Supernova research with VLBI

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Abstract:
We present recent results from radio VLBI observations of SN 1986J, 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 along the wind from the progenitor. The first three could be investigated in detail. SN 1986J shows an unusual shell, which is a long-standing feature of their deceleration parameters with time. All three show indications of their shell structure diminishing with time, implying that the reverse shock steadily moved 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 catastrophic supernovae beyond the LMC. The radio emission is produced as the ejecta interact with the stellar wind. 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 supernovae and GRBs, as well as placing limits on "orphan afterglows" or GRB events with jets not detected near the line of sight. With the expanding shock front method (ESM), which 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 are the only means of resolving the circumstellar remnant of the explosion, a neutron star or black hole.

The Evolution of SN 1986J: A sequence of VLBI images showing the expansion of the ejecta of SN 1986J along with the emergence of the central component. At 5 GHz, the central component first appeared at age ~19 yrs, and by age of ~31 yrs dominated the radio emission. The shell expands in a power law fashion, with r ~ t³/³, 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 of a low-density region in the circumstellar medium.

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 1000s of years before the star died, determines distances geometrically, searches for the stellar corpse of the explosion and illuminates the relation between SNe Ic and GRB. It appears to increasingly decelerate with age and show indications of a broadening of the shell.

Supernova VLBI

Youngest Neutron Star or Black Hole?

SN 1986J: Type II in NGC 891 at a distance of 3.96 Mpc, discovered in X-rays, approximately 16 yrs after the explosion. It is the strongest radio supernova so far detected. Unusually, X-rays are in the radio and 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 Wolf-Rayet wind sweeping up an earlier, slower wind.

SN 1993J: Type Ibc in M81, at 3.6 Mpc, discovered 1993 March 28. It is the best studied supernova in the radio. The image shows a fast-beam shell, very circular in projection, that has expanded almost freely during the first few years since the explosion and decelerated more utterly afterwards. Measured changes in the deceleration imply structure in the ejecta and 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, the ratio of the outer to the inner radius varies with time, indicating that the shell structure is diminishing.

SN 1996cr: Type II in M51 at 8 Mpc, discovered 2007 March 15, within one day of the explosion. A yellow supergiant was identified as the progenitor with its radius and surface temperature, R = 270 Rₖ, T = 6000 K. The radio image shows a shell with a hot-spot on one side. The expansion is almost free, with the radius, r ~ t³/³, 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 of a low-density region in the circumstellar medium.

Selected references
Bietenholz et al., 2007.
Bietenholz et al., 2013.
Bietenholz et al., 2010.
Bietenholz et al., 2007.
Bietenholz et al., 2016.

Notes:
1. The supernova shock hits a dense shell caused by the blue supergiant Wolf-Rayet wind sweeping up an earlier, slower wind.
2. The radio emission is produced as the ejecta interact with the stellar wind.
3. VLBI observations are the only means of resolving the expanding ejecta of catastrophic supernovae beyond the LMC.
4. The radio emission is produced as the ejecta interact with the stellar wind.
5. VLBI observations can place important constraints on the nature of both the ejecta and the wind.
6. Finally, VLBI observations are the only means of resolving the circumstellar remnant of the explosion, a neutron star or black hole.

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