Supernova 1987A:
The Birth of a Supernova Remnant

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Summary. I describe and interpret observations of the rapidly developing impact of the debris of SN1987A with its circumstellar ring.

1 Introduction

Today, we are observing SN1987A approximately 16 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 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.

About 7 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.

Here, I 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 decade or so.

2 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* [9]. Even before astronomers could image this matter, they could infer that:

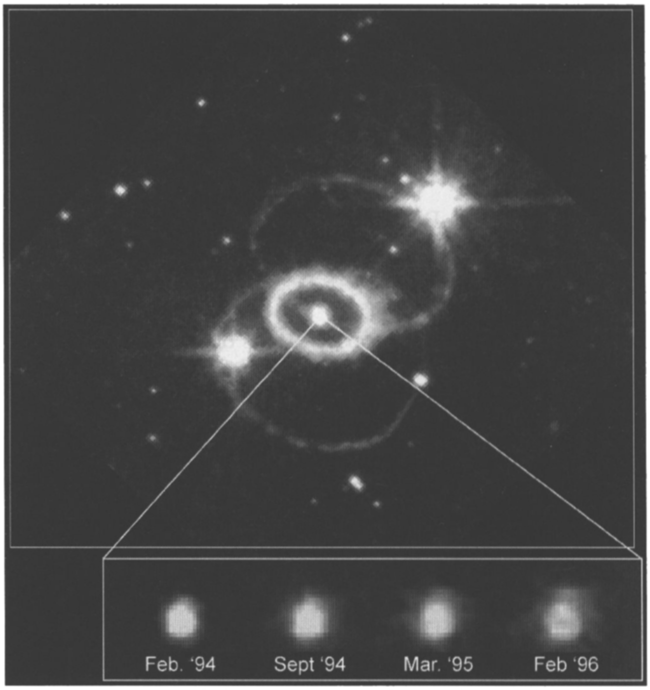

Fig. 1. HST image of SN1987A and its circumstellar rings. The inset at the bottom shows the evolution of the glowing center of the supernova debris.

- 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 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 [10]).

Figure 1 shows an image of the circumstellar rings of SN1987A taken with the WFPC on the *Hubble Space Telescope*. Dividing the radius of the inner ring (0.67 lt-year) by the radial expansion velocity of the inner ring (≈ 10 km s^{-1} [7]) 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* 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 [8] show that this

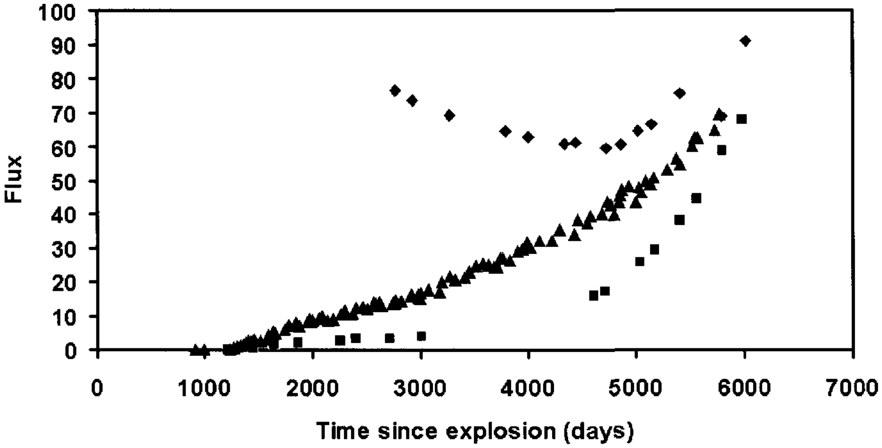

Fig. 2. Light Curves of SNR1987A. Diamonds – optical (Hα, 10^{-15} erg cm^{-2}s^{-1}, courtesy P. Challis); triangles – radio (4.7 GHz, mJy, courtesy R.N. Manchester); squares – X-rays (2.0 – 5 keV, 10^{-14} erg cm^{-2}s^{-1}, courtesy Sangwook Park).

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 ~ 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 [6, 22]. 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? I suspect 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 [18]. But we still lack a satisfactory explanation for the outer loops. If we could only see the invisible circumstellar

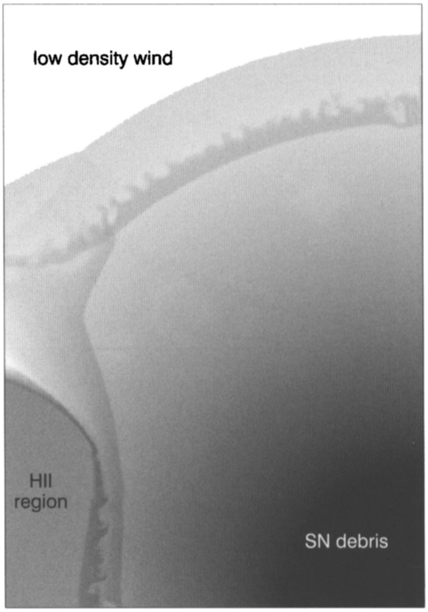

Fig. 3. Schematic illustrating the hydrodynamics of SNR1987A. As the freely expanding supernova ejecta first crosses a reverse shock, its temperature is elevated to $\gtrsim 10^7$ K. This high pressure X-ray-emitting gas drives a forward shock (blast wave) ahead into an HII region of low density ($n \sim 100\ \mathrm{cm}^{-3}$) gas. Optical hot spots appear behind the transmitted shock where the blast wave strikes an inward protrusion of the high density ($n \sim 10^4\ \mathrm{cm}^{-3}$) circumstellar ring.

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.

3 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 Fig. 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* (Plate 2). From subsequent observations, they found that the annulus was expanding with a radial velocity $\sim 3,000\ \mathrm{km\ s}^{-1}$ [12].

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 circumstellar matter, and the X-ray emission comes from the shocked circumstellar matter and supernova debris. [4, 5]

Until 1996, the circumstellar ring continued to fade as it cooled and recombined [10]. But then, the first "hot spot" appeared and began to brighten on the ring (Plate 2). Evidently, this spot marks the place where the supernova blast wave first strikes an inward protrusion of the ring (Fig. 3). Since then, many more hot spots have appeared and now encircle the entire ring. As this interaction develops, the newborn supernova remnant is brightening at an accelerating rate at optical, radio, and X-ray wavelengths (Fig. 2).

4 The Reverse Shock

Borkowski et al. [1] used a 2-D hydro code to simulate the impact of the outer atmosphere of the supernova with the circumstellar matter. Their model predicted that Lα and Hα 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 ($\Delta V \approx \pm 12,000$ km s^{-1}) Lα emission lines were detected [20]. Within the observational uncertainties, the flux was exactly as predicted [14].

The broad Lα and Hα emission lines are not produced by recombination. Instead, they 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. The observed flux of broad Lα 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.

These Lα and Hα emission lines give us a powerful tool to map this shock. Since any hydrogen in the supernova debris is freely expanding, its line-of-sight velocity, $V_{\|} = z/t$, 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 Lα line will be directly proportional to the depth of the reverse shock: $\Delta\lambda/\lambda_0 = z/ct$. Thus, by mapping the L$\alpha$ or Hα emission with STIS, we can generate a 3-dimensional image of the reverse shock.

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 Lα from this observation. The slit is black due to geocoronal Lα emission. The bright blue-shifted streak of Lα 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.

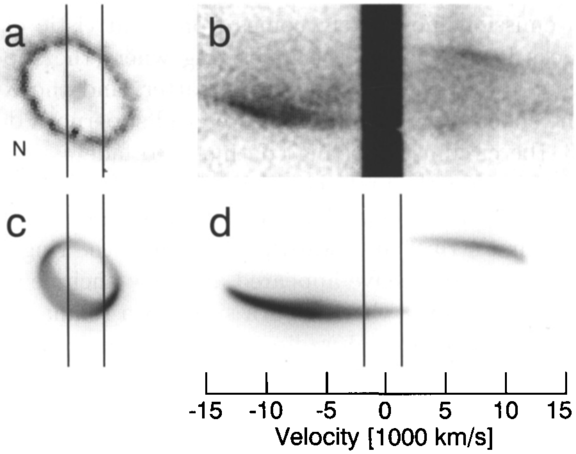

Fig. 4. STIS spectrum of Lα emission from the reverse shock [14].

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 Lα 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 [16].

5 The Hot Spots

In April 1997, Sonneborn et al. [20] obtained the first STIS spectrum of SN1987A. Images of the circumstellar ring were seen in several optical emission lines. No Doppler velocity spreading was evident in the ring images (Plate 2) 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.

Spot 1 evidently marks the location where the supernova blast wave first touches an inward protrusion of the dense circumstellar ring (Fig. 3). When a blast wave propagating with velocity $V_b \approx 4,000$ km s^{-1} through circumstellar matter (density $n_0 \approx 150$ cm^{-3}) encounters the ring (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.

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 $T_1 \approx 1.6 \times 10^5[V_r/(100 \text{ km s}^{-1})]^2$ K to a final temperature $T_f \approx 10^4$ K. As the shocked gas cools, it is compressed by a density ratio $n_f/n_r \approx (T_1/T_f) \approx 160[V_r/(100 \text{ km s}^{-1})]^2\ [T_f/(10^4\text{K})]^{-1}$. 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 [19].

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 likely 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 (§6). We would still see the optical and UV line emission from the slower oblique shocks on the sides of the protrusion, however.

Spot 2 did not appear until November 1998, but shortly thereafter, several more spots appeared [21]. By summer 2003, the entire ring was encircled by hot spots (Plate 2). The hot spots are brightening rapidly, with doubling timescales ranging from a few months to 2 years.

6 The X-ray Source

As I have already mentioned in §2, we believe that the X-ray emission from SNR1987A seen by *ROSAT* (Fig. 2) comes from the hot shocked gas trapped between the supernova blast wave and the reverse shock. But *ROSAT* could not image this emission; nor was it able to obtain a spectrum.

Our ability to analyze the X-rays from SNR1987A advanced dramatically with the launch of the *Chandra* observatory [3, 17]. Plate 2 shows the Chandra images at three epochs. We see immediately that the X-rays images have brightened and changed dramatically in the nearly 4 year interval spanned by these observations. The brightest regions of the early X-ray images were well within the optical ring and correlated rather well with the radio images; but as the optical hotspots brightened, the X-ray images were brightest along arcs that correlated well with the locations of the optical hot spots. Evidently, in 1999 the X-ray emission was dominated by the shocked gas between the blast wave and the reverse shock, but today it is dominated by the shocked gas in the denser hot spots.

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 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 Lα emission from the reverse shock (§3), 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 [15]. 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 (Borkowski et al 1997b). 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} 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 X-ray flux is now brightening exponentially with an e-folding timescale ~ 2.4 years. The X-ray flux is expected to increase by another order of magnitude during the coming decade as the blast wave overtakes the inner circumstellar ring [2].

7 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 $F_{\mathrm{H}\alpha} \gtrsim 3 \times 10^{-12}$ erg cm^{-2}s^{-1}, or $\gtrsim 30$ times brighter than it is today [11].

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] $2.58, 3.92\mu$m, [Si X] 1.43μm) 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 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. It will be wonderful to see images of SNR1987A from the *Atacama Large Millimeter Array* (*ALMA*), which should be available before the end of this decade. The images, which will have angular resolution better than the HST images, 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 Lα 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 $\sim$ 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 [13]. When such clumps cross the reverse shock, the fast Hα and Lα 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 as brightening of narrow emission lines in the vicinity of the hot spots.

In §1 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 [11] 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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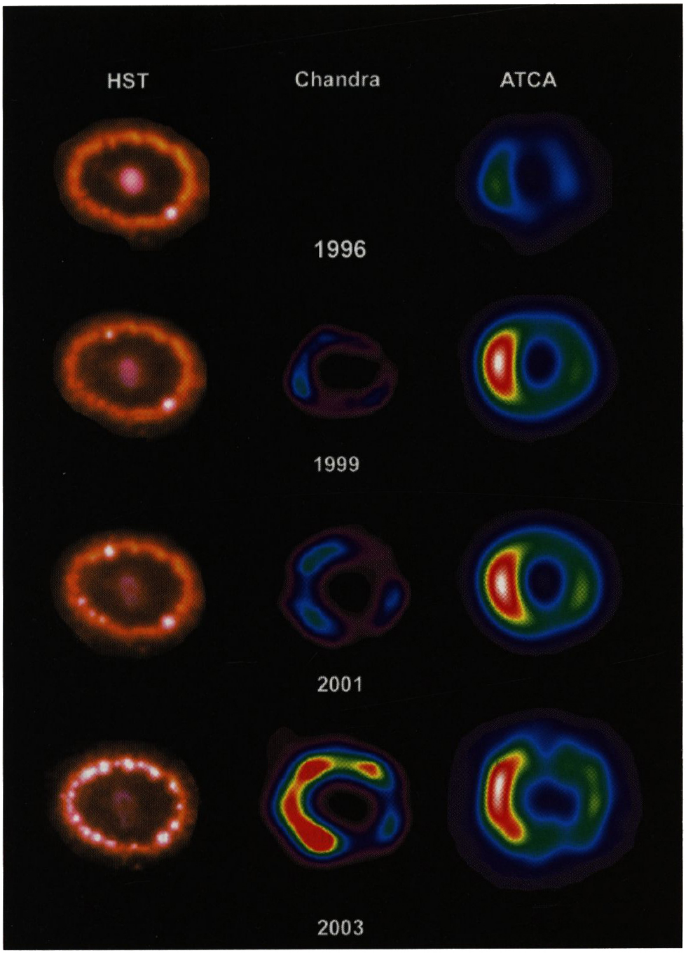

Optical, X–ray, and radio images of SNR 1987A at four epochs. The optical images in the first column are taken with broad Hα filter on the Hubble Space telescope (courtesy Peter Challis). The second column shows broadband (0.3–3.8 keV) images from Chandra (courtesy Sangwook Park), and the third column shows non–thermal radio images from the Australia Telescope Compact Array (courtesy Dick Manchester). The 1996, 1999, and 2001 radio images are taken at 8.7 GHz, while the 2003 image is taken at 18.5 GHz. In 1996, no hot spots are evident. The bright spot in the SW quadrant of the ring is a foreground star. In 1999, Spot 1, has appeared on the NE quadrant (position angle 29 deg) of the inner circumstellar ring. In 2001, Spots 2, 3, and 4 are evident in the SE quadrant. In 2003, the entire ring is encircled by hot spots.

Plate (McCray)

Plate 2.