SN 1987A at Radio Wavelengths

L. Staveley-Smith[1], R.N. Manchester[1], B.M. Gaensler[2], M.J. Kesteven[1], A.K. Tzioumis[1], N.S. Bizunok[3], and V.C. Wheaton[4]

[1] Australia Telescope National Facility, CSIRO, PO Box 76, Epping, NSW 1710, Australia;
Lister.Staveley-Smith@csiro.au
[2] Harvard-Smithsonian Center for Astrophysics, 60 Garden St. MS-6, Cambridge, MA 02138, USA
[3] Boston University, Boston, MA 02215, USA
[4] School of Physics, University of Sydney, NSW 2006, Australia

Summary. SN1987A has an intrinsic radio luminosity some four orders of magnitude less than SN1993J at maximum, largely a reflection of the tenuous wind from the progenitor of SN1987A before explosion. Both remnants have an edge-brightened, ring-like morphology though, in the case of SN1987A, the expansion rate is currently only around 3500 km s^{-1}. The flux density of the remnant of SN1987A continues to rise at all measured radio frequencies. Its spectral index is gradually flattening, indicating its transition into the supernova remnant phase. A campaign to increase the resolution of radio imaging by observing at higher frequencies is underway with the *Australia Telescope Compact Array* (ATCA).

1 Introduction

Radio observations of young supernovae are able to provide valuable information on stellar ejecta – its expansion rate, structure and kinetic energy. However, the most valuable and quantitative information relates to the structure of the surrounding medium with which this ejecta interacts. The density and structure of this medium is normally dominated by winds from the progenitor star, but its temperature and ionization state is strongly influenced by the ultraviolet flash created when the supernova shock erupts through the stellar photosphere. The minishell model [2] has been used with some success to explain radio observations of nearby supernovae, and appears to work reasonably well for SN1993J, the subject of this conference [8, 14]. However, the minishell model requires serious modification in order to account for clumpy progenitor mass-loss [25], the recently identified hypernovae/Gamma-Ray burst events [11] and, as we shall see, the late-time evolution of SN1987A.

2 Radio Luminosity Evolution

2.1 Early Times (< 1000 Days)

Radio emission from SN1987A in the Large Magellanic Cloud was detected immediately after outburst, with the 0.8 GHz flux density peaking at 140 mJy on day 3 [22]. The rapid flux density evolution and low radio luminosity was consistent with interaction of the shock wave with a fast low-density wind from the blue supergiant progenitor Sk$-69°$202. If the delay in the low-frequency radio emission was due to free-free absorption, the progenitor mass-loss rate was $\sim 10^{-5} M_{\odot}$ [3]. If due to synchrotron self-absorption [5, 10, 21], the progenitor mass loss was smaller. VLBI observations indicated a fast > 19000 km s^{-1} shock front [9], consistent with early optical spectroscopy.

The early phase of the radio emission was consistent with the minishell model, albeit the radio luminosity was very low, and only detected because of its proximity. The peak 5 GHz luminosity of SN1987A was about four orders of magnitude smaller than SN1993J in M81, and about five orders of magnitude smaller than SN1986J or SN1988Z [26].

2.2 Late Times ($\geq$ 1000 Days)

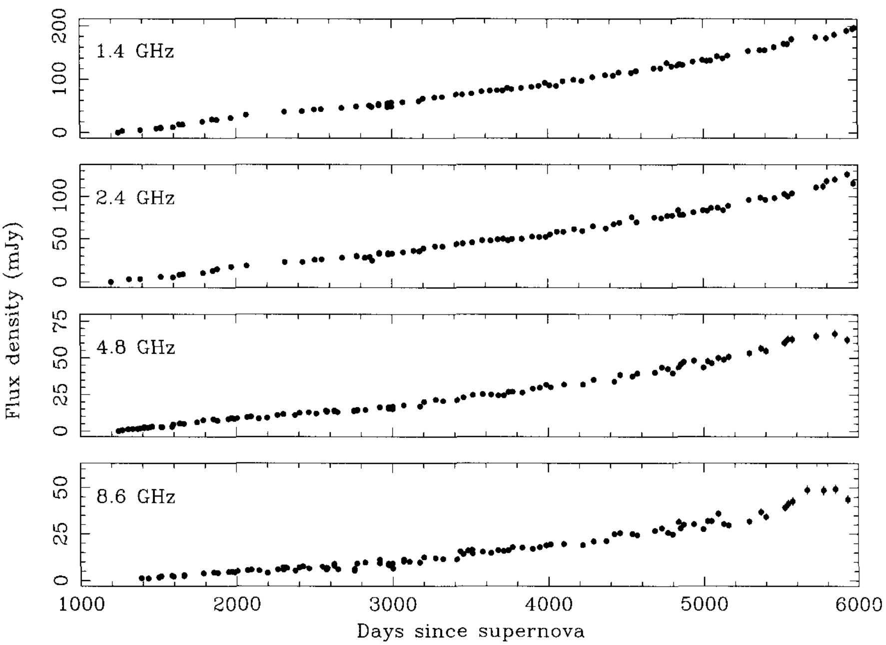

Fig. 1. The late-time evolution of the remnant of SN1987A at four different radio frequencies from 1.4 to 8.6 GHz. The flux density has increased in an approximately linear manner since day 1200. Some flux density fluctuations can be seen. All observations are from the ATCA.

SN1987A re-emerged as a radio source in 1990.5, first at low frequency (0.8 GHz) and, a month later, at higher frequencies (5 GHz) [19]. High resolution

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imaging (see also section 4) confirmed that this emission was edge-brightened [20], and therefore due to an interaction of the shock front with a density jump. This increase was not unexpected because of the inferred pre-outburst evolution of Sk−69°202 and the high density of the beautiful arcsecond-scale structure of the circumstellar nebula imaged by the NTT and HST [24].

Figure 1 shows the evolution of SN1987A from day 1000 at frequencies from 1.4 to 8.6 GHz, based on observations with the ATCA. These observations, and the even more closely spaced MOST observations at 0.8 GHz [1], indicate an approximate linear increase to date, with a 1.4 GHz flux density of around 200 mJy at day 5900. At frequencies less than 2 GHz, the flux density of the SN1987A remnant now exceeds the peak flux density reached at early times. In comparison to the peak flux density of SN1993J of 100 mJy at 5 GHz (day 200) [23], the flux density of SN1987A at day 5900 is still only 65 mJy at 5 GHz. This implies that, intrinsically, SN1987A is still 8000 times fainter than SN1993J at maximum. There are significant deviations from the simple picture of a linear increase which are discussed elsewhere [1, 12].

The spectrum of SN1987A is non-thermal with an index ($S_\nu \propto \nu^\alpha$) of $\alpha \approx -0.8$ (see section 3). This is consistent with optically-thin synchrotron emission with an differential electron energy spectral index of −2.6. The source of this emission is the accelerated electrons and compressed magnetic field produced at the shock front. The favored mechanism is ion-modified diffusive shock acceleration which heats the upstream plasma, producing a precursor shock and lowering the compression ratio for the main shock [7]. However, the time-dependence of the resultant synchrotron emissivity depends on the density structure of the circumstellar nebula. Whilst the high emission measure component of this is easily traced by high-resolution forbidden-line and hydrogen recombination-line observations, the structure of the lower density regions only becomes apparent once its energy density has been raised by the passing shock front. Thus the radio (and X-ray) light curves of SN1987A are difficult to predict.

However, if not able to produce detailed predictions, models of the structure of the nebula around SN1987A and inside the circumstellar ring are useful in providing a general picture of what might happen in the future, and at what stage rapid increases in thermal and non-thermal emission at various wavelengths might begin to happen [4, 6, 15]. A common feature of these models is that the triple-ring circumstellar structure was created by asymmetric outflow during the red supergiant phase of the progenitor star in a manner similar to the formation of planetary nebulae from red giants. However, the inner part of this nebula has been modified and pre-shocked by the fast wind from the later blue supergiant phase, therefore creating several discontinuities and transition zones. At this stage, the (mainly thermal) X-ray light curve appears to be rising exponentially [16], indicating that the shock front is very close to the ring.

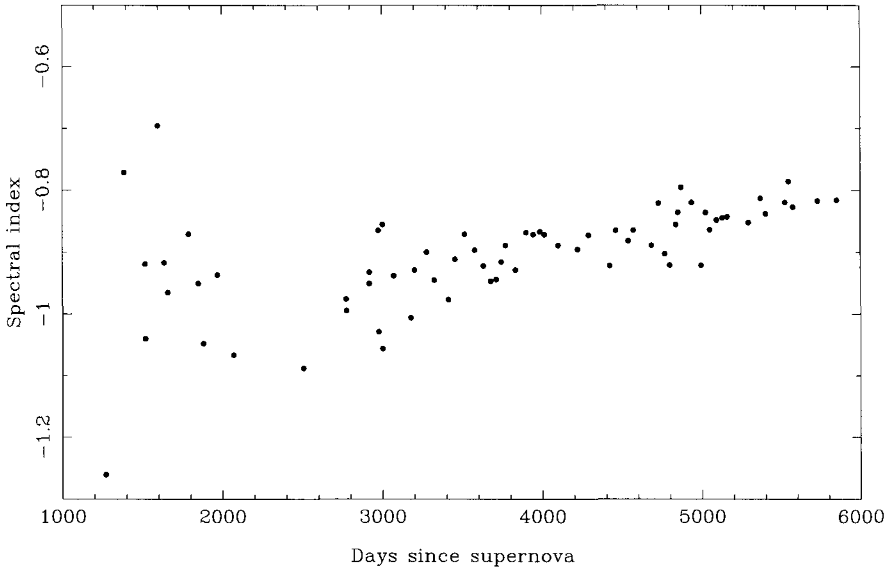

Fig. 2. The late-time spectral index evolution of the remnant of SN1987A derived from ATCA observations at 1.4 and 4.8 GHz, where the measurements are within a week of each other. After day 3000, a clear flattening of the spectral index is seen.

3 Spectral Evolution

As already shown for radio observations up to day 5000 [12], the spectral index of the SN1987A remnant is flattening with time. The index ($S_\nu \propto \nu^\alpha$) is currently $\alpha \approx -0.8$ and increasing at a rate of $\dot{\alpha} = 0.02$ yr^{-1} (Fig. 2). It may therefore reach the canonical -0.5 spectral index for shell-like remnants within 15 years. However, given the exponential evolution of the X-ray flux at the current time, it is likely that the radio evolution will not remain as regular as it has over the past few years.

It is interesting to note that, although the properties of SN1987A and SN1993J are in general quite different, the latter also appears to have a spectral index which is flattening with time [18]. The common implication is that the compression ratio of supernova shock fronts increases with time.

4 Structure in the Remnant of SN 1987A

A high resolution ATCA image taken at a frequency of 9 GHz in 2003 January is shown in Fig. 3. A ring-like structure is present, which has been modeled as a thin spherical shell and a number of hotspots [12]. In comparison with previous images, the east-west asymmetry is growing, and there appears to be enhanced emission in the southern part of the remnant. The latter feature

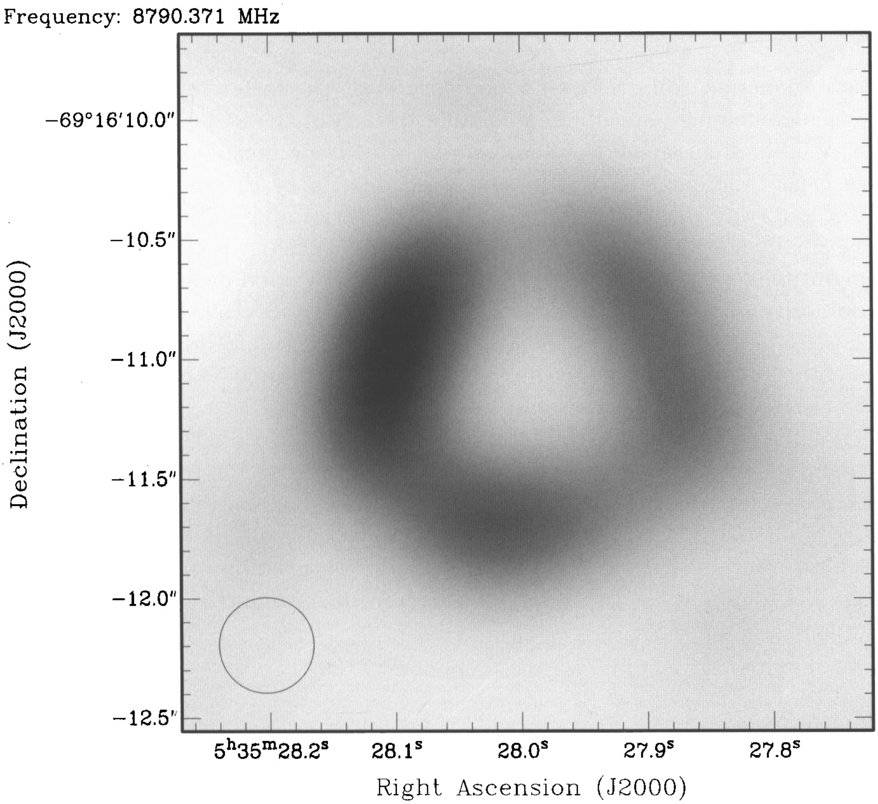

Fig. 3. An image of the radio remnant of SN1987A at day 5810. This image is a maximum entropy reconstruction of ATCA data at a frequency of 9 GHz, convolved with a beam (shown in the bottom left-hand corner) of 0.4 arcsec, resulting in an effective resolution of about 0.5 arcsec. A clear ring-link structure is seen.

may also be present in Chandra 1.2–8.0 keV data from late-2002 [16]. The remnant continues to expand at a rate of 3500 ± 100 km s^{-1} [12], which is similar to the newly derived X-ray expansion velocity of 5000 ± 1000 km s^{-1} [17].

The general picture that is emerging for the evolution of the remnant is that of a fast shock front interacting with gas of increasing density and, along with the increasing shock front area, producing increased levels of synchrotron and non-thermal X-ray emission. Asymmetries in the explosion and the circumstellar gas are responsible for the present-day shape of the remnant, though the general picture remains an almost-spherical shock front impinging on the interior of an hour glass-shaped nebula. Close to the equator, and along the rim of the hour glass, circumstellar densities are very high, and the shock is dramatically slowed down, giving rise to the thermal X-ray emission and the optical emission-line structure seen by HST.

5 Summary and Future Work

Radio emission from SN1987A and SN1993J, the latter being the subject of this conference, are different manifestations of the same basic physics – i.e. a subluminal shock front interacting with a circumstellar nebula. There are clear differences in the history and binarity of the progenitors which go a long way in explaining the very substantial observational differences. Principally these differences are in luminosity (SN1987A is still four orders of magnitude less bright than SN1993J at maximum), and evolution (the radio luminosity of SN1987A is increasing whilst that of SN1993J is decreasing). These difference arise from the fact that SN1987A is embedded in a complex planetary nebula-type structure, whereas SN1993J appears to have a simple r^{-2} circumstellar density profile.

Whilst optical and X-ray monitoring will remain valuable probes of the expanding shock front, a new regime of high-resolution radio imaging of SN1987A is opening up after the recent (2003) installation of 20 GHz receivers on the ATCA. This will allow images of resolution 0.2 arcsec to be regularly obtained, thus improving markedly on existing images such as in Fig. 3. Preliminary observations, which have been reported elsewhere, look promising [13].

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