The central point source in G76.9+1.0

V. R. Marthi[1], J. N. Chengalur[1], Y. Gupta[1], G. C. Dewangan[2] and D. Bhattacharya[2]

[1]National Centre for Radio Astrophysics, P. B. 3, Ganeshkhind, Pune 411 007, India.
email: {*vrmarthi, chengalur, ygupta*}@ncra.tifr.res.in

[2]Inter-University Centre for Astronomy and Astrophysics, P. B. 4, Ganeshkhind, Pune 411 007, India.
email:{*gulabd, dipankar*}@iucaa.ernet.in

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. Earlier studies have shown that this SNR has a bipolar structure within a filled morphology. The steep spectrum, as well as the location of the point source near the centre of this SNR make it a very promising pulsar candidate. 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. We underline the usefulness of low-frequency radio imaging as a good technique to prospect for pulsar candidates.

1. Introduction

The source G76.9+1.0 was first identified in a survey of the Cygnus-X region [1]. It is $9' \times 12'$ in extent. Those authors tentatively identified it as a Galactic supernova remnant(SNR) but, because of the limited resolution of their survey, were unable to come to a firm conclusion. Further observations [2] showed it to have a two-lobed structure, morphologically very similar to the pulsar wind nebula (PWNe) DA495 (see e.g. [3] for a detailed discussion on DA495). From the observed rotation measure [2] they concluded that it is further than 7 kpc. The spectral index they measured for the source was $\alpha = -0.62 \pm 0.04$ (where $S(\nu) \propto \nu^{\alpha}$). This is somewhat steep for a filled-center remnant. Nonetheless, based on its morphological similarity to DA495, both [2] and [4] suggest that G76.9+1.0 is also a PWNe. The morphological ambiguity motivated us to observe this SNR with the Giant Metrewave Radio Telescope (GMRT). The observations and results presented in this paper provide strong support for the interpretation that G76.9+1.0 is a PWNe..

The rest of this paper is organised as follows: in Section 2 we describe our 610-MHz GMRT observations and results, which led to the detection of the radio point source. In Section 3 we describe a search for pulsed emission at 610 MHz. We followed up the 610-MHz observations with 1160-MHz observations; the details and results are described in Section 4. Next, we present in Section 5 the analysis and modelling of *Chandra* X-ray data. A discussion of the results can be found in Section 6.

2. GMRT 610-MHz observations

The supernova remnant G76.9+1.0 was observed on 24 Jun 2009 at 610 MHz with the GMRT[1]. The continuum map is shown in Fig. 1. and has a resolution of $54'' \times 51''$. The morphology matches well with the double-lobed structure joined by a diffuse bridge of emission noted in earlier studies [2, 4]. 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. The GMRT 610-MHz flux measurement is plotted along with other previous flux measurements (from [2]) in Fig. 2. Including the new GMRT flux measurement, but following [2] 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 the earlier measurement of $\alpha = -0.62 \pm 0.04$.

We used the same 610-MHz data to search for compact sources by making an image after excluding all baselines shorter than 10 $k\lambda$. A point source with a peak flux of 680 μJy $\pm$ 58 μJy at $\alpha : 20^h22^m21.7^s$, δ : $38^o42'15''$(J2000) near the bridge of emission joining the two lobes is clearly detected. This is shown in Fig. 3(a), with the 610-MHz contours of Fig. 1 overlaid. Its location makes it a very promising candidate for the central pulsar associated with this PWNe.

[1]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.

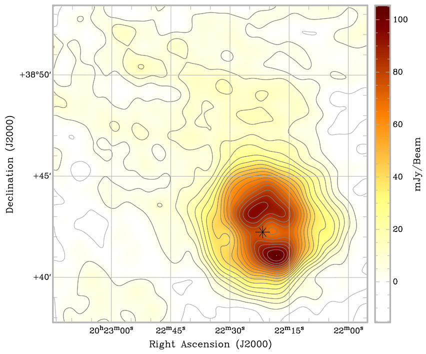


Figure 1: The GMRT 610-MHz map of G76.9+1.0 showing the bipolar structure. The peak is 102 mJy/bm and the resolution is 54″ X 51″.

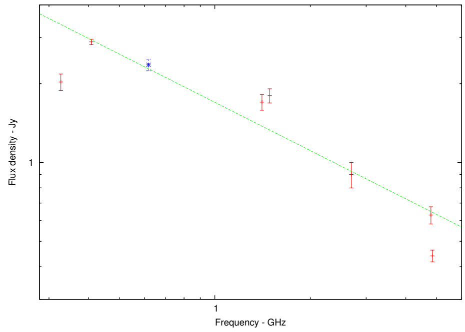


Figure 2: The radio spectrum of G76.9+1.0, with the 610-MHz flux measurement shown in blue. The green line is the power law fit with $\alpha = -0.61$

3. The search for a pulsar at 610 MHz

A pulsar search observation was carried out subsequently on 3 March 2010. In the image made from the simultaneously recorded inteferometric 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 [5] is $\sim$ 250 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.

4. GMRT L-band observations

The lack of pulsations at 610 MHz was puzzling and among many reasons, temporal broadening appeared the most likely cause. Therefore simulataneous pulsar search and interferometric imaging at a higher frequency - 1160 MHz - were carried out. The full-resolution image (Fig. 3(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 α = -$2.1^{-0.45}_{+0.36}$. The pulsar search attained a detectability limit of 100 μJy, similar to the 610-MHz search; however, no pulsed emission was detected. Therefore, it is difficult to assert with certainty that the point source that we see is indeed the central pulsar in this SNR. X-ray observations could however provide support to this interpretation.

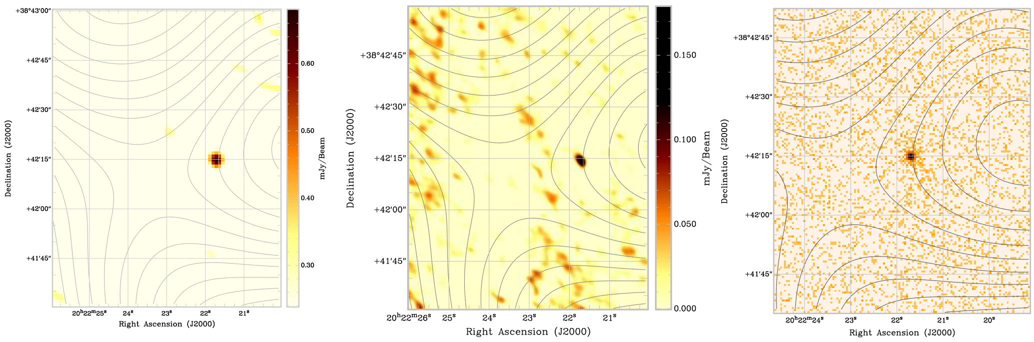
5. *Chandra* X-ray results

Archival ACIS-S detector data from the 01 Aug 2005 *Chandra* observation of G79.6+1.0 was downloaded. The unprocessed *Chandra* X-ray image in the 0.3 − 7 keV band is shown in Fig. 3(c). An unresolved source is detected at α : $20^h22^m21.692^s$, δ : $38^o42'14.81''$(J2000), establishing unambiguously that the radio counterparts at 610 MHz and 1160 MHz are the same object. The best-fitting model revealed an elliptically-shaped, diffuse component around a strong, unresolved core. The 7″ extended component can be identified as a synchrotron nebula around the neutron star, whose photon index $\Gamma = 2.0$ was fixed(similar to Crab nebula). Emission from the strong, unresolved, 2″ core is blackbody in nature with $T_{BB} \sim 1.8\,keV$. The unabsorbed fluxes of the blackbody and powerlaw components are 3.5×10^{-13} and 1.8×10^{-13} ergs cm^{-2} s^{-1} respectively.

6. The nature of the central point source

The blackbody component of the X-ray emission arises from a $\sim$ 100 m region on the surface of the neutron star(using Stefan-Boltzmann law). Such "hot-spot" emission, caused by backflowing particles, is not uncommon among pulsars [6]. The lack of detection of pulsed emission is however puzzling. A previous seacrch failed to detect pulsed emission from G76.9+1.0 [7]; 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 [8] is

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



(a) GMRT 610-MHz map (b) GMRT 1160-MHz map (c) *Chandra* X-ray image

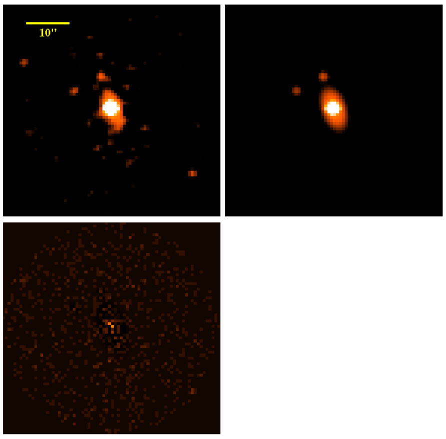
Figure 3: The point source in G76.9+1.0, seen in radio(3(a) and 3(b)) and X-ray(3(c))

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. While in the process of preparing this paper, we learnt [9] 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 $\sim 75\ \mu$Jy 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 turn now to the discussion of the diffuse emission seen in the X-ray image.

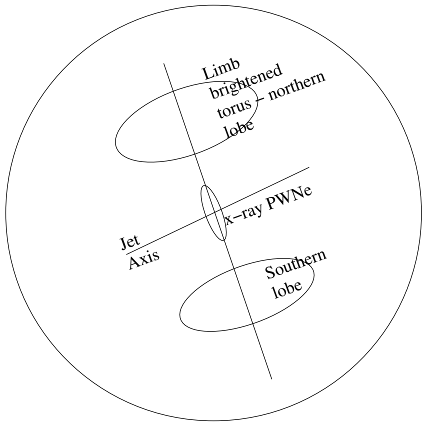
The diffuse X-ray emission has an elliptical structure, the major axis of which is aligned with the radio lobes. There is also a hint of jet-like features perpendicular to the major axis of the ellipse(see top-left in 4(a)). The diffuse component is assumed to be an equatorial wind [10] or the arcs carved by rotating beams of particles [11]. 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 alignement of the torus, it appears as a pair lobes due to *limb brightening*.

7. Conclusions

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. 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.



(a) Model from *Chandra* X-ray image



(b) Schematic model for G76.9+1.0 based on radio and X-ray data

Figure 4: The processed image is shown in the top left panel, model in the top-right panel and the bottom-left shows the residual in 4(a). 4(b) represents the PWNe located in G76.9+1.0.

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