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Supernova VLBI in the present and with the SKA

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VLBI is the only technology that will allow sub-milliarcsecond resolution imaging in the near future. As such, it is the only way to image expanding supernovae in nearby galaxies. Such images potentially allow us to study the early evolution of neutron stars or black holes left behind by core-collapse supernovae, the circumstellar wind history of the supernova progenitor stars, the shock acceleration of cosmic-ray particles in supernovae as well as the evolutionary process by which supernova shells merge into, and enrich, the ISM. I will discuss the results of the on-going VLBI imaging campaigns on supernova 1986J and 1993J. I will also discuss the impact on supernova VLBI of the proposed South-African Karoo Array Telescope and Australian ASKAP arrays, as well as the SKA itself, as these telescopes will greatly increase the sensitivity of the global VLBI network.

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1. Introduction

Although there are many supernova remnants in our Galaxy, studying the actual supernova events is difficult because the Galactic supernova rate is only on the order of one per century, with the last Galactic supernova occurring ∼300 yr ago. Many more supernovae can be observed in external galaxies, however, resolving them in the first few decades of their lives requires milliarcsecond resolution. Very-long-baseline interferometry (VLBI) is the only technology that will allow sub-milliarcsec resolution imaging in the near future (note that the diffraction limit of a 30 m optical telescope is ∼8 milliarcsec at 10,000 Å).

As the supernova ejecta plough out through the circumstellar medium (CSM), a forward shock is driven into the CSM and a reverse shock is driven into the ejecta. These shocks, and associated instabilities, can both amplify the magnetic field and accelerate particles to relativistic energies, resulting in synchrotron radio emission. Only supernovae with relatively dense CSM produce radio emission detectable with current technology, and so far, only core-collapse supernovae, that is, types Ib/c and II, have been studied with VLBI.

For the sample of supernovae which can be imaged with VLBI, the rewards are rich. VLBI allows us to study in detail the interaction of the expanding ejecta with the CSM, which is in most cases, the stellar wind from the supernova progenitor. Over just a few years, the supernova shock allows us to probe the last ∼10,000 yrs of wind history of the progenitor. VLBI imaging also allows us to study the evolution of the supernova shell, the shock acceleration process, and the possible emergence of a black hole or a neutron star. VLBI studies of supernovae are also an important tool for measuring the supernova rate, and thus the star formation rate, in star-forming regions, which are typically highly obscured in the optical.

Global VLBI at cm wavelengths can resolve young supernova shells out to distances of 10 – 20 Mpc. However, only a fraction of all core-collapse supernovae are radio bright, and so far, only two have been sufficiently close and radio bright to allow well resolved VLBI images since shortly after the supernova explosion: SN 1986J (NGC 891, ∼10 Mpc) and SN 1993J (M81, ∼4 Mpc), although several older supernovae in M82 also have well-resolved VLBI images (e.g., 1).

I will discuss some of the current results from VLBI observations of supernovae in the next few sections, and then proceed to elaborate on the prospects of radio supernova imaging with the SKA demonstrators and the SKA itself.

2. SN 1993J

The best studied radio supernova is SN 1993J. It was one of the brightest radio supernovae, and high-quality radio light-curves were obtained over a wide range of frequency (e.g., 2; 3). The VLBI images showed a remarkably symmetrical shell morphology (e.g., 4; 5). The angular expansion velocity could be accurately measured, and it is the first supernova for which a changing deceleration rate could be measured (e.g., 2; 6). Accurate astrometry has shown that the expansion of the shell is very symmetrical about the explosion center (7; 8). We show a high-resolution image of SN 1993J, accompanied by an animation showing its expansion over a decade of VLBI imaging, in Figure 1. By combining the angular expansion velocity measured with VLBI with the radial

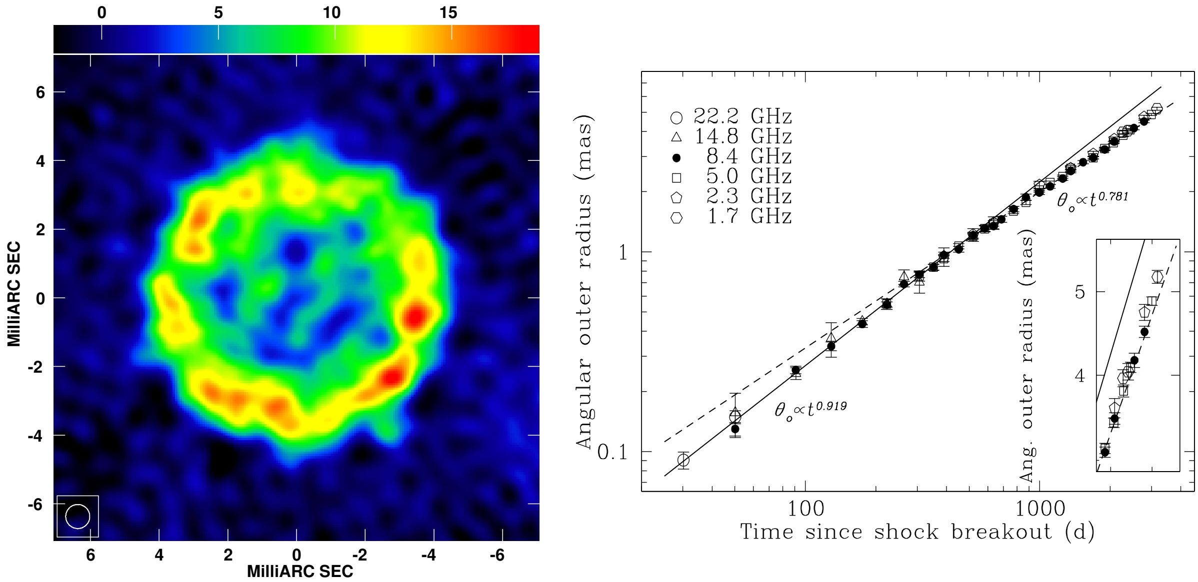

Figure 1: Left panel: Composite image of SN 1993J at 8.4 GHz made by combining the data sets from 1998 December, 2000 February and November (at times, $t = 2080$ d, 2525 d and 2787 d). The data sets were first aligned and scaled to compensate for the expansion of the supernova, (for details see 7). The `accompanying animation` shows the expansion of the supernova, and was made from 27 epochs of VLBI observations (1993 to 2003) at 8.4 and 5 GHz (for details, see 8). Right panel: the angular outer radius, $\theta_{\rm o}$, of SN 1993J as a function of time, t, showing the change of the exponent of the power-law expansion near day 900, and with the inset showing the most recent measurements (for details, see 2).

expansion velocities determined from optical spectra, a direct distance to M81 of 3.96 ± 0.29 Mpc could be determined (9).

3. SN 1986J

Supernova 1986J was first discovered in the radio, a few years after the explosion. An early VLBI image of it marked the first time shell-like structure was seen in an IAU-designated supernova (10). Until 1999, SN 1986J had a power-law radio spectrum ($S_\nu \propto \nu^\alpha$ where $\alpha \sim -0.6$) similar to that of most radio supernovae. After 1999, however, an inversion appeared in the spectrum. Multi-frequency VLBI imaging showed that this inversion was associated with a new component almost precisely in the center of the shell (11). The new component is likely radio emission associated with the black-hole or neutron-star compact remnant of the explosion, which has not been seen in any other modern supernova. We show a two-frequency image of SN 1986J, accompanied by an animation showing the evolution of the supernova from almost 20 years of VLBI imaging, in Figure 2.

4. Other Radio Supernovae and Supernovae in Star-Forming Galaxies

A number of other individual radio supernovae have been imaged with VLBI: there is a series of VLBI observations of SN 1979C (e.g., 12), and a handful of others including SN 2001em

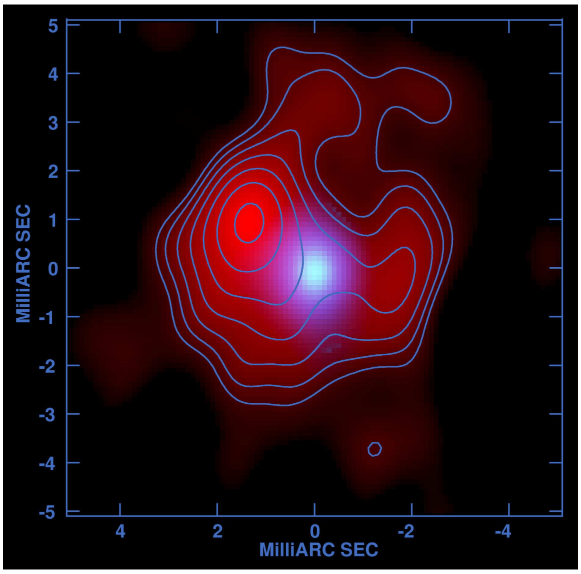

Figure 2: A dual-frequency VLBI image of SN 1986J, showing the compact, inverted-spectrum component located almost precisely in the center of the expanding shell. The red colour and the contours represent the 5 GHz radio brightness, showing the shell emission. The contours are drawn at 11.3, 16, 22.6, . . . , 90.5% of the peak 5 GHz brightness of 0.55 mJy beam^{-1}. The blue through white represents the 15 GHz radio brightness, showing the compact, central component which appeared around 1999. North is up and east to the left. The `accompanying animation` shows the expansion of the supernova, and the emergence of the central component.

(e.g., 13; 14; 15, the last being the first e-VLBI experiment on a supernova), SN 2001gd (16) and SN 2004et (17).

Wide-field VLBI images of star-forming galaxies have yielded fruitful results. Wide-field VLBI observations of the nearby starburst M82 have shown a number of supernova and supernova remnants (e.g., 1). The extreme starburst galaxy Arp 220 has been imaged with VLBI for over a decade, and the rate of new radio supernovae is 4 ± 2 yr^{-1} (18; 19). Radio observations of the starburst galaxy Arp 299 show that the radio of radio supernovae must be about 1 per year (20).

5. Supernova VLBI with the SKA Demonstrators

Supernova VLBI is limited both by the available resolution and sensitivity. Although the SKA demonstrators and the SKA itself will not allow an increase in resolution, they will greatly increase the sensitivity as well as the *u*-*v* coverage of the global VLBI array, particularly in the southern hemisphere, where the network of telescopes is notably less dense than in the northern hemisphere.

	Australian LBA & Hartebeesthoek	+ ASKAP	+ MeerKAT	+ ASKAP + MeerKAT	+ SKA (core) + ASKAP +MeerKAT	+ SKA (full) + ASKAP + MeerKAT
Bandwith (MHz)	64	128	128	128	512	512
Bitrate (Mbits/s)	512	1024	1024	1024	4096	4096
Image rms (μJy)	10	4.5	2.5	2.1	0.12	0.04

Table 1: Notes — All entries assume 8-hour observations using two polarizations and 2-bit digitization; ASKAP: assumes 45×12 m dishes with system temperatures of 35 K; MeerKAT: assumes 80×12 m dishes with system temperatures of 30 K; SKA (full): assumes a total collecting area of 10^6 m^2, distributed over 10 stations, with 25% of collecting area at distances > 180 km from the core.

Presently, only the radio-brightest supernovae can be imaged: in the last 30 years, only ∼10% of the observed core-collapse supernovae have been bright enough for a radio lightcurve to be determined.

The increased sensitivity available, especially once the SKA is operational, will also allow us detect far more supernovae and also to follow individual supernovae for much longer. It will allow us to resolve older and more distant supernovae, for example Cas A would have a 1-GHz flux density of 1 μJy and a size of 6 milliarcsec at a distance of 170 Mpc. We will be able to obtain a census of supernova remnants of nearby galaxies, and much more routinely monitor galaxies for the appearance of new radio supernova, which will do much to constrain supernova and star formation rates.

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