

23 GHz VLBI observations of SN 2008ax (Research Note)

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ABSTRACT

We report on phase-referenced 23 GHz Very-Long-Baseline-Interferometry (VLBI) observations of the type IIb supernova SN 2008ax, made with the Very Long Baseline Array (VLBA) on 2 April 2008 (33 days after explosion). These observations resulted in a marginal detection of the supernova. The total flux density recovered from our VLBI image is 0.8 ± 0.3 mJy (one standard deviation). As it appears, the structure may be interpreted as either a core-jet or a double source. However, the supernova structure could be somewhat confused with a possible close by noise peak. In such a case, the recovered flux density would decrease to 0.48 ± 0.12 mJy, compatible with the flux densities measured with the VLA at epochs close in time to our VLBI observations. The lowest average expansion velocities derived from our observations are $(1.90 \pm 0.30) \times 10^5$ km s⁻¹ (case of a double source) and $(5.2 \pm 1.3) \times 10^4$ km s⁻¹ (taking the weaker source component as a spurious, close by, noise peak, which is the more likely interpretation). These velocities are 7.3 and 2 times higher, respectively, than the maximum ejecta velocity inferred from optical-line observations.

Key words. galaxies: individual: NGC 4490 – radio continuum: stars – supernovae: individual: SN 2008ax – supernovae: general

1. Introduction

Supernova SN 2008ax was discovered in galaxy NGC 4490 on 3 March 2008 (Mostardi et al. 2008) at the position $\alpha = 12^{\text{h}}30^{\text{m}}40.799^{\text{s}}$ and $\delta = 41^{\circ}38'14.825''$. The host galaxy is ~ 8 Mpc distant (de Vaucouleurs 1976; we assume an uncertainty of 1 Mpc for the distance), and is dynamically interacting with NGC 4485 (forming the pair Arp 269). Likely as a consequence of this interaction, NGC 4490 has a relatively high star formation rate (Viallefond et al. 1980), which should result in a correspondingly high supernova rate.

We assume the discovery date of the supernova was the same as the explosion date, since 6 h before its discovery, the location of the supernova was imaged with a limiting magnitude of 18.3 and no emission was detected (Nakano 2008). Radio emission from SN 2008ax was monitored with the VLA beginning on 3 March 2008, shortly after its discovery (see

Stockdale et al. 2008a,b), with positive detections made at 4.9, 8.4, and 22.5 GHz, beginning on 7 March 2008. These detections were all in the millijansky range. The early part of the radio light curve of this supernova is qualitatively similar to that of SN 1993J. Since supernova SN 2008ax was also cataloged as type IIb (Chornock 2008), as was SN 1993J, there was evidence to believe that the radio emission of SN 2008ax would continue its evolution in a similar way to SN 1993J's. In such a case, the flux density of SN 2008ax should have risen well above the VLBI detectability limit near the end of March 2008.

On 11 March 2008, we proposed a target-of-opportunity set of global VLBI observations of SN 2008ax at 23 GHz, in order to detect the supernova radio structure and, possibly, its expansion. Only antennas of the VLBA were allocated and only on 2 April 2008. Unfortunately, the flux density started to drop faster than expected by that time, resulting in a marginal detection of

the supernova. In the next section we describe the details of our VLBI observations, and in Sect. 3 we present our results and conclusions.

2. Observations and data reduction

We observed supernova 2008ax on 2 April 2008, with the VLBA (10 identical 25 m diameter antennas spread over the USA from the Virgin Islands to Hawaii). The recording rate was set to 256 Mbps, with 2-bit sampling and single polarization mode (LCP), covering a total bandwidth of 64 MHz (8 baseband channels, of 8 MHz width each). Our observations were cross-correlated at the Array Operations Center of the National Radio Astronomy Observatory (NRAO) in Socorro (New Mexico, USA), using an averaging time of 2 s.

The observations of SN 2008ax were made in phase-reference mode. Each scan of the supernova was of ~ 2 min duration, and short observations (~ 40 s) of strong, close by sources were interleaved between these scans of the supernova. Since the 23 GHz flux densities of these close by radio sources were unknown at the time of the observations, we chose the two closest, which were also the strongest at 15 GHz. Each pass of the recording tapes (22 min long) was then assigned to one of these two calibrators in an alternating scheme. The 12-h long set of observations could, thus, be divided into two sets of roughly equal size. In the first one, we observed the supernova using the source J1224+4335 as the phase calibrator (located 2.23 degrees from the supernova) and in the second one we used the source J1225+3914 as the phase calibrator (located 2.57 degrees from the supernova).

After the cross correlation, the data were imported into the NRAO Astronomical Image Processing System (AIPS) for calibration. We performed the amplitude calibration using gain curves and system temperatures measured at all antennas. We then used in the scans of the supernova the time-interpolated antenna gains obtained from hybrid mapping of the calibrators. The phase calibration (with account taken of the structures of the calibrators) was performed with standard phase-reference calibration techniques. The data were then exported for further reduction in DIFMAP (Shepherd et al. 1995).

3. Results and conclusions

The flux density of the calibrator source J1224+4335, obtained from hybrid mapping, is 198 ± 1 mJy and the flux density of the other calibrator source, J1225+3914, obtained with the same procedure, is 122 ± 1 mJy. Uncertainties are 3 times the root-mean-square, rms, of the hybrid-map residuals (see Readhead & Wilkinson 1978). There is no clear detection of SN 2008ax in any of the phase-referenced images obtained using both calibrators. There is not even a clear flux density peak in the images obtained from the totality of supernova visibilities (i.e., dynamic range above ~ 6), regardless of the sky coverage of the image or the weighting scheme applied in Fourier space. However, when the phase-reference calibrator J1224+4335 (i.e., the strongest and closest calibrator) is used, there is a possible detection of the supernova. The detection arises from applying a visibility weighting in Fourier space with the weight of a pixel proportional to the square of the signal-to-noise ratio (SNR) of the visibilities inside that pixel (i.e., we increase the array sensitivity in the Fourier inversion). We additionally taper the visibilities using a Gaussian, centered at the origin of the uv-plane, with a Full Width at Half Maximum (FWHM) of $500 M\lambda$. The image

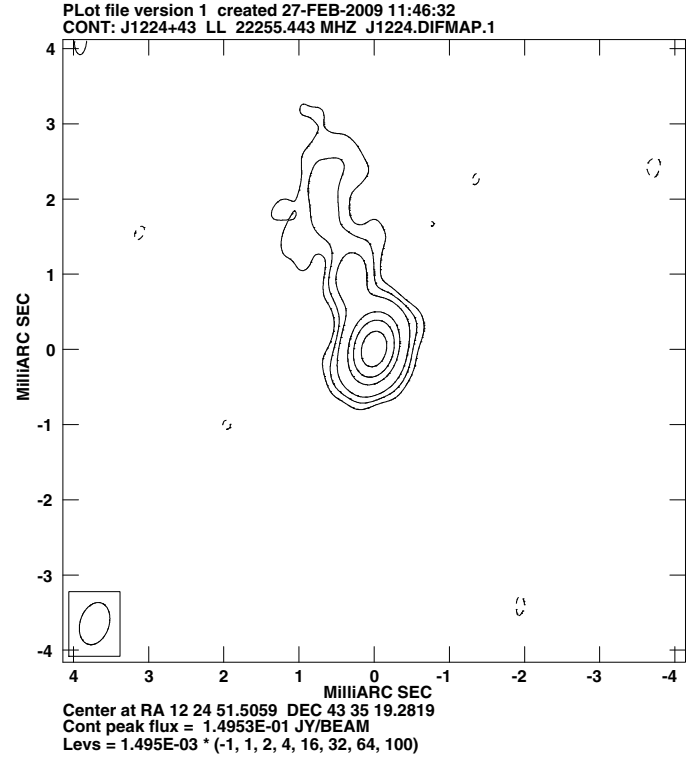


Fig. 1. Hybrid image of source J1224+4335 obtained from our observations. The FWHM of the convolving CLEAN beam is shown at the bottom-left corner.

obtained with such a visibility weighting has a peak flux density located at 0.08 mas to the West and 9.2 mas to the South of the position used at the correlator, which was taken from X-band VLA observations made on 8 March 2009. Therefore, the peak flux density detected is located at $\alpha = 12^{\text{h}}30^{\text{m}}40.79899^{\text{s}}$ and $\delta = 41^{\circ}38'14.81580''$, with an uncertainty of 0.05 mas, which is the size of the interferometric beam divided by 2 times the dynamic range of the image (Thomson et al. 1986). Since this position is based on a phase-reference to J1224+4335 at 23 GHz, we notice that opacity effects in the jet of this source (see Fig. 1) could introduce a systematic shift of several mas in the supernova position (the correlation position of J1224+4335 was taken from the VLBA Calibrator Survey at 8.4 GHz; see Beasley et al. 2002). Decreasing the FWHM of the Gaussian taper, or weighting each pixel with a higher power of the visibility SNR, results in a slightly better detection of the supernova but, due to the large decrease in resolution, at the price of a detailed detection of radio structure.

After performing a CLEAN deconvolution in the region of the flux density peak, we obtain the image shown in Fig. 2. The rms of the residuals is $0.087 \text{ mJy beam}^{-1}$ and the peak flux density is $0.395 \text{ mJy beam}^{-1}$, so the dynamic range of the image is 4.7. The total flux density obtained after a deconvolution using the CLEAN algorithm is 0.8 mJy. Remarkably, the flux density recovered from our VLBI image is a factor ~ 1.7 larger than the flux densities registered with the VLA by Stockdale et al. (2008b) at epochs close in time to the epoch of our observations (0.48 ± 0.12 mJy on April 1, and 0.45 ± 0.10 mJy on April 3). This large discrepancy indicates that the source structure shown in Fig. 2 may be a chance superposition of a marginal detection (North) and a prominent noise peak (South), as we explain below. The integrated flux density of each of the noise peaks of the residual image in a 40×40 mas square around the source is less

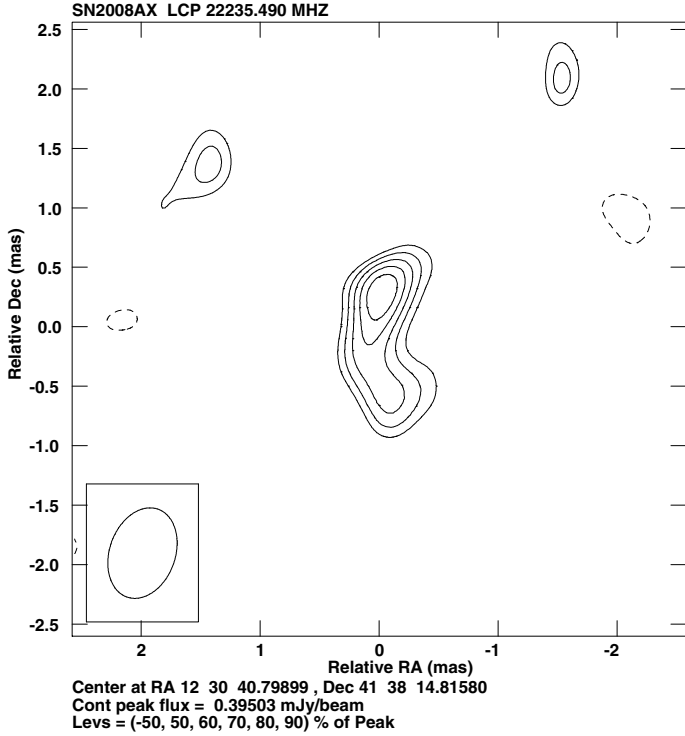


Fig. 2. CLEAN phase-referenced image of SN 2008ax (see text). The FWHM of the convolving beam is shown at the bottom-left corner.

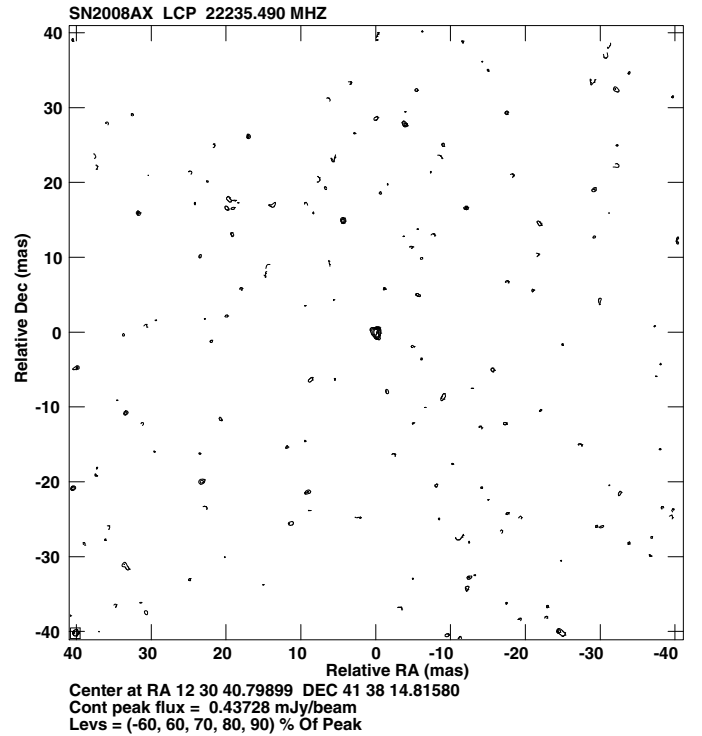


Fig. 3. Dirty image of SN 2008ax with a sky coverage of 40×40 mas. Due to the limitations of the FFT algorithm, around 10% of the visibilities (which correspond to the longest baselines) had to be removed in the Fourier inversion for obtaining this wide-field image.

than 0.4 mJy (i.e., less than 50% of the integrated flux density of the source). We show this wide-field image in Fig. 3.

If the structure shown in Fig. 2 is real, does it correspond to a core-jet or is it part of a shell? Or, as we suggest above, can this structure be a combination of a marginal detection (North) with a stronger noise peak (South) than elsewhere in the map? Difficult to say.

Case 1. Partial shell-like structure

For the radio structure part of a shell, we can compare its 50% contour level with that of a shell model convolved with the same beam. For a shell model with a fractional shell width of 0.3, which is the shell width found for SN 1993J by Marcaide et al. (2009), the outer radius of SN 2008ax would be 1.15 ± 0.15 mas (hereafter, all the uncertainties given are equal to the square root of the corresponding diagonal element of the covariance matrix, with the errors having been first uniformly scaled so that the reduced χ^2 is equal to 1). This size translates into an average expansion velocity of $(4.8 \pm 0.8) \times 10^5 \text{ km s}^{-1}$, which is superluminal. Indeed, we still obtain superluminal expansion velocities if we change the fractional shell width to different, unrealistic, values such as 0.1 (a narrower shell width translates into a smaller fitted shell size). Hence, it is unlikely that the radio structure is part of an expanding shell.

Case 2. Double source

If we instead fit the visibilities to two point sources, one to model the brightness peak (at the North) and the other one to model the source extension towards the South, we find components of 0.40 ± 0.11 and 0.24 ± 0.11 mJy, separated by 0.93 ± 0.10 mas. This result translates into an average relative velocity between components of $(3.90 \pm 0.62) \times 10^5 \text{ km s}^{-1}$, which is

superluminal. If the two components were moving in opposite directions with respect to the explosion center, the average expansion velocity of the radiostructure would be $(1.90 \pm 0.31) \times 10^5 \text{ km s}^{-1}$, a factor ~ 7.3 higher than the maximum ejecta velocity estimated from the optical-line emission of this supernova ($\sim 2.6 \times 10^4 \text{ km s}^{-1}$, Blondin 2008). This velocity is also much higher than the typical expansion velocities of the radiostructures of other supernovae ($\sim 1\text{--}2 \times 10^4 \text{ km s}^{-1}$). Hence, the two-point source model is also unlikely.

Case 3. Detection with a close by noise peak

Perhaps, then, we could consider that the structure shown in the map is due to a chance (near) superposition of a marginally detected radio source and a noise peak. In this case, the radio emission would not be resolved and its detection would be even more marginal. Fitting a shell model (with a fractional width of 0.3) to the northern flux density peak results in a source outer diameter of 0.25 ± 0.05 mas and a flux density of 0.48 ± 0.12 mJy. We notice that this flux density is consistent with the flux densities registered by Stockdale et al. (2008b) at the same radio frequency and at epochs enclosing that of our VLBI observations. The resulting average expansion velocity is $(5.2 \pm 1.3) \times 10^4 \text{ km s}^{-1}$, a factor of 2 larger than the velocity inferred from optical-line emission. This velocity is also ~ 3 times larger than the expansion velocities of the other radio supernovae that were observed with VLBI ($< 2.0 \times 10^4 \text{ km s}^{-1}$), and would imply (if we assume a non-decelerated expansion at least until the epoch of our observations) a fractional width of the shocked circumstellar region of ~ 0.5 . To obtain this estimate, we assume that the optical-line emission comes from a region close to the inner edge of the shocked ejecta (see Chevalier & Fransson 1994). This fractional

width is much larger than that found for SN 1993J and those predicted from different models of type II supernovae (Chevalier 1982). Considering a decelerated supernova expansion would result in even larger fractional-shell width estimates.

General remarks

In short, every model used in our analysis results in a supernova size much larger than expected from the optical-line velocities of this supernova and the expansion velocities found for all supernovae that could be imaged with VLBI. The lowest average expansion velocity compatible with our VLBI data is a factor of 2 larger than the velocity inferred from optical-line emission. However, despite the apparent significance of our measurements (4σ for the flux density and 5σ for the size), we have obtained only a marginal detection of SN 2008ax with our VLBI observations.

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References

- Beasley, A. J., Gordon, D., Peck, et al. 2002, *ApJ*, 141, 13
 Blondin, S., Filippenko, A. V., Foley, R. J., et al. 2008, *CBET*, 1285, 1
 Chevalier, R. A. 1982, *ApJ*, 258, 790
 Chevalier, R. A., & Fransson, C. 1994, *ApJ*, 420, 268
 Chornock, R., Filippenko, A. V., Li, W., et al. 2008, *CBET*, 1298, 1
 Marcaide, J. M., Martí-Vidal, I., Alberdi, A., et al. 2009, *ApJ*, submitted
 Mostardi, R., Li, W., & Filippenko, A. V. 2008, *CBET*, 1280, 1
 Nakano, S. 2008, *CBET*, 1286, 1
 Thomson, A. R., Moran, J. M., & Swenson, G. W. 1986, *Interferometry and Synthesis in Radio Astronomy* (New York: Wiley)
 Readhead, A. C. S., & Wilkinson, P. N. 1978, *ApJ*, 223, 25
 Shepherd M. C., Pearson T. J., & Taylor G. B. 1995, *BAAS*, 26, 987
 Stockdale, C. J., Weiler, K. W., Immler, S., et al. 2008a, *CBET*, 1299, 1
 Stockdale, C. J., Weiler, K. W., Immler, S., et al. 2008b, *ATEL*, 1439, 1
 de Vaucouleurs, G., de Vaucouleurs, A., & Corwin, J. R. 1976, *Second reference catalogue of bright galaxies* (Austin: University of Texas Press)
 Viallefond, F., Allen, R. J., & de Boer, J. A. 1980, *A&A*, 82, 207