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Supernova 1993J in M81

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Abstract. Twenty-two consecutive VLBI images of supernova 1993J in the galaxy M81 taken over 7 years show, in unprecedented detail, the dynamic evolution of the expanding radio shell of an exploded star. High precision astrometry using phase-referencing shows that the supernova expands isotropically, and that its geometric center has a formal proper motion of 190 ± 110 km s^{-1} w.r.t. the core of M81. Systematic changes in the images most likely reflect a pattern of inhomogeneities in the medium left over from the progenitor star, or possibly instabilities in the expanding shell. As the shockfront sweeps up the medium, it is progressively decelerated, and after 7 years it has slowed to less than $^1/_2$ its original expansion velocity. SN1993J is likely now entering the early stages of the adiabatic phase common in much older supernova remnants.

1. Introduction

Supernova 1993J in the nearby spiral galaxy M81 was one of the brightest, and at a distance of only 3.63 Mpc (Freedman et al. 1994), closest optical supernovae in recent history. Shock breakout occurred on March 28.0, 1993 UT (Wheeler et al. 1993). Radio emission was detected a few days later, and reached a peak of $\sim$ 120 mJy at 8.4 GHz (e.g. Weiler et al. 1993). Models suggest that the progenitor was likely a 15 $M_\odot$ red supergiant in a binary system.

VLBI observations were first undertaken 30 days after shock breakout and have been continued to the present. In Figure 1 we present a sequence of 22

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8.4 GHz VLBI images[1] from 50 days to 7 years after shock breakout. These images were made from data phase-referenced to the core of M81 (Bartel, Bietenholz, & Rupen, 2000; Bietenholz, Bartel, & Rupen, 2000; for results up to 1998, see Bartel et al. 2000; for parallel observations see Marcaide et al. 1997). The sequence of images has been made into a movie, which can be viewed at `http://aries.phys.yorku.ca/~bartel/SNmovie.html`.

In the earliest image, SN1993J is almost unresolved, having an angular radius of only ~ 0.14 mas or 520 AU for a distance of 3.63 Mpc. The first suggestion of shell structure is visible in Sep. 1993. As the supernova expands the shell structure becomes increasingly resolved. The brightness is modulated around the shell, and this modulation changes with time. For example, in Sep. 1993, an opening in the shell appears towards the west, while by Jun. 1994, it appears to the north. These changes imply a non-self-similar evolution of SN1993J, contrary to what is claimed by Marcaide et al. (1997), and most likely reflect inhomogeneities in the medium left over from the progenitor star, or possibly instabilities in the shock front region. Despite the modulation, the outer contours of the shell remain circular to within 3%.

For a quantative analysis of the expansion rate, we fit a model to the calibrated visibility data in the u-v plane by weighted least-squares. The model used is the two-dimensional projection of a three-dimensional spherical shell with uniform volume emissivity. These model fits allowed us to accurately determine the shell's center coordinates w.r.t. the stationary core of M81 (Bietenholz et al. 2000) as well as the outer and inner radii of the shell, θ_i and θ_o respectively. The average shell thickness, θ_o/θ_i is 1.27 ± 0.02 (our uncertainties are standard errors and include systematic and statistical contributions).

A least-squares linear fit of the center coordinates gives a proper motion estimate w.r.t. the core of M81 of $\mu_\alpha = -5 \pm 4$ μas yr^{-1} and $\mu_\delta = -10 \pm 5$ μas yr^{-1}. At a distance of 3.63 Mpc, this corresponds to a velocity of 190 ± 110 km s^{-1} to the south-southwest. The galactic rotation of SN1993J can be estimated from HI rotation curves (Rots & Shane, 1975), and subtracting it leaves a peculiar velocity for SN1993J of 360 ± 100 km s^{-1} to the south. Along with the 3% limit on the non-circularity of the structure, this allows us to determine that the expansion of SN1993J is isotropic to within 5%.

We also determined the rate of expansion: Figure 2 shows the outer radius of SN1993J as a function of time. At early times ($t \leq 306$ d), the outer angular radius, θ_o of SN1993J, behaves as $\theta_o \propto t^m$ with $m = 0.937 \pm 0.020$. At later times the deceleration grows, and m decreases to 0.784 ± 0.010. The shock velocity, $v_{\rm shock}$, for our last observation is only 7500 km s^{-1}, which is less than $^1/_2$ its original value of ~ 18000 km s^{-1}. The change in the deceleration is 7σ — the first time such a change has been directly monitored for any supernova.

The standard model of the interaction of the shock front with the circumstellar medium (Chevalier 1982) suggests that the expansion be self-similar. Our data show that the evolution of SN1993J is more complex than a straightforward self-similar solution, with a marked increase in deceleration. The decrease

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[1] We used a global array of up to 18 VLBI telescopes with an observing time of up to 18 hours per session. The data were correlated at the NRAO VLBA processor in Socorro, NM, USA, and further processed using the NRAO AIPS package at York University.

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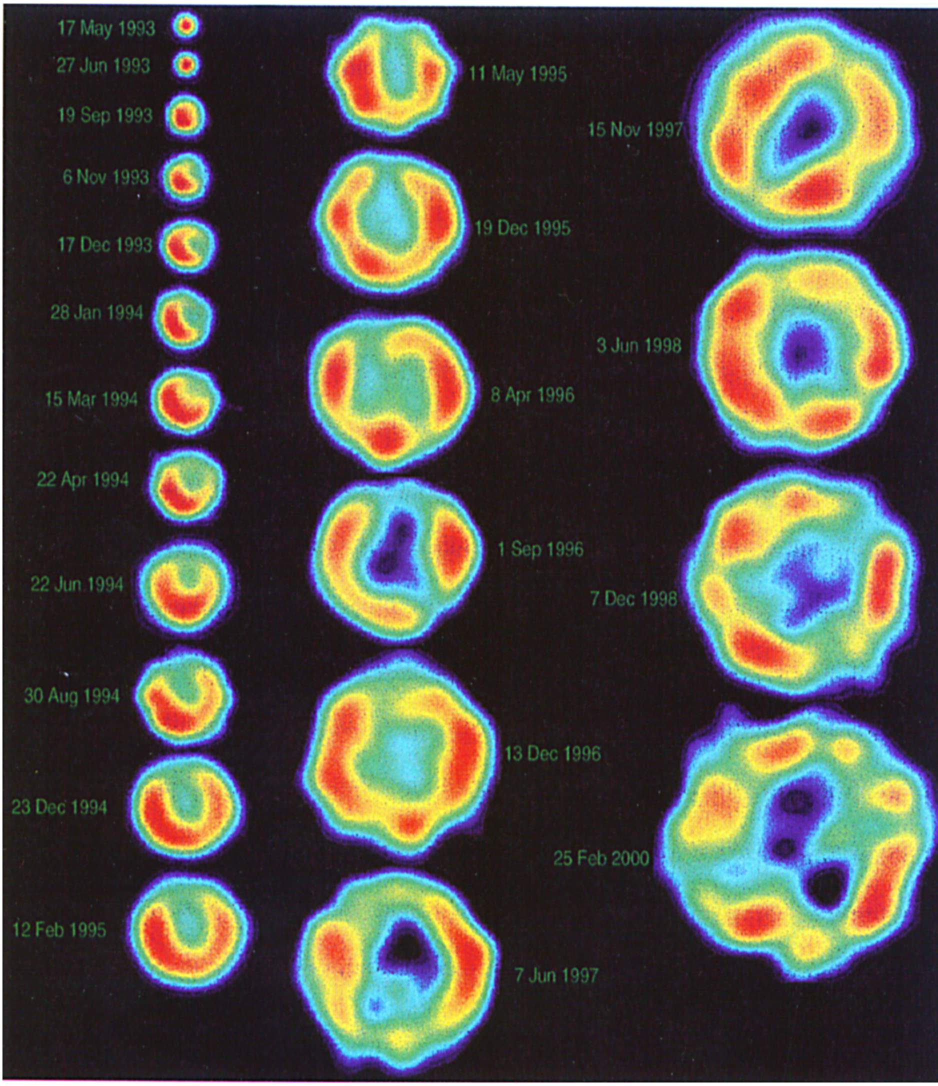

Figure 1. VLBI images at 8.4 GHz of SN1993J, made from $t = 50$ d to $t = 2525$ d after shock breakout. The convolving beam is conservatively chosen to be circular, and starts with a FWHM size of 0.5 mas, increases steadily to 1.12 mas by Nov. 1997, and remains constant therafter. The peak brightness for the representative 17 May 1993, 12 Feb. 1995, and 24 Feb. 1998 images was 15, 3.7 and 0.5 mJy beam^{-1} respectively, and the corresponding background rms values were 0.10, 0.06 and 0.04 mJy beam^{-1}.

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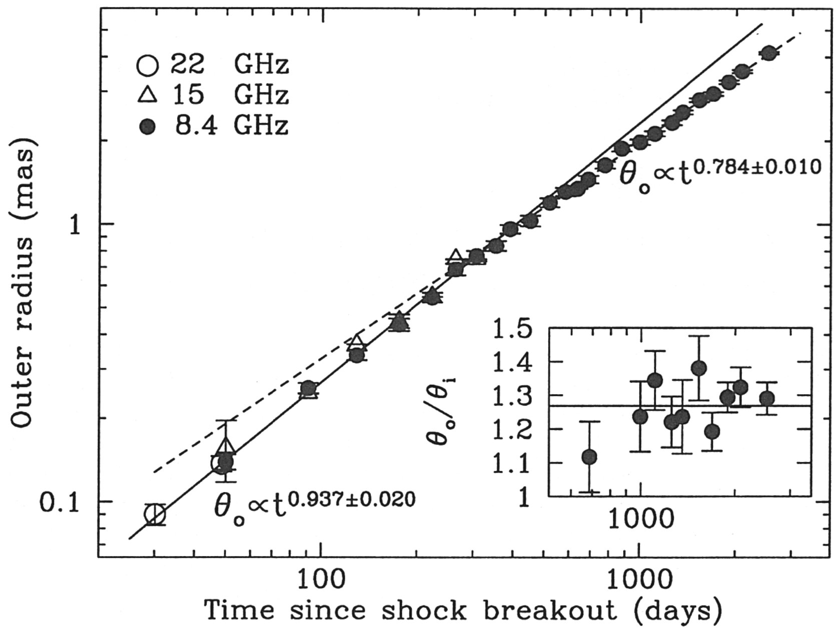

Figure 2. The outer angular radius, θ_o, of the shell model of SN1993J, plotted against time. The dashed and solid diagonal lines represent seperate weighted least-squares fits ($\theta_o \propto t^m$) to points with $t \leq 306$ days, and those with $t \geq 582$ days. Inset: the ratio of θ_o to the inner radius, θ_i for the observations for which both θ_o and θ_i could be estimated, with the horizontal line indicating the weighted mean.

of $v_{\rm shock}$ to $< {}^1/_2$ its original value suggests that the swept up mass is already comparable to the hydrogen shell mass. The implied low shell mass of $\sim 0.3\ M_\odot$ is compatible with the models of the progenitor where most of the mass has already been lost to the companion. It appears that SN1993J is now approaching the adiabatic expansion stage, common in much older supernova remnants in our own Galaxy.

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