# Supernova SN2001em

F. K. Schinzel, C. Wilcox, and T. E. Wofford

*Astr 423, Professor Greg Taylor*
*University of New Mexico*

May 8, 2007

## ABSTRACT

On February 18th, 2007, we observed SN2001em with the VLA in D configuration at 1.4 GHz, 4.8 GHz and 22 GHz. We obtained an upper limit for the true magnetic field strength, if observed to be synchrotron self-absorbed, of $B_{SSA} < 4 \cdot 10^{12} G$. The spectral index we found to be, $\alpha = -0.57 \pm 0.17$. The flux densities at 1.4 Ghz, 4.8 Ghz and 22 Ghz, (0.709 ± 0.269) mJy, (0.812 ± 0.070) mJy and (0.345 ± 0.056) mJy, thus the newly obtained flux density spectrum reveals no surprises. We weren't able to resolve SN2001em and therefore we can't find further evidence for the existence of a relativistic jet.

## 1. Introduction

The supernova remnant SN2001em is an odd Type I b/c supernova that occurred probably in the galaxy UGC11794 and was later redeclared to be of Type IIn based on narrow hydrogen line observation. On September 15, 2001, Papenkova and Li reported the discovery of an apparent supernova by Lick Observatory and Tenagra Observatory Supernova Searches (LOTOSS). Its apparent magnitude was approximately 18.5 determined by unfiltered images obtained by the Katzman Automatic Imaging Telescope (KAIT). It was reported to be located at R.A. = $21^{\rm h}\!.\,42^{\rm m}\!.\,23^{\rm s}\!.66$, Dec. = $+12^{\circ}\!.\,29'\!.\,50''\!.9$ (equinox 2000.0), Papenkova et al. (2001). Figure 1 shows their unfiltered image taken at that time.

Early spectral data by Filippenko & Chornock (2001) showed that it was a Type I b/c supernova but measurements by Soderberg et al. (2004) yielded broad (FWHM of 40 Å = 1800 km/s) $H_\alpha$ lines that are not typical for this class of supernova. Figure 2 presents the observed spectrum of SN2001em with those of typical Type IIn SN. Both Radio and X-ray emission was detected from this source just two years after the initial explosion. Stockdale et al. (2004) reported the radio flux density increased from (1.151 ± 0.051) mJy to (1.480 ± 0.052) mJy at 8.460 Ghz from October 2003 to January 2004. They also reported that the spectral index was quite steep at $\alpha$ = -0.36 0.16, where S $\propto \nu^{\alpha}$. This indicated optically thin synchrotron emissions which is astonishing for such a late observation of about 1000 days after the supernova explosion. Pooley & Lewin (2004), using Chandra, measured X-ray emission with a 0.5-8 keV luminosity of about 1041 erg/s. They

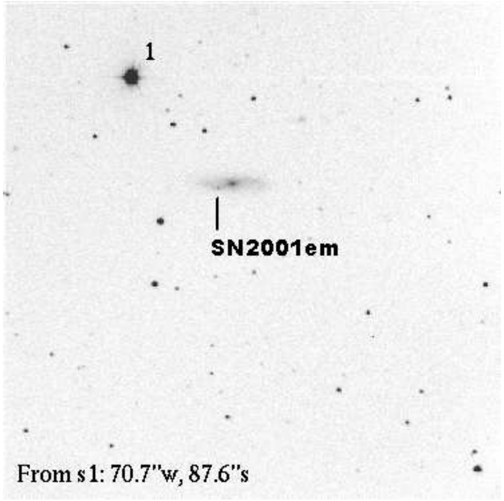

Fig. 1.— Image of SN2001em in UGC 11794, an unfiltered image taken with the 0.8-m Tenagra II telescope by J. Wray, C. W. Chleborad, and M. Schwartz on Sept. 15.3. The object can be seen on the lower left of the galaxy.

also determined its position to be R.A. = $21^{\rm h}\,42^{\rm m}\,23^{\rm s}\!.60$, Dec. = $+12^\circ\,29'\,50''\!.3$ (equinox 2000.0; $\pm\,0''\!.5$ in each coordinate), which compares very well with the coordinates obtained by radio and optical observations.

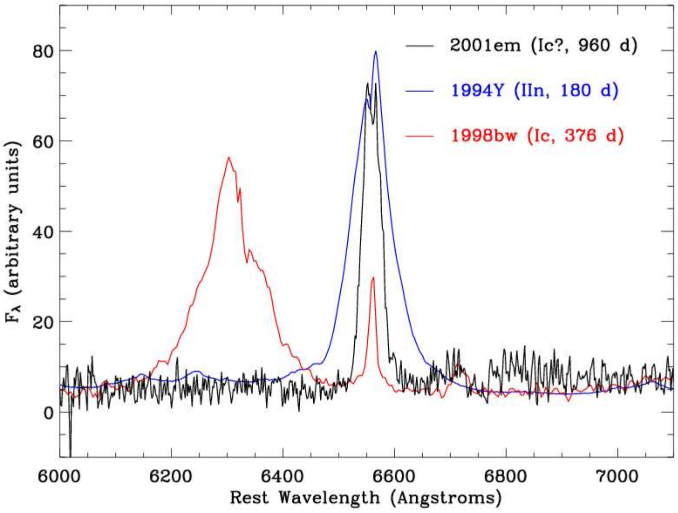

Fig. 2.— A comparison between the spectrum of SN 2001em obtained by Soderberg et al. (2004) and those of type IIn SN 1994Y (age 180 day; Filippenko 1997, ARA&A, 35, 309) and the type Ic SN 1998bw (age 376 days; Patat et al. 2001, ApJ, 555, 900), taken from the data base presented by Poznanski et al. (2002, PASP, 114, 833) and Gal-Yam et al. (2004, astro-ph/0403296).

It was suggested, first by Granot & Ramirez-Ruiz (2004), that SN2001em might be a jet-driven gamma ray burst candidate, with the jet oriented far from the line of sight so that the gamma ray burst (GRB) would not be visible from Earth. At a distance of approximately 80 Mpc, the supernova is close enough to be resolved if it is expanding relativistically. Bietenholz & Bartel (2005) made VLBI observations of SN2001em with the full high sensitivity array at 8.4 GHz in November of 2004, three years after the explosion, to test the conjecture that SN2001em be a jet-driven gamma ray burst with the jet oriented far from the line of sight. The image can be seen in Figure 3, below. They determined the size of SN2001em and were able to resolve it at a resolution of approximately 0.9 mas. The 3-$\sigma$ upper limit on the major axis angular size of the radio source was 0.59 mas, which is the full-width at half-maximum of an elliptical Gaussian. This corresponds to an expansion velocity of approximately 70,000 km/s at a distance of 80 Mpc. No low-brightness jet was seen in their observations to a level of 4% of peak brightness. Instead, assuming a spherical-shell geometry like typical supernovae, they found the angular radius of SN2001em to be 0.17 mas implying an expansion velocity of 20,000 km/s, which, of course, is much more comparable to the expansion velocities of typical supernova shells. Thus, their observations are inconsistent with a relativistically expanding radio source in SN2001em, but are consistent with a supernova show origin for the radio emission from the object.

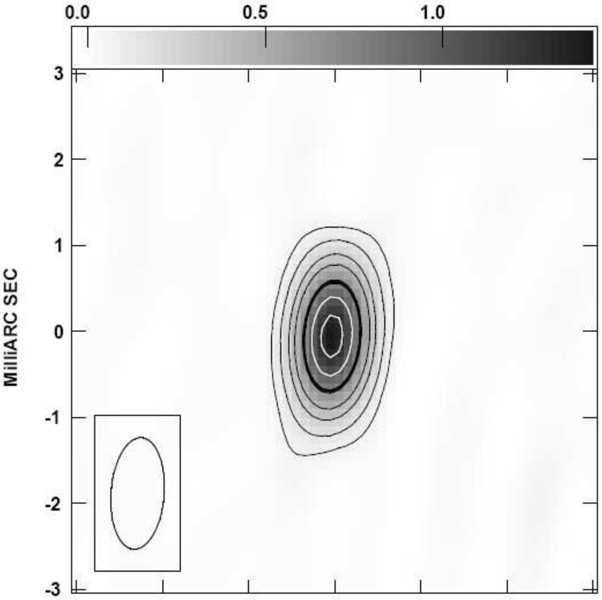

Fig. 3.— A VLBI image of SN 2001em on 2004 November 22. The peak brightness was 1.46 mJy bm$^{-1}$ and the rms background was 17 $\mu$Jy bm$^{-1}$. The contours are drawn at -4, 4, 10, 20, 30, 50, 70 and 90% of the peak brightness, with the lowest contour being at 3$\sigma$, and the 50% contour being emphasized. The greyscale is labeled in mJy bm$^{-1}$.(Bietenholz & Bartel 2005)

Some four months after Bietenholz & Bartel (2005) made their measurements, Paragi et al.

(2005) observed SN2001em using the e-VLBI with Arecibo, Cambridge, Jodrell Bank, Onsala, Torun and Westerbork, and the Multi-Element Radio Linked Interferometer Network (MERLIN). They observed SN2001em on March 11, 2005 at a frequency of 1.6 GHz. Paragi et al. (2005), analyzed the data taken with MERLIN and produced the image of SN2001em at 1.6 GHZ, seen in Figure 4.

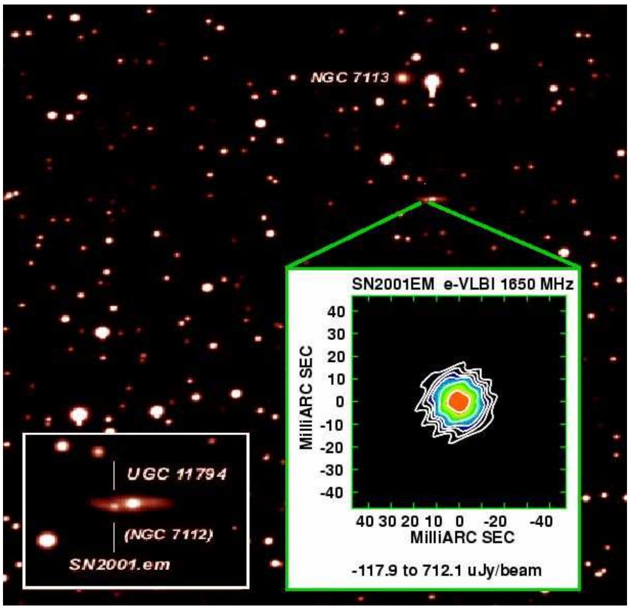

Fig. 4.— e-VLBI detection of SN2001em at 1.6 Ghz.(Paragi et al. 2005)

## 2. Observations

On February 18th, 2007, we used NRAO's Very Large Array (VLA) in D configuration, giving us high sensitivity, but not very great angular resolution. We had a total telescope time of 2 hours for the observation of SN2001em and a second project looking for water masers, which doesn't give us a great exposure time, but good enough for detecting and obtaining the flux of SN2001em. We used L-Band, C-Band and K-Band with two IFs, each having a bandwidth of 50 MHz (effective 43 MHz). 3C48 was chosen as absolute flux calibrator, J2139+143 was used for phase calibration in a switching cycle between SN2001em and calibrator of about 10 min. Table 1 shows time on source, expected thermal noise and angular resolution. We had cloud cover and windy weather conditions during our observation, which is not taken into account for the calculation of RMS noise and brightness temperature. First evaluation of the obtained data showed that EVLA antenna 21 was out, as well as some problems with baselines concerning antenna 17 and 18, which have been flagged. During the whole observation no shadowing of antennas occurred, due to SN2001em's high position in the sky.

Table 1: Parameters of Observation, RMS noise and brightness temperature obtained by using the VLA exposure calculator provided by NRAO, the synthesized beam width was obtained from "THE VERY LARGE ARRAY OBSERVATIONAL STATUS SUMMARY" (20 October 2006), NRAO.

| Band | time on source | time on flux cal. | RMS noise phase cal. | RMS brightn. (mJy/beam) | HPBW Temp. in K | arcsec |
|---|---|---|---|---|---|---|
| L (1.46 GHz) | 640s | 90s | 140s | 0.084 | 0.025 | 44.0 |
| C (4.89 GHz) | 530s | 90s | 130s | 0.089 | 0.027 | 14.0 |
| K (22.49 GHz) | 1170s | 120s | 240s | 0.108 | 0.032 | 2.8 |

The analysis was carried out with NRAO's Astronomical Image Processing System (AIPS). For absolute flux calibration we used the provided models of 3C48, for phase calibration, as well as SN2001em, we used the default point source model. The absolute flux calibration was set with the AIPS task SETJY. Calibration for each source was done using the task CALIB and GETJY to derive the flux density of the gain calibrator. L-Band data showed a poor dynamic range, which we tried to improve by using several iterations of self calibration using CALIB, but showed little success. Maybe by playing with the myriad of provided input parameters of CALIB, the dynamic range can be even more improved. The large error bar of the L-Band flux density is a result of this. The flux density of SN2001em was determined using the tasks IMAGR and JMFIT, as well as the procedure INPFIT, to define the area and approximate peak flux density, the Gaussian is fit onto.

## 3. Results

Analysis of our data shows the expected spectral distribution, peaking somewhere between 5 GHz and 1.4 GHz (refer to table 2). Comparing our results to the already reduced 8 GHz data provided by G. B. Taylor, which had a very long exposure time and therefore lower thermal noise, there seems to be a systematic problem with either calibration or the short observation time. Our data points are consistently lower. Another explanation could be, that the background galaxy contributes towards the integrated flux. Note, the bad detection at 1.46 GHz with a dynamic range of only 3, which doesn't seem very convincing, see previous section.

Despite the above problems we can determine the spectral index to be, $\alpha = -0.57 \pm 0.17$ (figure 5), within a reasonable limit, if the 8 GHz point is ignored. This steepening of the spectral index, compared to the one determined by Stockdale et al. (2004), was expected. Figure 5 also shows a comparison of our data, to the data published by Stockdale et al. (2004), Bietenholz & Bartel (2005) and Paragi et al. (2005). We see the expected overall decline in flux density over the period of about 3.5 years and the shift of the spectral peak toward lower frequencies.

To determine its angular size, we used the fitted Gaussian component of JMFIT. This gives us an upper limit for its actual size and the true magnetic field strength if we assume that the

Table 2: Results of our data retrieved using JMFIT and assuming an error of peak RMS + 3% flux calibration error. The 8 GHz data was observed Feb. 4th 2007 (BG162) and reduced by G. B. Taylor.

| Band | Peak flux<br>mJy/beam | RMS<br>mJy/beam | Dynamic range | Integrated flux<br>mJy | Peak position<br>(R.A./Dec.) |
|---|---|---|---|---|---|
| L (1.46 GHz) | 0.864 | 0.296 | 3 | 0.709 ± 0.269 | $21^{h}_{.}42^{m}_{.}23^{s}_{.}03$,<br>$+12^{\circ}_{.}29'_{.}52''_{.}5$ |
| C (4.89 GHz) | 0.866 | 0.049 | 18 | 0.812 ± 0.070 | $21^{h}_{.}42^{m}_{.}23^{s}_{.}57$,<br>$+12^{\circ}_{.}29'_{.}49''_{.}9$ |
| X (8.41 Ghz) | 0.700 | 0.017 | 40 | 0.778 ± 0.042 | $21^{h}_{.}42^{m}_{.}23^{s}_{.}61$,<br>$+12^{\circ}_{.}29'_{.}50''_{.}4$ |
| K (22.49 GHz) | 0.380 | 0.050 | 8 | 0.345 ± 0.056 | $21^{h}_{.}42^{m}_{.}23^{s}_{.}63$,<br>$+12^{\circ}_{.}29'_{.}49''_{.}9$ |

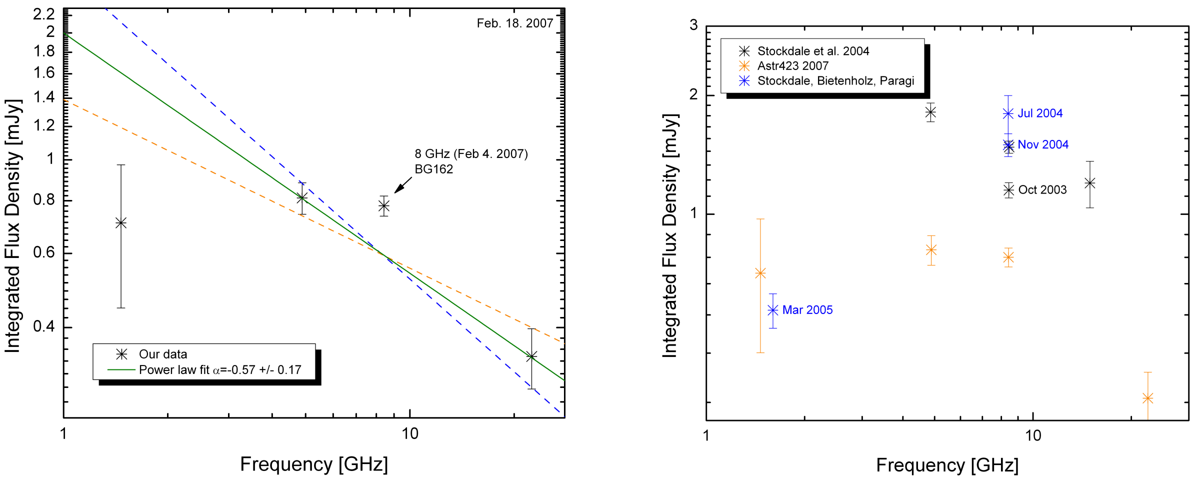

Fig. 5.— Left: Our obtained data points plotted to determine spectral index $\alpha$, $S \propto \nu^{\alpha}$. Right: Our data compared with those of Stockdale et al. (2004), Bietenholz & Bartel (2005) and Paragi et al. (2005).

observed mechanism is synchrotron self-absorbed (SSA). We obtain the magnetic field using the parameters of table 3, the integrated flux density of table 2 and equation 1,

$$B_{SSA}(\nu,\theta,S_\nu) = \left(\frac{2}{3}\cdot\left(\frac{2\pi}{e}\right)^{1/2}\cdot\frac{m_e^{3/2}\theta^2\nu^{5/2}}{S_\nu}\right)^2 \tag{1}$$

for $e = 4.8\cdot 10^{-10}\,e.s.u.$ and $m_e = 9.109\cdot 10^{-28}\,g$. Figure 6 shows a contour plot of SN2001em in 8.4 GHz using the already reduced data by G. B. Taylor and the AIPS task CNTR. To the right of SN2001em, we can see a slope which seems to be part of the background galaxy UGC 11794.

Table 3: Major and minor axes of the fitted Gaussian models using JMFIT, results for magnetic fields assuming synchrotron radiation, calculated using equations 1 and 4.

| Freq. $\nu$ $10^9$ Hz | major axis arcsec | minor axis arcsec | $\theta$ $10^{-4}$ rad | B SSA $10^{12}$ G | B mE $10^{-8}$ G |
|---|---|---|---|---|---|
| 1.46 | 53 ± 44 | 31 ± 18 | 2.6 ± 2.1 | 2.5 ± 8.3 | 9.8 ± 5.5 |
| 4.89 | 11.805 ± 0.038 | 10.026 ± 0.032 | 0.5723 ± 0.0018 | 2.00 ± 0.35 | 26.4 ± 6.0 |
| 8.41 | 6.81 ± 0.16 | 2.894 ± 0.066 | 0.3299 ± 0.0075 | 3.62 ± 0.51 | 47.6 ± 9.6 |
| 22.49 | 3.23 ±0.41 | 1.69 ± 0.22 | 0.156 ± 0.020 | 126 ± 76 | 64 ± 12 |

The calculated magnetic fields assuming SSA is in the order of $10^{12}$ G, which sounds to be a reasonable upper limit compared to the approximate surface field of a neutron star of $10^{12}$ G, which might have formed or is at the verge to form, when the core collapsed. The error for $B_{SSA}$ was calculated using error propagation, assuming no error for the frequency $\nu$ (equations 2 and 3).

$$\sigma_{B_{SSA}} = \sqrt{\left(\frac{dB_{SSA}(\theta,S_\nu)}{d\theta}\right)^2\cdot\sigma_\theta^2 + \left(\frac{B_{SSA}(\theta,S_\nu)}{dS_\nu}\right)^2\sigma_{S_\nu}^2} \tag{2}$$

$$= \sqrt{\left(\frac{32m^3\pi\theta^3\nu^5}{9eS_\nu^2}\right)^2\sigma_\theta^2 + \left(-\frac{16m^3\pi\theta^4\nu^5}{9eS_\nu^3}\right)^2\sigma_{S_\nu}^2} \tag{3}$$

Now we also compare the result of $B_{SSA}$ with the calculated minimum energy magnetic field produced by synchrotron radiation of this source $B_me$, (equation 4) as given by Miley (1980) using the suggested simplifications. Here we use both major ($\theta_x$) and minor ($\theta_y$) axis of the Gaussian fit for our calculation. Results are shown in table 3. The errors are calculated the same way like for $B_{SSA}$, using error propagation.

$$B_{me} = 5.69\cdot 10^{-5}\left[2\cdot(1+z)^{3-\alpha}\frac{1}{\theta_x\,\theta_y\,s\,\sin^{\frac{3}{2}}\Phi}\cdot\frac{S_\nu}{\nu^\alpha}\cdot\frac{\nu_2^{\alpha+\frac{1}{2}}-\nu_1^{\alpha+\frac{1}{2}}}{\alpha+\frac{1}{2}}\right]^{\frac{2}{7}} G \tag{4}$$

The distance to SN2001em is given by Papenkova et al. (2001) to be s ≈ 80 Mpc, assuming $H_0 = 70$ km Mpc$^{-1}$ s$^{-1}$, using the redshift of UGC 11794, z = 0.019493. For the spectral index, we use the value determined above, the angle between the uniform magnetic field and the line of sight, is assumed to be $\Phi = 90°$, because we think the radiation is beamed toward us. For the frequency range, we used the values suggested by Miley (1980), $\nu_1 = 0.01$ GHz and $\nu_2 = 100$ GHz. By comparing the results between SSA and minimum energy approach, we see that the minimum energy magnetic field strength seems to be missing out a lot of the field strength, also I would be careful to draw to many conclusions by this. The calculated field using SSA is only an upper limit, the actual field is probably smaller than what the calculation yields. Obviously a major part of the emission is driven by SSA, but as Chugai & Chevalier (2006) suggests, we should also have a look at free-free absorption, which seems to be playing a role, if we try to find a conclusive fit to our data points. This fit should work for the data by Stockdale et al. (2004) as well as for ours, in order to tell us something about the underlying energy source.

$$T_b = \frac{S_\nu \cdot \lambda^2}{2\,k\,\theta_x\,\theta_y} \tag{5}$$

We determined the brightness temperature of the emission using equation 5. For 1.4 GHz, 4.8 GHz, 8.4 GHz and 22 GHz we determined it to be, (0.28 ± 0.30) K, (0.397 ± 0.034) K, (0.774 ± 0.049) K and (0.173 ± 0.039) K.

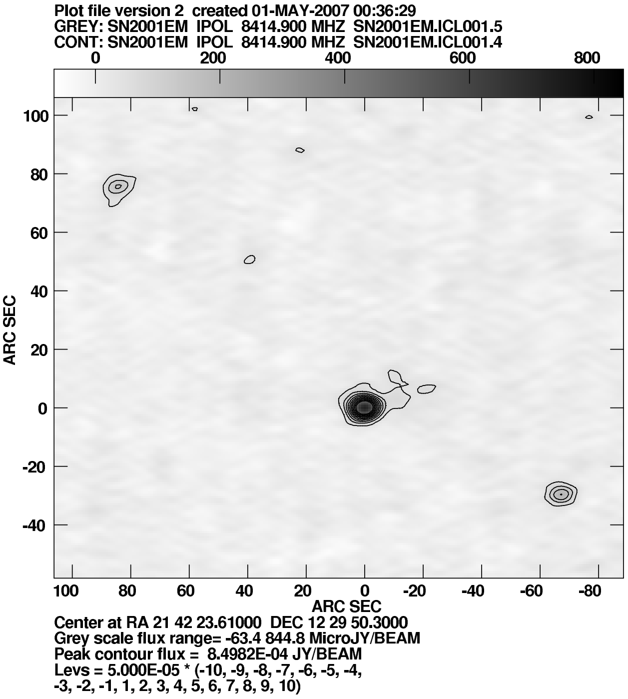

Fig. 6.— Unresolved long time exposure of SN2001em at 8.4 GHz, note some part of the background galaxy is visible toward the right of SN2001em.

The 8 GHz lightcurve (figure 7) didn't reveal any surprises, because of a lack in data between 2004 and 2007 we don't know enough to tell something about how steep the decline was. The

Gaussian fit gives an idea and suggests only a very slow decrease of flux density over the future.

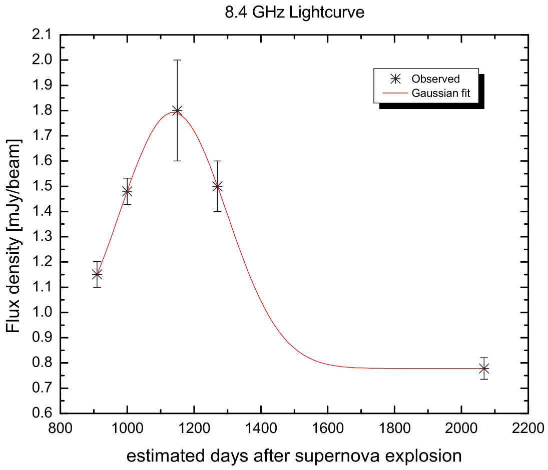

Fig. 7.— 8.4 GHz lightcurve, with Gaussian fit to it, which suggests that the peak flux density was around July 2004 and decreased since then. The slow decline of the lightcurve over time fits the classification as Type IIn SN.

## 4. Discussion

We were able to give some upper limits for size between 30 and 3 arcsec, but recent and maybe future VLBI observations will give much better limits and also a limit for the expansion velocity. Our observation was limited in resolution, because of the VLA being in D configuration. We also got an upper limit for the minimum energy magnetic field as well as the magnetic field assuming synchrotron self absorption, which seems to be a major mechanism, $B_{SSA} < 4 \cdot 10^{12} G$. The spectral index we found to be, $\alpha = -0.57 \pm 0.17$, within reasonable error limits and doesn't seem to be affected by the short exposure time of our observation. Unfortunately the 1.4 GHz observation wasn't as good as expected, we got a detection, but even though trying self-calibration we couldn't get a better result in our data reduction.

For future analysis and observations, we should have a closer look at spectral line data. Maybe we can learn more about the constituents of the perceived hydrogen envelope. We could also rule out the existence of late-time spectrum emissions from O-I and Ca-II. If these emissions are detected, we might have to rethink what we actually know about the composition of ejecta and our classification of supernovae, because finding O-I, Ca-II as well as Hydrogen lines would fit only in the category of Type IIb supernovae, but suggests the detection of He lines as well. For understanding the underlying energy source of the radiation, we should also have a look at free-free absorption in combination with synchrotron emission as it was already suggested by Chugai &

Chevalier (2006).

At the end we want to thank G. B. Taylor for his support, advise and time. We also thank NRAO for this great opportunity, to use two hours of VLA time for our own observations.

## REFERENCES

Papenkova, M., Li, W. D., Wray, J., Chleborad, C. W., & Schwartz, M. 2001, IAU Circ., 7722, 1

Filippenko, A. V., & Chornock, R. 2001, IAU Circ., 7737, 3

Soderberg, A. M., Gal-Yam, A., & Kulkarni, S. R. 2004, GRB Coordinates Network, 2586, 1

Stockdale, C. J., Van Dyk, S. D., Sramek, R. A., Weiler, K. W., Panagia, N., Rupen, M. P., & Paczynski, B. 2004, IAU Circ., 8282, 2

Pooley, D., & Lewin, W. H. G. 2004, IAU Circ., 8323, 2

Granot, J., & Ramirez-Ruiz, E. 2004, ApJ, 609, L9

Bietenholz, M. F., & Bartel, N. 2005, ApJ, 625, L99

Paragi, Z., Garrett, M. A., Paczyński, B., Kouveliotou, C., Szomoru, A., Reynolds, C., Parsley, S. M., & Ghosh, T. 2005, Memorie della Societa Astronomica Italiana, 76, 570

Chugai, N. N., & Chevalier, R. A. 2006, ApJ, 641, 1051

Miley, G. 1980, ARA&A, 18, 165

---

This preprint was prepared with the AAS LaTeX macros v5.2.