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e-VLBI observations of SN2001em – an off-axis GRB candidate

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Abstract.
Studying transient phenomena with the Very Long Baseline Interferometry (VLBI) technique faces severe difficulties because the turnaround time of the experiments from the observations to the scientific result is rather long. The e-VLBI technique has made it possible to transfer the data from a number of European VLBI Network (EVN) telescopes to the central data processor at JIVE through optical fibres, and correlate them in real time. The main goal of this paper is to introduce this rapidly developing new technique, by presenting observational results from a recent experiment. We observed SN2001em, a Type Ib/c supernova with an e-VLBI array and the Multi-Element Radio Linked Interferometer Network (MERLIN) in the UK. The source is marginally detected in our observations. We cannot make definite conclusions whether it is resolved at 1.6 GHz or not. Our data show that SN2001em either started fading in the last couple of months, or its radio spectrum is inverted at low frequencies, indicating free-free or synchrotron self-absorption. This is quite unusual, but not unprecedented in radio SNe.

Key words. Techniques: interferometry – Stars: supernovae: individual (SN2001em) – Radio continuum: general – Gamma rays: bursts

1. Introduction

There have been significant developments in the EVN in the recent years. Among these, the most substantial is the replacement of the MarkIV tape-based recording system with the Mark 5 Whitney (2003a,b) disk-based recording system. The advantages of disk recording are improved recording performance, and the possibility of monitoring the stations during the observations (e.g. transfer of small amounts of telescope data via the Internet, the so-called ftp fringe tests), which allows more robust operations. There is ongoing development to make the EVN operationally capable of electronic VLBI (e-VLBI), where the data are transfered to the correlator through opti-

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cal fibres, and correlated in real time Garrett (2003, 2004); Parsley et al. (2003); Szomoru et al. (2004), without any intermediate recording on disk.

e-VLBI – especially when combined with the data calibration pipeline Reynolds et al. (2002) – offers a unique opportunity to carry out target-of-opportunity style experiments, with a very quick science turnaround time that has been hitherto unavailable in VLBI. We demonstrate this by presenting e-VLBI observations of the faint supernova SN2001em with the EVN. A full discussion of these observations will be presented in Garrett et al. (2005, in prep.).

2. SN2001em

On 15 September 2001, Papenkova (2001) discovered SN2001em in UGC 11794, a nearby galaxy at a distance of 80 Mpc. The early spectrum indicated a Type Ib/c SN Filippenko & Chornock (2001), but later broad Hα lines appeared Sodeberg et al. (2004) that are not typical of this class. Radio and X-ray emission from the source was detected only two years after the initial explosion. The radio flux density increased from 1.15 to 1.48 mJy between October 2003 and January 2004, as measured by the VLA Stockdale et al. (2004). The spectral index was steep, $\alpha = -0.36 \pm 0.16$ ($S \propto \nu^{\alpha}$), indicating optically thin synchrotron emission. In the X-rays the source was detected with Chandra with a 0.5-8 keV luminosity of $\sim 10^{41}$erg s^{-1} Pooley & Lewin (2004).

It is puzzling why the radio and X-ray emission came so late, especially at the observed high luminosities. Granot and Ramirez-Ruiz (2004) investigated two scenarios: *a)* the emission comes from interaction of the SN shell with the circumstellar medium, or, *b)* it originates in a mildly relativistic jet. In the latter case the jet Lorentz factor is initially very high ($\Gamma_0 \geq 2$), and the emission is highly beamed. For an observing line of sight far from the direction of the jet, the emission is strongly de-boosted. As a result, the jet is initially not observed, and only becomes apparent when it decelerates to mildly relativistic speeds. Granot and Ramirez-Ruiz (2004) ruled out the shell-interaction scenario in favor of the jet model.

The idea that Type Ib/c SNe may be related to relativistic jet GRBs originally came from Paczyński (2001). Long duration GRBs tend to appear near star-forming regions, which indicates a supernova origin. Paczyński (2001) estimated that one out of 100-1000 core-collapse supernovae generate ultra-relativistic jets, but only the ones that are aligned with our line of sight produce GRBs. Nearby SNe that show late time radio emission (possibly related to a decelerated jet) could be resolved with the VLBI technique see also Granot & Loeb (2003).

3. Observations

We observed SN2001em on 11 March 2005 at a frequency of 1.6 GHz (corresponding to 18 cm in wavelength), with Arecibo, Cambridge, Jodrell Bank, Onsala, Torun and Westerbork (see Table 1). The data were transfered to the EVN Data Processor at JIVE through optical fibres, using the pan-European research network GÉANT (http://www.geant.net/), and correlated in real time. Initially we observed fringe-finder sources and corrected for clock errors. At this early phase we observed at 128 Mbps data rate with the European telescopes only. The data rate was lowered to 64 Mbps when Arecibo joined the observations. The target was phase-referenced to J2145+1115 (1.4 degrees away), in an 11 minutes switching cycle. During the whole experiment the data quality was monitored and real time fringe plots were made available to the telescope operators through the Internet. All stations produced good data. In parallel to the e-VLBI recording, the MERLIN array in the UK also observed the source.

The weather conditions were not ideal during this experiment. The Lovell Telescope at Jodrell Bank had to be stopped soon after the start because of high winds. Some hours later the Cambridge telescope was also lost for the same reason, before the target source observations had started. Additionally, there were other problems like severe inter-

Table 1. Parameters of the participating telescopes: aperture, diameter, system temperature, and the maximum capacity of the Internet or dedicated fibre connection. Baseline sensitivities to Arecibo are also given, assuming 10 minutes integration time, and 64 Mbps data rate. At the time of the observations, Arecibo was limited to 100 Mbps. The Cambridge data rate was limited by the microwave link between the station and Jodrell Bank.

Telescope	Diameter	T_{sys}	Maximum capacity	Baseline sensitivity
Arecibo	305m	3K	100 Mbps	–
Cambridge	32m	212K	~112 Mbps	364μJy
Jodrell Bank	76m	44K	1024 Mbps	165μJy
Onsala	25m	390K	1024 Mbps	493μJy
Torun	32m	230K	1024 Mbps	379μJy
Westerbork	14x25m	30K	1024 Mbps	136μJy

ference at Arecibo at the end of the experiment. Eventually we collected limited, but valuable data on SN2001em. A detailed description of these observations, together with a thorough review of the e-VLBI developments at the EVN will be published by Garrett et al. (2005, in prep.).

4. Data reduction and results

The uv-FITS file was prepared right after the observations, and the data were immediately pipelined. The FITS file, AIPS calibration tables, and the pipeline plots are publicly available from the EVN Data Archive (http://archive.jive.nl/, experiment IG002B). The target source was not visible on the dirty map produced by the EVN pipeline. But since the MERLIN data showed the target as a ~880 μJy unresolved source, we took a closer look at the e-VLBI data in Difmap.

In phase-referencing most but not all of the atmospheric phase errors are corrected by using a nearby reference source. However, there are systematic phase errors that arise during the transfer of solutions from one source to the other, due to the limitations of the correlator model. This may be corrected for by self-calibrating the target, with solution intervals much longer than the initial coherence time. Indeed, we detected SN2001em after self-calibrating with a 30 minutes solution interval (assuming a point source model). This was further improved by correcting for Arecibo phases using 10 minutes self-calibration intervals. The phases at other stations were kept fixed, because only the Westerbork-Arecibo baseline had sufficient sensitivity for self-calibration with shorter solution intervals.

SN2001em is marginally detected with a signal-to-noise ratio of 4–5 (after the 30 minutes self-calibration), with a correlated flux density of 571 μJy/beam on trans-Atlantic baselines (Fig. 1). This is significantly fainter than measured by MERLIN, even if one assumes a conservative 10% accuracy level for amplitude calibration of both arrays. One may argue that phase-referencing failed, and the 10 minute solution time in self-calibration was not short enough to recover the Arecibo phases properly. However we carried out direct fringe-fitting on the Westerbork-Arecibo baseline and got only occasional, very weak solutions, which is unexpected for a 1 mJy compact source (unless Arecibo and/or Westerbork was much less sensitive than expected – the calibrator data show that this is not the case). This indicates that SN2001em is slightly resolved in our observations. We performed model fitting to the uv data. Because of the very limited dataset, we constrained the Gaussian model to be circular. Our result is a 900 μJy component (in perfect agreement with the MERLIN results) with a size of 2.45 mas. A unifomly

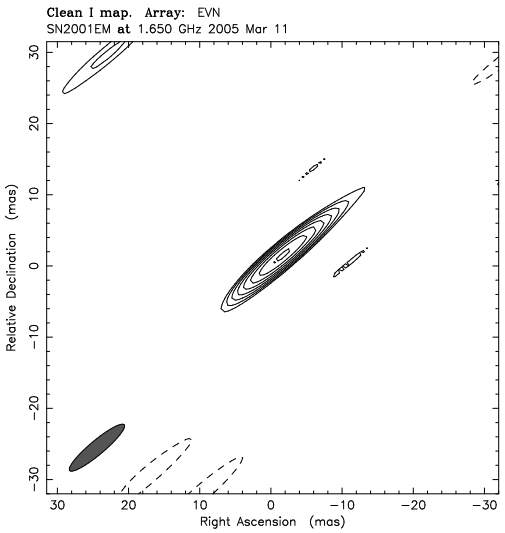

Fig. 1. Naturally weighted map of SN2001em in our e-VLBI experiment. The peak brightness is 529 μJy/beam using a restoring beam of 15x2 mas (slightly over-resolved), with major axis PA at −50 degrees. The contour levels are -1, 1, $\sqrt{(2)}$, 2 etc. times 44 μJy/beam.

bright disk model was also fitted, which resulted in a size of 1.09 mas. Due to the limited amount of data and the low-SNR detection, the error in our size measurement is rather large (about the size of the beam, with a 2.44 milliarcsecond minor axis).

5. Discussion

SN2001em had been observed by two other independent groups before our experiment. Both projects were carried out at 8.4 GHz, a significantly higher frequency than used in our observations. Stockdale et al. (2005) measured 1.8 ± 0.2 mJy flux density with the VLBA on 1 July 2004, and the source appeared unresolved with a resolution of 1.9×0.8 mas. Bietenholz and Bartel (2005) used the High Sensitivity Array (a global array consisting of the VLBA, Arecibo, GBT, phased VLA and Effelsberg) on 22 November 2004. They detected a 1.5 ± 0.1 mJy, practically unresolved source, with a 3σ upper limit of $0.35 - 0.59$ mas, depending on the type of model fitted. This indicates that the size measured in our experiment indeed has a large error, unless the lower frequency flux originates in a different emitting region.

It should be noted that the flux measured in our experiment is significantly lower than the earlier measurements indicate, which showed that the source had been permanently brighter than 1 mJy since its detection. Either SN2001em has faded in the last couple of months, or the spectrum between 1.6-8.4 GHz is inverted. The spectral index reported earlier was $\alpha = -0.36 \pm 0.16$ Stockdale et al. (2004) between 5 and 15 GHz. If the flux was constant, our data would indicate a spectral index of $\alpha \sim +0.3$. Although this is atypical of radio SNe, it is not unprecedented. Bietenholz et al. (2004) detected an inverted spectrum compact component in SN1986J, 20 years after the explosion. It may be that these inverted spectrum compact sources in SNe are related to a newly born plerion nebula around a young pulsar, but the jet origin cannot be fully excluded yet.

6. Conclusions

We detect SN2001em, a sub-mJy source that is two orders of magnitude fainter than the other objects observed by e-VLBI to date. Our attempts at measuring the source size remain inconclusive, but we show that SN2001em either faded, or has a spectrum that is inverted at lower frequencies, possibly indicating free-free or synchrotron self-absorption. Such an inverted spectrum radio component in SNe is not unprecedented.

The main results of this experiment became available within a couple of days after the observations. With the aid of e-VLBI, high-resolution radio images of e.g. transient sources can be made available in a very short turnaround time. We believe that this will change the impact VLBI has in contributing to the study of transient phenomena.

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