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How is really decelerating the expansion of SN1993J?

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Abstract. SN 1993J is to date the radio supernova whose evolution has been monitored in greatest detail and the one which holds best promise for a comprehensive theoretical-observational analysis. The shell-like radio structure of SN 1993J has expanded in general accord with models of shock excited emission, showing almost circular symmetry for over 8 years, except for a bright feature at the south-eastern region of the shell that has been observed at every epoch. The spectrum of SN1993J has flattened from $\alpha \simeq -1$ to $\alpha \simeq -0.67$ ($S_\nu \propto \nu^\alpha$). The decelerated expansion can be modeled well with a single slope but apparently better with two slopes. There are also intriguing hints of structure in the expansion curve. The results by the two VLBI groups carrying out this research show general agreement, but also some differences. A comparison of the optical and VLBI results about the details of the deceleration show some discrepancies.

1. Introduction

Radio emission from supernovae has been successfully modeled in terms of the standard interaction model (SIM; Chevalier 1982). This model considers fast-moving supernova ejecta with steep density profiles ($\rho_{\rm ej} \sim r^{-n}$) sweeping a circumstellar medium (CSM) of density profile $\rho_{\rm csm} \sim r^{-s}$, resulting in the formation of a high energy-density shell. For $n > 5$, self-similar solutions exist, and the shell radius evolves in time with a power law $R \sim t^m$, where t is the time since explosion and $m = (n-3)/(n-s)$ is the deceleration parameter. The radio emission is attributed to synchrotron emission from relativistic electrons in the shell, partially suppressed by external free-free absorption from thermal electrons in the CSM.

Due to its proximity and its radio emission level, SN 1993J in M81 has offered an unprecedented occasion for VLBI studies. The harvest of results includes: a) an initial source detection and evolution by Marcaide et al. (1994) and Bartel et al. (1994), respectively; b) the discovery of shell-like radio structure (Marcaide et al. 1995a); c) the first "movie" of an expanding supernova (Marcaide et al. 1995b); d) determinations of the deceleration in the expansion by Marcaide et al. (1997) and Bartel et al. (2000); e) a determination of the center of explosion of SN1993J relative to the quasi-stationary core of M81 (Bietenholz et al. 2001). Results by the two groups carrying out this research show general agreement, but also some differences like the determination of the shell thickness (∼30% of the shell external radius by Marcaide et al. (1995b); ∼20% of the shell external radius by Bartel et al. (2000)). The angular expansion has so far been rather smooth and circular and in accord with the SIM model. However, the supernova shell has displayed, for every epoch and wavelength, an enhancement of emission at its south-eastern part (see, for instance, Fig. 1 and Fig. 2, corresponding to supernova images in September 1999 and November 2000, respectively, two of our last observing epochs) probably related to the existence of small anisotropies in the density distribution of the CSM. On the other hand, our maps do not show yet any structures or protrusions developing in the shell.

However, a closer look to the previous figures shows also something not uncommon, namely, the changing enhancement of that emission in the south-eastern part relative to other parts of the structure. To be sure: the emission from the south-eastern part is always enhanced, while the emission from other parts of the shell seems to slightly come and go. Bartel et al. (2000) have even suggested that there may be a cyclic pattern of changes in shell azimuth. We do not have yet evidence of such thing from our data. Even so, there may be at least two possibilities: (a) the changing emission enhancements may be spurious due to, for example, imperfect closure phases or artifacts associated with the CLEAN algorithm, or (b) the changes are real and we should worry to understand them. As said, we do not have evidence from our data that the changes in different parts of the shell are any regular, but perhaps our source sampling has not been appropriate. In any case, the matter has to be systematically addressed with new observations.

To further complicate the picture, we show in Fig. 3 a preliminary 18 cm image from November 2000. As expected, the shell is not yet clearly delineated at this wavelength. However, is the emission enhancement location well determined by the closure phases?

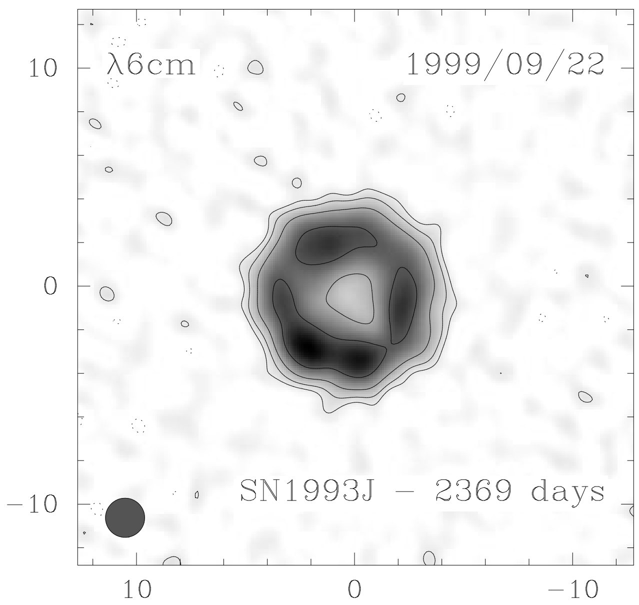

Fig. 1. 6-cm global VLBI image of SN1993J in M81 corresponding to epoch 2369 days after the explosion. The contours are spaced by $2^{1/2}$ factors, from a lower level of 160 μJy beam^{-1} to a brightness peak of 1939 μJy beam^{-1}. The convolving beam is circular, with FWHM diameter of 1.8 mas. The shell is still clearly defined, and though its shape is not perfectly circular, it does not show any evidence for strong asymmetries.

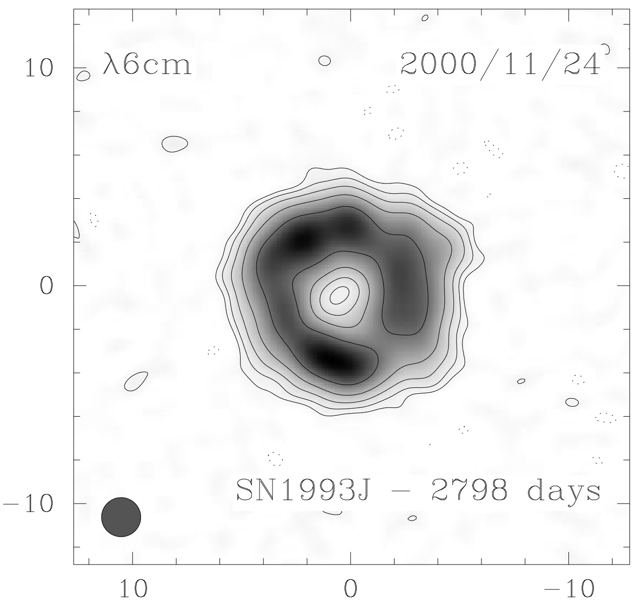

Fig. 2. 6-cm global VLBI image of SN1993J in M81 corresponding to epoch 2798 days after the explosion. The contours are spaced by $2^{1/2}$ factors, from a lower level of 47 μJy beam^{-1} to a brightness peak of 1327 μJy beam^{-1}. The convolving beam is circular, with FWHM diameter of 1.8 mas. The emission enhancements appear somewhat different to Fig. 1

2. Data Analysis

From our VLBI measurements of SN 1993J at 3.6 and 6 cm, which spanned from day 180 through day 1304 after explosion, we determined a value for the deceleration parameter, $m = 0.86 \pm 0.02$ (Marcaide et al. 1997). Bartel et al. (2000), based on their VLBI observations at 1.3, 2, and 3.6 cm for the period from day 30 through day 1893, have claimed that for 30$\leq$ t $\leq$ 306 days, $m_1 = 0.94 \pm 0.02$, while for 582$\leq$ t $\leq$1893 days, m_2 = 0.77$\pm$ 0.01. Adding the results for 30$\leq$ t $\leq$ 175 days as given by Bartel et al. (2000) to our data set, we have re-analyzed our data through day 2798 allowing for a time-break in the expansion of SN1993J (implying two deceleration parameters). We obtain the best fit with the following parameters: $m_1 = 0.933 \pm 0.019$, $m_2 = 0.827 \pm 0.008$, and $t_{\rm br} = 403 \pm 111$ days (Fig. 4). This fit has a reduced χ^2_ν=0.51. Analyzing the same data set with one deceleration parameter we obtain $m = 0.87 \pm 0.02$, with a reduced χ^2_ν=1.37. Though the latter result is compatible with our earlier one (Marcaide et al. 1997), it has a threefold larger reduced χ^2_ν. Then, although the deceleration parameter for the early epochs is compatible with that of Bartel et al. (2000) (not a surprise, since the result is highly influenced by our use of the Bartel et al. (2000) data for the period 30$\leq$ t $\leq$ 175 days when we have no data), the deceleration we obtain for late epochs is significantly different. We should note here that, for every epoch, the inferred source size depends on how the map is constructed and how it is measured. Due to the finite size of the VLBI beam, a positive bias is introduced in the size estimate of each map. Marcaide et al. (1997) showed how to account for this bias in order to obtain a correct estimate of the deceleration parameter.

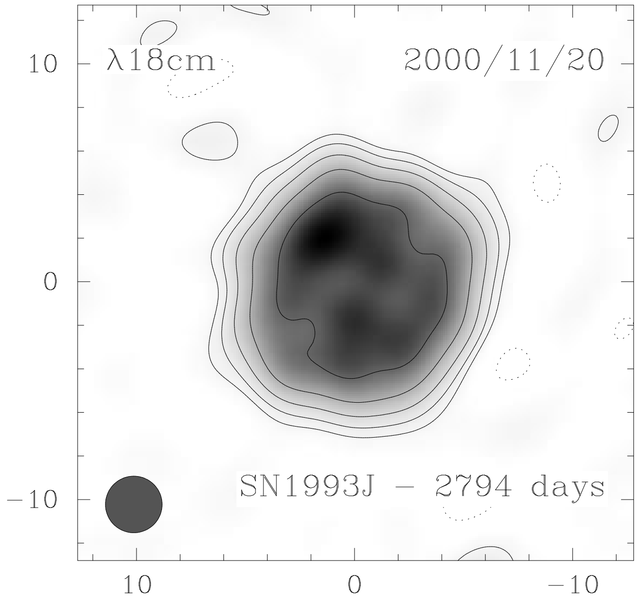

Fig. 3. 18-cm global VLBI image of SN1993J in M81 corresponding to epoch 2369 days after the explosion. The contours are spaced by $2^{1/2}$ factors, from a lower level of 130 μJy beam^{-1} to a brightness peak of 3430 μJy beam^{-1}. The convolving beam is circular, with FWHM diameter of 2.6 mas. The shell is not yet clearly defined and its structure is reminiscent to that at 3.6-cm prior to shell discovery from data 239 days after the explosion.

This picture gets even more complex if we consider the results of the detailed analysis of early to late-time spectra of SN1993J (Matheson et al. 2000). Matheson et al. show that the SN1993J velocity around 450-500 days, as given by the FWHM of the H_α line, suffers a clear deceleration from about 23,000 km/s down to 17,000 km/s. However, from then on, and up to about 2400 days the velocity of the H_α line stays remarkably constant at about 15,000 km/s. The VLBI data do not show such a clear sign of deceleration (though our $t_{\rm br}$ of 403 ± 111 days is compatible with the epoch range given by Matheson et al. 2000). A fit to their data (equally weighted) for epochs later than 500 days gives a deceleration parameter, $m_{\rm Matheson} = 0.87{\pm}0.01$ [$v = v_0\,(t/t_0)^{m-1}$]. This value, which is essentially our $m = 0.87 \pm 0.02$ (single deceleration parameter), is closer to our $m_2 = 0.83 \pm 0.01$ than to $m_{2,\rm Bartel} = 0.77{\pm}\ 0.01$, as reported by Bartel et al. (2000) for the period 582≤ t ≤1893 days. The situation is not completely satisfactory. Additionally, we are intrigued by an apparent modulation in the expansion curve in the period 1200≤ t ≤2100 days (Fig. 5). This modulation could be an artifact of the measurement process, but, so far, we have been unable to trace it to anything or to relate it to our measurement method. Mioduszewski et al. (2001) have calculated the time evolution of the expansion parameter from hydrodynamical simulations and have predicted the existence of a time-dependent deceleration.

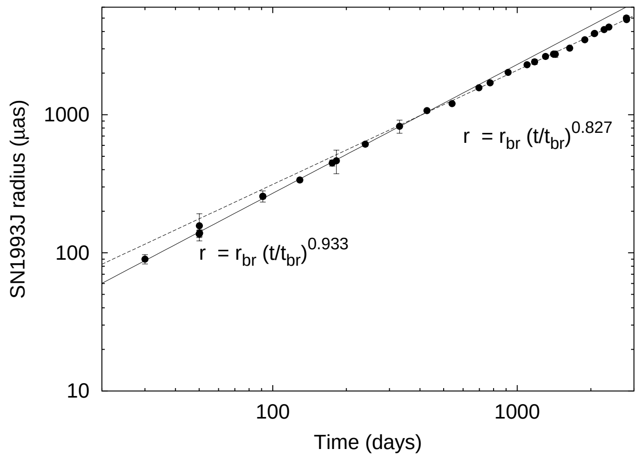

Fig. 4. Weighted least squares fit to the outer shell radius of SN1993J as a function of the time since explosion, allowing for a change in its deceleration rate. The VLBI data up to $t \le t_{\rm br}$=403 days (where the solid and dashed lines in the figure cross each other) can be well fitted by a power-law with index m_1=0.933 (solid line), while for $t \ge t_{\rm br}$ the best fit is given by power-law of index m_2=0.827 (dashed line). The VLBI data for epochs below 180 days are taken from Bartel et al. (2000). Note the logarithmic scale.

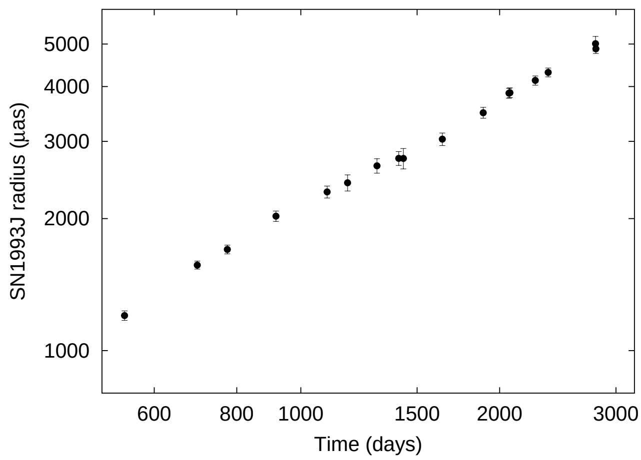

Fig. 5. The same data as in Fig. 4 but for the period from t=500 days on, to enhance the fact that there might be a modulation in the expansion of SN1993J between t ∼1200 and t ∼2100 days. (See also the main text.)

The spectral index of SN1993J is also changing as shown in Fig. 6 (Pérez-Torres et al. 2002). Quickly after explosion the supernova developed a steep spectrum, characterized by an almost constant index α=-1.0 ($S_\nu \propto \nu^\alpha$), but later, around day 1000, this spectrum became progressively less steep. Recent VLA observations (Pérez-Torres et al. 2002), which include observations at 90 cm, show that the spectral index around day 2820 has a value of α=-0.67, that is, the spectrum of the supernova is evolving towards a typical SN type II spectrum. Pérez-Torres et al. (2002) have found that a power-law spectrum, free-free absorbed by an homogeneous –or clumpy, but not a mixture of both– distribution of ionized gas, yields the best fit to the radio data.

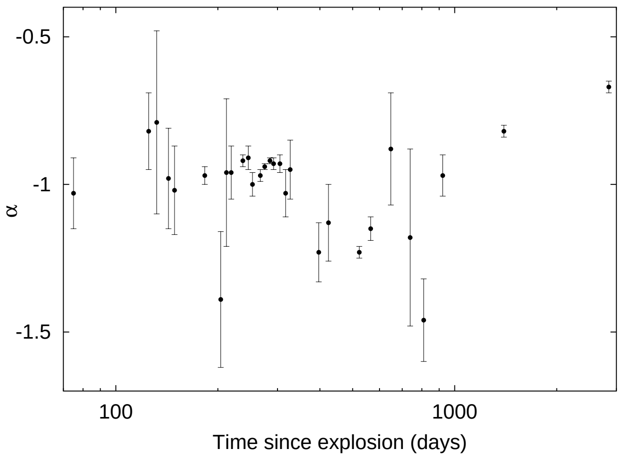

Fig. 6. Observed spectral index, α, of SN1993J from t ∼70 days up to t=2820 days, as obtained from fitting at each epoch the available VLA data to a synchrotron spectrum, partially suppressed by free-free absorption. After t ∼1000 days the spectrum becomes clearly flatter. The data used for the fits comes from measurementes made by K. W. Weiler, except for the last data point (Pérez-Torres et al. 2002).

3. Future Prospects and Conclusions

Over the coming years, we will try to carry on the VLBI monitoring at 6 cm until the source becomes undetectable (∼ 5 years), and simultaneously observe at 18 cm. With these observations, we will carefully monitor the deceleration, shell width, shell brightness, and spectral index distribution. We will be able to discern any possible dependence of those relevant parameters with frequency and time. Such essential information will constitute the input to our numerical simulation code (Pérez-Torres et al. 2001) and hence it will strongly influence our ability to characterize the physics involved. Also, our monitoring of the structure of SN1993J should help to understand how the spectral index changes in different parts of the structure.

Observations at 18cm are of outmost importance. Indeed, for SN1993J it can be expected that years after an emission decline (at 18 cm perhaps as long as 20 years) a nebular phase of expansion of progressively increasing emission will appear as in the case of SN1987A (Gaensler et al. 1997) and SN1979C (Montes et al. 2000). Then, the appropriate wavelengths of observation will be the longest ones. Thus, it is relevant to establish a long record of 18 cm observations of SN 1993J of the maximum sensitivity now that the emission is optically thin and the shell structure is becoming conspicuous at this wavelength.

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Final note: A comprehensive publication (Marcaide et al. 2002) and a new movie on the expansion of SN1993J are now being prepared. We will make soon the movie available to everybody. A previous movie has been publicly available at the JIVE and NRAO Image Galleries. It could also be retrieved by anonymous ftp from jansky.uv.es/pub/jmm (sn93j-marcaide.avi, 33MB, or sn93j-marcaide.avi.gz, 12MB)).