Strong deceleration in the expansion of radio supernova SN 1979C

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We observed SN 1979C in M100 on 4 June 1999, about twenty years after explosion, with a very sensitive four antenna VLBI array at the wavelength of λ18 cm. The distance to M100 and the expansion velocities are such that the supernova structure cannot be fully resolved by our Earth-wide array. A model-dependent size for the source has been determined and compared with previous results. We conclude that the SN shock was in free expansion for 5–10 yrs and then experimented strong deceleration, possibly coincident in time with the abrupt trend change in the radio total flux density curves.

1. Introduction

Supernova SN 1979C in M100 was discovered on 1979 April 19 by G.E. Johnson (Mattei *et al.* 1979) at around magnitude 12 in the visible. At the distance of 16.1 ± 1.3 Mpc estimated for M100 (Ferrarese *et al.* 1996), it is also one of the intrinsically strongest radio supernovae (RSN) (Weiler *et al.* 1996). From Hα widths an initial expansion speed of $\sim$9 200 km s^{-1} was estimated for epoch around 45 d by Fransson *et al.* (1984); see also Weiler *et al.* (1986). Fesen *et al.* (1999), hereafter F99, studied the late-time optical properties of SN 1979C and estimated from Hα widths a speed of $\sim$6 200 km s^{-1} at epoch 21 May 1993 (age 14.09 yr).

The evolution of the integrated radio emission from SN 1979C has been interpreted within the mini-shell model (Chevalier 1982) as due to synchrotron emission from the outer part of the shock swept shell attenuated by thermal absorption from the surrounding ionized CSM (Weiler *et al.* 1986; Montes *et al.* 2000). The modulation present in the radio light curves of SN 1979C has led Weiler *et al.* (1992) and Montes *et al.* (2000) to model the SN progenitor as possibly being in a detached eccentric binary system with a less massive companion. From a study of the emission environment of SN 1979C, van Dyk *et al.* (1999) have estimated the mass of the progenitor to be $17-18\,(\pm 3)\,\mathrm{M}_{\odot}$. Hydro-dynamical simulations by Schwarz & Pringle (1996) confirm that a binary system similar to that proposed by Weiler *et al.* (1992), with a spiral shaped stellar wind density around the progenitor, is feasible for SN 1979C. Such modulation of the density of the gas surrounding the RSN and now being shocked, might have dramatic effects in the shape of the radio structure. A determination of such radio structure would be a powerful way to further understand the pre-supernova phase of the progenitor of SN 1979C.

The integrated radio emission of this RSN, monitored by van Dyk *et al.* (1998) and Montes *et al.* (2000), has started to show an interesting trend: after years of decline the radio emission has started to slightly increase after 1990 ($\sim$ 10 yr) in a steady way. It appears that after a standard RSN radio emission decline phase (Weiler *et al.* 1996) the expanding shock may be encountering denser ionized gas which boosts the energetics of the shock and hence the radio emission. These results may be in accord with those of F99 which show that high electron densities (10^{5-7} cm^{-3}) are necessary to explain the absence of several lines, such as [O II] 3726, 3729 Å in their optical spectra. VLBI observations at 3.6, 6, 13 and 18 cm by Bartel *et al.* (1985), hereafter B85, determined the size of SN 1979C during the interval Dec 1982 to May 1984, assuming a synchrotron emitting optically thin spherical model for the source. At those early epochs the source could not be resolved by any VLBI array. In this paper we present the results of another attempt to determine the structure of SN 1979C and its evolution.

2. Observations

SN 1979C was observed on 4 June 1999 from 19:30 UT to 01:30 UT at 1.6 GHz with a sensitive transatlantic VLBI array. The antennas used were [name (diameter, location)]: Effelsberg (100m, Germany), Robledo (70m, Spain), phased-VLA (130m-equivalent, NM, US), and Goldstone (70m, CA, US). Data were recorded using a standard VLBA mode with a data rate of 256Mb/s, covering a bandwidth of 64 MHz. The data were correlated at the VLBA Correlator Center of the National Radio Astronomy Observatory (NRAO) in Socorro, NM, US. The observations were made with a duty cycle of about 26 min consisting of observations of the calibrators PKS B1157+156 and TXS 1214+161, and the source SN 1979C. The correlated data were analyzed using the Astronomical Image Processing System (AIPS). SN 1979C was phase-referenced to PKS B1157+156. Using stand-alone 1.6 GHz observations of PKS B1157+156 in Effelsberg adjacent to those reported in this paper, we estimated for SN 1979C a total flux density of 5.4±0.2 mJy. Further model fitting analysis was carried out in DIFMAP and also with some Caltech VLBI Analysis Programs. Details of the data will be given in a forthcoming paper (Marcaide *et al.* 2000).

3. Results and discussion.

We assumed spherical symmetry in the modeling. We proved to ourselves that all data are on the main lobe of the interferometric response. A good definition of the closure phases (all being around zero and none around 180°) was of much help. Then, because the model remains indeterminate and Marcaide *et al.* (1997) and references therein determined for SN 1993J a shell structure with a shell width 30% that of the outer radius, somewhat larger than that predicted by Chevalier & Fransson (1994), we adopted a shell of width 30% of the external radius as a model in this paper. Henceforth our discussion will be based on this model. We obtained a size estimate of 3.60 ± 0.17 milliarcseconds (mas). The uncertainty corresponds to a $\Delta\chi^2$ increase of 0.13 for a system with 1 350 degrees of freedom and include the values and uncertainty estimates of the above cited analysis packages.

At a distance of 16.1 Mpc to M100 an angular size of 1 mas corresponds to a linear size of 0.0781 pc = $2.408 \cdot 10^{15}$ m. Hence, the source outer radius of 1.80 mas corresponds to $3.673 \cdot 10^{12}$ km. Since 20.12 yr had elapsed since the explosion, the corresponding average supernova expansion velocity is $\sim$5 800 km s^{-1}. On the other hand, early expansion speeds were estimated around age 45 days from the Hα lines as $\sim$9 200 km s^{-1}. Thus, the

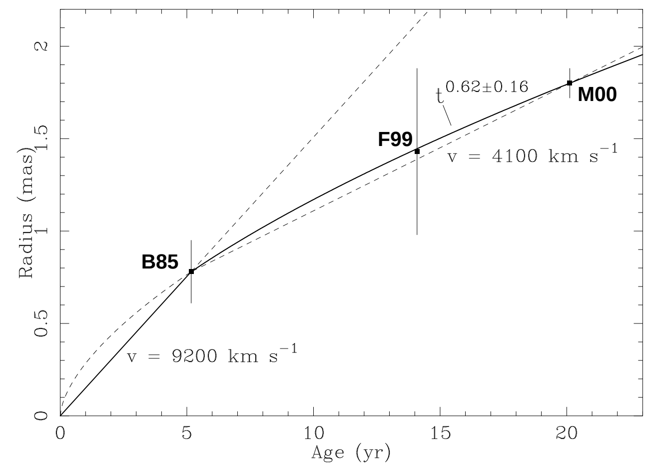

FIGURE 1. Radius vs. age of SN 1979C. The solid line indicates a likely expansion, which is free for the first 5-6 yrs and decelerated from then on. **B85** indicates the size estimate from Bartel *et al.* (1985), **F99**, the size estimated by us based on the optical results by Fesen *et al.* (1999); and **M00** indicates the size estimated from our λ18 cm VLBI observations.

expansion appears to have been strongly decelerated by the action of the circumstellar matter. How strongly? It is difficult to make a detailed analysis to answer such a question since there are not many intermediate size estimates available. Nevertheless, we will try.

B85 determined a diameter of $2.16^{+0.44}_{-0.50}$ mas at 5.17 yr after explosion, at 1.67 GHz for an optically thin uniform sphere, which translates into a radius of $0.78^{+0.15}_{-0.18}$ mas for our model. This size corresponds to an average speed for the first 5.17 yr of $\sim$9 700 km s^{-1} which is, not unexpectedly, slightly higher than the speed determined by the width of the Hα line. Thus, the deceleration parameter m ($R \propto t^m$) is close to unity and all deceleration apparently takes place after age 5.17 yr. An estimate of m using the size estimate of B85 and our estimate results in $m = 0.62 \pm 0.16$. Such result indicates that for the period between 5.17 and 20.12 yr the deceleration is rather steep with an index $m \leq 0.62$.

F99 determined speeds of $\sim$6 200 km s^{-1} for epoch 14.09 yr from the width of the Hα line. Considering that $R \propto t^m$ implies $v \propto t^{m-1}$ we may obtain a rough estimate of m using the speed of 9 200 km s^{-1} for epoch 5.17 yr and 6 200 km s^{-1} for epoch 14.09 yr. It yields $m = 0.61 \pm 0.10$. From this, we can roughly estimate the radius at age 14.09 years, which turns out to be 1.43 ± 0.45 mas. Let us note that our method of estimating the size of the source from the optical results of F99 is insensitive to which epoch of free expansion is used due to the very form of $R \propto t^m$ and $v \propto t^{m-1}$.

It appears unlikely that the deceleration set in immediately after the observations of B85. There is nothing in the integrated radio light curves, for example, to indicate such is the case. On the other hand the free expansion appears to have ended by the epoch of the optical observations of F99 for which we have a radius estimate of 1.43 ± 0.45 mas. A free expansion would make the source have a radius of 1.43 mas by about 9-10 yr. Thus, even though there are large uncertainties in our size and velocity estimates, it is reasonable to assume that, prior to the epoch of the observations of F99, the source grew at speeds much greater than 6 000 km s^{-1}, and that the greatest age at which the expansion could be a free one is not much greater than 5-6 yrs. Fig. 1 shows diagramatically a likely expansion of SN 1979C. It can be seen that the initial free expansion is followed by a strong deceleration. If we consider that the deceleration set in abruptly some time after the B85 measurement at age 5.17 years and before the F99 measurements at age 14.09 years, say at age ~10 years when Montes *et al.* (2000) found the start of a constant or slightly rising integrated radio flux density, then our VLBI results would be compatible with those of F99 with an $m \simeq 0.4$ and would indicate an even stronger deceleration. This alternative is plotted in Fig. 1.

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