Supernova 1987A: A Young Supernova Remnant in an Aspherical Progenitor Wind

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Abstract. The interaction between the ejecta from Supernova 1987A and surrounding material is producing steadily brightening radio and X-ray emission. The new-born supernova remnant has been significantly decelerated by this interaction, while its morphology reflects the axisymmetric nature of the progenitor wind.

1. Introduction

The circumstellar material around SN 1987A shows striking deviations from spherical symmetry, in particular in the form of the “three-ring circus” spectacularly imaged by \textit{HST} (Burrows et al. 1995). This nebulosity shows a distinct bipolar structure, resembling many of the planetary nebulae shown at this meeting. In the case of SN 1987A, supernova ejecta are rapidly propagating outwards from the center of this structure, producing radio, optical and X-ray emission as they collide with surrounding material. Observations of SN 1987A are thus an excellent probe of the mass-loss history of a supernova progenitor.

Many authors have considered the nature of the triple-ring system surrounding SN 1987A. For the purposes of interpreting the interaction between the supernova ejecta and this material, we adopt the “standard model” (Blondin & Lundqvist 1993; Martin & Arnett 1995), namely that:

- the progenitor star was a red supergiant (RSG) until \(\sim 20,000\) yr, during which time it produced a slowly moving, dense wind;

- the star then evolved into a blue supergiant (BSG), producing a fast moving and low density wind;

- the rings correspond to the bipolar interface produced by the interaction between the RSG and BSG winds;

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• the RSG wind was densest in the equatorial plane (perhaps produced by rotation and/or binarity in the progenitor), while the BSG wind was isotropic.

We note that this model certainly has its problems, and that many alternatives have been proposed (e.g. Soker 1999).

2. Radio Flux Monitoring

Radio emission was detected from SN 1987A just 2 days after the supernova explosion (Turtle et al. 1987). This emission peaked on day 4, before following a power law decay to become undetectable by day 150 (Ball et al. 1995). This radio outburst has been interpreted as synchrotron emission produced as the supernova shock passed through the innermost regions of the BSG wind (Storey & Manchester 1987).

After >3 years of radio silence, radio emission was re-detected from SN 1987A in mid-1990 (Staveley-Smith et al. 1992). Since then, emission has shown a monotonic increase with a spectral index \( \alpha \approx -1 \) (\( S_\nu \propto \nu^\alpha \)) (Gaensler et al. 1997). X-ray emission from the system turned on at around the same time, and has since also steadily increased (Hasinger, Aschenbach & Trümper 1996). This behavior suggests that the shock, having freely expanding through the BSG wind, has now run into a density jump.

3. Radio Imaging

Observations of SN 1987A with the Australia Telescope Compact Array (ATCA) at 9 GHz can resolve the radio emission from SN 1987A. By fitting a thin spherical shell to the radio emission at each epoch, the expansion of the source with time can be quantified. These data, shown in Figure 1, show a linear expansion rate of \( \sim 3500 \) km s\(^{-1}\) from day 1500 onwards. Interpolating between day 0 and day 1500 implies an initial expansion rate \( > 35000 \) km s\(^{-1}\), consistent with VLBI and H\(\alpha\) measurements made shortly after the explosion. These data thus indicate that the supernova shock experienced a rapid deceleration at or just before radio and X-ray emission were re-detected in mid-1990.

The diffraction-limited resolution of the ATCA is \( 0.9'' \), but using super-resolution we can produce a sequence of radio images of SN 1987A with a slightly higher resolution of \( 0.5'' \) (see Gaensler et al. 1997). These images (see Figure 2) show the emission to have a shell-like structure; the morphology is dominated by two lobes to the east and west.

An overlay between the optical ring system and the radio data (Reynolds et al. 1995; Gaensler et al. 1997) shows the radio shell to be centered on the position of the supernova, but with a radius only \( \sim 90\% \) of that of the optical ring. Thus although the supernova shock appears to have run into a density jump, this jump must be located within the interface between the RSG and BSG winds. The radio/optical overlay also shows that the radio lobes align with the major axis of the optical rings, when projected onto the sky. Gaensler et al. (1997) interpret this as indicating that radio emission is confined to the
Figure 1. The radius of the radio remnant as a function of time.

4. Interpretation

The abrupt radio and X-ray turn-on in mid-1990, as well as the rapid deceleration of the shock at around the same time, can be explained in terms of the “standard” interacting winds model, with the addition of a dense H ii region just inside the bipolar interface (Chevalier & Dwarkadas 1995). This region, produced by UV photons from the BSG ionizing the surrounding RSG wind, can, at least to first order, account for the observed light curves, expansion rate and X-ray emission measure. The double-lobed morphology is then interpreted as an axisymmetry in this surrounding material, as discussed in detail by Gaensler et al. (1997).

5. The Future

Radio monitoring and imaging of SN1987A will certainly continue; in 2001 the ATCA will be upgraded to a maximum frequency of 100 GHz, giving a significant improvement in spatial resolution. Meanwhile, Chandra and XMM will soon spatially and spectrally resolve the X-ray emission from SN 1987A, giving us a wealth of information about the conditions at the shock. All this is just a prelude to the collision of the supernova ejecta with the inner optical ring, expected in around 2004. At this point SN1987A will drastically evolve and brighten (perhaps by a factor of $10^3$ in every waveband!), providing us with much new information about the progenitor’s circumstellar material. Into the next century and beyond, we can expect that SN1987A will evolve into a “classical” supernova remnant (SNR), at which point we can perhaps start
Figure 2. Super-resolved ATCA images of SN 1987A. Contour levels are from 0.5 to 3.0 mJy beam$^{-1}$, at 0.4 mJy beam$^{-1}$ intervals.

to relate the complex morphologies of SNRs to the mass-loss histories of their progenitors.

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