Supernova VLBI

Michael Bietenholz, Hartebeesthoek Radio Observatory, South Africa
1984, 1.7 GHz

Wilkinson & de Bruyn, 1984
1988.8, 8 GHz

Bartel et al., 1990
Introduction and History

• Radio emission from a supernova was first detected in the 1972 (SN 1970G; Gottesman et al., Goss et al.)
• First paper about supernova and VLBI was in 1974 – Cass A at meter wavelengths
• First determination of the size of a supernova in 1983: SN 1979C (Bartel et al.)
• First image of a radio supernova in 1984: 41.95+575 in M82 (Wilkinson & de Bruyn)
Radio Emission from Supernovae

- Thermonuclear:
  - Type Ia: no detections to radio date (see Panagia et al 2006)

- Core Collapse:
  - Type Ib/c (no Hydrogen in spectrum; stripped envelope stars)
    - Generally have steep spectra: $\alpha < -1$ ($S \propto \nu^\alpha$)
    - Fast turn-on/turn-off, peak at 5 GHz near optical maximum
  - Type II: (Hydrogen in spectrum; supergiant progenitors) large range in radio luminosities
    - Relatively slow turn-on/turn-off, radio peak often significantly after optical peak.

- Approximately 30 RSNe (all core-collapse) with flux densities > 1 mJy have been detected, and >100 have upper limits (Weiler et al.) Most are at <30 Mpc
Radio Detection of SNe

• Several hundred SNe are detected each year in optical
• Only a few SNe detected each year in radio
  – Total radio SNe detections: a few dozen
  – ‘All’ radio detected SNe are core collapse (Type II, Type Ib/c etc)
• Even fewer have been resolved by radio observations (so every VLBI observation is of great value)....
• A few SNe detected in radio but NOT in optical (e.g. a supernova in NGC7469 – Colina et al 2001; several SNe in Arp220 – Smith et al., Lonsdale et al., Parra et al.)
Standard Model of SN Radio Emission

from Chevalier, 1982
Early Radio Lightcurve of SN1993J

Curves are fits of a standard model to the data

(Weiler et al)
Why Image Supernovae with VLBI?

- Interaction of the expanding ejecta with the circumstellar medium (CSM) – usually the wind of the SN progenitor
- Stellar wind history of star: supernova shock front overruns CSM wind with $1000\times$ wind speed
  → time machine that records progenitor wind history in reverse
- Evolution of SN shells, shock acceleration, eventual merging with ISM
- Compact remnant of a core-collapse SN?
- Supernova rates, especially in dusty environments
- Direct distances with the expanding shock front method – out to Virgo cluster
- Imaging jets of nearby GRB events
### RSNe Observed with VLBI

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Host galaxy</th>
<th>Distance (Mpc)</th>
<th>Peak (mJy at 8 GHz)</th>
<th>Reference</th>
</tr>
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<tbody>
<tr>
<td>Several SN/SNR</td>
<td>?</td>
<td>M82</td>
<td>3.2</td>
<td></td>
<td>Beswick et al 2006</td>
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<td>Several SN/SNR</td>
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<td>77</td>
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<td>SN1978K</td>
<td>II</td>
<td>NGC 1313</td>
<td>4</td>
<td>&gt;100?</td>
<td>Smith et al 2007</td>
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<td>SN1979C</td>
<td>II</td>
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<td>16</td>
<td>6</td>
<td>Bartel &amp; Bietenholz 2008</td>
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<td>2</td>
<td>Bartel 1985</td>
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<td>NGC891</td>
<td>10</td>
<td>100</td>
<td>Bietenholz et al 2004</td>
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<td>SN1987A</td>
<td>II</td>
<td>LMC</td>
<td>0.05</td>
<td>80</td>
<td>Jauncey, Gaensler, Manchester</td>
</tr>
<tr>
<td>SN1993J</td>
<td>II</td>
<td>M81</td>
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<td>100</td>
<td>Bietenholz, Bartel, Marcaide</td>
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<td>SN1994I</td>
<td>Ic</td>
<td>M51</td>
<td>8</td>
<td>20</td>
<td>Bietenholz &amp; Bartel, unpublished</td>
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<td>SN1996cr</td>
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<td>Circinus</td>
<td>3.6</td>
<td>~100</td>
<td>Bauer et al 2008</td>
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<td>SN2001em</td>
<td>Ib/c</td>
<td>NGC 7112</td>
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<td>Bietenholz, Paragi, Schinzel</td>
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<td>SN2001gd</td>
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<td>13</td>
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<td>Pérez-Torres et al 2008</td>
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<td>SN2008D</td>
<td>Ib/c</td>
<td>NGC 2770</td>
<td>27</td>
<td>3</td>
<td>Soderberg, Bietenholz Paragi</td>
</tr>
</tbody>
</table>

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SN1993J in M81

Contours: 5 GHz VLA Radio observations of M81 (Nov. 1997)

Optical image from A. Sandage, *The Hubble Atlas of Galaxies*
22 Jun 1994; day 451 ~ 1.5 years after the explosion. Shell clearly visible with some asymmetry: a hot-spot to the south and a gap to the North.
Expansion velocity depends on density profiles of both ejecta and circumstellar (pre-SN wind)

Bartel et al, 2002; see also Marcaide et al
Geometrical Distance to SN 1993J in M81

\[ D = 3.96 \pm 0.29 \text{ Mpc} \]

Bartel et al. 2007
Deceleration of SN1993J

Deceleration parameter, $m$:

$$\theta \propto t^{m(t)}$$
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Hydrodynamical modelling
(Mioduszewski, Dwarkadas, & Ball 2001)
SN 1993J

24 May 2002, day 3345 ~ 9 years after the explosion

Global array VLBI: Bietenholz et al, Bartel et al 1993-2008;
See also Marcaide et al

- Spherical shell of material thrown off in the explosion
- Expanding at 8,000 km/sec
- Size: 32,000 AU, 0.15 parsec = $4.8 \times 10^{17}$ cm

5.0 GHz
Astrometry w.r.t. the Core of M81

Location of explosion center determined to 45 μas or 160 AU

Peculiar proper motion:
320 ±160 km/s to south
(2 ~ 3% of expansion velocity)

Bietenholz et al 2002
VLBI Movie of SN 1993J

- Global Array VLBI at 8.4 GHz and 5 GHz for last few epochs
- 33 Epochs of VLBI from 1993 to 2006 (and continuing!)
SN 1979C

- Galaxy observations in Feb 2005 using a global array
- SN 1979C
- Age = 26 yrs
- 50% contour is circular to ≤ 8%
- Galaxy M100
- 15 Mpc
- SN 1979C discovered 19 Apr. 1979
- Peak = 7 mJy

Bartel & Bietenholz 2008
Supernova 1986J

- Supernova 1986J discovered in August 1986 in NGC 891
- Distance: ~10 Mpc
- Explosion date: 1983.2 ± 1.1 yr
- Among the most luminous radio supernovae ever
- Models suggest that the progenitor was a red supergiant, with mass > 20 \( M_\odot \)
VLBI Images: 1987 to 2005 (and continuing...)

Bietenholz & Bartel 2007
Central Component in SN1986J

- Not visible in any earlier image
- $\forall \leq 0.8$ milli-arcsec ($10^{17}$ cm)
- Too bright to be an HII region
- $200 \times$ the current radio luminosity of the Crab Nebula at 15 GHz

Multi-frequency VLBI Image:
Contours, red: 5 GHz
Blue $\rightarrow$ white: 15 GHz

Bietenholz, Bartel & Rupen 2004
Central Component in SN1986J

Multi-frequency VLBI Image:
Contours, red: 5 GHz
Blue → white: 15 GHz

Youngest Neutron Star or Black Hole?

Bietenholz, Bartel & Rupen 2004
SN 1987A

Optical ring, enhancement of radio and X-ray brightness at same position angle

SN 1987A VLBI (2$^{nd}$ Epoch)

Greyscale: Australian Long Baseline Array, 1.3 GHz, Oct. 2007

Contours: ATCA 9 GHz

Tzioumis et al
Expansion of SN1987A

ATCA: 3600 → 5200 km s⁻¹
Chandra: 6100 → 1400 km s⁻¹

~ 38 000 km s⁻¹

Gaensler et al 2007
Supernova 1987A: Equatorial Ring?

- Two-lobed structure in radio, X-ray
- Lobes aligned with optical ring
- Brighter lobe is at larger radius
- True geometry: likely a tilted torus

Michael et al 2003
SN 1996cr in Circinus Galaxy

- VLBI (LBA): source radius \(\sim 5\text{mas}\)
- Dense CSM shell

Bauer et al 2008; Bartel et al in prep.
Other Radio Supernovae

Type II
$\Theta = 0.37 \pm 0.08$
(Pérez-Torres et al)

Type II
$V_{\text{exp}} 15000 \pm 2000 \text{ km/s}$
(Martí-Vidal et al)
Relativistic Expansion: SNe and GRBs

- Long Duration GRB’s associated with Type Ibc supernovae
- Collapse of massive star into a black hole powers highly relativistic jet
- GRB’s are jets oriented near the line of sight
- The jets *not* near the line of sight may be visible in radio
SN 2001em

- SN2001em was discovered on 15 Sep. 2001 in UGC11794 (Papenkova 2001).
- 80 Mpc.
- Type Ib/c, most likely Ic.
- Exceptional radio and X-ray luminosities
- Late turn on of radio and X-ray emission
- Possible off-axis GRB event (Granot & Ramirez-Ruiz 2004)
- Several different VLBI experiments: non-relativistic upper limits on expansion velocity ($5800 \pm 10000$ km/s) and on the proper motion (corresponding to $33000 \pm 34000$ km/s)
- First faint target detected ($4.5 \sigma$) with EVN e-VLBI (Paragi et al 2005).
- See poster #28 by Schinzel
SN 2008D: Caught in the Act!

• Normally, super-novae detected in optical light come chiefly from decay of $^{56}$Ni - doesn’t start till a few days after shock breakout.
• Shock breakout has been thought to produce a brief, bright flash in X-rays.
• Flash from SN 2008D was seen during observations of SN 2007uy (NGC 2770; 27 Mpc).
• Duration ~5 minutes!
• Subsequent optical spectra confirmed a supernova (Type Ibc).
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SN 2008D VLBI

- Epoch May 2008
- VLBA + Ef + Y27
- 5 GHz
- Total flux density: ~200 $\mu$Jy
- Preliminary result on angular size: 3σ limits on apparent expansion speed: <1.0 c for isotropic expansion

Bietenholz et al, in prep
ULIRGS: Supernova Factories

- Arp 220 (Parra, Lonsdale, Conway) SN rate 4±2/yr
  - different IMF for ULIRGs?
- Arp 229 (Neff, Ulvestad & Teng) – LIRG; original starburst; 41 Mpc; several optical supernovae;
  - VLBI sources probably SNe/SNR: 100 to 1000×Cas A
  - Supernova rate of 0.1 – 1/yr

See also poster by Romero-Cañizales: EVN-Merlin observations of IRAS 23365+3604
Supernovae in Arp 220

False colour: MERLIN 1.4GHz
Spots: Global VLBI 1.6GHz contours of supernovae
Radio Supernovae in M82

• Over 50 compact sources discovered in M82, most are supernovae/supernova remnants

• Rob Beswick will tell you more!
Comparison of RSNe & SNRs

CAS A

SN 1993J

41.95+575

43.31+592

McDonald et al., 2001
The Future of Supernova VLBI

• More sensitivity – follow supernova for longer
• Resolve older, more distant supernovae: Cas A is 1 μJy and 6 mas at 170 Mpc
• Fill in the gap between supernovae and supernova remnants
• Census of supernova remnants of nearby galaxies
• Supernova rates $\rightarrow$ star formation rates
• Type Ia?