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An e-VLBI image of SN1987A from Australian radio telescopes and the JIVE correlator

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We present an image of the expanding shell of the remnant associated with supernova 1987A at the highest resolution to date at radio wavelengths, 85 milliarcseconds, using the e-VLBI technique, from 2007 October. This is comparable to the angular resolution obtained with the Hubble Space Telescope and is approximately 3 times higher than has been possible with the Australia Telescope Compact Array or 5 times higher than with the Chandra X-ray Observatory. The e-VLBI data at 1.4 GHz show good agreement with the ATCA data at 9 GHz, resolving the substructure in the equatorial brightness enhancements of the remnant (allowing for the fact that the e-VLBI observations are sensitive to structure on angular scales <0.4”). We place a 3σ upper limit on the time-averaged pulsar emission or a compact pulsar-powered nebula at this frequency of 1 mJy/beam. These observations were made using telescopes in Australia, with the data transferred in real-time to the European VLBI Network correlator at the Joint Institute for VLBI in Europe, in The Netherlands, via high-speed networks, as part of the EXPReS project, demonstrating the feasibility of a real-time global e-VLBI network at 512 Mbps per antenna.

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1. Introduction

Supernova 1987A has been the only nearby supernova in the age of modern astrophysical instrumentation and has been intensively studied over the last 20 years [2]. At radio wavelengths, supernova 1987A has been studied in detail since its first detection with the Molonglo Observatory Synthesis Telescope (MOST) [11]. A long series of observations with the Australia Telescope Compact Array (ATCA) [1,10] reveals an expanding (~5200 km/s) shell with persistent brightness enhancements on the eastern and western sides of the remnant. At the ATCA observing frequencies of 9 and 22 GHz, the size of the structures in the remnant shell are at the limit of what can be resolved with the array, even using super-resolution techniques.

Higher resolution (longer baseline) observations are required to resolve the remnant at radio frequencies. The first very long baseline interferometry (VLBI) observations of supernova 1987A were made 5.2 days after the neutrino burst. No detection of radio emission was made, at a level greater than 20% of the total flux, indicating a size greater than 2.2 mas [3]. A subsequent attempt at VLBI in 2003 September also resulted in a non-detection (Lovell & Hunstead 2007, private communication).

We present new VLBI observations at 1.4 GHz which have comparable angular resolution to optical images produced from the HST [4] and are the highest resolution radio images to date of the remnant of supernova 1987A, revealing the sub-structure of the expanding shell of ejecta as it interacts with the surrounding interstellar material. The observations were made as part of an EXPReS (Express Production Real-time e-VLBI Service) demonstration of a global real-time interferometer, in which the telescopes (in Australia) were on the opposite side of the Earth to the correlation facility (European VLBI Network [EVN] correlator in The Netherlands).

2. Observations and results

The e-VLBI observations were made using the ATCA (6 x 22 m antennas), Parkes (64 m), and Mopra (22 m) telescopes of the Australia Telescope National Facility (ATNF) on 2007 October 07. The digital data for four dual-polarisation 16 MHz bands (circularly polarised, Nyquist sampled, centered at 1.382 GHz) were transferred in real-time from each antenna via a dedicated 1 Gbps lightpath to the EVN MarkIV correlator at JIVE, in The Netherlands (an aggregate data rate of 1.536 Gbps). The observation was sustained for a period of 11 hours. The lightpaths were provided as a collaboration between National Research and Education Networks, specifically AARNet, CENIC, CANARIE and Surfnet. Data from the Australian LBA Data Recorder (LBADR), which is essentially a standard server class PC with a custom built digital input card (Phillips 2009, in preparation), were converted in software in real-time to the Mark 5B format, suitable for streaming into the EVN data processor [8] at the Joint Institute for VLBI in Europe (JIVE), which has been recently upgraded to correlate incoming e-VLBI data-streams in real-time.

Standard gigabit Ethernet network adapters and switches were used within the observatories to copy the data to the start of the lightpath, which is presented as standard gigabit Ethernet. Data transport used UDP (User Datagram Protocol).

At the EVN correlator all four Stokes parameters were correlated. A nearby phase reference source (0530-727: α=05:29:30.0422; δ=-72:45:28.507) was observed along with supernova 1987A in a 10 minute target/calibrator cycle and was used to calibrate the visibility phases of the supernova 1987A data, via standard phase referencing techniques in post-correlation processing using AIPS[1]. The visibility amplitudes were calibrated using measured Tsys and gain for each telescope, with the calibration refined by checking the calibrated amplitudes for the phase reference source against the amplitude observed with the ATCA at the same frequency (at this frequency, the phase reference source is unresolved on these baselines). The aperture plane coverage for the observation is shown in Figure 1.

An image of supernova 1987A was made using standard techniques in DIFMAP [9] (Figure 2). The phase corrections derived from the phase-reference source were of high enough quality to allow the deconvolution of the data without phase self-calibration against a starting model. Phase self-calibration was used in later imaging cycles, with a three minute timescale. Minimal improvement in the image was obtained with the use of self-calibration. The angular resolution (restoring beam FWHM) of the image is 85 x 168 mas and the RMS noise in the residual image is 350 μJy/beam. The peak flux density in the image is 13 mJy/beam. The total cleaned flux is 127 mJy.

The high resolution structure closely matches the structure observed with the ATCA at 9 GHz, allowing for missing structure due to resolution effects, by comparison to Gaensler et al. (2007). The regions of enhanced brightness in the ATCA images are well resolved in the e-VLBI image and clearly have an extent greater than the size of the restoring beam. The radial extents of the eastern and western regions are approximately 250 and 300 mas, respectively. The separation between the centroids of emission of the two components is 1.57”.

3. Discussion

The morphology of supernova 1987A as seen in the 1.4 GHz e-VLBI image is dominated by the regions of enhanced brightness, also prominent at 9 GHz in ATCA data. Regions of lower brightness temperature tracing the remainder of the remnant ring, seen in the low resolution ATCA images, are fully resolved in the e-VLBI images, falling below the brightness temperature sensitivity of the e-VLBI array, and are not detected in the e-VLBI image. The shortest e-VLBI baseline length of ~100 km determines that the e-VLBI image is not sensitive to structure on angular scales greater than ~0.4”, which is the scale probed with ATCA observations.

An extrapolation of the ATCA measurements of the shell expansion (based on a simple model of a thin expanding shell fitted to the ATCA data) of the remnant places the shell

[1] The Astronomical Image Processing System (AIPS) was developed and is maintained by the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under co-operative agreement with the National Science Foundation

diameter at 1.8 arcseconds near the end of 2007. The value measured with the e-VLBI observations is smaller than this, approximately 1.6 arcseconds (angular distance between the centroids of the two approximately diametrically opposed lobes), closer to the value measured from Chandra data [7]. A combined analysis of Chandra and ATCA data from 2004 suggests a shell diameter of 1.7”. This is in reasonable agreement with the e-VLBI result, given the difference in frequency between the ATCA and e-VLBI data, the subsequent difference in angular resolution and potential frequency dependance in the source morphology, the difference in observing epoch, and the different measurement techniques (in image and aperture planes).

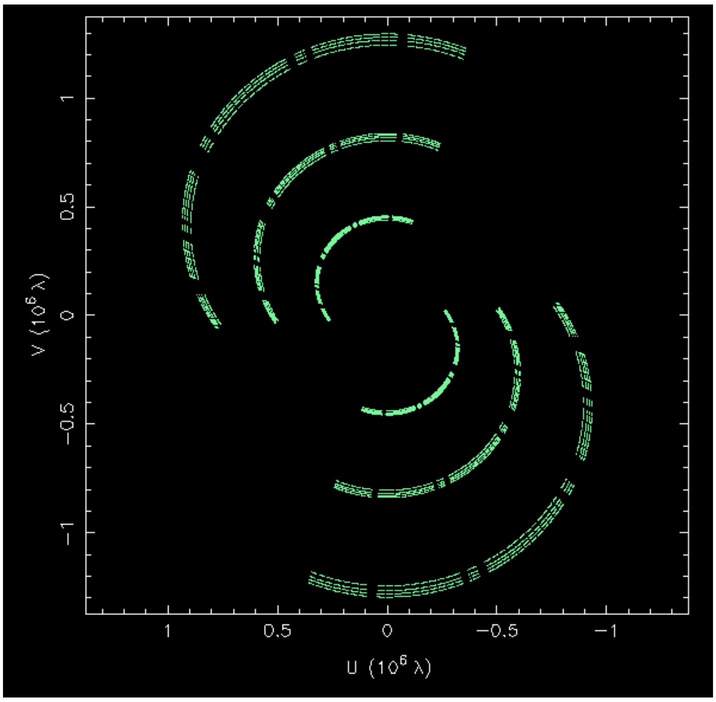

Figure 1: The aperture plane coverage for the e-VLBI observations.

The regions of enhanced brightness on the eastern and western edges of the shell seen in Figure 2 are clearly more extended than the dimensions of the restoring beam of the e-VLBI image. The deconvolved radial extent of both lobes is close to 300 mas, or approximately 40% of the shell radius as seen with the ATCA. [1] suggest the brightness enhancements represent the longest path length regions along our line of sight through an optically thin torus, with an intrinsic thickness equal to 25% of the shell radius, tilted 43^{o} to the plane of the sky.

The potential existence of compact sub-structure in the remnant is interesting, as it may trace enhanced regions of interaction between the expanding shell and the circumstellar ring of material, possibly providing a probe of density variations in this ring. With higher resolution and higher quality images, the observed distribution of sub-structure in the radio emission, and hence perhaps in the ring material itself, will need to be accounted for in any detailed model for the interaction of expanding remnant with the pre-existing circumstellar ring of material.

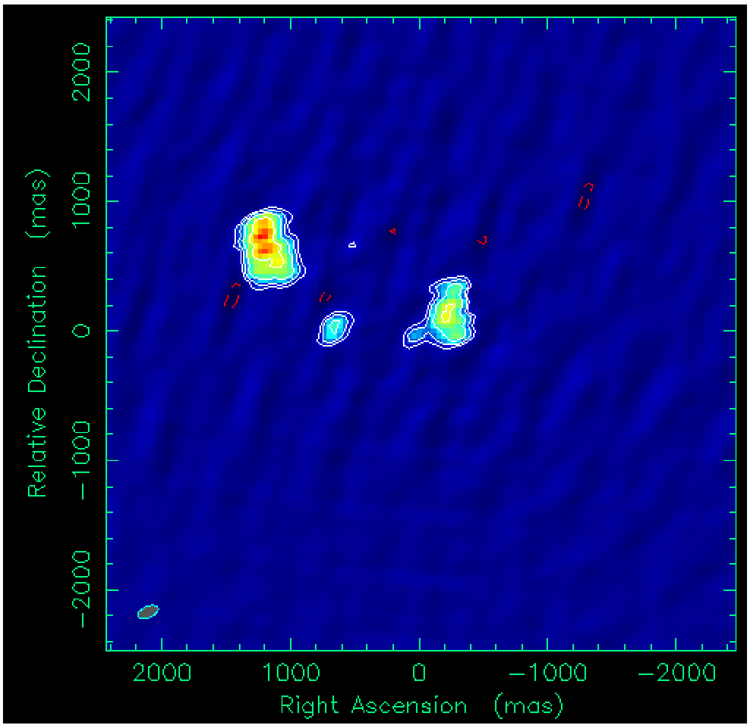

Figure 2: e-VLBI image of SN1987A at 1.4 GHz. Contours are -7, 7, 14, 28, & 56% of the peak brightness of 13 mJy/beam. The beam dimensions are 85 x 168 mas at a position angle of -67^{o}, shown at lower right.

Regular observations are made to search for a pulsar, or pulsar nebula, associated with the 1987A remnant which, to date, show no evidence for such a pulsar or nebula. [5] place an upper limit of 0.05 mJy (9σ) at 1.4 GHz in a pulsation search, and 1 mJy at 9 GHz for a steady source of emission, such as a nebula. From our e-VLBI data, we can place a 3σ upper limit to a pulsar-powered nebula of 1 mJy at 1.4 GHz, assuming that any nebula would be unresolved (less than quarter of a beam FWHM, ~0.05 pc at the 50 kpc distance of the LMC).

Further VLBI observations with the full Australian array of telescopes, taking advantage of a recent high sensitivity upgrade to the system (recording up to 1 Gbps), will allow images of the supernova 1987A remnant with both higher resolution and higher sensitivity. Such observations will help to constrain the tilted torus model for the brightness enhancements [6], quantifying the distribution of substructure that needs to be accounted for in any such model, and place more stringent limits on the existence of a pulsar-powered nebula, at a number of frequencies.

The continued development of global e-VLBI networks and the concept of a distributed set of processing facilities, all connected via high speed data links, will allow a dynamic allocation of resources to a variety of observational programs. A mixture of radio telescopes with hardware and software processing elements around the world are capable of contributing to such a system. In particular, the real-time correlation of data, thousands of kilometres remote from the telescopes, has particular relevance for next generation radio telescopes such as the high resolution component of ASKAP (the Australian Square Kilometre Array Pathfinder), LOFAR (the LowFrequency ARray) and the SKA (Square Kilometre Array).

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