SN 2001em: NOT SO FAST

F. K. SCHINZEL1,5, G. B. TAYLOR1,6, C. J. STOCKDALE2, J. GRANOT3, and E. RAMIREZ-RUIZ4

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

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ABSTRACT

SN 2001em, originally classified as type Ibc, 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 $H\alpha$ 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 $2\sigma$ 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 $t^{-1.23\pm0.06}$ 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: 21h42m22.9 decl: 12°29′54″; $z = 0.019493$ J2000.0). Throughout the paper, we use $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and $\Omega_m = 0.72$ (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 Ibc (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 $F_{\nu} \propto \nu^{0.9 \pm 0.4} - 0.36 \pm 0.16$ (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 Ibc SNe that may be associated with gamma-ray bursts (Paczynski 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 $H\alpha$ (FWHM 40 Å = 1800 km s$^{-1}$) lines that are not typical of type Ibc 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
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 (1.4 away) and J2139+1423 (2.1 away). The switching intervals were ∼ 180 s for J2145+1115, ∼ 93 s for SN 2001em, and ∼ 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° 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) gave a relative motion of the 4 components between 0.108 and 0.593 mas year\(^{-1}\) separated up to 3 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 \(< 40 \mu\)mas year\(^{-1}\) (Feissel-Vernier 2003). We also assume our reference source J2145+1115 to be stationary. Using a linear relationship between the stationary phase center and the apparently moving J2139+1423, that are 3° apart from each other, we find an error for the proper motion of SN 2001em of ±0.184 mas year\(^{-1}\).

This high error is not very satisfactory and yield unreasonably small \(\chi^2\) 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 \(\chi^2\) 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, as well as the total projected velocity for a period of 2.201 years (three epochs of HSA observations).

![Figure 1](image)

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Positions of SN 2001em from 2004 to 2007, centered at R.A. 21\(^{h}\)42\(^{m}\)23\(':\)619 decl. 12\(^{\circ}\)29\('\)50\(':\)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).

\textbf{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        |

\textbf{Notes.} AR = 305 m Arecibo telescope. EB = 100 m Effelsberg telescope. GBT = 105 m GBT. Y27 = phased VLBA.
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

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

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

### 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 $\times$ 0.858) mas at $-7^\circ 17$.

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 $\chi^2$ 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 2$\sigma$ 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 4. Weighted least square fits for position vs. time in R.A. and decl. This gives a proper motion for SN 2001em of $(0.030 \pm 0.037)$ mas year$^{-1}$ in R.A. and $(-0.053 \pm 0.071)$ mas year$^{-1}$ in decl.

Table 2

| Epoch (Years) | Flux Density (mJy) | Offset R.A. (mas) | Offset decl. (mas) | RMS ($\mu$Jy/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 $21^h42^m23^s.619$ R.A. and $+12^d29^m50^s.299$ decl.

Bietenholz & Bartel (2007) report a 2$\sigma$ 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 2$\sigma$ 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 discovery on 2001.704, we find a 2$\sigma$ upper limit for the expansion velocity of 0.015 mas year$^{-1}$, which corresponds to

$$v_{\text{exp}} \leq 6,000 \text{ km s}^{-1}.$$  (3)
The linear curve represents the 2σ upper limit for the expansion velocity of 6000 km s\(^{-1}\) plotted from 2001.7041.

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, 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 \(\beta_{\text{drop}} = 0.38 \pm 0.18\) and between 4.9 and 8.4 GHz it is \(\beta_{\text{plateau}} = 0.077 \pm 0.011\).

**Table 3**

| 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 (IIIL), 1986J (IIn), 1987A (II peculiar), 1993J (Ib), 2001gd (Ib), and 2004et (IIP) (Bartel & Bietenholz 2003; Bietenholz et al. 2002; P´erez-Torres et al. 2005; Marcaide et al. 2008; P´erez-Torres et al. 2005; Mart´ı-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\(^{-1}\) ≈ 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     | Ipec | ~ 3.5                   | Manchester et al. (2002) |
| 1997C     | III  | 7.4 ± 0.5               | Bartel & Bietenholz (2003) |
| 2004et    | IIP  | > 15.7 ± 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 |

A very dense CSM. Preliminary models of VLA observations suggest an average mass loss of \( \sim 2.5 \times 10^{-5} \, M_\odot \) 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 \( \times 10^{-4} \, M_\odot \) year^{-1} for SN 1988Z and 4.28 \( \times 10^{-5} \, M_\odot \) 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 \( 0.98 \times 10^{13} \, \text{cm} \) 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 \( \sim 6 \times 10^{16} \, \text{cm} \) after \( \sim 2.6 \, \text{yr} \) (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 Hz line (Soderberg et al. 2004). This detection indicates the existence of cool shocked circumstellar gas (Chugai & Chevalier 2006).

The large X-ray luminosity of \( L_X \approx 10^{41} \, \text{erg s}^{-1} \) at \( t \approx 950 \, \text{days} \) implies a radiated energy in the X-ray range (0.5–8 keV) of the order of \( L_X(t) \approx 10^{49} \, \text{erg} \) (assuming the typical time for variation in \( L_X \) is \( \Delta t \approx 1 \)). This sets a strict lower limit on the energy that was dissipated and converted into internal energy by that time of \( E_{\text{dis}}(t) \approx 10^{49} \, \text{erg} \). However, the true value of \( E_{\text{dis}}(t) \) 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 \( v F_v \) is still rising within the observed energy range (\( v F_v, \propto \nu^{0.9+0.35} \); 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 \( E_{\text{dis}}(t) \approx 10^{51} \, \text{erg} \) 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 \( t_{\text{dec}} \approx 10^3 \, \text{days} \), 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 \( t_{\text{dec}} \approx 10^3 \, \text{days} \), while our limits on the source size imply that the typical initial velocity \( v_0 \) of the mass that has decelerated by \( t_{\text{dec}} \) is \( \lesssim 8000 \, \text{km s}^{-1} \). For an external density \( \rho \sim A r^{-2} \), this implies \( A_e = A/(5 \times 10^{11} \, \text{cm g}^{-1}) \gtrsim 7.3 \times 10^3 (E/10^{41} \, \text{erg}) (v_0/8 \, \text{km s}^{-1})^{-3} \approx 10^{-2} \, M_\odot \, \text{yr}^{-1} \) that corresponds to a mass-loss rate of \( \dot{M} \gtrsim 0.075 (v_0/8 \, \text{km s}^{-1})^{-3} (E/10^{41} \, \text{erg}) (v_0/8 \, \text{km s}^{-1})^{-3} \approx 10^{-2} \, M_\odot \, \text{yr}^{-1} \), where \( v_0 \) 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 $t_{\text{dec}}$: $M_{\text{shell}} \gtrsim M_0 = 2E/v_0^2 = 1.57(\text{E}/10^{51}\text{erg})(v_0/8 \times 10^3\text{ km s}^{-1})^{-2}M_\odot$. 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 $t < t_{\text{dec}}$ would be 

$$\tau_T = \sigma_T E/(2\pi m_p v_0^4 t^2) = 23(\text{E}/10^{51}\text{erg})(v_0/8 \times 10^3\text{ km s}^{-1})^{-4}(t/30\text{ days})^{-2},$$

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 $(t \sim 30\text{ days})$, 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 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.

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