# Supernova research with VLBI


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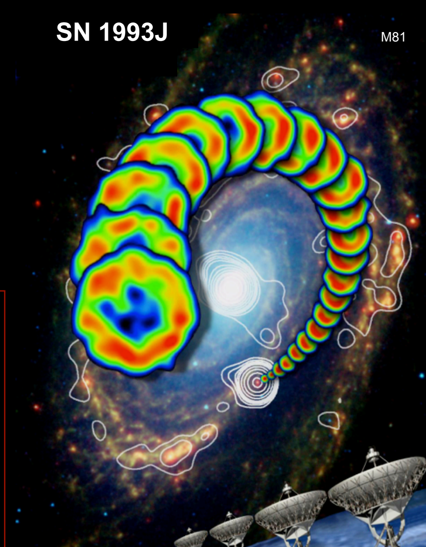
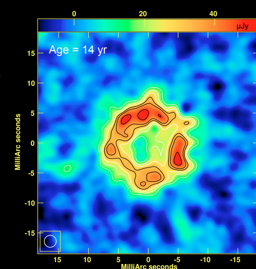
### Abstract:

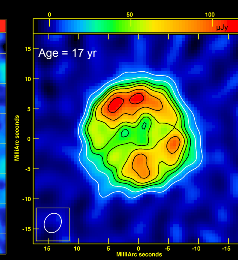
We present recent results from radio VLBI observations of SN 1993J, SN 1986J, SN 1979C, SN 1996cr and SN 2011dh. These supernovae are well resolved and show strong modulation of the brightness around the ridge, indicating significant density variations in the ejecta and/or the wind from the progenitor. The first three could be investigated in detail. SN 1993J and SN 1979C both show a change in their deceleration parameters with time. All three show indications of their shell structure diminishing with time, implying that the reverse shock possibly moves inward. SN 1986J is now dominated at 5 GHz by a central component which could be associated with the youngest neutron star or a black hole.

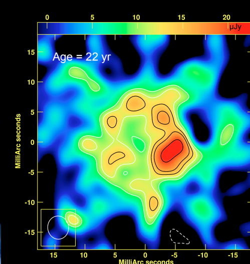

VLBI observations are the only means of resolving the expanding ejecta of extragalactic supernovae beyond the LMC. The radio emission is produced as the ejecta interact with the stellar wind of the progenitor. VLBI observations can place important constraints on the nature of both the ejecta and the wind. They can also be used to determine whether or not the ejecta are relativistic, and therefore help clarify the relationship between stripped-envelope or Type Ib/c supernovae and GRBs, as well as placing limits on "orphan afterglows," or GRB events with jets not directed near the line of sight. With the expanding shock front method (ESM) witch combines the radial expansion velocity measured spectroscopically with the transverse expansion velocity measured with VLBI, the distance to the host galaxy can be determined geometrically. Finally, VLBI observations can search for the central stellar remnant of the explosion, a neutron star or black hole.

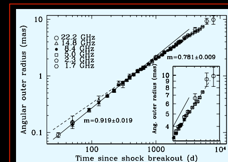
## SN 1993J

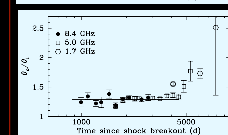


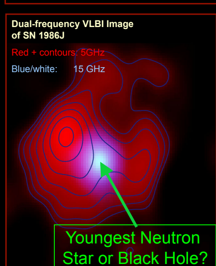



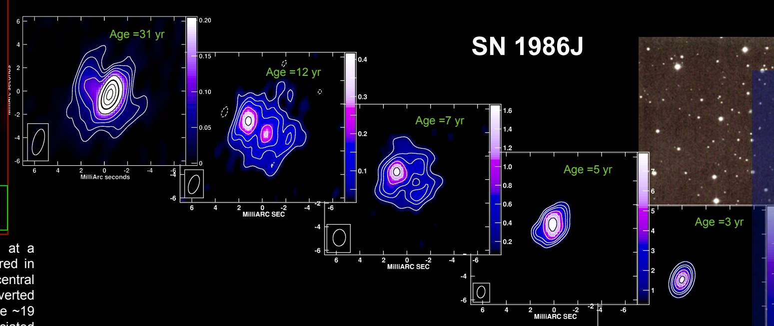



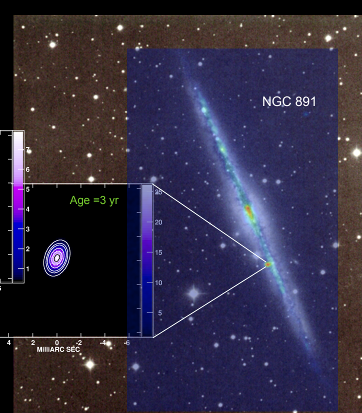

SN 1993J, Type IIb, in M81, at 3.96 ± 0.29 Mpc determined geometrically for the SN with the expanding shock front method (ESM), and discovered 1993 March 28. It is the best studied supernova in the radio. The image shows a text-book shell, very circular in projection, that has expanded almost freely during the first years since the explosion and decelerated more strongly afterwards. Measured changes in the deceleration imply structure in the ejecta and/or circumstellar medium. While the ratio of the outer to the inner radius of the shell, corresponding to the ratio of the radii of the forward to the reverse shock, was constant at about 1.2 to 1.3 during the first 12 years, the shell broadened thereafter, implying that the reverse shock moved inward. Here and in all other images but the dual-frequency one, colour scale and/or contours show radio brightness, and the FWHM restoring beam is in the lower left.

## SN 1986J



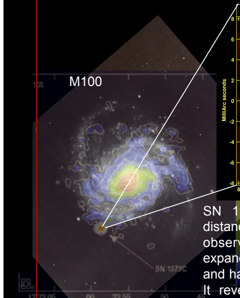

SN 1986J, Type II, in NGC 891 at a distance of 10 Mpc, was discovered in the radio. The supenova shows a central component in the radio with an inverted spectrum that first appeared at age ~19 yrs. The component could be associated with an unusually dense condensation in the shell lying near the projected center, caused by more complex interaction with a medium close to the center, or be linked to a neutron star or black hole - the stellar corpse left over from the explosion.

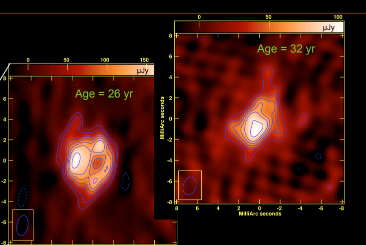


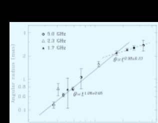

**The Evolution of SN 1986J:** A sequence of VLBI images showing the expansion of the shell of SN 1986J, along with the emergence of the central component. At 5 GHz, the central component first appeared at age ~ 23 yrs, and by age of ~ 31 yrs dominated the radio emission. The shell expands in a power law fashion, with $r \propto t^{0.69}$ till at least age 23 yrs. Little expansion has been apparent since then. The flux density scale is in mJy.

## SN 1979C

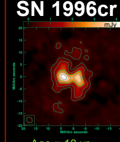


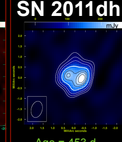

SN 1979C, Type II, in M100 at a distance of 20 Mpc, is the supernova observed with VLBI the longest. It expanded freely for the first ~17 years and has since then decelerated strongly. It revealed shell structure after ~ 25 years that evolved into a filled structure.



## SN 1996cr




## SN 2011dh




SN 2011dh, Type IIb, in M51 at 8 Mpc, discovered 2011 May 31, within one day of the explosion. A yellow supergiant was identified as the progenitor with its radius and surface temperature, $R_{prog} \sim 270\ R_{\odot}$, $T_{eff} = 6000$ K. The radio image shows a shell with a hot-spot on one side. The expansion is almost free, with the radius, $r \propto t^{0.961\pm0.011}$, where t is the age of the supernova. The most recent results show a flattening of the lightcurve suggesting a dense shell in the ejecta or a low-density region in the circumstellar medium.

SN 1996cr, Type II, in Circinus galaxy, at 3.6 Mpc, discovered in X-rays, approximately 10 yrs after the explosion. It is the strongest radio supernova so far detected. Unusually, at X-rays and in the radio it brightened at age ~ 500 d – reminiscent of SN 1987A but it was 1000 fold more luminous. The interpretation is that at age ~1 yr, the supernova shock hit a dense shell caused by the blue supergiant or Wolf-Rayet wind sweeping up an earlier, slower wind.

## Selected references


**SN 1986J**: Bietenholz, Bartel, & Rupen, 2010. ApJ, 712, 1057.
Chevalier, R. A., 2012, ApJ, 752, L2.

**SN 1993J**: Marti-Vidal et al., 2011, A&A, 526, 142.
Bietenholz et al., 2010. PoS (10th EVN Symposium), 057.
Bartel,et al., 2007. ApJ, 668, 924.

**SN 1996cr**: Bietenholz et al. 2016 (in prep).
Bauer et al., 2008, ApJ, 688, 1210.

**SN 2011dh**: de Witt et al., 2016, MNRAS, 455, 511.
Bietenholz et al., 2012. ApJ, 751, 125.

**Reviews**: Bartel & Bietenholz, 2014. IAU Symposium 296, 53.
Bietenholz, 2014. PASA, 31, 2.


## Conclusions

Supernova VLBI continues to make unique contributions to the study of core collapse supernovae. It sheds light on the interaction of the shock front with the circumstellar medium, helps to determine the density profiles of the ejecta and the wind from the progenitor star, monitors the wind history over 1000's of years before the star died, determines distances geometrically, searches for the stellar corpse of the explosion and illuminates the relation between SN Ibc and GRB. SNe appear to increasingly decelerate with age and show indications of a broadening of the shell.