The Astrophysical Journal, 691:1380–1386, 2009 February 1 doi:10.1088/0004-637X/691/2/1380

SN 2001em: NOT SO FAST

F. K. Schinzel[1,5], G. B. Taylor[1,6], C. J. Stockdale[2], J. Granot[3], and E. Ramirez-Ruiz[4]
[1] Department of Physics and Astronomy, University of New Mexico, 800 Yale Blvd NE, Albuquerque, NM 87131, USA; schinzel@mpifr.de
[2] Marquette University, Physics Department, P.O. Box 1881, Milwaukee, WI 53214-1881, USA
[3] Centre for Astrophysics Research, University of Hertfordshire, College Lane, Hatfield, Herts, AL10 9AB, UK
[4] Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA
Received 2008 August 13; accepted 2008 October 2; published 2009 February 3

ABSTRACT

SN 2001em, originally classified as type Ib/c, is a peculiar supernova. It was observed in the radio about two years after its optical detection, showing a rising radio flux with an optically thin spectral slope; it also displayed a large X-ray luminosity ($\sim 10^{41}$ erg s^{-1}). Thus, it was suspected to harbor a decelerating (by then, mildly) relativistic jet pointing away from us. About three years after its discovery, the optical spectrum of SN 2001em showed a broad Hα line, and it was therefore, reclassified as type IIn. Here, we constrain its proper motion and expansion velocity by analyzing four epochs of VLBI observations, extending to 5.4 years after the SN. The supernova is still unresolved 5.4 years after the explosion. For the proper motion, we obtain $(23{,}000 \pm 30{,}000)$ km s^{-1}, while our 2σ upper limit on the expansion velocity is 6000 km s^{-1}. These limits are somewhat tighter than those derived by Bietenholz & Bartel, and confirm their conclusion that late time emission from SN 2001em, a few years after the explosion, is not driven by a relativistic jet. VLA observations of the radio flux density, at 8.46 GHz, show a decay as $t^{-1.23\pm0.40}$ starting $\sim$ 2.7 years after the SN. Collectively, the observations suggest interaction of the SN ejecta with a very dense circumstellar medium, though the implied opacity constraints still present a challenge.

Key words: supernovae: general – supernovae: individual (SN 2001em)

1. INTRODUCTION

On 2001 September 15, Papenkova & Li (2001) reported the discovery of an apparent Supernova (SN) in the galaxy UGC 11794, also mistakenly called NGC 7112 (RA: $21^{\rm h}42^{\rm m}22\overset{\rm s}{.}9$ decl: $12^{\rm d}29^{\rm m}54^{\rm s}$; $z = 0.019493$ J2000.0). Throughout the paper, we use $H_0 = 70$ km s^{-1} Mpc^{-1}, and $\Omega_\Lambda = 1 - \Omega_M = 0.72$ (Hinshaw et al. 2008), for which the measured redshift corresponds to a proper distance of $D_p = 83.14$ Mpc and an angular distance of $D_A = 81.55$ Mpc. Early spectral line data suggested it was of type I b/c (more likely Ic; Filippenko & Chornock 2001). It was detected in the radio about two years after the explosion (Stockdale et al. 2004a), initially displaying a rising flux together with an optically thin spectral slope $F_\nu \propto t^{1.9\pm0.4}\nu^{-0.36\pm0.16}$ (4.9–15 GHz). It also showed a high X-ray luminosity of $\sim 10^{41}$ erg s^{-1} at 0.5–8 keV (Pooley & Lewin 2004). This made it a good candidate for harboring a bipolar relativistic jet pointing away from our line of sight (Granot & Ramirez-Ruiz 2004), which has by then decelerated to mildly relativistic velocities. Such late-time radio emission is expected in some type Ib/c SNe that may be associated with gamma-ray bursts (Paczyński 2001; Granot & Loeb 2003) or alternatively produce only mildly relativistic bipolar outflows, and could naturally produce a rising radio flux in the optically thin regime (Granot et al. 2002), as the jets interact with the circumstellar medium (CSM) and are decelerated.

Later observations, about three years after the explosion, Soderberg et al. (2004) showed broad Hα (FWHM 40 Å = 1800 km s^{-1}) lines that are not typical of type Ib/c SN. Observations using very long baseline interferometry (VLBI) were proposed to resolve the source or detect proper motion if it is powered by decelerating relativistic jets (Granot & Ramirez-Ruiz 2004). However, despite several attempts with various instruments, the source has not been resolved (Paragi et al. 2005; Bietenholz & Bartel 2005, 2007; Stockdale et al. 2005). An alternative explanation was suggested by Chugai & Chevalier (2006), who developed a model in which regular Newtonian ejecta from the supernova explosion collides with a dense, massive circumstellar shell (CS).

In addition to previously published VLBI observations, we add the most recent high sensitivity array (HSA) observation from 2007 February (about 5.4 years after the explosion). In order to provide the most accurate measurements and a conclusive picture for the proper motion, as well as the expansion velocity of SN 2001em, we use our observation in combination with those of Stockdale et al. (2004b) and Bietenholz & Bartel (2005, 2007).

2. OBSERVATIONS & DATA REDUCTION

We observed SN 2001em with the HSA, which consists of NRAO's Very Long Baseline Array (VLBA), the phased Very Large Array (VLA), the Robert C. Byrd Green Bank Telescope (GBT), the Arecibo Radio Telescope (AR), and the Effelsberg Radio Telescope (EB). The observation was conducted on 2007 February 5th with a total time of 10 hr at 8.4 GHz (bandwidth 32 MHz, total recording bit rate 256 Mbit s^{-1}). The VLBI data were correlated with the NRAO VLBA processor at Socorro. An analysis for modeling was done with NRAO's Astronomical Image Processing System (AIPS) and Caltech's Difmap. In addition, we also used the VLA (in A configuration) observation on 2007 February 18th, which observed the continuum of SN 2001em in L, C, and K bands over a total time of about one hour. The three previous VLBA/HSA observations from 2004 July (Stockdale et al. 2004b), 2004 November (Bietenholz & Bartel 2005), and 2006 May (Bietenholz & Bartel 2007) were re-reduced in a consistent fashion. A summary of the observations

[5] Now: Max-Planck-Institut fuer Radioastronomie, Auf dem Huegel 69, D-53121 Bonn, Germany.
[6] G.B. Taylor is also an Adjunct Astronomer at the National Radio Astronomy Observatory.

Table 1
Observational Summary

Date	Time after SN (Days)	Frequency (GHz)	Integration Time (Minutes)	Bandwidth (MHz)	Polarization	Instrument
2004 Jul 01	1021	8.410	178	32	2	VLBA
2004 Nov 22	1165	8.410	400	32	2	VLBA+AR+EB+GBT+Y27
2006 May 27	1717	8.406	423	32	2	VLBA+AR+EB+GBT+Y27
2007 Feb 04	1969	8.410	300	32	2	VLBA+AR+EB+GBT+Y27
2007 Feb 18	1983	1.465	12	50	2	VLA
		4.885	9	50	2	VLA
		22.485	20	50	2	VLA

Notes. AR = 305 m Arecibo telescope. EB = 100 m Effelsberg telescope. GBT = 105 m GBT. Y27 = phased VLA.

is presented in Table 1 including important parameters of these observations.

The data were corrected for ionospheric delay, Faraday rotation, and parallactic angle as well as for Earth's orientation. We used fringe fitting to calibrate the data for group delay and phase rate. The three datasets from previous VLBI observations have been treated equally, to ensure comparable results. Our VLBI observation of SN 2001em was phase referenced to JVAS J2145+1115 (1$^\circ\!\!.$4 away) and J2139+1423 (2$^\circ\!\!.$1 away). The switching intervals were $\sim$ 180 s for J2145+1115, $\sim$ 93 s for SN 2001em, and $\sim$ 39 s for J2139+1423, which were observed in addition about every fifth cycle. We used J2145+1423 to check our phase reference (J2145+1115) to get a measure for the quality of our phase referencing as well as a position fixed to the International Celestial Reference Frame (ICRF). In addition, we used J2139+1423 to check astrometry and the results for the possible motion within J2145+1115.

3. RESULTS

3.1. Position and Proper Motion

We obtained the results for absolute position for proper motion by fitting the fully calibrated and phase-referenced $(u,\ v)$ plane data of the observations from four epochs to a circular Gaussian model. This is a good fit for a point source, as we did not see any resolved extended emission. However, the first VLBI observation of 2004 July does not use J2139+1423 as phase-reference check as described above; instead it uses J2139+1316, which is 1$^\circ\!\!.$0 away from our pointing center. Furthermore, only the VLBA was used in this initial observation.

We plot the position including errorbars in Figure 1. We find a circle with a radius of 0.170 mas that encompasses all the observed positions. This suggests that SN 2001em shows little or no proper motion.

To get an estimate for the error of the proper motion, we plotted the positions of J2139+1423 phase referenced to J2145+1115 as shown in Figures 2 and 3, which shows according to our data a proper motion of 0.45 mas year^{-1} in the northwest direction. Piner et al. (2007) give a relative motion of the 4 components between 0.108 and 0.593 mas year^{-1} separated up to 3.5 mas from the core. This can be explained by changes in the extended emission of J2139+1423, which shows an extremely curved jet (Savolainen et al. 2006), in combination with any proper motion of the phase check calibrator. The intrinsic motion of J2139+1423 has been determined to be $< 40\ \mu$as year^{-1} (Feissel-Vernier 2003). We also assume our reference source J2145+1115 to be stationary. Using a linear relationship

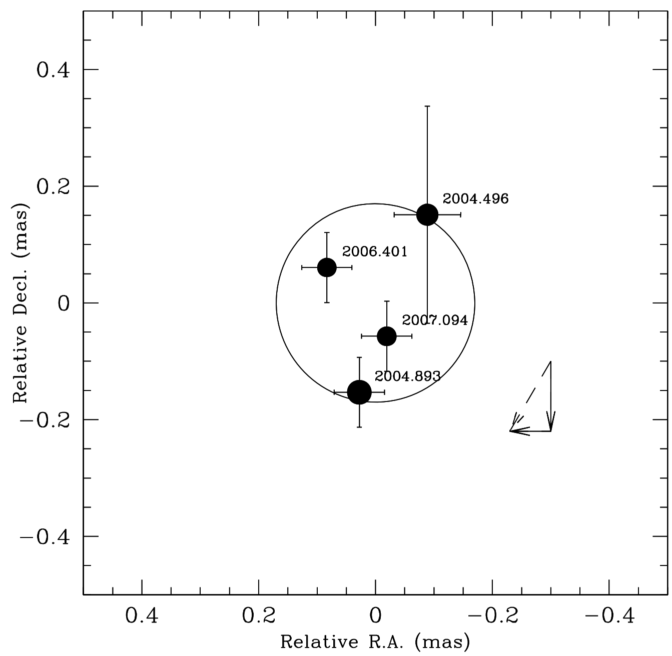

Figure 1. Positions of SN 2001em from 2004 to 2007, centered at R.A. $21^{h}42^{m}23^{s}\!\!.619$ decl. $12^{d}29^{m}50^{s}\!\!.299$ (J2000). Circle centered at the origin has a radius of 0.170 mas. The triangle on the middle right shows the projected velocity vectors in R.A. and decl. respectively, as well as the total projected velocity for a period of 2.201 years (three epochs of HSA observations).

between the stationary phase center and the apparently moving J2139+1423, that are 3$^\circ\!\!.$49 apart from each other, we find an error for the proper motion of SN 2001em of $\pm$0.184 mas year^{-1}.

This high error is not very satisfactory and yield unreasonably small χ^2 values. As shown by Pradel et al. (2006), the linear approach is not reliable. Thus, we had to find a better way to obtain a reasonable error for the positions. Using the discussion of astrometric accuracies of VLBA observations by Pradel et al. (2006) and the χ^2 value of the weighted least squares fit, we were able to reduce the position errors to 0.013 mas and 0.051 mas in R.A. and decl. respectively. Using a weighted least squares fit for the motion in R.A. and decl. separately (Figure 4), we get an error of 0.037 mas year^{-1} in R.A. and 0.071 mas year^{-1} in decl.

We obtained a proper motion of (0.030 $\pm$ 0.037) mas year^{-1} in R.A. and ($-$0.053 $\pm$ 0.071) mas year^{-1} in decl., which gives a total proper motion of

$$\mu = (0.061 \pm 0.080)\ \text{mas year}^{-1}. \tag{1}$$

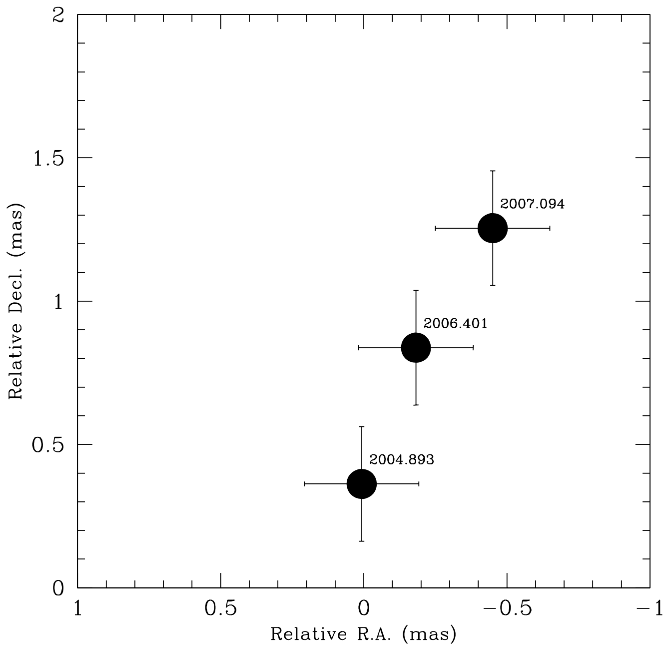

Figure 2. Positions of the phase-check calibrator, J2139+1423, from 2004 to 2007. Eight epochs of VLBA observations show an apparent relative motion of its components between 0.108 and 0.593 mas year^{-1} (Piner et al. 2007).

The proper distance to SN 2001em is 83.14 Mpc, then the proper motion gives us a projected velocity on the sky of

$$v = (24,000 \pm 32,000)\,\mathrm{km\,s^{-1}}\,. \quad (2)$$

Bietenholz & Bartel (2007) report a proper motion based on two epochs of (0.089 ± 0.093) mas year^{-1} or (33,000 ± 34,000) km s^{-1}, respectively, whereas, for the cosmological parameters we use, the latter becomes (35,000 ± 37,000) km s^{-1}.

3.2. Size Limits of the Radio-Emitting Region

Again we used the fully calibrated and phase referenced to J2145+1115/J2139+1423 (u, v) plane data to image the SN using Difmap. Figure 5 shows the VLBI image of SN 2001em on 2007 February 5. The source is not resolved. The resolution of our observation was (2.02 × 0.858) mas at $-7\overset{\circ}{.}17$.

A precise determination of the upper limit for the size of SN 2001em was obtained using Monte Carlo simulation. We again used model fitting in the (u, v) plane with a circular Gaussian model. We created 100 (u, v) datasets for a range of sizes for each epoch based on flux density and corresponding image RMS noise using AIPS task UVMOD. This creates simulated datasets with similar properties to the actual data. We found the minimum χ^2 for each simulated dataset and examined the Gaussian distribution of model fit sizes depending on the simulated source diameter defined in UVMOD. This has been done for all four epochs and a range of simulated source sizes. The combined results of the upper limits for size (FWHM diameter of the circular Gaussian) with a confidence of 95% are listed in Table 2. This means that 95% of the Gaussian distribution is below the upper size limit thus giving us a 2σ upper limit.

In Figure 6, we show a plot of the upper limit radii versus time and the linear fit to obtain an upper limit for the expansion velocity. Assuming this linear expansion behavior since its

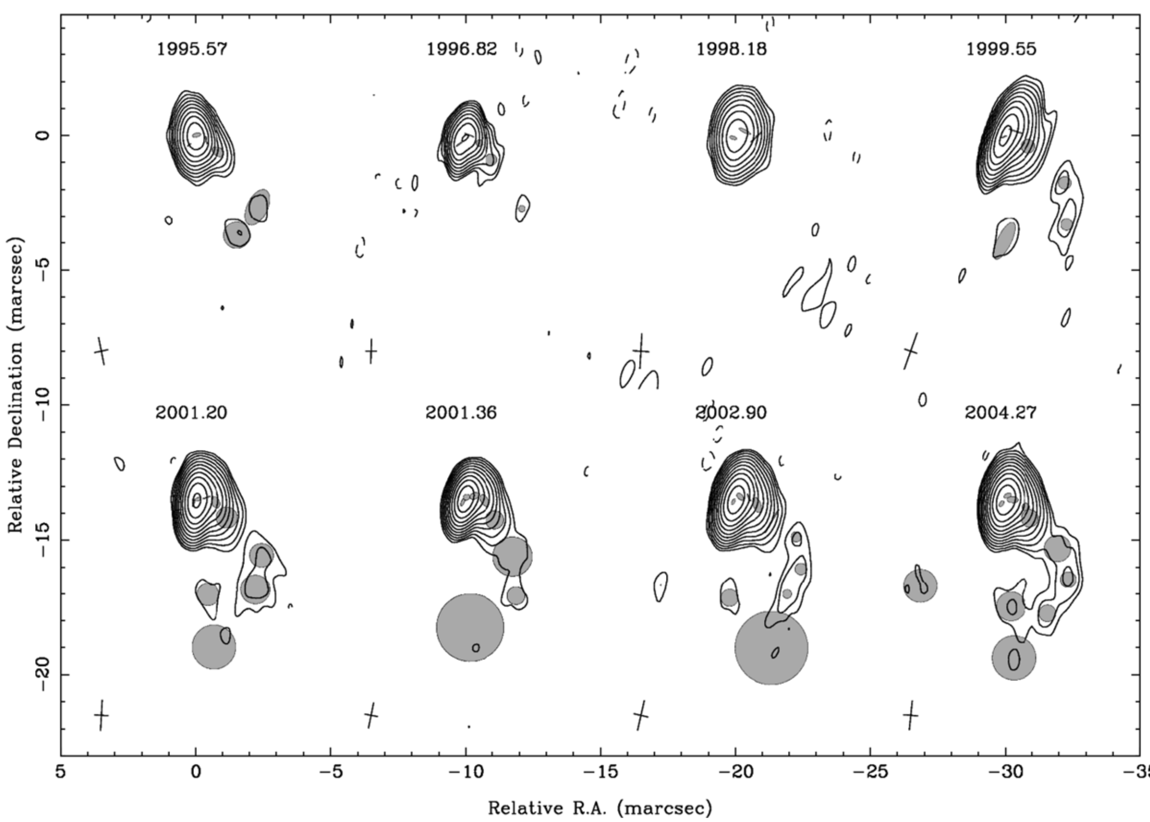

Figure 3. VLBA images of J2139+1423 (PKS 2136+141) at 15 GHz. The figure includes observations from the VLBA 2 cm survey, from the MOJAVE survey and a 15 GHz image from the multifrequency dataset observed in 2001.36 by Savolainen et al. (2006). In all images, a uniformly weighted (u, v)-grid is used. The Gaussian components fitted to the visibility data are shown as ellipses overlaid on each image. The size and orientation of the beam is shown in the lower left corner of each image (Savolainen et al. 2006). The images show clearly the existence of an extremely curved jet with an inner position angle ranging from −30° to −90°.

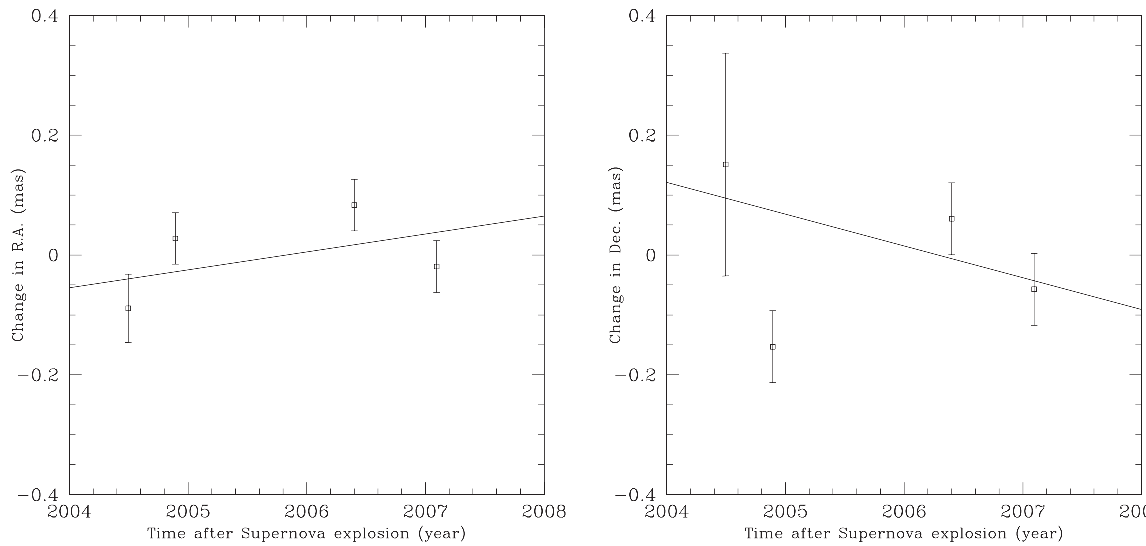

Figure 4. Weighted least square fits for position vs. time in R.A. and decl. This gives a proper motion for SN 2001em of (0.030 ± 0.037) mas year^{-1} in R.A. and (−0.053 ± 0.071) mas year^{-1} in decl.

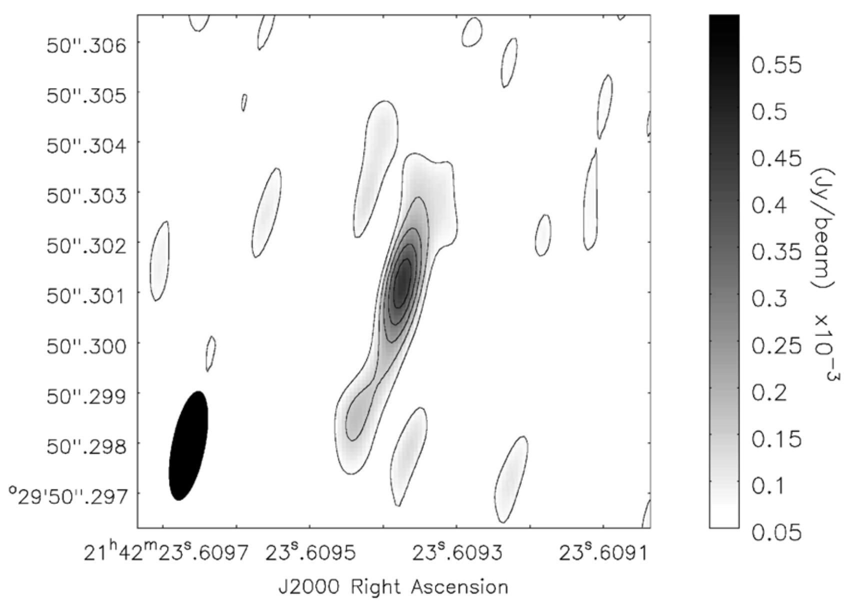

Figure 5. VLBI image of SN 2001em from 2007 February 4th. Peak brightness is 586 μJy bm^{-1}, the rms background noise was 21 μJy beam^{-1}. The contours are drawn at levels 11, 25, 39, 53, 67, 81, 95 and times 1% of the peak brightness. The lowest contour is at 3.1σ. The grey scale flux range is 550 μJy beam^{-1}. The beamsize is shown in the lower left corner.

Table 2
Results for the 2σ Upper Size Limit of the FWHM Diameter of a Circular Gaussian Point Source, Obtained from Monte Carlo Simulation

Epoch (Years)	Flux Density (mJy)	Offset R.A. (mas)	Offset decl. (mas)	RMS (μJy/beam)	Size Limit (mas)
2004.496	1.41	−0.089	0.15	59	0.19
2004.893	0.60	0.028	−0.15	36	0.23
2006.401	0.52	0.083	0.061	21	0.19
2007.094	0.59	−0.019	−0.057	21	0.16

Note. Position offsets are given using the reference position 21^{h}42^{m}23^s.619 R.A. and +12^{d}29^{m}50^s.299 decl.

discovery on 2001.704, we find a 2σ upper limit for the expansion velocity of 0.015 mas year^{-1}, which corresponds to

$$v_{\rm exp} \leqslant 6,000\,{\rm km\,s^{-1}}. \quad (3)$$

Bietenholz & Bartel (2007) report a 2σ upper limit for the average expansion velocity since the explosion of 25,800 km s^{-1}, about 4.6 years after the SN. For that same epoch, when reanalyzing the same data, we obtain a 2σ upper limit of 8,100 km s^{-1}. In contrast to Bietenholz & Bartel (2007), we used a circular Gaussian model for model fitting instead of an elliptical one which already reduces the size limit by a factor of about 2. In addition, we fit directly to the visibility data and used the Monte Carlo simulation method which, in the case of an unresolved source, improves results further compared with image plane fitting the elliptical Gaussian using the AIPS task JMFIT.

3.3. Radio Light Curve and Spectrum

Many multifrequency observations of SN 2001em have been conducted with the VLA since 2003. We present the published values and the observations from 2007 February. In Figure 7, we show the 8.46 GHz detections plotted over time since the

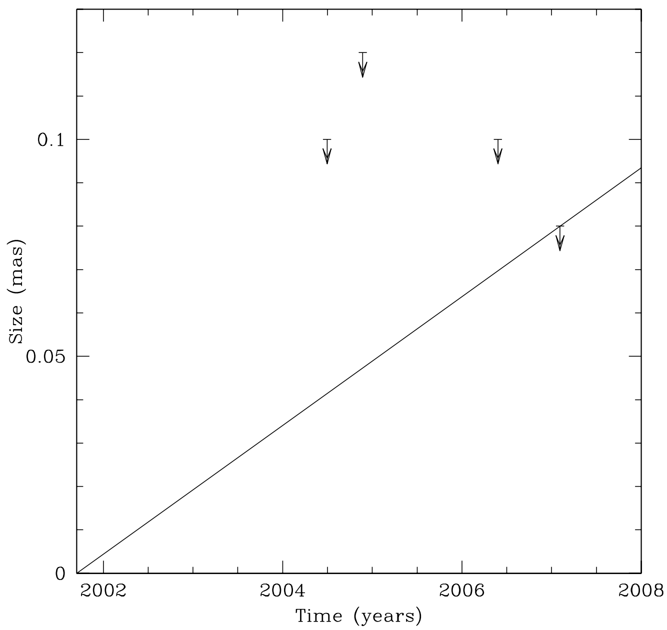

Figure 6. 2σ upper limits for the radius of SN 2001em plotted over time. The linear curve represents the 2σ upper limit for the expansion velocity of 6000 km s^{-1} plotted from 2001.7041.

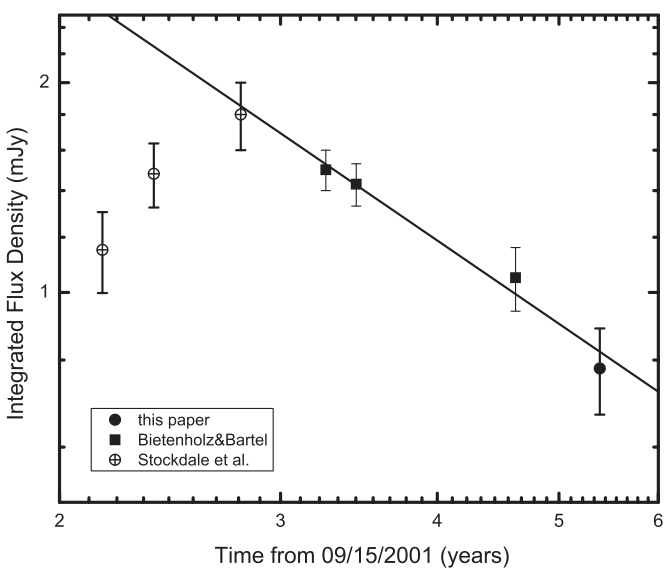

Figure 7. Plot of the 8.46 GHz light curve using our data from 2007 February and previously published values (Bietenholz & Bartel 2007; Stockdale et al. 2004a, 2004b, 2005). The plot shows a power-law decay in the light curve since the peak around 2003. The slope of the power-law fit is $y \propto t^{-1.23\pm0.40}$.

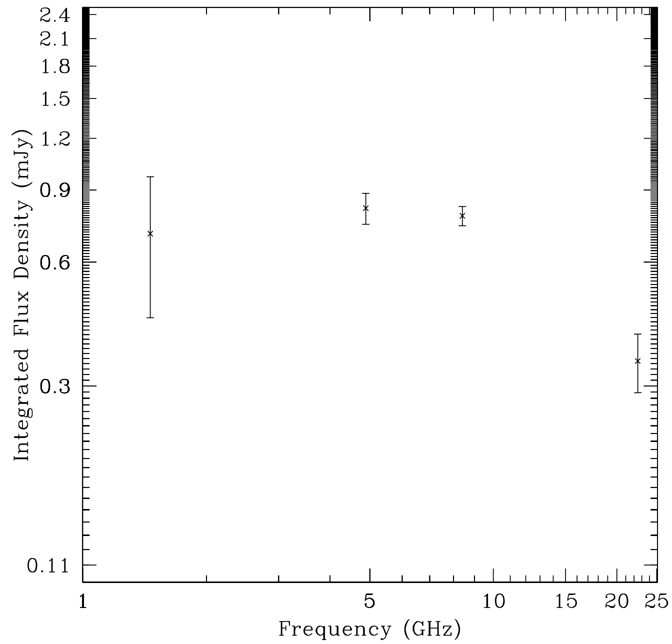

Figure 8. Observed radio spectrum using the 8 GHz flux density from the phased VLA as on 2007 February 4 and 1.2 GHz, 5 GHz, and 22 GHz observed on 2007 February 18th.

supernova explosion. From the peak brightness, the 8.46 GHz peak luminosity is $(1.54 \pm 0.10) \times 10^{28}$ erg s^{-1} Hz^{-1}. We see a power-law decay in the flux densities since its peak around 2004 (or $\sim$ 2.7 yr since the SN) with an index of $\alpha = 1.23 \pm 0.40$, i.e., $F_\nu \propto t^{-\alpha}$.

Figure 8 shows the spectrum at the time of our observations ($t = 2007.094, 2007.132$) where our measurements are at 1.46 GHz, 4.9 GHz, 8.4 GHz, and 22 GHz; the values are listed in Table 3. The 22 GHz point is a 5σ detection. The spectral index ($F_\nu \propto \nu^{-\beta}$) at the cut-off between 8.4 GHz and 22 GHz is $\beta_{\rm drop} = 0.38 \pm 0.18$ and between 4.9 and 8.4 GHz it is $\beta_{\rm plateau} = 0.077 \pm 0.011$.

Table 3
Results for Flux Densities and Corresponding Noise of SN 2001em on 2007 February 18

Frequency (GHz)	Flux Density (mJy)	Noise (mJy)
1.465	0.704	0.264
4.885	0.812	0.070
22.485	0.345	0.056

4. DISCUSSION

The lack of any apparent proper motion is consistent with other VLBI measurements of SNe. Some of these other VLBI monitored SNe include SNe 1979C (IIL) 1986J (IIn), 1987a (II peculiar), 1993J (IIb), 2001gd (IIb), and 2004et (IIP) (Bartel & Bietenholz 2003; Bietenholz et al. 2002; Pérez-Torres et al. 2002; Manchester et al. 2002; Marcaide et al. 2008; Pérez-Torres et al. 2005; Martí-Vidal et al. 2007). With a fourth epoch, we have further constrained the value reported to (24,000 ± 32,000) km s^{-1}. While such constraints on the proper motion may sometimes indicate a symmetric blast wave centered on the supernova position, in our case the 2σ upper limit on the average proper velocity (87,000 km s^{-1} $\approx 0.29c$) is much larger than that on the average expansion velocity (6000 km s^{-1}), and therefore, no proper motion is expected to be detected even for a reasonably asymmetric supernova (i.e., given the limit on the expansion velocity, we would expect to detect proper motion only for an extremely asymmetric explosion, which has not yet been observed in ordinary supernovae).

The constraint on the proper motion does, however, rule out a relativistic jet pointing away from us (Granot & Ramirez-Ruiz 2004) as the source of the radio (and X-ray) emission. In such a scenario, the current limit on the size of the emitting region allows only for a very compact emission region, and rules out a double-sided jet where both sides are visible (even if the emission from each side is from a compact region). Moreover, the limit on the proper motion rules out the possibility that only one side of the jet is visible, since for a compact

Table 4
Expansion Velocities for Type II Supernovae

Supernova	Type	Velocity (10^3 km s^{-1})	Reference
1987A	IIpec	~ 3.5	Manchester et al. (2002)
1979C	IIL	$7.4^{+0.5}_{-0.4}$	Bartel & Bietenholz (2003)
2004et	IIP	$> 15.7 \pm 2.0$	Martí-Vidal et al. (2007)
2001gd	IIb	23.0	Pérez-Torres et al. (2005)
1993J (outer shell)	IIb	~ 10.0	Marcaide et al. (2008)
1993J (inner shell)	IIb	~ 7.0	Marcaide et al. (2008)
1986J (measured 1988)	IIn	7.5	Pérez-Torres et al. (2002)
1986J (measured 1999)	IIn	6.3	Pérez-Torres et al. (2002)
2001em (measured 2006)	IIn	< 8.1	This manuscript
2001em (measured 2007)	IIn	< 6.0	This manuscript

relativistic emission region moving at an angle θ relative to our line of sight, the observed limit on the apparent velocity $\beta_{ap} = \beta \sin\theta/(1 - \beta\cos\theta) < 0.29$ implies, e.g., $\theta < 1.^{\circ}86 = 0.032$ rad for $\beta > 0.9$. Such a small angle relative to our line of sight would not produce an optically thin rising flux $\sim$ 2 years after the SN (since by that time the Lorentz factor is no more than a few and our line of sight would be well within the beaming cone of the radio emission), which was the original motivation for suggesting such an explanation.

Comparing results for SN 2001em to SN/GRB pairs 1998bw, 2003lw, and 2006aj, peak luminosities at first suggest a possible GRB event of SN 2001em, but its peak late in time does not match the pattern of SN/GRB pairs (Kaneko et al. 2007). In addition, GRB SN show much larger expansion velocities, >100,000 km s^{-1}, than what we obtained (Pihlström et al. 2007). Moreover, our results rule out even a mildly relativistic outflow with an energy comparable to that of the SN ejecta (which is $\gtrsim 10^{51}$ erg), which would not be capable of producing a GRB, and may potentially be much more common in core collapse SNe compared to highly relativistic outflows of similar energy (Granot & Ramirez-Ruiz 2004).

Our 1σ limiting value for the velocity of the radio-emitting region of a blast wave of $\sim$3000 km s^{-1} is unusually low (see Table 4) and is close to the lowest measured velocity of the radio-emitting region of any SN, reported for SN 1987A by Manchester et al. (2002) of $\sim$3500 km s^{-1}. Martí-Vidal et al. (2007) report a minimum, measured expansion velocity of (15,700 $\pm$ 2000) km s^{-1} for the radio-emitting region of the type IIP SN 2004et. Pérez-Torres et al. (2005) reported an upper limit for the expansion velocity for the radio-emitting region of the type IIb SN 2001gd of 23,000 km s^{-1}. Marcaide et al. (2008) report an evolving velocity for the radio-emitting region with the outer velocity of the radio-emitting shell to be $\sim$ 10,000 km s^{-1} and the inner velocity to be $\sim$ 7000 km s^{-1} occurring between days 1063 and 1399 since explosion. The only other type IIn SN with a measured velocity of its radio-emitting region was SN 1986J, Pérez-Torres et al. (2002) report an average expansion velocity that dropped from 7500 km s^{-1} in 1988 to 6300 km s^{-1} in 1999.

What is of particular interest is that SN 2001em, originally classified as a type Ic SN, has a low average expansion velocity. Soderberg et al. (2003) estimate that the radio-emitting region's expansion velocity, if similar to the type Ic SN 2003L, should exceed 16,000 km s^{-1} and likely be as high as 30,000 km s^{-1}. Assuming the early optical classification of Filippenko & Chornock (2001) to be valid, we might expect the blast wave of SN 2001em to have been resolved near the limit we establish had it undergone a period of rapid expansion prior to hitting a very dense CSM. Preliminary models of VLA observations suggest an average mass loss of $\sim 2.5 \times 10^{-4}$ $M_\odot$ year^{-1}, assuming wind-driven, clumpy/filamentary CSM (Weiler et al. 2002; Stockdale et al. 2007). Weiler et al. (2002) indicate that such a radio-derived mass-loss rate is slightly higher than values determined for other type IIn SNe, 1.14×10^{-4} $M_\odot$ year^{-1} for SN 1988Z and 4.28×10^{-5} $M_\odot$ year^{-1} for SN 1986J. However, depending on when this shell of material was ejected, the actual mass-loss event was likely much higher than this average value. Due to lack of any radio observations within the first two years following the explosion, we are unable to place any reasonable upper bound on this mass-loss rate.

We obtained a 2σ upper size limit of the radio-emitting region of 0.98×10^{17} cm after 5.4 years, which is marginally consistent with the model of Chugai & Chevalier (2006), in which the ejecta collides with a dense circumstellar shell at a radius of $\sim 6 \times 10^{16}$ cm after $\sim$ 2.6 yr (note that a thin-emitting shell, that is more relevant for their model, gives an upper limit on the radius and average expansion velocity that is smaller by $\sim$ 10% compared to the circular Gaussian that we have used). Our results support the view that at a very early epoch, this supernova has evolved from a type Ib/c SN with little circumstellar interaction to a type IIn with strong circumstellar interaction. The classification as type IIn SN was in part due to the late-time observation of a narrow Hα line (Soderberg et al. 2004). This detection indicates the existence of cool shocked circumstellar gas (Chugai & Chevalier 2006).

The large X-ray luminosity of $L_X \approx 10^{41}$ erg s^{-1} at $t \approx$ 950 days implies a radiated energy in the X-ray range (0.5–8 keV) of the order of $t\,L_X(t) \sim 10^{49}$ erg (assuming the typical time for variation in L_X is $\Delta t \sim t$). This sets a strict lower limit on the energy that was dissipated and converted into internal energy by that time of $E_{\rm dis}(t) \gtrsim 10^{49}$ erg. However, the true value of $E_{\rm dis}(t)$ is most likely significantly higher than this lower limit, due to the combination of various inefficiencies in the conversion of the dissipated energy into radiation in the X-ray range within the dynamical time. First, the total radiated energy is probably somewhat larger than the measured value, since νF_ν is still rising within the observed energy range ($\nu F_\nu \propto \nu^{0.9\pm0.35}$; Pooley & Lewin 2004) and should therefore peak at higher energies. Second, not all of the dissipated energy is given to the electrons, and most of it can go into protons (or other ions; both the thermal population or cosmic rays) or magnetic fields, and thus would not be radiated away. Finally, even the energy that does go into electrons is not always radiated away efficiently on the dynamical time. Given all the above, we consider $E_{\rm dis}(t) \gtrsim 10^{51}$ erg to be a more realistic estimate of the energy that has been dissipated by time t (although a somewhat lower value might still be possible under some circumstances). This would suggest a deceleration time of $t_{\rm dec} \lesssim 10^3$ days, i.e., that by that time the ejecta had interacted with a surrounding mass comparable to its own mass (Granot & Ramirez-Ruiz 2004; Chevalier 2007).

Moreover, the radio light curve also suggests a deceleration time of $t_{\rm dec} \sim 10^3$ days, while our limits on the source size imply that the typical initial velocity v_0 of the mass that has decelerated by $t_{\rm dec}$ is $\lesssim$ 8000 km s^{-1}. For an external density $\rho = Ar^{-2}$, this implies $A_* = A/(5 \times 10^{11}\ {\rm g\ cm^{-1}}) \gtrsim 7.3 \times 10^3 (E/10^{51}\ {\rm erg})(t_{\rm dec}/10^3\ {\rm days})^{-1}(v_0/8 \times 10^3\ {\rm km\ s^{-1}})^{-3}$ that corresponds to a mass-loss rate of $\dot{M} \gtrsim 0.073 (v_w/10^3\ {\rm km\ s^{-1}}) (E/10^{51}\ {\rm erg})(t_{\rm dec}/10^3\ {\rm days})^{-1}(v_0/8 \times 10^3\ {\rm kms^{-1}})^{-3}\ M_\odot\ {\rm yr^{-1}}$, where v_w is the stellar wind velocity of the progenitor star, assuming a quasi-steady wind during the relevant timescale.

Such a high mass-loss rate may suggest an episodic mass-ejection event, rather than a steady wind, that would result in a dense CSM shell. The required mass of such a CSM shell is at least comparable to that of the SN ejecta that was decelerated until $t_{\rm dec}$, $M_{\rm shell} \gtrsim M_0 = 2E/v_0^2 = 1.57(E/10^{51}\,{\rm erg})(v_0/8\times10^3\ {\rm km\ s^{-1}})^{-2}\ M_\odot$. Now, let us consider the opacity of this part of the original SN ejecta, of mass M_0 and initial velocity v_0, at earlier times. Assuming one free electron per proton mass, its Thompson optical depth at $t < t_{\rm dec}$ would be $\tau_T = \sigma_T E\big/\big(2\pi m_p v_0^4 t^2\big) = 23(E/10^{51}\,{\rm erg})(v_0/8\times10^3\ {\rm km\ s^{-1}})^{-4}(t/30\,{\rm days})^{-2}$, while additional opacity from other parts of the ejecta could only add to the total optical depth. This opacity is somewhat large for the time near the peak of the supernova optical light curve ($t \sim 30\,{\rm days}$), and may become a more severe problem if v_0 turns out to be lower than the current upper limit on it.

5. SUMMARY & FUTURE OBSERVATIONS

It is clear that SN 2001em exhibits radio properties consistent with a type II SN with a significant CSM/blast wave interaction. Future VLBI monitoring is recommended. As the blast wave expands, we will be able to further constrain or eventually determine the average velocity of the blast wave. SN 2001em has faded considerably at 8 GHz over the last few years but is still readily detectable with an estimated flux density at the end of 2008 of 0.55 mJy. With HSA recording rates expected to increase to 4096 Mbps by 2011, the thermal noise level of the HSA at 8 GHz should decrease to $\sim$1.40 μJy beam^{-1} at an integration time of 8 hr, thus keeping pace with the fading of SN 2001em which is expected to follow a power-law decay. At the end of 2008, an HSA observation (512 Mbit s^{-1}) would have a signal-to-noise ratio (S/N) of 139 and by 2011 with 4096 Mbit s^{-1} bandwidth an S/N of 288 based on 1σ using natural weighting.

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. J.G. gratefully acknowledges a Royal Society Wolfson Research Merit Award. E.R. acknowledges support from the DOE Program for Scientific Discovery through Advanced Computing (SciDAC; DE-FC02-01ER41176). C.J.S. is a Cottrell Scholar of the Research Corporation. We thank an anonymous referee for constructive comments.

REFERENCES

Bartel, N., & Bietenholz, M. F. 2003, ApJ, 591, 301
Bietenholz, M. F., & Bartel, N. 2005, ApJ, 625, L99
Bietenholz, M. F., & Bartel, N. 2007, ApJ, 665, L47
Bietenholz, M. F., Bartel, N., & Rupen, M. P. 2002, ApJ, 581, 1132
Chevalier, R. A. 2007, RevMexAA Conf. Ser., 30, 41
Chugai, N. N., & Chevalier, R. A. 2006, ApJ, 641, 1051
Feissel-Vernier, M. 2003, A&A, 403, 105
Filippenko, A. V., & Chornock, R. 2001, IAU Circ., 7737, 3
Granot, J., Panaitescu, A., Kumar, P., & Woosley, S. E. 2002, ApJ, 570, L61
Granot, J., & Loeb, A. 2003, ApJ, 593, L81
Granot, J., & Ramirez-Ruiz, E. 2004, ApJ, 609, L9
Hinshaw, G., et al. 2008, ApJS, in press, arXiv:0803.0732
Kaneko, Y., et al. 2007, ApJ, 654, 385
Manchester, R. N., Gaensler, B. M., Wheaton, V. C., Stavely-Smith, L., Tzioumis, A. K., Bizunok, N. S., Kesteven, M. J., & Reynolds, J. E. 2002, PASA, 19, 207
Marcaide, J. M., et al. 2008, ApJ, submitted
Martí-Vidal, I., et al. 2007, A&A, 470, 1071
Paczyński, B. 2001, Acta Astron., 51, 1
Papenkova, M., Li, W. D., Wray, J., Chleborad, C. W., & Schwartz, M. 2001, IAU Circ., 7722, 1
Paragi, Z., Garrett, M. A., Paczyński, B., Kouveliotou, C., Szomoru, A., Reynolds, C., Parsley, S. M., & Ghosh, T. 2005, Mem. Soci. Astronom. Itali., 76, 570
Pérez-Torres, M. A., Alberdi, A., Marcaide, J. M., Guirado, J. C., Lara, L., Mantovani, F., Ros, E., & Weiler, K. W. 2002, MNRAS, 335, L23
Pérez-Torres, M. A., et al. 2005, MNRAS, 360, 1055
Pihlström, Y. M., Taylor, G. B., Granot, J., & Doeleman, S. 2007, ApJ, 664, 411
Piner, B. G., Mahmud, M., Fey, A. L., & Gospodinova, K. 2007, AJ, 133, 2357
Pooley, D., & Lewin, W. H. G. 2004, IAU Circ., 8323, 2
Pradel, N., Charlot, P., & Lestrade, J.-F. 2006, A&A, 452, 1099
Savolainen, T., Wiik, K., Valtaoja, E., Kadler, M., Ros, E., Tornikoski, M., Aller, M. F., & Aller, H. D. 2006, ApJ, 647, 172
Soderberg, A. M., Gal-Yam, A., & Kulkarni, S. R. 2004, GRB Coordinates Network, 2586, 1
Soderberg, A. M., Kulkarni, S. R., Berger, E., Chevalier, R. A., Frail, D. A., Fox, D. B., & Walker, R. C. 2003, ApJ, 621, 908
Stockdale, C., Kelley, M. T., Weiler, K. W., Panagia, N., & Sramek, R. A. 2007, American Astronomical Society Meeting Abstracts, 211, #105.21
Stockdale, C. J., et al. 2005, IAU Circ., 8472, 4
Stockdale, C. J., Kelley, M. T., Weiler, K. W., Panagia, N., Sramek, R. A., Marcaide, J. M., Williams, C. L. M., & Van Dyk, S. D. 2007, American Institute of Physics Conference Series, 937, 264
Stockdale, C. J., Van Dyk, S. D., Sramek, R. A., Weiler, K. W., Panagia, N., Rupen, M. P., & Paczynski, B. 2004a, IAU Circ., 8282, 2
Stockdale, C. J., Van Dyk, S. D., Weiler, K. W., Sramek, R. A., Panagia, N., Rupen, M. P., Paczynski, B., & Weiler, K. W. 2004b, BAAS, 36, 1464
Weiler, Kurt W. Panagia, Nino Montes, Marcos J., & Sramek, Richard A. 2002, ARA&A, 40, 387