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1.6 GHz VLBI observations of SN 1979C: almost-free expansion
(Research Note)

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ABSTRACT

We report on 1.6 GHz Very-Long-Baseline-Interferometry (VLBI) observations of supernova SN 1979C made on 18 November 2002. We derive a model-dependent supernova size. We also present a reanalysis of VLBI observations made by us on June 1999 and by other authors on February 2005. We conclude that, contrary to our earlier claim of strong deceleration in the expansion, SN 1979C has been undergoing almost-free expansion ($m = 0.91 \pm 0.09$; $R \propto t^m$) for over 25 years.

Key words. radio continuum: stars – supernovae: individual: SN 1979C

1. Introduction

Supernova SN 1979C was discovered in the Virgo Cluster galaxy M 100, at a distance of 16.1 ± 1.3 Mpc (Ferrarese et al. 1996), on 19 April 1979 (Mattei et al. 1979). It reached an absolute magnitude of $\sim$−20, becoming one of the brightest supernovae ever observed in the optical band (e.g., Young & Branch 1989). Radio emission from SN 1979C was detected and monitored by Weiler & Sramek (1980) at several frequencies. From the analysis of the radio lightcurves, Weiler et al. (1986) estimated the explosion date of the supernova to be 4 April 1979, 15 days before its discovery. The peak flux density observed by Weiler et al. was $\sim$9.8 mJy at 20 cm. This emission level and the large distance to the host galaxy, M 100, made supernova SN 1979C the most luminous radio supernova (RSN) at its time.

Several VLBI observations of this supernova have been made since year 1982 through year 2005 at 5, 2.3, and 1.6 GHz (see Bartel et al. 1985, 2003, 2008; Bartel 1991; and Marcaide et al. 2002). From these observations, the expansion curve of the supernova was determined by two research groups. Each one arrived at very different conclusions. Bartel (1991) found that SN 1979C was freely expanding over the first 7 years after explosion. Later, Marcaide et al. (2002), using the early expansion curve published by Bartel et al. (1985) together with optical-line data and new VLBI observations made in year 1999, claimed a "strong deceleration" in the supernova expansion, starting $\sim$6 years after explosion. In year 2002, we performed new VLBI observations of SN1979C in order to confirm this strong deceleration. Later, Bartel & Bietenholz (2003) reported on VLBI observations made in years 1990, 1996, and 2001, and claimed a practically free expansion over almost two decades. These results were in clear conflict with those published by Marcaide et al. (2002).

In the next section, we describe the details of these new VLBI observations of SN 1979C and the calibration scheme used. In Sect. 3, we present the results obtained from the data

analysis. In Sect. 4, we describe the results obtained after a reanalysis of the observations reported in Marcaide et al. (2002). In Sect. 5, we present a reanalysis of the observations recently reported by Bartel & Bietenholz (2008). In Sect. 6 we report on the expansion curve of SN 1979C. Finally, in Sect. 7 we summarize our conclusions.

2. Observations and data reduction

Our 1.6 GHz observations were made on 18 November 2002, from 2:20 UT to 21:00 UT. The participating stations were: the complete Very Long Baseline Array (VLBA; 10 antennas, 25 m diameter each, spread over the USA), Green Bank (100 m diameter, West Virginia, USA), Effelsberg (100 m diameter, Germany), Robledo (70 m, Spain), Westerbork (phased array of size equivalent to a 93 m diameter antenna, The Netherlands), and Arecibo (300 m diameter, Puerto Rico). The recording rate was set to 256 Mbps, 2-bit sampling, obtaining a total bandwidth of 64 MHz for all stations. The data were cross-correlated at the Array Operations Center of the National Radio Astronomy Observatory (NRAO), in Socorro, New Mexico, USA.

The observations were scheduled in phase-reference mode. Each cycle time was divided into a $\sim$5 min long scan of the calibrator source PKS B1157+156 and a $\sim$15 min long scan of SN 1979C. The slewing time of the slowest antenna between sources lasted typically about 1.5 min. Every 2−3 duty cycles, a 5 min scan of a secondary calibrator, TXS 1214+161, was added. The source 3C 274 was also observed as a fringe finder at the beginning of each VLBI tape.

Given the long duration of the experiment and the different latitudes of the stations, it was not possible to assign only one reference antenna for the calibration of the whole data set. Therefore, the observations were divided into two parts for their calibration, the first one (from 2:20 UT to 8:20 UT) was calibrated using Robledo as reference antenna, and the second one
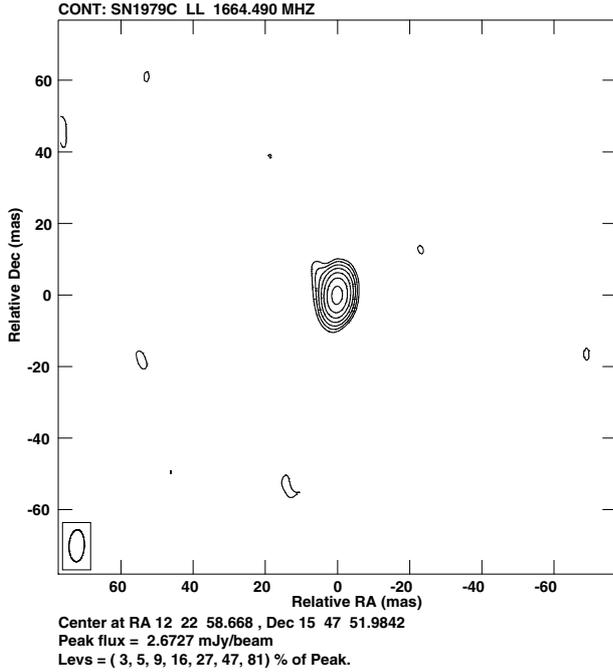
CONT: SN1979C LL 1664.490 MHZ

Center at RA 12 22 58.668 , Dec 15 47 51.9842
Peak flux = 2.6727 mJy/beam
Levs = (3, 5, 9, 16, 27, 47, 81) % of Peak.

Fig. 1. CLEAN image of SN 1979C obtained from the observations made on 18 November 2002. The Full Width at Half Maximum (FWHM) of the convolving beam is shown at the bottom-left corner (a 8.9×4.2 mas beam at a position angle of $-2.6°$).

(from 8:20 UT onwards) was calibrated using North Liberty as reference antenna.

The cross-correlated data were imported into the NRAO program AIPS for calibration. The phases of the 8 different IFs (of 8 MHz width each) were manually aligned by fringe-fitting scans of 3C 274 and applying the resulting antenna phases and delays to all observations. Afterwards, the amplitude calibration was performed using system temperatures registered at all the stations and gain curves for the antennae. Once a hybrid image of PKS B1157+156 was obtained, a standard phase-reference calibration of SN 1979C was performed taking into account the structure of PKS B1157+156. Finally, the visibility amplitude calibration for SN 1979C was refined by performing an amplitude self-calibration of the PKS B1157+156 visibilities and interpolating the resulting gains to the SN 1979C scans. The calibrated data were then exported from AIPS into the Caltech software DIFMAP (Shepherd et al. 1995) for further reduction and imaging.

3. Results

We Fourier-inverted the calibrated visibilities of SN 1979C in DIFMAP. Using a CLEAN deconvolution, we obtained the image shown in Fig. 1. The total flux density of the image is 2.96 mJy and the root-mean-square (rms) of the image residuals 0.07 mJy/beam. This phase-referenced image of SN 1979C is point-like. However, a modulation of the real part of the visibilities as a function of uv-distance is readily observable in the data (see Fig. 2). That is, the source structure is partially resolved by the interferometer. We fitted two models (a uniform sphere and a 30%-wide spherical shell) to the visibilities and obtained the corresponding estimates of the source size. The χ^2-minimization was performed using the Levenberg-Marquardt algorithm (e.g., Gill & Murray 1978), as implemented in the *Mathematica 5.0* package (Wolfram 2003). The parameter
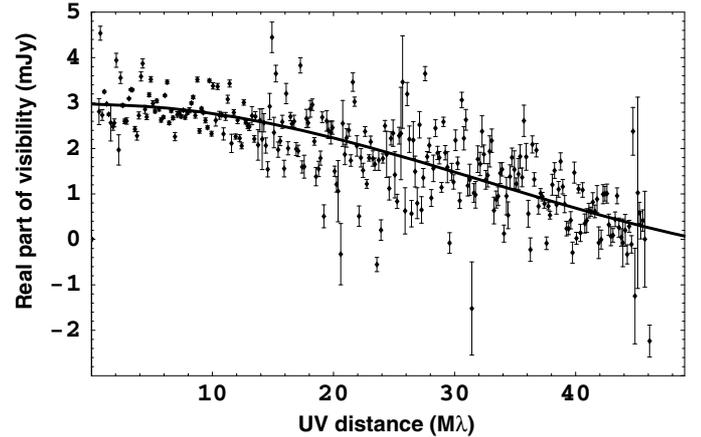

Fig. 2. Real part of the visibilities taken at epoch 18 November 2002 as a function of distance in Fourier space. The visibilities have been averaged into 300 radial bins for obtaining a clear plot. The solid line corresponds to a 30%-wide spherical shell model fitted to the visibilities (see text and Table 1).

Table 1. Results of modelfitting to the SN 1979C visibilities.

Age	Freq.	Radius (mas)	
(years)	(GHz)	Uniform Sphere	30%-Wide Shell
20.12^a	1.6	2.70 ± 0.10	2.27 ± 0.10
23.65^b	1.6	3.31 ± 0.10	2.81 ± 0.08
$25.92\ ^a$	5.0	3.30 ± 0.30	2.84 ± 0.26

[a] Re-analysis of the observations reported in Marcaide et al. (2002).
[b] Observations reported in this paper.
[c] Re-analysis of the observations reported in Bartel & Bietenholz (2008).

uncertainties were computed from the diagonal elements of the post-fit covariance matrix. In Table 1, we summarize the results of the fits performed. The fitted radii are incompatible with those reported in Marcaide et al. (2002).

4. Reanalysis of our previous observations

We reanalyzed the observations reported in Marcaide et al. (2002). In Table 1, we show the results of such a reanalysis, which differ substantially from those reported in the original paper. Thus, our conclusion is that something was not correctly reported in Marcaide et al. (2002). In fact, the model used in the fit reported by Marcaide et al. (2002) was not really a 30%-wide shell, as said, but a uniform disc with its inner region removed (i.e., the flux density from radii smaller than 0.7 times the disc radius had been removed). The use of such a modified disc model results in a radius estimate of 78% of the radius estimate of the correct 30%-wide spherical-shell model. Actually, Marcaide et al. (2002) also reported the sizes corresponding to an optically thick source (uniform disc) and a ring. These two size estimates were correct, and therefore inconsistent with the size reported for the optically-thin 30%-wide shell model. However, this miscalculation went unchecked and the inappropriate size estimate was used to compare with the optical data and early results by other authors, thus leading to an inaccurate conclusion about the expansion of the source.

The deceleration parameter derived by Marcaide et al. (2002) from optical-line velocities was obtained assuming that the supernova had been expanding with a constant velocity during the
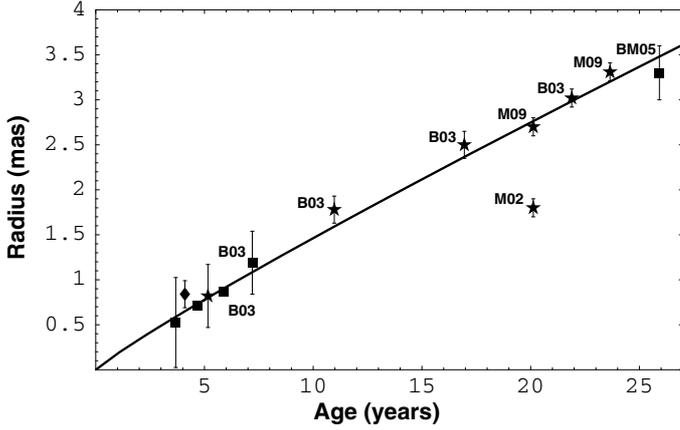
Fig. 3. Expansion curve of SN 1979C using all the available VLBI data. Squares are data at 5 GHz, diamonds at 2.3 GHz, and stars at 1.6 GHz. All these values (except the one marked with M02) have been obtained using the same model fitted to the visibilities (a homogeneous sphere). Epochs until year 5 after explosion are taken from Bartel et al. (1985), M02 refers to Marcaide et al. (2002), B03 refers to Bartel & Bietenholz (2003), M09 refers to the observations here reported (included the re-analysis of the observations reported in Marcaide et al. 2002), and BM05 refers to the observations reported in Bartel et al. (2008), which we have reanalyzed for estimating the source size (see text). The solid line is a fit with a time power law (i.e., $R = K t^m$, with $m = 0.91 \pm 0.09$).

first 5 years after explosion. Basically, the authors assigned the mean optical-line velocity measured during the first 6 weeks after explosion to the expansion velocity during the fifth year after explosion. The main argument for such an assumption was that the ratio of the early optical-line velocity and the velocity derived from VLBI at year 5 after explosion was ~0.7, that expected for a 30%-wide shell of a supernova (Marcaide et al. 2002, 2009). However, if the assumption of a free expansion over the first 5 years is relaxed, things look different.

With an assumption of deceleration of the supernova beginning on day 70 after explosion, the ejecta velocity at year 5 after explosion would be ~25% lower than the velocity estimated from a free expansion, but the estimated fractional shell width would be 0.53; an unrealistically wide shell. However, this shell width estimate should be interpreted as an upper bound, given that the optical-line emission may originate in a cool region behind the shocked ejecta (Chevalier & Fransson 1994) and, thus, any comparison between optical-line velocities and those inferred from VLBI (which are additionally affected by any uncertainty in the distance estimate) should not be taken at face value for the derivation of the supernova expansion curve.

The fit of a homogeneous sphere to the data was registered in the research logs, but it was not reported in Marcaide et al. (2002). A direct comparison of that size with those reported by Bartel et al. (1985) is also totally compatible with an almost free expansion, as is now shown in Fig. 3. Given that Bartel et al. used a uniform sphere to fit all their observations, Marcaide et al. (2002) should have also used this same model but instead, and unfortunately, they used a scaling factor, based on simulations, to *convert* the sizes reported by Bartel et al. (1985) into sizes corresponding to a shell model.

5. Reanalysis of observations by other authors

Bartel & Bietenholz (2008) have recently reported on new VLBI observations of SN 1979C, made at 5 GHz on 25 February 2005. From these observations, the authors found a shell-like structure
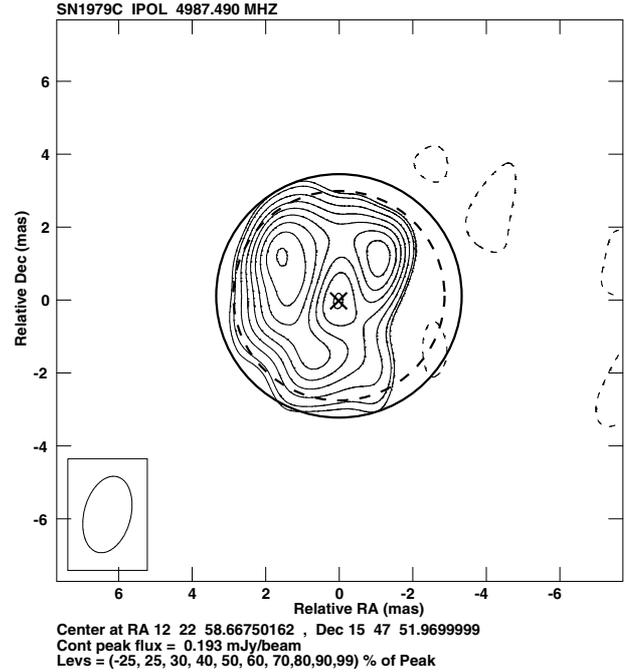

SN1979C IPOL 4987.490 MHZ

Center at RA 12 22 58.66750162 , Dec 15 47 51.9699999
Cont peak flux = 0.193 mJy/beam
Levs = (-25, 25, 30, 40, 50, 60, 70,80,90,99) % of Peak

Fig. 4. CLEAN image obtained after a reanalysis of the observations reported in Bartel & Bietenholz (2008). The continuous and dashed lines correspond to a sphere and a 30%-wide spherical shell fitted to the visibilities. The center of the models has been fixed at the location of the central minimum intensity of the image (marked with a cross).

for SN 1979C. However, the authors postponed an estimation of the source size to a future publication. In order to obtain the most complete expansion curve, we have reanalyzed their data (already public NRAO archive data), following the same steps described in Bartel & Bietenholz (2008), except for our decision not to phase self-calibrate the data given the high noise of the visibilities compared to the flux density of the supernova. Our decision translates into a slightly higher rms of the map residuals (20 μJy beam^{-1} in our image compared to the 11 μJy beam^{-1} reported by Bartel & Bietenholz). Otherwise, our image (shown in Fig. 4) is similar to that reported in Bartel & Bietenholz (2008).

In our fits to determine the size of the source, we only used the visibilities with distances in Fourier space shorter than 50 Mλ. This way we avoided any possible bias arising from the use of different shell resolutions between epochs. We centered the fitting models at the location of the central intensity minimum of the image (where the shell center is supposed to be). Had we set the source position as a free parameter in the fit, it would have biased the estimated source size, due to the large shell inhomogeneities. The center of the fitted source would have fallen close to the image peak and the fitted size would have been, therefore, mainly related to the size of the main blob of the image, instead of to the size of the shell.

The CLEAN image of SN 1979C, together with the fitted sphere and spherical-shell model, is shown in Fig. 4. The sizes estimated from the fits to the visibilities are also shown in Table 1.

6. The expansion curve

Figure 3 shows all the available size estimates of SN 1979C over the last 25 years. Estimates from epochs earlier than 5 years after explosion are from Bartel et al. (1985), estimate labelled M02 is from Marcaide et al. (2002), estimates labelled B03 are from

Bartel & Bietenholz ([2003](#)), estimates labelled M09 refer to the observations reported here and to those wrongly reported as M02 and here reanalyzed, and estimate BM05 refers to the observations reported in Bartel et al. ([2008](#)) and here reanalyzed. All size estimates (but M02) have been obtained model fitting a homogeneous sphere to the visibilities as in Bartel et al. ([1985](#)).

Modelling the expansion curve with a standard χ^2 minimization using a time power law (i.e., $R \propto t^m$, see Chevalier [1982](#)) gives an expansion index $m = 0.91 \pm 0.09$, compatible with a free expansion ($m = 1$). Thus, we conclude that supernova SN 1979C has been expanding without significant deceleration for more than two decades. Actually, including BM05 in the fit does not change the result at all. At this epoch the size appears a bit smaller than expected but the uncertainty in the size determination is large (and it could be even larger considering that our criteria to center the fitting model may be partially inadequate).

7. Conclusions

We report on 1.6 GHz VLBI observations of SN 1979C made on November 2002. The phase-referenced image of the supernova does not show a clear structure and has a total flux density of 2.96 ± 0.06 mJy. The size estimates, compared to all the other available VLBI results (but those reported in Marcaide et al. [2002](#)) are compatible with a nearly-free expanding supernova for more than two decades. We reanalyzed the observations reported in Marcaide et al. ([2002](#)) and found that, for reasons given in the text, the results and conclusions then published were not correct.

The expansion curve resulting from the reanalysis of all the VLBI data (including the observations reported in Bartel & Bietenholz [2008](#)) results in a new expansion model which is compatible with a nearly-free expansion for over more than two decades (expansion index of 0.91 ± 0.09).

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