

Radio Imaging of SN1993J

1 Introduction

SN1993J is a Type IIb supernova located in the M81 galaxy. It was discovered in March 1993, on the same day as the supernova shock breakout [1]. Figure 1 illustrates SN1993J's location, hypothesised structure and formation.

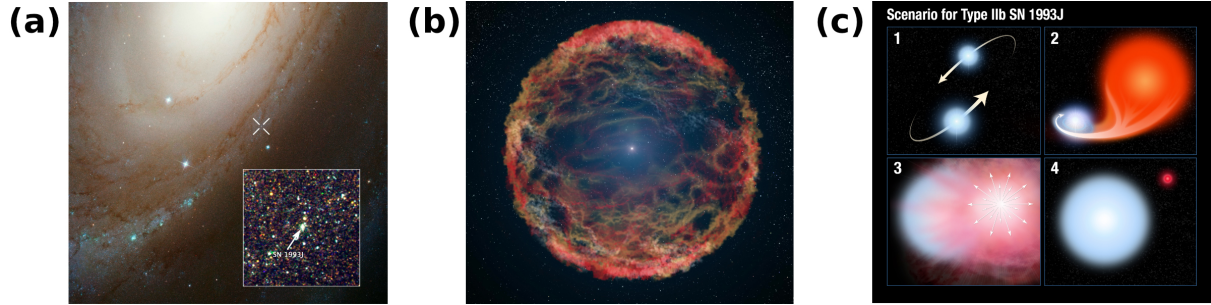


Figure 1: (a) Hubble Space Telescope composite image of galaxy M81 with SN1993J's location in spiral arm highlighted and an enlarged in the panel inset. (b) Artist's impression of the structure of SN1993J. (c) Illustration of the origin of SN1993J as Type IIb supernova. All images courtesy of ESA/Hubble.

Figure 1(c) illustrates a binary stellar system where the slightly higher mass star accretes most of the hydrogen to the other, leaving the less massive star almost entirely comprised of Helium. This star then explodes as a supernova, producing a characteristic Type IIb light curve [2].

SN1993J's evolution was tracked by radio surveys for over a decade [3, 4]. Radio emission is accepted to be produced via the standard circumstellar interaction model: an expanding supernova shell forms a forward shock outward into the circumstellar medium (CSM) and a reverse shock propagating inwards. Electrons are accelerated to relativistic energies by the shock front, and magnetic fields are amplified by the contact discontinuity between the shocked CSM and expanding shell. In between the two shock fronts, relativistic electrons produce synchrotron radio emission [5].

2 Method

2.1 Imaging Using Very Long Baseline Interferometry

This study employed Very Long Baseline Interferometry (VLBI) observations from the High Sensitivity Array (HSA): a combination of the Very Long Baseline Array, Very Large Array and Effelsberg radio telescope, shown in Figure 2(a). The HSA has a synthesised aperture of approximately 8000 km, almost the entire diameter of the Earth [6]. The observation took place on 25th February 1997, when SN1993J was 1430 days old, for approximately ten hours.

Synchrotron radiation is typically observed between 0.01 and 10 GHz [7]. Higher frequency observations produce increased resolution of the supernova's structure, and initial study of SN1993J took place at 8.4 GHz. However, within eight months of the supernova's discovery, high frequency flux had decreased sufficiently for the shell structure to be unresolvable from side-lobe noise [8]. As a result, this later observation takes

place at 5 GHz, a compromise between high structural resolution and sensitivity.

SN1993J has a high declination of 69° [9], enabling excellent UV-plane coverage using the HSA, as seen in the sampling function shown in Figure 2(b).

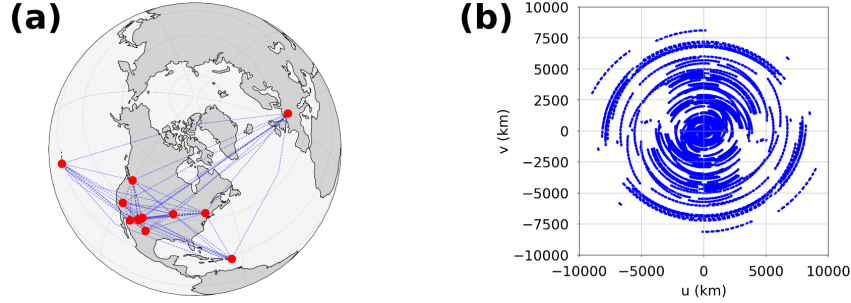


Figure 2: (a) Antennae distribution for the High Sensitivity Array, with baselines indicated between each antennae pair. (b) Sampling function, or UV-track, produced for ten-hour observation of SN1993J.

A smaller array would capture a much smaller area of the UV-plane, due to reduced number and extent of baselines, and a low-latitude array would produce a sampling function with as large coverage over the course of the Earth's rotation.

2.2 Image Reconstruction

APSYNTRU was used to produce an image of SN1993J using the HSA observational data. Figure 3 shows the measured visibility amplitudes as a function of UV-distance, with the point source function (PSF), or ‘dirty beam’, and corresponding ‘dirty image’ as generated by APSYNTRU.

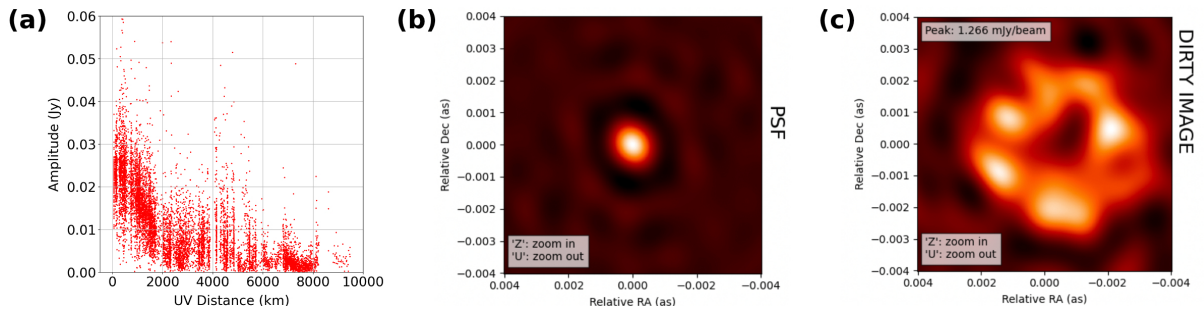


Figure 3: (a) Scatter of measured amplitude against UV-distance for measured visibilities. (b) Point spread function (PSF), or ‘dirty beam’ of observation, generated by APSYNTRU. This is the inverse Fourier transform of the visibility sampling function shown in Figure 2(b). (c) APSYNTRU-generated dirty image using pixel size = 42 Nyq, robustness, $R = -1.4$, and weight power = 1.

Figure 3(a) shows a generally uniform spread of data collection points across a large region of UV-distance, reflecting the large sampling function shown in Figure 2(b). Small UV-distance signals generally measured the largest amplitudes, corresponding to signals at large extents in the real image, suggesting SN1993J should be considered

an extended source for image reconstruction. Furthermore, the amplitude distribution broadly follows a Bessel function, suggesting a generally spherical source.

The dirty beam, $B(l, m)$, shown in Figure 3(b) is the inverse Fourier transform of the sampling function, $S(U, V)$ shown in Figure 2(b). The dirty image, I_D , shown in Figure 3(c), is the inverse Fourier transform of the measured visibilities, and therefore the convolution of the dirty beam and the ‘true’ source image, as shown in Equation 1. Producing the true image via deconvolution is discussed in Section 2.3.

$$I_D = \underbrace{\mathcal{F}^{-1}[S(U, V)]}_{\text{Dirty Beam, } B(l, m)} * \underbrace{\mathcal{F}^{-1}[V(U, V)]}_{\text{True Image, } I(l, m)} \quad (1)$$

A large pixel size of 42 Nyq was selected such that the main lobe of the dirty beam would be well sampled. Furthermore, pixel size of 42 Nyq was found to ‘fill the frame’ of the dirty image while preserving detail in the outer fringes of the structure: smaller pixel size made the structure too small to resolve and larger pixel size caused edge features to be lost.

The robustness refers to the Briggs R-parameter [10]. Highly ‘uniform’ weighting was employed using $R = -1.4$. This increases the resolution in the dirty image by increasing the contribution of the side lobes, at the compromise of reduced sensitivity and increased noise from spurious side-lobe sources. This robustness was selected based on the UV-amplitudes distribution in Figure 3(a) suggesting SN1993J as an extended source. A weight power of 1 was selected to apply the robustness weighting fully.

2.3 Deconvolution of Dirty Image

The dirty beam was deconvolved from the dirty image using the CLEAN algorithm [11], depicted in Figure 4 using APSYNTRU.

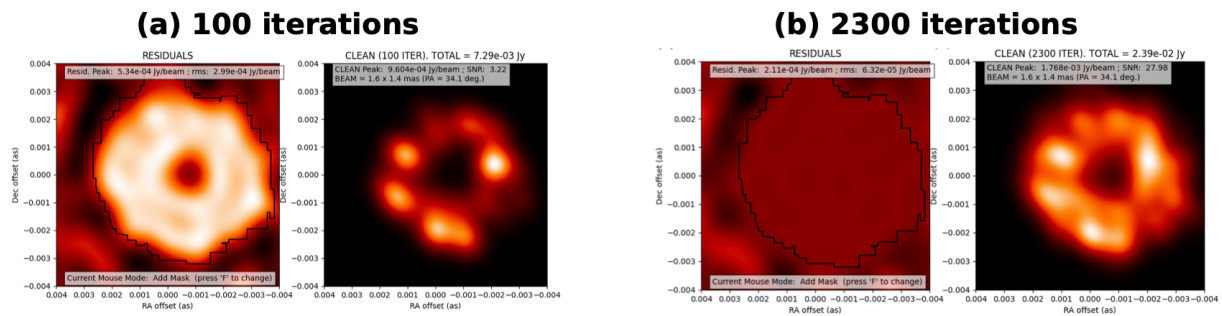


Figure 4: Implementing the CLEAN algorithm with APSYNTRU at **(a)** 100 iterations and **(b)** 2300 iterations. In each case, the left panel shows the residuals and the right panel the CLEANed image. The applied residuals mask is indicated by the black outline.

An initial mask was selected to cover the circular structure seen in the dirty image in Figure 3(c). This was CLEANed for 100 iterations and the residuals rescaled. The mask was re-adjusted to increase the precision of the fit to the bright region in the residuals, as shown in Figure 4(a). The CLEAN algorithm was re-run for a total of 2300 iterations, shown in Figure 4(b). At this stage, the signal-to-noise ratio (SNR) no

longer increased with additional iterations and plateaued at SNR = 27.98. The CLEAN-peak intensity also stabilised at 1.768 mJy/beam. Visually, the masked region of the residuals plot appeared homogenous. Further CLEANing risked adding noise sources as true signals.

3 Results and Discussion

Figure 5 shows the false-colour, processed image of SN1993J's 5 GHz radio emission.

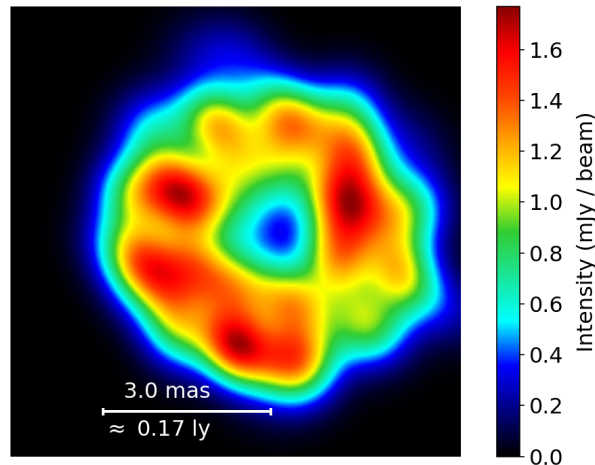


Figure 5: 5 GHz radio emission of SN1993J at 1430 days old. The supernova is measured with a radius of approximately 3 mas, equal to approximately 0.17 lightyears.

The radius of SN1993J is measured to be approximately 3 mas, concurring with previous literature studies using the same dataset, measuring 2.81 ± 0.05 mas [12]. At this age, the radius of the supernova in 5 GHz and 1.6 GHz emission are very similar, but after ~ 1500 days the 5 GHz emission is progressively smaller. This discrepancy is likely due to the combined effects of the ejecta becoming opaque to 5 GHz emission and a changing radial magnetic field in the emitting region affecting synchrotron radiation characteristics [12]. In the centre of the supernova, the radio intensity is very low, likely due to the material in the inner ejecta still being opaque to radio waves [13].

The outer shell structure is highly spherical compared to other radio supernovae [14]. However, significant internal asymmetry is present. This is likely driven by ‘fingers’ of shocked envelope material extending into an anisotropic CSM due to Rayleigh-Taylor instability at the interface [13]. A diffuse protrusion in the north corner of the image is seen in 8.4 GHz images at a similar age [15], and is possibly due to a low density ‘clump’ of CSM which allows the shock to propagate faster but produce less synchrotron emission [13].

Three ‘hotspots’ are observed in the east, south and west corners, also present in 5 GHz and 8.2 GHz images at a similar age [13, 15]. Such features provide evidence for the progenitor of SN1993J being a member of a binary system, which would have disrupted the spherical symmetry in the pre-supernova CSM [8]. Complimentary observations in ultraviolet and x-ray wavelengths also demonstrate a complex distribution of the CSM, re-enforcing the model of SN1993J as a Type IIb supernova [16]. However, this model of the azimuthal asymmetry in SN1993J has been brought under doubt by

modern interpretation suggesting the observations can be explained as artefacts of incomplete UV-plane sampling and not a real phenomena at all [17].

4 Conclusion

An image of Type IIb supernova SN1993J has been produced using VLBI observation of its 5 GHz radio emission. The image was reconstructed using the APSYNTRU software and the CLEAN deconvolution algorithm. The observed structure concurred with literature observations of SN1993J, depicting a highly asymmetric interior structure, most likely driven by anisotropy in the circumstellar medium.

References

1. Ripero J et al. Supernova 1993J in NGC 3031. *International Astronomical Union Circular* 1993; 5731
2. Woosley S et al. SN 1993J: a type IIb supernova. *The Astrophysical Journal* 1994; 429
3. Van Dyk SD et al. SN 1993J: The early radio emission and evidence for a changing pre-supernova mass-loss rate. *Astrophysical Journal* 1994; 432
4. Van Dyk SD et al. A Decade of Radio and X-ray Observations of SN 1993J. *International Astronomical Union Colloquium*. Vol. 192. Cambridge University Press. 2005
5. Chevalier RA. The radio and X-ray emission from type II supernovae. *Astrophysical Journal* 1982; 259
6. Saha SK. Aperture synthesis: methods and applications to optical astronomy. 2010
7. Dubner G et al. Radio emission from supernova remnants. *The Astronomy and Astrophysics Review* 2015; 23
8. Marcaide J et al. Discovery of shell-like radio-structure in SN1993J. *Nature* 1995; 373
9. Wenger M et al. The SIMBAD astronomical database. *Astronomy and Astrophysics Supplement Series* 2000; 143
10. Briggs DS. High fidelity deconvolution of moderately resolved sources. PhD Thesis 1995
11. Högbom J. Aperture synthesis with a non-regular distribution of interferometer baselines. *Astronomy and Astrophysics Supplement* 1974; 15
12. Marcaide J et al. A decade of SN 1993J: discovery of radio wavelength effects in the expansion rate. *Astronomy & Astrophysics* 2009; 505
13. Bietenholz MF et al. SN 1993J VLBI. III. The evolution of the radio shell. *The Astrophysical Journal* 2003; 597
14. Beswick R. Radio supernovae. *Proceedings of the 8th European VLBI Network Symposium*. 2006
15. Bartel N et al. The changing morphology and increasing deceleration of supernova 1993J in M81. *Science* 2000; 287
16. Wheeler JC et al. Review of Contributions to the Workshop on SN1993J. *International Astronomical Union Colloquium*. Vol. 145. Cambridge University Press. 1996
17. Heywood I et al. The radio remnant of SN 1993J: an instrumental explanation for the evolving complex structure. *Monthly Notices of the Royal Astronomical Society* 2009; 392