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VLBI of supernovae and gamma-ray bursts

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I discuss Very Long Baseline Inteferometry (VLBI) observations of supernovae (SNe) and gamma-ray bursts (GRBs). Such observations allow us to place a direct observational constraint on the size of the emission region, and thus on the speed of the ejected material and the forward shock. In a small number of well-resolved cases, the morphology can also be determined. I show well-resolved images of SN 1993J, SN 1986J and two SNe for which VLBI images could recently be obtained, SN 1996cr and SN 2011dh. Most resolved SNe seem to have shell structure indicating interaction of the ejecta with the circumstellar medium, and VLBI observations can provide an important observational window on this interaction. VLBI observations of GRB 030329 showed that the expansion was superluminal and therefore confirmed the fireball model. VLBI observations can also be important in resolving GRB events where the jet is near the plane of the sky (orphan afterglows), although to date no conclusive determination or relativistic ejection in such an object has occurred.

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Supernovae (SNe) and Gamma-ray bursts (GRBs) involve explosive ejection of material moving at speeds ranging from several thousand km s^{-1} to near c. It would obviously be desirable to image this ejected material to study the explosive process and its aftermath. However, in the last millennium, only about a dozen SNe and no GRBs have been recorded in our Galaxy, so we must turn to extragalactic events. At distances beyond the Magellanic clouds, Very Long Baseline Interferometry (VLBI) observations are the only way of attaining the required resolution: at a typical frequency of 5 to 10 GHz global VLBI observations give an angular resolution of order of 1 mas, which corresponds to a linear size of $\sim$1 light-month at 5 Mpc and $\sim$1.6 light-years at a distance of 100 Mpc.

In this review I restrict myself to core-collapse SNe (those of Type Ib, Ic or II), and long GRBs (with durations $\gtrsim$ 2 sec), both of which involve an explosive ejection of material associated with a core-collapse event in a massive star. I do not discuss Type Ia SNe or short GRBs, neither of which are associated with massive-star core collapses, and neither of which have been detected with VLBI. As the ejecta produced in these events expand, they interact with the surrounding material, giving rise to a forward shock and a reverse shock driven back into the ejecta. These shocks, and associated instabilities, can both amplify the magnetic field and accelerate the particles, which are the ingredients necessary for synchrotron emission. The surrounding medium could be either the circumstellar medium (CSM) around the progenitor star, formed from the stellar wind emitted by the star before the explosion, or the interstellar medium (ISM).

The brightness of the radio emission depends on the density of the surrounding medium as well as on the dynamics of the shock. Generally, it is only cases with relatively dense CSM (or ISM) that produce sufficient radio emission to be detectable with current technology. Almost all SNe are first discovered in the optical rather than in the radio, and almost all GRBs are first detected in the gamma-ray, with only a fraction of either having detectable radio emission. Global VLBI at e.g. 5 GHz wavelengths can resolve a non-relativistic young SN shell out to distances of 10 to 20 Mpc, whereas relativistic SNe or GRBs can be resolved out considerably farther. So far, approximately 19 SNe have been detected with VLBI (see [1] for a tabulation of those observed up to 2008; see [2] for a recent review specific to Type I b/c SNe). Only a few have been sufficiently close and radio-bright to allow well-resolved imaging since shortly after the supernova explosion: SN 2011dh (M51; $\sim$8 Mpc; e.g. [3]), SN 2008iz (M82, $\sim$4 Mpc, [4]), SN 1996cr in the Circinus galaxy, SN 1993J (M81, $\sim$4 Mpc), SN 1986J (NGC 891, $\sim$10 Mpc), SN 1979C (M100, $\sim$16 Mpc, e.g. [5]), and of course SN 1987A (LMC; $\sim$50 kpc, e.g. [6]) which was close enough to image using connected-element interferometry, although it was also observed using VLBI. There are also well-resolved VLBI images of several SNe in M82 which were not optically detected which are likely a few decades old. GRBs, on the other hand, are considerably rarer than SNe, and only one relatively nearby one, GRB 030329 ($z = 0.1685$), has been imaged with VLBI.

The VLBI images of expanding SNe or GRBs that have so far been obtained provide a fascinating picture of the interaction of the ejecta with the surrounding CSM or ISM. In addition to studying the actual ejection event, the shock provides a probe of the CSM or ISM, allowing us to study for example the wind history of a supernova progenitor over the period before the explosion.

Finally, in star-forming regions in distant galaxies, which are typically highly obscured in the optical, VLBI studies of SNe are an important tool for measuring the SN rate, and thus the star formation rate.

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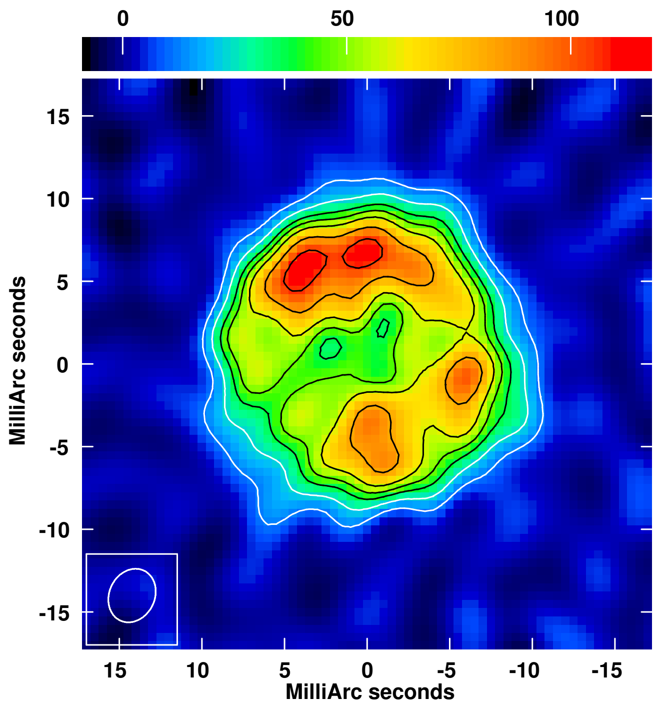

Figure 1: VLBI image of SN 1993J at 1.7 GHz, taken on 2010 March 5-6, at $t = 16.9$ yr after the explosion, using a global array of telescopes. Contours are at 10, 20, 30, 40, 50, 70 and 90% of the peak brightness of 117 μJy bm^{-1}, and the rms background brightness was 3.7 μJy bm^{-1}. The FWHM of the convolving beam is indicated at lower left. North is up and east to the left.

1. SN 1993J

SN 1993J remains the supernova that is the best studied with VLBI. It reached a peak flux density of $\sim$100 mJy (8.4 GHz) making it one of the radio-brightest SNe ever seen. VLBI observations were obtained after only one month, and continue to the present. The VLBI images show a remarkably circular shell morphology (see [7, 8, 9] and references therein). The angular expansion velocity could be accurately measured, and SN 1993J is the first case in which a changing deceleration rate could be directly measured [10, 11]. A direct distance to SN 1993J of 3.96 ± 0.29 Mpc, slightly larger than the commonly used Cepheid distance (3.6 ± 0.3 [12]), was determined using the “expanding shock front” method [13]. We show a recent VLBI image of SN 1993J in Figure 1. At early times, there are clear, time-dependent modulations around the ridge of the shell, by at least a factor of two in brightness [8]. Such modulations likely persist till late times, but the low signal-to-noise ratio does not allow conclusive determination of the degree of modulation.

2. SN 1986J

SN 1986J is one of the few SNe first discovered in the radio, probably about 3 years after the explosion. An early VLBI image of it marked the first time that shell-like structure was seen in an IAU-designated supernova [14]. Its structure is rather more distorted than the text-book shell of SN 1993J, as can be seen in the image in Figure 2. However, despite the distortions, the outline remains roughly circular, suggesting that the expansion is relatively symmetric, rather than, for example, being bipolar. SN 1986J also unique in that it has a central component, which has a notably different radio spectrum than the shell, as can clearly be seen in the dual-frequency image in Figure 2 [15]. The nature of this component has not been conclusively established, however

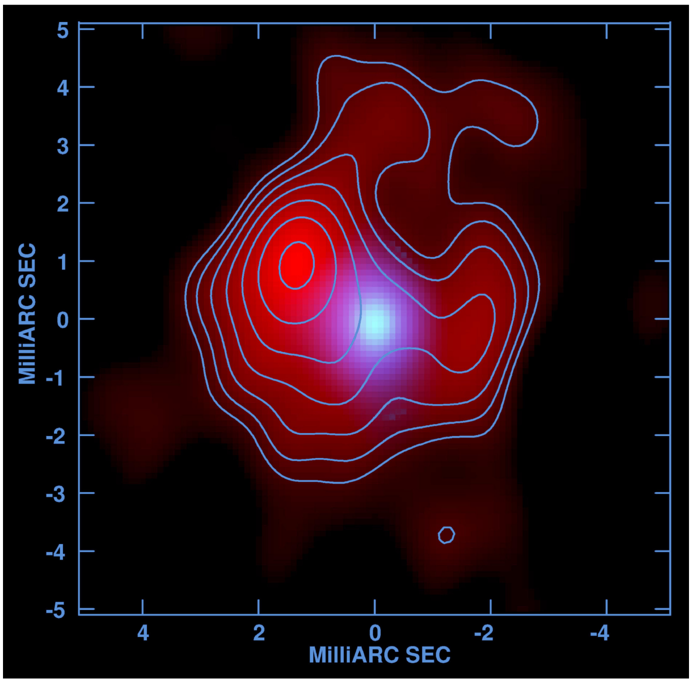

Figure 2: A phase-referenced dual-frequency VLBI image of SN 1986J from data taken 2002 to 2003, showing the compact, inverted-spectrum component located almost precisely in the projected centre of the expanding shell. The red colour and the contours represent the 5 GHz radio brightness, showing the shell emission. The contours are drawn at 11.3, 16, 22.6, . . . , 90.5% of the peak 5 GHz brightness of 0.55 mJy bm^{-1}. The blue through white colours show the 15 GHz radio brightness distribution, which is dominated by the compact, central component which appeared around 1999. North is up and east to the left. For details see [15].

an obvious possibility would be that it is emission associated with the compact remnant of the explosion, which in the case of SN 1986J could be either a black hole or a neutron star [16].

3. SN 1996cr

SN 1996cr, in the Circinus galaxy (∼4 Mpc), was first detected in the radio and X-ray about a decade after the explosion [17]. Its behaviour is reminiscent of SN 1987A in that it showed a marked increase in both radio and X-ray luminosity some years after the explosion. It was fairly radio bright, but due to its southern declination and a resolved calibrator source, VLBI imaging has been difficult. We show a VLBI image of SN 1996cr in Figure 3. The average expansion speed since the explosion could be determined to be ∼9000 km s^{-1} (Bietenholz et al., in preparation).

4. SN 2011dh

SN 2011dh occurred in the nearby galaxy M51 (∼8 Mpc). Radio emission was detected within 4 days of shock breakout [18]. SN 2011dh is unusual in that a yellow supergiant, which has now disappeared from the Hubble Space Telescope (HST) images, was identified as the progenitor, [19]. Recently, the progenitor's blue binary companion star has also been identified [20]. We show a recent VLBI image of SN 2011dh in Figure 3 [21].

5. Other Supernovae observed with VLBI

A total of about a dozen more SNe have been observed with VLBI, including SN 1987A [22, 23], SN 2001em (more below), SN 2001gd [24], SN 2004et [25], and SN 2007gr [26]. Most of them were only marginally resolved. SN 1987A however is close enough that its structure

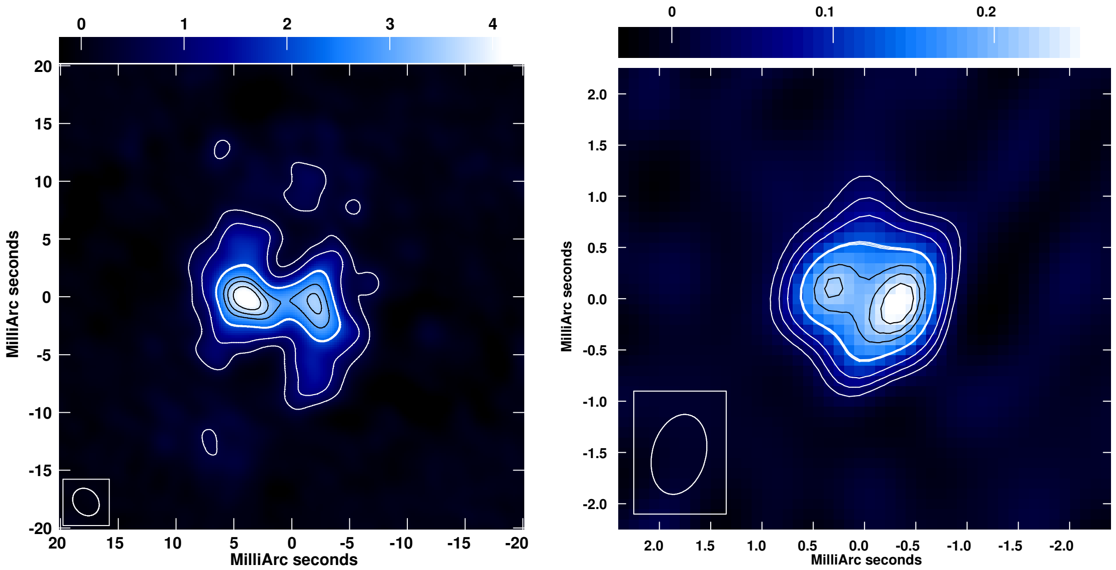

Figure 3: In each panel, both the colour scale and the contours show the brightness, the colour-scale is labelled in mJy bm^{-1}, and the contours are drawn at -12, 12, 20, 30, 40, 50 (emphasized), 70 and 90% of the peak brightness. North is up and east is to the left, and the FWHM CLEAN beam is indicated at lower left. **Left:** An 8.4-GHz VLBI image of SN 1996cr at age ∼18 yr on 2014 Aug 17, from observations with the Australian Long Baseline Array. The image rms was 0.1 mJy bm^{-1}. **Right:** An 8.4-GHz VLBI image of SN 2011dh at age 453 days on 2012 Aug 26, from observations made with the NRAO Very Long Baseline Array, and the Effelsberg and the Green Bank telescopes. The image rms was 12μJy bm^{-1}. A fuller discussion of these observations and results is in preparation (de Witt et al).

could be resolved in radio, optical and X-rays (e.g. [27]), and it has a shell structure at all three wavelengths, although the HST images show it to be very complex.

Wide-field VLBI observations of distant star-forming galaxies provide an important complement to VLBI studies of individual SNe. Such observations of several star-forming galaxies have detected a number of radio-emitting (but optically obscured) SNe or SN remnants in M82 [28] and other galaxies. Such observations provide an important constraint on the core-collapse SN-rate, and hence on the star formation rate. For example in the case of the starburst galaxy Arp 299 the rate of radio SNe has been determined to be ∼0.4 per year [29, 30], while in Arp 220 a rate of 4 ± 2 was obtained [31] (however, there is recent evidence that a number of the sources are not in fact SNe, implying a lower supernova rate [32]).

6. SNe and GRBs: Relativistic Ejecta?

Long-duration gamma-ray bursts (GRBs) are associated with Type I b/c SNe. GRB 030329 was associated with SN 2003dh and is the single GRB which was sufficiently near and radio bright for VLBI observations. These observations clearly showed superluminal expansion with apparent speed of $\sim 8c$ in the first 25 days, and slowing at later times. These observations provided the most compelling observational evidence for a relativistic outflow and the fireball model [33, 34].

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As GRBs are thought to be highly beamed, events which are observed off-axis should be at least 10$\times$ more common than the ones seen as GRBs. The prospect of resolving the jet of an off-axis GRB event (or orphan afterglow) associated with a Type I b/c SN is therefore a tantalizing possibility. However, this prospect has so far remained elusive: no emission clearly associated with an off-axis burst has yet been identified. Although fairly strong afterglow emission was generally expected from such jets, particularly in the radio, it was recently shown that the range in possible radio brightness is quite large, and that only a fraction of such off-axis jets may be radio-bright [35]. Several candidate Type I b/c SNe have been observed with VLBI (see review in [2]). However, in most cases, such as that of SN 2003gk [35], instead of confirming a relativistic jet, the VLBI observations in fact ruled out relativistic expansion, so only a small fraction of Type I b/c SNe produce relativistic ejecta. So far, the best evidence for relativistic ejection was in SN 2009bb, although the VLBI observations could only provide a 3σ upper limit of 1.74c on the shock velocity [36]. Nonetheless, VLBI imaging of future candidates is crucial as it will provide the most definitive test of the presence and morphology of relativistic ejecta.

7. Summary and Conclusions

VLBI imaging has proved invaluable in the study of young SNe and GRBs. The direct measurement of superluminal expansion in GRB 030329 conclusively confirmed relativistic ejection and the fireball model. In the case of SNe, the determination of the expansion speed and deceleration have provided important constraints on the mass-loss history of the star. VLBI imaging has also allowed us to determine the morphology of the expanding shell of ejecta in a number of SNe, and so far all SNe which have been imaged with sufficient resolution show an edge brightened structure which is roughly circular in outline[1], which is in fact the expected morphology of an optically thin spherical shell of emission. This suggests that the maximum velocity of the SN ejecta is relatively isotropic, in other words the explosions tend not to be one-sided or bipolar. However, all the resolved SNe also show significant asymmetries in the brightness, with one-sided and bipolar and possibly more complex brightness enhancements of the basic shell structure. This finding implies that significant density anisotropies, either in the CSM or the ejecta, or both, are a common feature. Since SNe which are near and radio-bright enough to be observable with VLBI are not common, it will be important to continue to observe any which occur in the future.

References

[1] N. Bartel, *Supernova VLBI*, in *Approaching Micro-Arcsecond Resolution with VSOP-2: Astrophysics and Technologies* (Y. Hagiwara, E. Fomalont, M. Tsuboi, and M. Yasuhiro, eds.), vol. 402 of *Astronomical Society of the Pacific Conference Series*, p. 243, Aug., 2009.

[2] M. F. Bietenholz, *VLBI Constraints on Type I b/c Supernovae*, *PASA* **31** (Jan., 2014) 2, [arXiv:1310.6567].

[3] M. F. Bietenholz, A. Brunthaler, A. M. Soderberg, M. Krauss, B. Zauderer, N. Bartel, L. Chomiuk, and M. P. Rupen, *VLBI Observations of the Nearby Type IIb Supernova 2011dh*, *ApJ* **751** (June, 2012) 125, [arXiv:1201.0771].

[1] A possible exception is [MPW94] 41.95+57.5 in M82, although it is not clear that this object is in fact a SN/SN remnant [37].

[4] A. Brunthaler, et al., *VLBI observations of SN 2008iz. I. Expansion velocity and limits on anisotropic expansion*, *Astron. Astrophys.* **516** (June, 2010) A27, [arXiv:1003.4665].

[5] N. Bartel and M. F. Bietenholz, *Shell Revealed in SN 1979C*, *ApJ* **682** (Aug., 2008) 1065–1069, [arXiv:0806.3482].

[6] C.-Y. Ng, G. Zanardo, T. M. Potter, L. Staveley-Smith, B. M. Gaensler, R. N. Manchester, and A. K. Tzioumis, *Evolution of the Radio Remnant of Supernova 1987A: Morphological Changes from Day 7000*, *ApJ* **777** (Nov., 2013) 131, [arXiv:1310.3913].

[7] M. Bietenholz, N. Bartel, M. P. Rupen, V. V. Dwarkadas, A. J. Beasley, D. A. Graham, T. Venturu, G. Umana, W. Cannon, and J. Conway, *Radio Imaging of SN1993J: The Story Continues*, in *10th European VLBI Network Symposium and EVN Users Meeting: VLBI and the New Generation of Radio Arrays*, 2010. arXiv:1103.1783.

[8] M. F. Bietenholz, N. Bartel, and M. P. Rupen, *SN 1993J VLBI. III. The Evolution of the Radio Shell*, *ApJ* **597** (Nov., 2003) 374–398, [astro-ph/].

[9] I. Martí-Vidal, J. M. Marcaide, A. Alberdi, J. C. Guirado, M. A. Pérez-Torres, and E. Ros, *Radio emission of SN1993J: the complete picture. II. Simultaneous fit of expansion and radio light curves*, *Astron. Astrophys.* **526** (Feb., 2011) A143, [arXiv:1007.1224].

[10] N. Bartel, M. F. Bietenholz, M. P. Rupen, A. J. Beasley, D. A. Graham, V. I. Altunin, T. Venturi, G. Umana, W. H. Cannon, and J. E. Conway, *SN 1993J VLBI. II. Related Changes of the Deceleration, Flux Density Decay, and Spectrum*, *ApJ* **581** (Dec., 2002) 404–426.

[11] J. M. Marcaide, et al., *How is really decelerating the expansion of SN1993J?*, in *Proceedings of the 6th EVN Symposium*, p. 239, June, 2002.

[12] J. R. Gerke, C. S. Kochanek, J. L. Prieto, K. Z. Stanek, and L. M. Macri, *A Study of Cepheids in M81 with the Large Binocular Telescope (Efficiently Calibrated with Hubble Space Telescope)*, *ApJ* **743** (Dec., 2011) 176, [arXiv:1103.0549].

[13] N. Bartel, M. F. Bietenholz, M. P. Rupen, and V. V. Dwarkadas, *SN 1993J VLBI. IV. A Geometric Distance to M81 with the Expanding Shock Front Method*, *ApJ* **668** (Oct., 2007) 924–940, [arXiv:0707.0881].

[14] N. Bartel, M. P. Rupen, I. I. Shapiro, R. A. Preston, and A. Rius, *A high-resolution radio image of a young supernova*, *Nat* **350** (Mar., 1991) 212–214.

[15] M. F. Bietenholz, N. Bartel, and M. P. Rupen, *Discovery of a Compact Radio Component in the Center of Supernova 1986J*, *Science* **304** (June, 2004) 1947–1949.

[16] M. F. Bietenholz, N. Bartel, and M. P. Rupen, *Supernova 1986J Very Long Baseline Interferometry. II. The Evolution of the Shell and the Central Source*, *ApJ* **712** (Apr., 2010) 1057–1069.

[17] F. E. Bauer, V. V. Dwarkadas, W. N. Brandt, S. Immler, S. Smartt, N. Bartel, and M. F. Bietenholz, *Supernova 1996cr: SN 1987A's Wild Cousin?*, *ApJ* **688** (Dec., 2008) 1210–1234, [arXiv:0804.3597].

[18] A. M. Soderberg, et al., *Panchromatic Observations of SN 2011dh Point to a Compact Progenitor Star*, *ApJ* **752** (June, 2012) 78, [arXiv:1107.1876].

[19] S. D. Van Dyk, W. Zheng, K. I. Clubb, A. V. Filippenko, S. B. Cenko, N. Smith, O. D. Fox, P. L. Kelly, I. Shivvers, and M. Ganeshalingam, *The Progenitor of Supernova 2011dh has Vanished*, *ApJL* **772** (Aug., 2013) L32, [arXiv:1305.3436].

[20] G. Folatelli, M. C. Bersten, O. G. Benvenuto, S. D. Van Dyk, H. Kuncarayakti, K. Maeda, T. Nozawa, K. Nomoto, M. Hamuy, and R. M. Quimby, *A Blue Point Source at the Location of Supernova 2011dh*, *ApJL* **793** (Oct., 2014) L22, [arXiv:1409.0700].

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[21] A. de Witt, M. F. Bietenholz, A. Kamble, A. M. Soderberg, A. Brunthaler, B. Zauderer, N. Bartel, and M. P. Rupen, *Imaging the Expanding Shell of SN 2011dh*, *ArXiv e-prints* (Mar., 2015) [arXiv:1503.0083].

[22] D. L. Jauncey, A. Kemball, N. Bartel, I. I. Shapiro, A. R. Whitney, A. E. E. Rogers, R. A. Preston, and T. A. Clark, *Supernova 1987A - A radiosphere resolved with VLBI five days after the neutrino burst*, *Nat* **334** (Aug., 1988) 412–415.

[23] C.-Y. Ng, T. M. Potter, L. Staveley-Smith, S. Tingay, B. M. Gaensler, C. Phillips, A. K. Tzioumis, and G. Zanardo, *First VLBI Detection of the Radio Remnant of Supernova 1987A: Evidence for Small-scale Features*, *ApJL* **728** (Feb., 2011) L15, [arXiv:1012.5092].

[24] M. A. Pérez-Torres, A. Alberdi, J. M. Marcaide, M. A. Guerrero, P. Lundqvist, I. I. Shapiro, E. Ros, L. Lara, J. C. Guirado, K. W. Weiler, and C. J. Stockdale, *High-resolution observations of SN 2001gd in NGC 5033*, *MNRAS* **360** (July, 2005) 1055–1062, [astro-ph/0504647].

[25] I. Martí-Vidal, *8.4 GHz VLBI observations of SN 2004et in NGC 6946*, *Astron. Astrophys.* **470** (Aug., 2007) 1071–1077, [0705.3853].

[26] Z. Paragi, C. Kouveliotou, M. A. Garrett, E. Ramirez-Ruiz, H. J. van Langevelde, A. Szomoru, and M. Argo, *e-VLBI detection of SN2007gr*, *The Astronomer's Telegram* **1215** (Sept., 2007) 1.

[27] B. M. Gaensler, L. Staveley-Smith, R. N. Manchester, M. J. Kesteven, L. Ball, and A. K. Tzioumis, *Fifteen Years of High-Resolution Radio Imaging of Supernova 1987A*, in *American Institute of Physics Conference Series* (S. Immler and R. McCray, eds.), vol. 937 of *American Institute of Physics Conference Series*, pp. 86–95, Oct., 2007. astro-ph/.

[28] D. Fenech, R. Beswick, T. W. B. Muxlow, A. Pedlar, and M. K. Argo, *Wide-field Global VLBI and MERLIN combined monitoring of supernova remnants in M82*, *MNRAS* (Aug., 2010) 1141, [arXiv:1006.1504].

[29] C. Romero-Cañizales, S. Mattila, A. Alberdi, M. A. Pérez-Torres, E. Kankare, and S. D. Ryder, *The core-collapse supernova rate in Arp 299 revisited*, *MNRAS* **415** (Aug., 2011) 2688–2698, [arXiv:1104.1955].

[30] M. Bondi, M. A. Pérez-Torres, R. Herrero-Illana, and A. Alberdi, *The nuclear starburst in Arp 299-A: from the 5.0 GHz VLBI radio light-curves to its core-collapse supernova rate*, *Astron. Astrophys.* **539** (Mar., 2012) A134, [arXiv:1201.3220].

[31] R. Parra, J. E. Conway, P. J. Diamond, H. Thrall, C. J. Lonsdale, C. J. Lonsdale, and H. E. Smith, *The Radio Spectra of the Compact Sources in Arp 220: A Mixed Population of Supernovae and Supernova Remnants*, *ApJ* **659** (Apr., 2007) 314–330, [astro-ph/].

[32] F. Batejat, J. E. Conway, A. Rushton, R. Parra, P. J. Diamond, C. J. Lonsdale, and C. J. Lonsdale, *Rapid variability of the compact radio sources in Arp220. Evidence for a population of microblazars?*, *Astron. Astrophys.* **542** (June, 2012) L24, [arXiv:1205.3173].

[33] G. B. Taylor, D. A. Frail, E. Berger, and S. R. Kulkarni, *The Angular Size and Proper Motion of the Afterglow of GRB 030329*, *ApJL* **609** (July, 2004) L1–L4.

[34] Y. M. Pihlström, G. B. Taylor, J. Granot, and S. Doeleman, *Stirring the Embers: High-Sensitivity VLBI Observations of GRB 030329*, *ApJ* **664** (July, 2007) 411–415, [0704.2085].

[35] M. F. Bietenholz, F. De Colle, J. Granot, N. Bartel, and A. M. Soderberg, *Radio limits on off-axis GRB afterglows and VLBI observations of SN 2003gk*, *MNRAS* **440** (May, 2014) 821–832, [arXiv:1310.7171].

[36] M. F. Bietenholz, A. M. Soderberg, N. Bartel, S. P. Ellingsen, S. Horiuchi, C. J. Phillips, A. K. Tzioumis, M. H. Wieringa, and N. N. Chugai, *VLBI Observations of the Type I b/c Supernova 2009bb*, *ApJ* **725** (Dec., 2010) 4–10.

[37] T. W. B. Muxlow, A. Pedlar, R. J. Beswick, M. K. Argo, T. J. O'Brien, D. Fenech, and W. Trotman, *Is 41.95+575 in M82 actually an SNR?*, *Memorie della Societa Astronomica Italiana* **76** (2005) 586.

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