PROCEEDINGS OF SCIENCE

Radio Imaging of SN 1993J: The Story Continues

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We present the most recent VLBI images of SN 1993J, taken at 1.7 GHz on 2010 March 5-6, along with a discussion of its evolution with time. The new image is the latest in a sequence covering almost the entire lifetime of the supernova. For these latest observations we used an "in beam calibrator" technique, and obtained a background rms brightness of 3.7 μJy bm^{-1}. The supernova shell remains quite circular in outline. Modulations in brightness are seen around the rim which evolve relatively slowly, having remained generally similar over the last several years of observation. We determine the outer radius of the supernova using visibility-plane model-fitting. The supernova has slowed down to around 30% of its original expansion velocity, and continues to expand with radius approximately $\propto t^{0.8}$, however, deviations from a strict power-law evolution are seen. We do not find any clear-cut evidence for systematically frequency-dependent evolution, suggesting that the radii as determined from visibility-plane model-fitting continue to provide reasonable estimates of the physical outer shock-front radius.

10th European VLBI Network Symposium and EVN Users Meeting: VLBI and the new generation of radio arrays
September 20-24, 2010
Manchester Uk

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1. Introduction

SN 1993J, in the nearby galaxy M81, was one of the nearest as well as one of the radio-brightest core-collapse supernovae observed in recent history [e.g., 1, 2, 3]. We undertook an extensive campaign of VLBI imaging (see [4] and references therein; note that a second, parallel campaign of VLBI observations was also undertaken, see [5] for the most recent results from this second campaign). One of the results of our VLBI campaign was in fact a direct, geometrical estimation of the distance to SN 1993J and M81 using the expanding shock front method, which resulted in a value of 3.96 ± 0.29 Mpc. This value is consistent with that obtained from Cepheid measurements by Huterer et al. [6], but $9 \pm 13\%$ larger than the more commonly cited value of Freedman et al. [7], (see [8] for a fuller discussion). In this paper, we briefly present some of the most recent developments in our continuing VLBI campaign.

Our latest VLBI image was obtained on 2010 March 5 - 6, using a global array of 18 telescopes from the European VLBI Network and the National Radio Astronomy Observatory. We observed at a frequency of 1.7 GHz, with a total time of 24 hours. As throughout our campaign, we used M81*, the active core of M81, as a phase reference source [9]. Since SN 1993J and M81 are only $3'$ apart and are within the same primary beam of all the telescopes[1] at 1.7 GHz, we performed the phase-referencing using an in-beam calibrator technique where the telescopes were pointed at a location between the two sources. The total CLEAN flux density recovered for SN 1993J was 1.7 mJy, while the rms background brightness was 3.7 μJy bm^{-1}. We show the image of SN 1993J in Figure 1. Although the dynamic range in the image was modest (peak/rms = 32), the main features of the image are quite consistent with those seen earlier and at other wavelengths. The outline of the emission region remains highly circular. Along the ridge line, we see a broad enhanced brightness just east of north, and a smaller one just south of west, characteristics which are already apparent in the images from 2001 and 2002 [4]. We defer a fuller discussion of the deviations from uniform emissivity around the ridge-line to a future paper. There is no central brightening, in contrast to what is seen in SN 1986J, where a prominent central brightening may mark the appearance of a young pulsar-wind nebula [10].

In addition to producing an image, we also determined precise values for the supernova's inner and outer angular radii, $\theta_{\rm in}$ and $\theta_{\rm out}$ respectively, by fitting an optically-thin spherical shell model[2] directly to the visibility measurements [see 11]. The Chevalier mini-shell model [12] for a supernova predicts that its radius should evolve with time in a power-law fashion, provided the densities in both the circumstellar medium (CSM) and the ejecta are also power-law functions of radius. In this model, the radius of the supernova's shock-front is $\propto t^m$, where t is time, and m is the power-law index. SN 1993J has indeed, over its history, shown an evolution quite close to such a canonical power-law (see, e.g., [11, 5]), with an average value of $m \sim 0.8$. However, the measurements of SN 1993J are of sufficient quality that relatively small deviations from a power-law, or changes in time of the value of m, can be determined. In particular, both changes in the lightcurve decay and in the expansion index show that the evolution of SN 1993J is not self-similar.

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[1] We did not use the data from the phased Westerbork array in these preliminary results, as the two sources are not within the synthesized beam of the phased array. We defer a fuller discussion of results including the Westerbork data to a future publication.

[2] The other free parameters in our model are the center position and the total flux density of the supernova

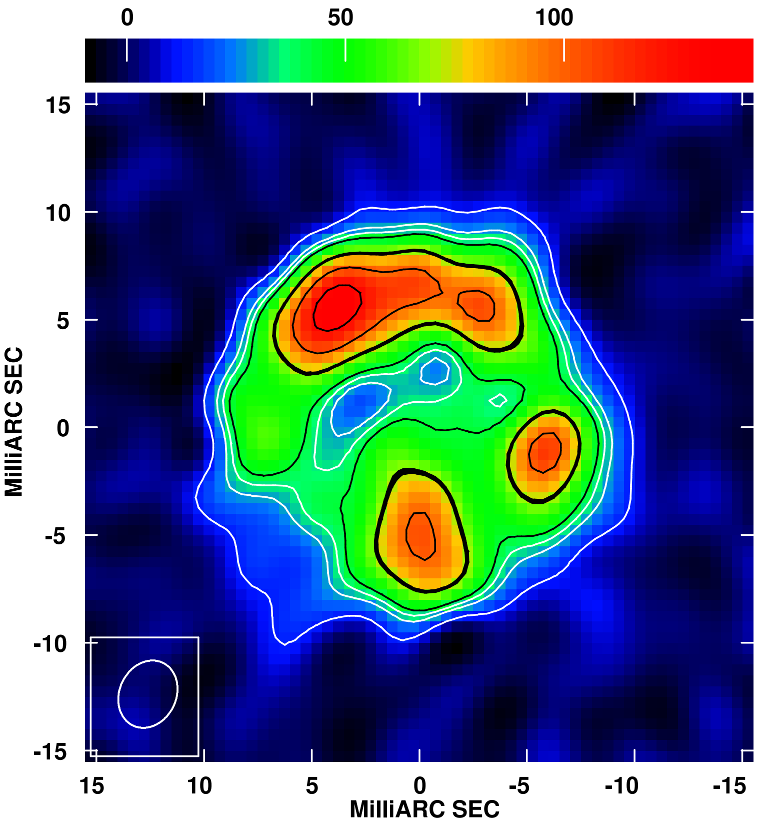

Figure 1: VLBI image of SN 1993J at 1.7 GHz, taken on 2010 March 5-6, or at $t = 16.9$ yr after the explosion. Contours are at 10, 20, 30, 40, 50, 70 and 90% of the peak brightness of 117 μJy bm^{-1}, and the rms background brightness was 3.7 μJy bm^{-1}. The FWHM of the convolving beam is indicated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

In Fig. 2 we compare the evolution of the outer angular radii of SN 1993J to a canonical power-law with $\theta \propto t^{0.8}$. The most clear break from a single power-law expansion curve is seen in at $t \simeq 1$ yr, after which a distinct increase in the deceleration occurs. Smaller changes in the slope of the power-law expansion occur at later times.

We note here that Marti-Vidal et al. [5] prefer determining the supernova angular radius in the image plane using a method they call the "Common Point Method" or CPM [13]. They re-reduced our earlier observations and determined radii at these epochs using CPM, which they claim produces results superior to those obtained from *u*-*v* plane model-fitting. We find however, that a comparison of CPM values determined by Marti-Vidal et al. for our observations with our originally published radii, determined by *u*-*v* plane fitting, with does not support this claim. Although the agreement between the CPM and our *u*-*v* plane radius values is generally good, our original values show significantly less scatter than those determined using CPM. In Fig. 3, we compare Marti-Vidal et al.'s determinations of the radius with our own for those epochs for which both determinations are available. Our original values show significantly lower scatter with respect to a smooth power-law evolution as well as having smaller uncertainties. We therefore continue to use *u*-*v* plane model-fitting as the method of choice for determining accurate values for the angular radius of SN 1993J as a function of time. We note also both *u*-*v* plane model-fitting and the CPM produce values of the radius that are model-dependent in the sense that they can only be precisely related to a physical radius by assuming some particular form for the brightness profile of the supernova.

The measured angular radii at different frequencies do not always agree within the experimen-

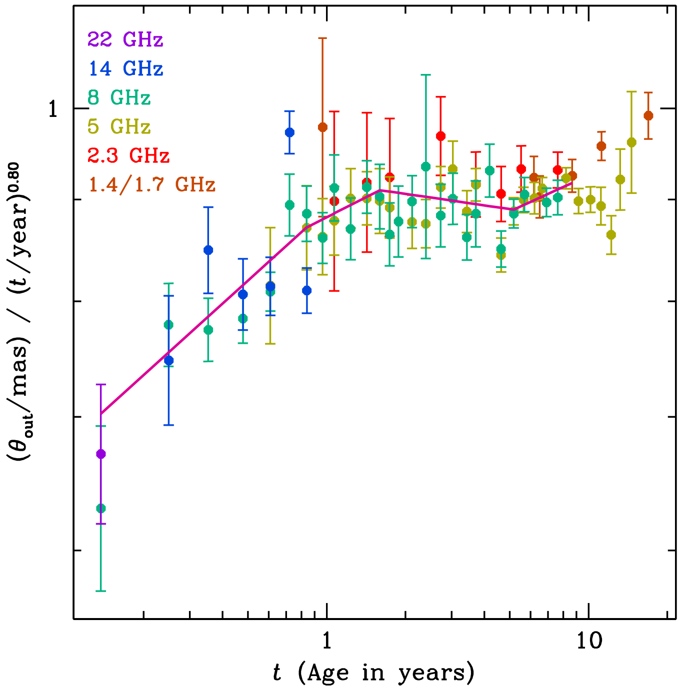

Figure 2: The scaled outer angular radius of SN 1993J as a function of time. The scaled angular radii are $\frac{\theta_{\rm out}/({\rm mas})}{(t/{\rm yr})^{0.8}}$. In other words we plot the deviation of the measured angular radii from a simple power-law expansion with $\theta \propto t^{0.8}$. This scaling of the measured radii highlights the observed deviations from a simple power-law expansion. The points show the measured outer radii along with their uncertainties, with different colours representing measurements at different frequencies. The purple broken line indicates the fit of Bartel et al., [11] to the measurements up to $t = 8$ yr. For $t < 2.7$ yr, a ratio of $\theta_{\rm out}/\theta_{\rm in} = 1.25$ was assumed, while for later times $\theta_{\rm in}$ was fit simultaneously with $\theta_{\rm out}$ [see 11, 8].

tal uncertainties, and we note a tendency for the radii determined from data at lower frequencies to be slightly larger than those from higher frequencies. Over the period between $t = 8$ yr and the last observations, the scaled radius at 1.7 GHz was, on average, 5.7% ± 5.2% larger than that at frequencies > 4 GHz. Our values, however, do not suggest any clearly systematic frequency-dependence in the evolution of the radius as claimed by other authors [5, 13]. We rather think that small time- and frequency-dependent deviations of the true brightness distribution from our geometrical model are likely responsible for the small variations of the fitted radii with frequency. Since our determinations show no clear frequency dependence, we think that the radii as determined by u-v plane model-fitting continue to provide a reasonable estimate of the outer shock front radius.

Our u-v plane model allows a simultaneous fit of $\theta_{\rm out}$ and $\theta_{\rm in}$ when the resolution is sufficient. For times later than 2.7 yr we therefore obtained separate estimates for $\theta_{\rm out}$ and $\theta_{\rm in}$, and can study the evolution of the supernova's shell thickness. We plot these values of $\theta_{\rm out}$ and $\theta_{\rm in}$ in Figure 4, again scaled to the nominal power-law expansion with $\theta \propto t^{0.8}$. For times between $t = 2.7$ yr and $t = 8$ yr the ratio $\theta_{\rm out}/\theta_{\rm in}$ does not change dramatically, being 1.29 on average (as we reported in [11]). However after $t \simeq 8$ yr, it can be seen that the shell thickness increases systematically, with $\theta_{\rm out}/\theta_{\rm in}$ reaching $\sim$1.7 by the time of our latest observations at $t \simeq 15$ yr. This increasing thickness of the shell is seen at different frequencies and observing epochs, and is notably larger than the observational uncertainties. We argue in [8] that the outer radius of our shell model likely corresponds well to the average radius of the outer shock. Although the relation of the inner radius of our shell model to the reverse shock is less unambiguous, and is likely somewhat model-dependent, we think that our results nonetheless reflect a real increase in the ratio between outer and inner shock front radii since $t \simeq 8$ yr. A thickening shell is also seen in simulations [14],

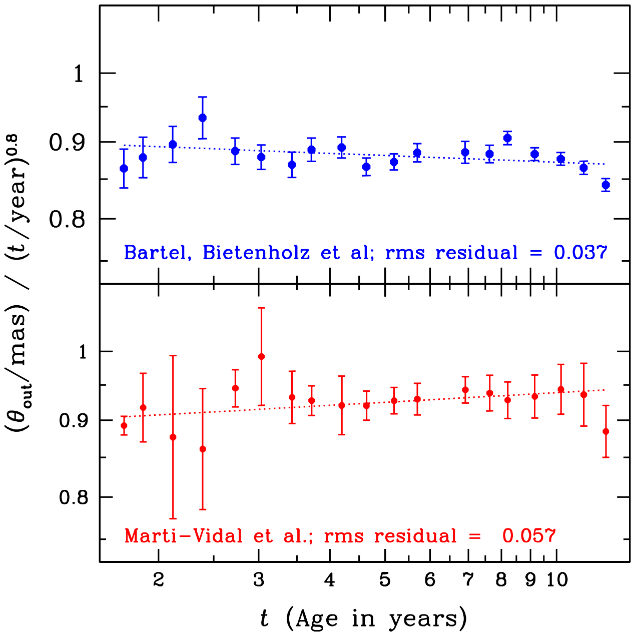

Figure 3: Comparison of the outer angular radii determined using u-v plane model-fitting with those obtained using the image-plane CPM ("common-point" method) by [5]. We plot the published values with uncertainties for only those epochs of our observations for which radii have been determined by both methods and for which the supernova is large enough to apply the CPM (i.e., $t > 1.6$ yr). As in Fig. 2 above, we plot the ratio $\frac{\theta_{out}/(\text{mas})}{(t/\text{yr})^{0.8}}$, or the radii as scaled by nominal power-law expansion with $\theta \propto t^{0.8}$. In each panel, the dotted lines indicate a weighted least-squares fit of a simple power-law to the plotted data, and the rms residual to this fit (in unitless scaled radii) is indicated. **Top:** our values [11], obtained using u-v plane model fitting. **Bottom:** the CPM values of [5].

although the thickening is not as rapid as we have observed. Our observations therefore imply further deviations from self-similar evolution of the supernova, with the outer radius continuing to increase in an approximately power-law fashion, but with the average inner radius increasing more slowly, perhaps as a result of instabilities growing inwards into the unshocked ejecta.

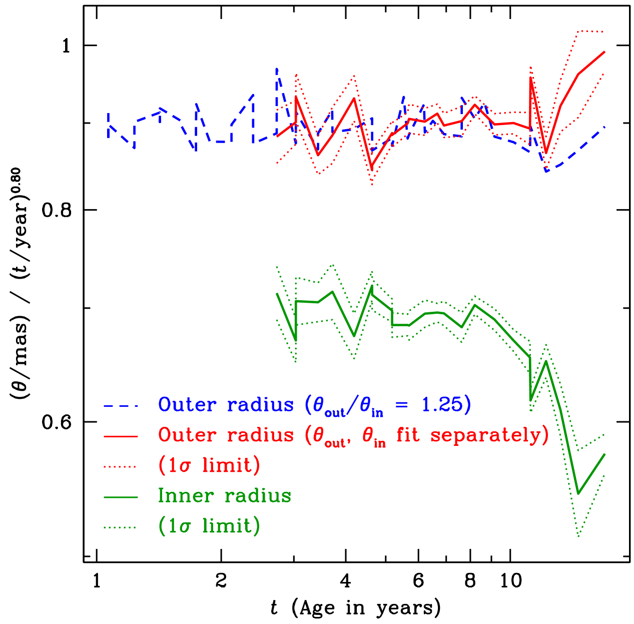

Figure 4: A plot showing the evolution of the outer and inner angular radii of SN 1993J as a function of time. Again, as in Figs. 2 and 3 above, we plot the radii as scaled to a nominal power-law expansion with $\theta \propto t^{0.8}$, in order to highlight any deviations from a simple power-law evolution. The red and green solid lines show the outer and inner radii, respectively, when the two are fit separately. For comparison, we also show in blue the outer radius obtained when using a fixed assumed ratio of $\theta_{out}/\theta_{in} = 1.25$. Note that for $t < 2.7$ yr, the resolution was insufficient to reliably determine θ_{in} separately, and we determined θ_{out} by assuming $\theta_{out}/\theta_{in} = 1.25$. (For further details, see [11] and [8].)

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