) and blue-shifted (with ΔV ≈ −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 \( V_b \approx 4,000 \text{ km s}^{-1} \) through circumstellar matter with density \( n_0 \approx 150 \text{ cm}^{-3} \), encounters the ring, having density \( n_r \approx 10^4 \text{ cm}^{-3} \), one would expect the transmitted shock to propagate into the ring with \( V_r \approx (n_0/n_r)^{1/2} V_b \approx 500 \text{ km s}^{-1} \) 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 at HST archival data, one finds that Spot 1 was first detected in March 1995. Spot 2, did not appear until November 1998, but shortly thereafter, several more spots appeared [47]. By May 2002, 16 spots were evident. The hot spots are brightening rapidly, with doubling timescales ranging from a few months to 2 years.

![Fig. 6. WFPC narrow-band Hα images of the inner ring. Left: February 1996. Center: February 1998. Right: May 2002. Both the inner ring and the central supernova debris have faded monotonically, while Spot 1, located at P.A. 029°, has evidently brightened by February 1998. By May 2002, 16 hot spots have appeared.](image)

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 \( T_1 \approx 1.6 \times 10^5 \frac{V_r}{(100 \text{ km s}^{-1})]^2 K \) to a final temperature \( T_f \approx 10^4 \text{ K} \) or less. As the shocked gas cools, it is compressed by a density ratio \( n_f/n_r \approx (T_1/T_f) \approx 160 \left[ \frac{V_r}{(100 \text{ km s}^{-1})]^{2/3} \left[ T_f/(10^4 \text{ K}) \right]^{-1} \right. \). We see evidence of this compression in the observed ratios of forbidden lines, such as \([\text{NII}]\lambda6548,6584\) and \([\text{SII}]\lambda6717,6731\), from which we infer electron densities in the range \( n_e \approx 10^6 \text{ cm}^{-3} \) using standard nebular diagnostics [46].

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 the HST Wide Field Planetary Camera (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. For
example, I estimated above that a blast wave entering the protrusion at normal incidence might have velocity $\sim 500 \text{ km s}^{-1}$. Faster shocks would be invisible in optical and UV line emission, but we are probably seeing evidence of such shocks in soft X-rays (§9). We would still see the optical and UV 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 [46]. Our efforts to date have met with only partial success. A model that fits the ultraviolet emission line spectrum under-predicts the intensities of the optical emission lines by a factor $\sim 3$. 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 [48], which we have not included in our initial attempts to model the shock emission.

9 The X-ray Source

As I have already mentioned in §6, 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.

Our ability to analyze the X-rays from SNR1987A advanced dramatically with the launch of the Chandra observatory [49][50]. Figure 7 is a montage of images of SNR1987A, showing, for two epochs, the X-ray images in three bands. We see immediately that the X-rays images have brightened and changed substantially in the 18 month interval between these two observations. In the soft (0.3 – 0.8 keV) band, the locations of the bright X-ray emission correlate fairly well with the optical hot spots (cf. Fig. 6). This fact suggests that the softer X-rays are coming from shocks where the blast wave is entering the inner ring. But we can be sure that the X-rays do not come from exactly the same shocks as the optical hot spots. As we discussed in §8, the shocks responsible for the optical emission are too slow to emit X-rays, but we would not be surprised if faster shocks are present in the same interaction region.

In the hard (1.2–8 keV) band, the locations of bright X-ray emission correlate better with the images from the ATCA radio array than with the optical hot spots. This fact suggests that the harder X-rays are produced primarily by the hotter gas between the reverse shock and the blast wave (cf. Fig. 3). We presume that the radio emission would correlate with the harder X-rays because the relativistic electrons 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 (left) 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 appeared first on the E side favors the latter hypothesis. If

(a) 0.3 – 0.8 keV with HST  
(b) 0.3 – 0.8 keV with HST  

c) 0.8 – 1.2 keV with HST  
(d) 0.8 – 1.2 keV with HST  

e) 1.2 – 8.0 keV with ATCA  
(f) 1.2 – 8.0 keV with ATCA

Fig. 7. Optical, radio and X-ray images of SNR 1987A. North is to the top. The images on the left (a, c, e) represent observations of Dec. 2000, while those on the right (b, d, f) represent observations of May 2002. The gray scale images represent the X-ray brightness in three bands. The contour lines in the top four images (a - d) represent the optical ring as seen by HST, while those in the bottom two represent the radio image as seen by ATCA.
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 (§7), which show that the flux of mass across the reverse shock is greater on the W side.

These observations highlight a new puzzle about SN1987A: 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, we have also obtained a spectrum of the X-rays from SNR1987A, shown in Figure 8 [52]. 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 [53]. 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 $V_i \approx 4,000$ km s$^{-1}$ and that inferred from the widths of the X-ray emission lines. This result is a consequence of the fact that Coulomb collisions are too slow to raise the electron temperature to equilibrium with the ions.

The Chandra observations (Fig. 2) show that the current X-ray flux from SNR1987A is more than 3 times the value that would be estimated by extrapolating the ROSAT light curve to December 2001 (Figure 2). The acceleration in the brightening rate suggests that most of the X-rays are now coming from the impact of the blast wave with the ring. 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 [53].

10 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 [45].

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, 3.92μm, [Si X] 1.43μm) that may be too faint to see with HST.
Fig. 8. X-ray spectrum of SNR 1987A.

Observations in such lines will complement X-ray observations to measure the physical conditions in the very hot 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 correlation 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.

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 56Co (and probably also clumps of oxygen and other elements) were mixed fairly far out into the supernova envelope by instabilities following the explosion [10]. 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.

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 §5 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. We have estimated [45] 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.

References

28. see http://oposite.stsci.edu/pubinfo/PR/97/03.html