J. Astrophys. Astr. (2011) **32,** 451–455

The Central Point Source in G76.9+1.0

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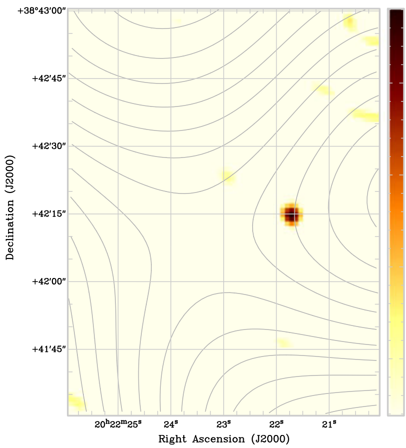
Abstract. We describe the serendipitous discovery of a very steep-spectrum radio point source in low-frequency Giant Metrewave Radio Telescope (GMRT) images of the supernova remnant (SNR) G76.9+1.0. The steep spectrum, as well as the location of the point source near the centre of this SNR confirm that this indeed is the pulsar J2022+3842. Archival *Chandra* X-ray data shows a point source coincident with the radio point source. However, no pulsed radio emission was detected despite deep searches at 610 MHz and 1160 MHz – which can be understood to be due to temporal broadening of the pulses. Weak pulsed emission has indeed been seen at 2 GHz with the Green Bank Telescope (GBT), establishing the fact that scattering is responsible for its non-detection at low radio frequencies. We underline the usefulness of low-frequency radio imaging as a good technique to prospect for pulsar candidates.

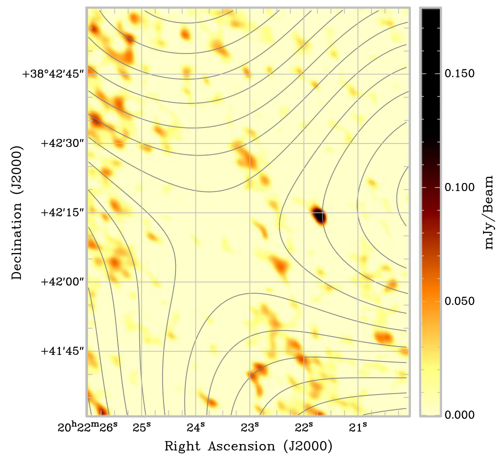
Key words. Supernova remnants: pulsars: radiation mechanisms.

1. Introduction

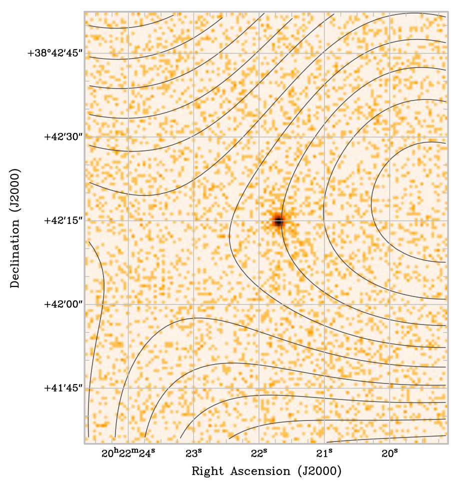
The supernova remnant (SNR) G76.9+1.0 was observed on 24 June 2009 at 610 MHz with the Giant Metrewave Radio Telescope (GMRT). The total flux from the remnant, uncorrected for foreground contribution or absorption, is 2.36 Jy $\pm$ 0.28 Jy. The RMS noise on the integrated flux is 45 mJy; however we have folded in a 10% error to account for possible systematics in the calibration. Some measurements were excluded (Landecker *et al.* 1993) from the calculation of the spectral index citing poor UV-coverage and possible under-representation of large-scale features. We have followed them in keeping out those measurements for measuring our own spectral index. Including the new GMRT 618-MHz flux measurement along with those at 408 MHz, 2.695 GHz and 4.8 GHz, but following Landecker *et al.* (1993) in excluding the discrepant measurements at 327 MHz, 1408 MHz, 1490 MHz and 4850 MHz, the spectral index we measure is $\alpha = -0.61 \pm 0.03$, in excellent agreement with their earlier measurement of $\alpha = -0.62 \pm 0.04$. A high-resolution image made by excluding baselines shorter than 10 kλ revealed a point source of 680 μJy within



(a) GMRT 610-MHz map



(b) GMRT 1160-MHz map



(c) *Chandra* X-ray image

Figure 1. The point source in G76.9+1.0, seen in radio ((**a**) and (**b**)) and X-ray (**c**).

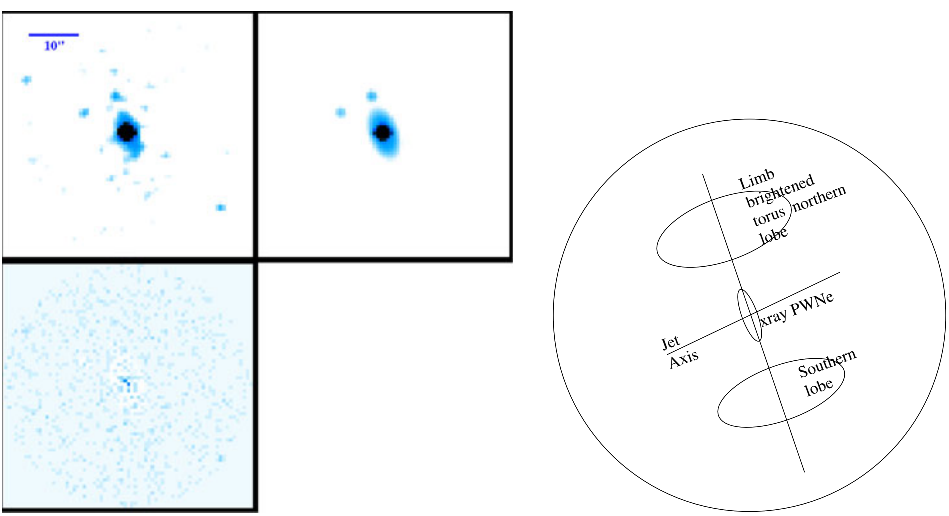
the remnant: this is shown in Fig. 1(a). Its co-ordinates are α : $20^{\mathrm{h}}22^{\mathrm{m}}21.7^{\mathrm{s}}$, δ : $38°42'15.00''$(J2000).

2. Search for a pulsar at 610 MHz and 1170 MHz

A pulsar search observation was carried out subsequently on 3 March 2010. In the image made from the simultaneously recorded interferometric data the same point source was clearly detected. The flux measured at this epoch was 660 μJy $\pm$ 80 μJy, consistent with the earlier measurement. For the assumed distance of 7 kpc the range of dispersion measures (DM) given by the Galactic Free Electron Density Model (Cordes & Lazio 2003) is 175–275 pc/cc. Since the true DM could differ from this estimate by as much as a factor of 2, a search was made over a DM range 1 to 500 pc/cc in steps of 1 pc/cc. The limit of detectability attained as per calculations was $\sim$100 μJy. Although the phase-averaged flux of the unresolved source is significantly higher than the detectable limit, no pulsed emission was detected. The lack of pulsations at 610 MHz was puzzling and among many reasons, temporal broadening appeared the most likely cause. Therefore simultaneous pulsar search and interferometric imaging at a higher frequency – 1160 MHz – were carried out. The full-resolution image in Fig. 1(b) shows a clear detection of the point source at the same position seen earlier at 610 MHz. The measured flux density at 1160 MHz is 171 μJy $\pm$ 22 μJy, giving a spectral index of $\alpha = -2.1^{-0.45}_{+0.36}$. The pulsar search attained a detectability limit of 100 μJy, similar to the 610-MHz search; however, no pulsed emission was detected.

3. *Chandra* X-ray results

Archival ACIS-S detector data from the 01 August 2005 *Chandra* observation of G79.6+1.0 reveals an unresolved source at the same position as the radio point source, establishing unambiguously that the radio counterparts at 610 MHz and 1160 MHz are the same object. The unprocessed *Chandra* image is shown in Fig. 1(c) The best-fitting model revealed an elliptical-shaped, diffuse component around a strong, unresolved core, as seen in Fig. 2(a). The 7$''$ extended component can be identified as a synchrotron nebula around the neutron star, whose photon index $\Gamma = 0.9 \pm 0.2$ and unabsorbed flux is 5.9×10^{-13} erg cm^{-2} s^{-1}.



(a) (b)

Figure 2. (**a**) Model from *Chandra* X-ray image. The processed image is shown in the top left panel, model in the top-right panel and the bottom-left shows the residual in Fig. 2(a). (**b**) Schematic model for G76.9+1.0 based on radio and X-ray data which represents the PWNe located in G76.9+1.0.

4. The nature of the central point source

Non-detection of pulsed emission is however puzzling. A previous search failed to detect pulsed emission from G76.9+1.0 (Lorimer *et al.* 1998); however their limits are substantially weaker than those presented here. The most likely cause for the lack of pulsed emission appears to be temporal broadening. The expected temporal broadening using equation (7) from Bhat *et al.* (2004) is

$$\log(\tau_d) \approx a + b\ \log(\mathrm{DM}) + c\ (\log(\mathrm{DM}))^2 - \alpha\ \log(\nu), \tag{1}$$

where $a = -6.46$, $b = 0.154$, $c = 1.07$ and $\alpha = 3.86$. Here, the temporal broadening τ_d is in ms and observing frequency ν is in GHz. For the DM range of 250–500 pc/cc the expected pulse broadening at 610 MHz and 1160 MHz are 8–380 ms and 0.6–30 ms respectively. Clearly if the DM lies in the upper end of the likely range and the pulsar has a period in the 10–30 ms range, the pulse broadening will be comparable to the pulse period, making it very difficult to detect the pulsar. We note in this context that during the pulsar search candidates were identified by summing up to 16 harmonics, and hence even if only the fundamental alone was statistically significant the pulsar should have shown up as a candidate in our search. Subsequently, we learnt (Arzoumanian & Ransom 2010) that pulsed emission has been detected at the Green Bank Telescope (GBT) at 2 GHz. Its period is $\sim$24 ms, and the DM is 430 pc/cc, consistent with the non-detections at lower frequencies. Their 2-GHz flux of $\sim$75 μJy agrees well with the spectral index measured with the GMRT. This establishes beyond any ambiguity that the pulsar non-detections at the GMRT were not sensitivity-limited, but because of the large DM and the lower observing frequencies, the pulsed signal would be appreciably broadened. It seems a reasonable conclusion, therefore, that the radio emission seen in the GMRT images as the unresolved source comes from the pulsar, but that only because of temporal broadening we do not detect any pulsed emission. We now turn to the discussion of the diffuse emission seen in the X-ray image.

The diffuse X-ray emission has an elliptical structure, the major axis of which is aligned with the radio lobes. The diffuse component is assumed to be an equatorial wind (Lai *et al.* 2001) or the arcs carved by rotating beams of particles (Radhakrishnan & Deshpande 2001). Either case could explain the observed perpendicularity between the jet-like features on one hand, and the radio lobes aligned with the major axis on the other hand. We therefore suggest that a wind arising from the neutron star surface continues to flow equatorially to large distances. As it continues to expand and cool, the particles radiate in radio synchrotron. However because of the alignment of the torus, it appears as a pair of lobes due to *limb brightening*. The proposed model is shown in Fig. 2(b).

5. Summary

We report the serendipitous discovery of an unresolved, steep-spectrum radio source in the SNR G76.9+1.0. Analysis of archival *Chandra* X-ray data shows this to be coincident with an unresolved X-ray source. Despite a deep search no pulsed emission was detected at 610 MHz and 1160 MHz with the GMRT. We understand this as a consequence of temporal broadening of the pulse due to the large dispersion measure along the line-of-sight to the pulsar and the low radio frequencies with which it was observed at the GMRT. This is established by the fact that this pulsar has indeed been seen with the GBT at 2 GHz. The X-ray emission also shows a diffuse elliptical structure aligned along the bipolar structure seen in the radio. We suggest that these structures arise because of an equatorial wind from the pulsar. We underline the usefulness of a high-resolution radio imaging study in locating and prospecting for pulsar candidates in supernova remnants, which could otherwise be missed in a time-series pulsar search observation.

Acknowledgements

We thank the GMRT staff for having made possible the observations of G76.9+1.0. The GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research. VRM thanks A. A. Deshpande of Raman Research Institute, Bangalore, India for useful discussions.

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