VLBI observations of SN 2011dh: imaging of the youngest radio supernova

I. Martí-Vidal¹, V. Tudose²,³,⁴, Z. Paragi⁵, J. Yang⁵, J. M. Marcaide⁶, J. C. Guirado⁶, E. Ros⁶,⁷, A. Alberdi⁷, M. A. Pérez-Torres⁷, M. K. Argo⁸, A. J. van der Horst⁸, M. A. Garrett⁹,⁸, C. J. Stockdale¹⁰, and K. W. Weiler¹¹

¹ Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn (Germany) e-mail: imartiv@mpifr-bonn.mpg.de
² Netherlands Institute for Radio Astronomy, Oude Hoogeveensedijk 4, 7991 PD Dwingeloo (the Netherlands) e-mail: tudose@astron.nl
³ Astronomical Institute of the Romanian Academy, Cuitul de Argint 5, RO-040557 Bucharest (Romania)
⁴ Research Center for Atomic Physics and Astrophysics, Atomistilor 405, RO-077125 Bucharest (Romania)
⁵ Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo (the Netherlands)
⁶ Dpt. Astronomia i Astrofísica, Univ. Valencia, C/ Dr. Moliner 50, 46100 Burjassot (Spain)
⁷ Instituto de Astrofísica de Andalucía, CSIC, Apdo. Correos 3004, E-18080 Granada (Spain)
⁸ Universities Space Research Association, NSSTC, Huntsville, AL 35805 (USA)
⁹ Leiden Observatory, Leiden University, PO Box 9513, 2300RA Leiden (the Netherlands)
¹⁰ Marquette University, Milwaukee, WI, USA
¹¹ Naval Research Laboratory, Washington D.C., USA

Letter accepted for publication in Astronomy & Astrophysics

ABSTRACT

We report on the VLBI detection of supernova SN 2011dh at 22 GHz using a subset of the EVN array. The observations took place 14 days after the discovery of the supernova, thus resulting in a VLBI image of the youngest radio-loud supernova ever. We provide revised coordinates for the supernova with milli-arcsecond precision, linked to the ICRF. The recovered flux density is a factor ~2 below the EVLA flux density reported by other authors at the same frequency and epoch of our observations. This discrepancy could be due to extended emission detected with the EVLA or to calibration problems in the VLBI and/or EVLA observations.

Key words. ISM: supernova remnants – radio continuum: general – supernovae: general – supernovae: individual: SN 2011dh – radiation mechanisms: nonthermal

1. Introduction

Radio emission from core-collapse supernovae (CCSNe) is relatively rare. (Around 20–30% of the CCSNe are detected in radio; see, e.g., Weiler et al. 2002.) There is, indeed, only a handful of these objects for which the radio structure has been (at least partially) resolved with very-long-baseline interferometry (VLBI) observations. However, it is definitely worth monitoring any potential radio emission from this kind of events, in order to perform detailed studies of the physical conditions in the expanding supernova shocks. The case of supernova SN 1993J is the best example of such a study (see, e.g., Bartel et al. 2002).

Marcaide et al. 2010, Martí-Vidal et al. 2012, and references therein). The intense VLBI/VLA observing campaign of this supernova allowed these authors to constrain much of the parameter space of the models (density profiles of ejecta and circumstellar medium, hydrodynamical instabilities and their role in the magnetic-field amplification, energy equipartition, etc.) and to discover unexpected effects that led to the revision and extension of the standard supernova interaction model (Martí-Vidal et al. 2011a, 2011b).

SN 2011dh is a recent example of a radio-loud supernova. Located in the galaxy M 51 (distance of 7–8 Mpc; e.g., Takáts & Vinkó 2006) at the coordinates $α = 13^h30^m05.124^s$ and $δ = +47^°10’11.301’’$ (Sárneczky et al. 2011), it was discovered with the Palomar Transient Factory project (PTF) on 2011 June 01 (Silverman et al. 2011). Arcavi et al. 2011). Radio emission from SN 2011dh was detected just three days after its discovery, with the Combined Array for Research in Millimeter-wave Astronomy (CARMA) at 86 GHz (Horesh et al. 2011), and monitoring was also started with the Expanded Very Large Array (EVLA) and the Submillimeter Array (SMA) at several frequencies, running from 8 GHz to 107 GHz (K.W. Weiler et al., in preparation).

The expansion velocity of the shock, as estimated from the Hα blueshift, is 17 600 km s⁻¹ (Silverman et al. 2011). Arcavi et al. 2011), similar to those of other supernovae of types II and Ib/c. Early X-ray emission was reported from Swift observations (Kasliwal & Ofek 2011). A good candidate for the progenitor star was isolated from HST observations (Li et al. 2011), and it shows very similar characteristics to the progenitor of the Type II-L (or spectroscopically-peculiar II-P) supernova SN 2009kr (Elias-Rosa et al. 2010). However, the results reported in Li et al. 2011 on the progenitor of SN 2011dh conflict with more recent results reported by Arcavi et al. 2011 and Soderberg et al. 2011. Based on a detailed monitoring of SN 2011dh in X-rays (using the Swift and Chandra satellites) and radio (using the SMA, CARMA, and EVLA), Soderberg et al. 2011 report a fit to the data at all frequencies using a model of non-thermal synchrotron emission plus inverse-Compton upscattering of a thermal population of optical photons. According to these authors, SN 2011dh would match a type Ib supernova better (i.e., similar to SN 1993J), but with a compact progenitor and a shock expansion speed of...
~30 000 km s\(^{-1}\) (a factor ~2 higher than that of SN 1993J). Based on
VLBI observations, Bietenholz et al. (2011) do report a barely
resolved image of SN 2011dh, on day 83 after the optical dis-
covery, with an angular radius of 0.11\(^{+0.09}\)\(^{-0.11}\)" (i.e., an average
expansion speed of 1.9\(^{+1.6}\)\(^{-1.9}\) km s\(^{-1}\)).

In this letter, we report on an earlier VLBI detection of
SN 2011dh made at the frequency of 22 GHz, just 14 days af-
fter the discovery of the supernova. We provide a revised posi-
tion of the supernova with milli-arcsecond precision, based on
phase-referencing observations with a calibrator in the interna-
tional celestial reference frame (ICRF). This position may be
useful for improving future VLBI observations of the supernova.
(Indeed, the position estimate reported here has been used in the
correlation of the observations already reported in Bietenholz et
al. 2011). In the next section, we describe our observations and
the calibration strategy followed in the data analysis. In Sect. 3, we
report on the results obtained. In Sect. 4 we summarize our
conclusions.

2. Observations and data reduction

The observations were performed on 2011 June 14 using part
of the European VLBI Network (EVN) at 22 GHz. The partic-
ipating antennas were Effelsberg (100 m diameter, Germany),
Robledo and YeBes (70 m and 40 m, respectively, Spain), Onsala
(20 m, Sweden), Metsahovi (14 m, Finland), and the MK IV tele-
scope at Jodrell Bank (25 m, United Kingdom).

The recording rate was set to 1 Gbps (dual-polarization
mode), with a total bandwidth coverage of 128 MHz (divided
into eight equal sub-bands for the data recording) and a two-
bit sampling. The observations lasted 11 hours and 24 minutes
(about 120 hours of overall baseline time), but only a total of
~70 hours of useful baseline time was obtained after the data
correlation and calibration, mainly due to the more limited par-
ticipation of some of the stations and the nondetection of fringes
related to Robledo (likely related to issues in the antenna sub-
reflector) and Metsahovi (problem with MK IV formatter).

The observations were scheduled in phase-reference mode,
using the source J1332+4722 (about 0.5 degrees away from the
 supernova) as the main phase calibrator. Additional sources were
observed as fringe finders and flux calibrators (3C286, 3C345, and
J1156+295, observed every 40–50 duty cycles), as a sec-
ondary calibrator (B1333+459, observed once every six to ten
cycles), and to allow the calibration of the evolution in the
tropospheric delay at each station (see, e.g., Brunthaler et al.
2005) for details). Duty cycles with two different periods (90 and
120 seconds) were used in the observations, since the coherence
time and the optimum on-calibrator integration time for success-
ful detections were not known with precision. All sources were
also observed in single-dish mode at the Effelsberg radio tele-
scope to have simultaneous estimates of the total flux densities
of the calibrators.

The data were correlated at the Joint Institute for VLBI in
Europe (JIVE, the Netherlands) using 128 channels per sub-band
and an integration time of one second per visibility. Only the
parallel hand data were correlated (i.e., the LCP and RCP data),
but not their cross correlations.

The data calibration was performed using the astron-
omical image processing system (AIPS) of the National Radio
Astronomy Observatory (NRAO, USA) with standard algo-
rithms. First, the contribution of parallactic angle and ionosphere
were calibrated out. The visibility phases in the different sub-

bands were aligned by fringe-fitting a scan of a strong source
(3C345, in our case), following a procedure commonly known as
“manual phasecal”. Then, the multiband delays and rates of the
resulting visibilities of all calibrators were fringe-fitted. The
resulting gains (also corrected for the tropospheric effects with
the AIPS task DELZ2N) were then interpolated into the scans of
SN 2011dh. The a priori amplitude calibration was based on the
gain curves of each antenna and the system temperatures mea-
sured at each station.

After this calibration, the behavior of the visibility ampli-
tudes was checked as a function of time (for the different base-
lines) and as a function of baseline length (for similar directions
in Fourier space), in a search for any parts of the experiment with
bad amplitude calibration. Then, edition was applied to the obvi-
ous amplitude outliers. An image of the phase-calibrator source,
J1332+4722, was generated by applying phase self-calibration
(every 1–2 minutes) and a later amplitude self-calibration (one
solution per antenna) until convergence in the gains and the
model image was achieved. The recovered flux density was com-
pared to the flux-density measurements performed with the
Effelsberg radio telescope. We obtained compatible values of the
flux density between Effelsberg, (307 ± 93) mJy, and the VLBI
image, (231 ± 10) mJy.

The antenna-based amplitude factors found in the im-
aging and self-calibration of the J1332+4722 visibilities were
then applied to the SN 2011dh visibilities. Finally, an image of
SN 2011dh was generated from the calibrated visibilities, as de-
scribed in the following section.

3. Results and discussion

3.1. VLBI detection of SN 2011dh

After the calibration described in the previous section, an image
of the supernova was synthesized by Fourier inversion from the
space of visibilities into the sky plane. Natural weighting
was applied to the visibilities, in order to improve the sensitivity of
the array. We show the resulting image of the supernova in Fig.
1. Due to the limited dynamic range achieved, no further self-
calibration was applied to the data to avoid the eventual gen-
eration of a spurious contribution to the flux density (see, e.g.,
Martí-Vidal & Marcaide 2008).

There is a clear detection of a compact source with a dy-
namic range of ~10 and flux density of 2.5 ± 0.5 mJy, which
we identify as SN 2011dh. According to the phase-reference cal-
ibration with respect to J1332+4722, the J2000.0 coordinates
of the image peak are \( \alpha = 13^h30^m5.105559^s \) \( (\pm 0.000007^s) \)
and \( \delta = +47^\circ10'10.9226'' \) \( (\pm 0.0001'') \). The uncertainties above
contain the contribution from the error in the estimate of the cal-
ibrator position and the error inherent to the phase-referencing
 calibration, as estimated from Pradel et al. (2006).

The source is very compact, and we do not see any clear hint
of structure on the scale of the synthesized angular resolution.
Indeed, the fit of a uniform-disk model to the visibilities results
in a size compatible with zero (upper limit of 0.45 mas, \( 1\sigma \) cut-
toff, for the disk radius). We notice that the maximum source
size that is compatible with our observations is similar to the
size of our synthesized beam (as is indeed expected in observa-
tions of compact sources with a low signal-to-noise ratio, SNR).

1 See Schwab & Cotton (1983) for a detailed description of the global
 fringe-fitting (GFF) algorithm.

2 With this scheme, the weight of each pixel in the Fast Fourier
 Transform (FFT) is inversely proportional to the scatter of the visibili-
ties.
We therefore conclude that the angular size of SN 2011dh is well below our resolution limit at this epoch of observations. This is an expected result, since the expansion velocity in the shocks of these types of supernovae is typically a few 10,000 km s$^{-1}$, at most. (The early ejecta velocity of SN 2001dh from the $H_\alpha$ is, indeed, 17,600 km s$^{-1}$, Silverman et al. [2011].) Assuming a distance to M 51 of 7–8 Mpc (e.g., Takáts & Vinkó [2006]), a size similar to our beamwidth at this epoch would have implied a superluminal expansion. However, it is intriguing that, even though the emission comes from a very compact region at this epoch, we are unable to recover the total flux density measured with the EVLA by Soderberg et al. [2011]. The lack of flux density in our VLBI observations may come either from a contribution from an extended source in the EVLA observations or from calibration biases in the VLBI (and/or EVLA) data, as discussed in Sect. 3.2.

3.2. VLBI vs. EVLA flux density

A systematic difference between the single-dish flux density of a source and the total recovered flux density in a VLBI-synthesized image is quite common. This effect takes place at all VLBI observing frequencies (with varying strength, but typically ranging from 10 to 20% at most), and is due to either a limited coherence in the correlation or to extended components in the sources that are resolved out in the VLBI fringes. However, it must be noticed that the flux density of SN 2011dh reported in Soderberg et al. [2011] implies a flux density of about 5 mJy at 22 GHz at the epoch of our observations (see their Fig. 3). This value is a factor 2 above the recovered flux density in our observations. The ratio of single-dish-to-VLBI flux density of SN 2011dh should be similar to that of J1332+4722, since the instrumental effects in the VLBI observations should be very similar in both sources. As a result, the Effelsberg-to-VLBI flux-density ratio of the calibrator, J1332+4722, should also be similar to the EVLA-to-VLBI flux-density ratio for SN 2011dh. This similarity should allow us to estimate the amount of lost flux density in the VLBI image of SN 2011dh, and to compare it to the extra recovered EVLA flux density. However, the uncertainty in the flux-density measurement at the Effelsberg radio telescope is so high that such a comparison gives no statistical significance. The flux density of J1332+4722 recovered with the Effelsberg radiotelescope is 1.33 ± 0.45 times higher than that recovered in the VLBI image. Therefore, the relative amount of flux-density loss in the VLBI image of SN 2011dh seems to be slightly larger than (although still compatible with) the one found in the image of the phase-reference calibrator. Nevertheless, the level of significance for this statement is very low.

It must also be noticed that Bietenholz et al. [2011] report a VLBI (VLBA + GBT + Effelsberg) peak intensity for SN 2011dh of only 0.63 mJy at 22 GHz (on day 83 after the optical discovery) using the same phase calibrator (J1332+4722). This peak intensity is also lower than what would be expected from the extrapolation of the model reported in Soderberg et al. [2011].

In addition to the well-known loss of flux density in VLBI images, caused mainly by the resolution of extended emission, there is an additional loss of flux density from the effect of atmospheric turbulence in phase-referenced observations (Martí-Vidal et al. [2010]). To estimate the atmospheric contribution to the flux-density loss in our VLBI observations, we measured the total flux density in the image of B1333+459, phase-referenced to J1332+4722, and compared it to the total flux density in the image obtained from the self-calibrated visibilities of B1333+459. The observed flux-density loss in B1333+459 due to phase referencing is about 40%, which is within a factor 2 of the loss predicted in Martí-Vidal et al. [2010] for the VLBA (~25%, as computed from their Eq. 4). These results indicate a similar performance of the EVN and the VLBA in phase-referencing observations, even using a very small subset of the EVN in our observations (only four stations had useful detections; see Sect. 2) and a higher observing frequency. If Eq. 4 in Martí-Vidal et al. [2010] is used to estimate the flux-density loss of SN 2011dh due to phase referencing, the result is only ~2% (using the constants reported in that publication, which are based on VLBA observations) or ~3.5% (if we calibrate Eq. 4 using our estimated flux-density loss of B1333+459, phase-referenced to J1332+4722). In any case, the expected flux-density loss of SN 2011dh due to phase referencing (based on Eq. 4 of Martí-Vidal et al. [2010]) is very small, given the small separation from its phase calibrator (about 3.4 times smaller than the distance between B1333+459 and J1332+4722).

In case that the missing flux density in our SN 2011dh VLBI observations (and in those reported by Bietenholz et al. [2011]) was not completely due to instrumental limitations (no robust conclusion can be extracted only from our data), such a loss might also be related to a contribution of extended emission (e.g., from the background galaxy, from the continuum of the whole region, or even from the supernova environment) in the EVLA flux densities reported in Soderberg et al. [2011]. We note, though, that such a contribution from an extended component in the supernova would imply that there is extended emission as strong as what comes from the (still compact) expanding shock, and this would thus conflict with the model reported in Soderberg et al. [2011], which assumes that all the emission detected with the EVLA comes from interaction of the expanding shock (with an expansion velocity of ~30,000 km s$^{-1}$).
4. Summary

We report on the VLBI detection of SN 2011dh at 22 GHz using a subset of the EVN array. The observations took place 14 days after the discovery of the supernova. Therefore, this is the VLBI image of the youngest radio-loud supernova. The source is very compact, with a size compatible with zero and upper bound of 0.45 mas for the radius of a uniform-disk model fitted to the visibilities.

We provide revised coordinates for the supernova with milliarcsecond resolution and linked to the ICRF. The recovered flux density is a factor $\sim 2$ below the flux density reported in Soderberg et al. (2011), at the same frequency and day as our observations. Such a difference may indicate a contribution by extended emission in the EVLA flux densities or calibration problems in the VLBI and/or the EVLA observations. Further VLBI observations of this supernova will be decisive in helping resolve this conflict.

Acknowledgements. The European VLBI Network is a joint facility of European, Chinese, South African, and other radio astronomy institutes funded by their national research councils. We acknowledge the EVN chair and related staff for the swift answer and scheduling of the VLBI observations. The single-dish flux densities reported are based on observations with the 100-m telescope of the MPIfR. This research has been partially supported by projects AYA2009-13036-C02-01 and AYA2009-13036-C02-02 of the MINECO and by grant PROMETEO 104/2009 of the Generalitat Valenciana. E.R. was partially supported by the COST action MP1005 “Black Holes in a Violent Universe”.

References

Arcavi I., Gal-Yam A., Yaron O. et al. 2011, [arXiv:1106.3551]
Bartel N., Bietenholz M.F., Rupen M.P. et al. 2002, ApJ, 581, 404
Bietenholz M. F., Brunthaler A., Bartel N., et al. 2011, ATel, # 3641
Brunthaler A., Reid M.J., &Falcke H. 2005, ASPC, 340, 455
Elias-Rosa N., van Dyk, S.D., Li W., et al. 2010, ApJ, 714L, 254
Horesh A., Zauderer A., & Carpenter J. 2011, ATel, #3405
Kasliwal M.M. & Ofek E.O. 2011, ATel #3402
Li W., Filipenko A.V., & van Dyk S.D. 2011, ATel #3401
Marcaide J.M., Marí-Vidal I., Alberdi A., et al. 2010, A&A, 505, 927
Marí-Vidal I., & Marcaide J.M. 2008, A&A, 480, 289
Marí-Vidal I., Ros E., Pérez-Torres M.A., et al. 2010, A&A, 515, A53
Marí-Vidal I., Marcaide J.M., Alberdi A., et al. 2011a, A&A, 526A, 143
Marí-Vidal I., Pérez-Torres M. A., & Brunthaler A. 2011b, A&A, 529A, 47
Pradel N., Charlot P., & Lestrade J.-F. 2006, A&A, 452, 1099
Sárneczky K., Szalai N., Kun M., et al. 2011, ATel #3406
Schwab F.R., & Cotton W. D. 1983, AJ, 88, 688
Shepherd M.C., Pearson T.J., & Taylor G.B. 1994, BAAS, 26, 987
Silverman J.M., Filippenko A.V., & Cenko S.B. 2011, ATel #3398
Soderberg A.M., Margutti R., Zauderer B.A., et al. 2011, [arXiv:1107.1876]
Takáts K. & Vinkó J. 2006, MNRAS, 372, 1735
Weiler K.W.W., Panagia N., Montes, M.J. et al. 2002, ARA&A, 40, 387