Discovery of a radio nebula around PSR J0855–4644

C. Maitra1*, S. Roy2, F. Acero3, Y. Gupta2
1.Max-Planck-Institut für extraterrestrische Physik,Giessenbachstraße, 85748 Garching, Germany
2.National Centre for Radio Astrophysics, TIFR, Pune University Campus, Post Bag 3, Pune 411 007, India
3.Laboratoire AIM, CEA/DRF - CNRS - Université Paris Diderot, IRFU/DAp, CEA-Saclay, 91191 Gif-sur-Yvette, France

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ABSTRACT

We report the discovery of a diffuse radio emission around PSR J0855–4644 using an upgraded GMRT (uGMRT) observation at 1.35 GHz. The radio emission is spatially coincident with the diffuse X-ray pulsar wind nebula (PWN) seen with XMM-Newton but is much larger in extent compared to the compact axisymmetric PWN seen with Chandra. The morphology of the emission, with a bright partial ring-like structure and two faint tail-like features strongly resembles a bow shock nebula, and indicates a velocity of 100 km/s through the ambient medium. We conclude that the emission is most likely to be associated with the radio PWN of PSR J0855–4644. From the integrated flux density, we estimate the energetics of the PWN.

Key words: stars: pulsars: PSR J0855–4644; radio continuum: ISM

1 INTRODUCTION

Young rotational powered pulsars are the powerhouses of pulsar wind nebulae (PWNe from now). Rotational powered pulsars lose a significant part of their energy via relativistic winds which, upon interactions with the ambient medium, produce a synchrotron powered nebulae emitting from radio to beyond the X-ray bands. The integrated energy spectrum is of synchrotron type, with a power-law having a spectral break around $10^{15} - 10^{15}$ Hz. In the radio band, the spectrum is expected to be flat, $F_{\nu} \propto \nu^{-\alpha}$, with $\alpha$ between 0 and 0.3, while $\alpha > 1$ in the X-ray band. The steepening of the spectrum in X-rays, and hence the spectral break is most commonly associated with losses due to synchrotron cooling. Furthermore, in the radio band the PWN luminosity traces the integrated history of the pulsar spin-down, while in X-rays the PWN luminosity traces the current energy output of the central pulsar (Reynolds & Chevalier 1984). The PWN morphology provides crucial information on the properties of the outflow, the interacting ambient medium and also the geometry of the pulsar powering it (Reynolds et al. 2017).

PSR J0855–4644 is a young and energetic pulsar discovered by the Parkes multibeam radio survey (Kramer et al. 2003). It lies in the Vela region ($l \approx 265^\circ, b \approx -1^\circ$) which is a complex region in the sky with many overlapping supernova remnants (SNRs) along our line of sight. Especially worth mentioning is the Vela remnant, one of the brightest and most extended remnants in the sky (Duncan et al. 1996). Having a large angular size of 8° diameter, it overlapps several SNRs such as Puppis A and RX J0852.0-4622. PSR J0855–4644 is located on the south-eastern rim of RX J0852.0-4622 aka the Vela Jr, but is not associated with it. The measured spin period $P$ of 65 ms and the period derivative ($\dot{P}$) of 7.3 x $10^{-15}$ s s$^{-1}$ result in a spin-down luminosity ($\dot{E}$) of 1.1 x $10^{36}$ erg s$^{-1}$ (assuming a moment of inertia ($I$) of 10$^{45}$ g cm$^2$ for standard neutron star parameters). The characteristic age ($\tau_c = P/2\dot{P}$) is estimated to be 140 kyr.

The source was observed with XMM-Newton, which revealed the X-ray counterpart of the pulsar surrounded by a diffuse non-thermal extended emission which is the PWN associated with it (Acero et al. 2013). Additionally, comparison of column densities provided an upper limit of 900 pc for the distance to the source. A dedicated Chandra observation revealed a further compact X-ray nebula with an axisymmetric morphology resembling a double torus PWN, analogous to the Vela PWN which has an $E$ similar to PSR J0855–4644 (Maitra et al. 2017). However, this nearby energetic PWN has not been reported to be followed up in the radio wavelengths so far.

In this letter we report the discovery of the radio counterpart of the PWN surrounding PSR J0855–4644 using an observation with the upgraded GMRT (uGMRT) (Gupta et al. 2017). Sect. 2 presents the observations and analysis, Sect. 3 the results, Sect. 4 the discussion on the nature of the radio emission and the inferred properties. Finally Sect. 5 presents the summary and conclusions.

2 OBSERVATION & ANALYSIS

Observations with the uGMRT were carried out on 30 January 2017 for 6 hours. All 30 antennas of the array were used to obtain maximum $u$–$v$ coverage. The pointing centre was RA: 08h55m36.0s and DEC: -46°44′13.2″. Observations were carried out at 1.35 GHz with a bandwidth of 200 MHz using 1024 spectral channels. 3C147

* Contact e-mail: cmaitra@mpe.mpg.de

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was used as primary flux density and bandpass calibrator. The VLA calibrator 0835-451 \(^1\) was observed as a secondary calibrator. This calibrator was observed every 30 minutes. After calibration and editing, frequency channels were averaged by a factor of 8 to provide a channel width of 1.56 MHz in the output data. This process significantly reduced the data volume while keeping bandwidth smearing smaller than the synthesized beam during imaging up to half power point of the antennas. The initial images were improved by phase-only calibration and at the last stage by an amplitude and phase self-calibration. The data were then used to image the target source with a short UV cutoff of 0.7 kilo-lambda which resolved out extended structures of angular size \(\gtrsim 2.5'\) in the field. The imaging methodology used in the current work could have missed a possible large scale structure of size \(\gtrsim 4'\). To verify this we made another image with a lower UV cutoff as set by the data to 200 lambda. No significant emission brighter than 2 \(\sigma\) or \(\sim 110 \mu\text{Jy/beam}\) (beam size \(9'' \times 5''\)) was seen around the emission.

3 RESULTS

Fig. 1 (right) shows the 1.35 GHz \textit{uGMRT} image of the region around PSR J0855–4644 showing the diffuse structure around the pulsar. The integrated flux density of the radio emission is 14 \pm 2 mJy, and the significance of the emission is 7 \(\sigma\). Enhanced emission is also detected at the position of the pulsar at a flux density of \(\sim 0.5\) mJy. This is consistent with the estimated flux of the pulsar at 1.4 GHz from Kramer et al. (2003). We find the position of the pulsar to be at RA: 08\(^{h}\)55\(^{m}\).36,29\(^{s}\) \pm 0.02\(^{s}\) and DEC: -46\(^{d}\)44\(^{m}\).15,29\(^{s}\) \pm 0.42\(^{s}\). The difference in RA between the originally reported radio position and the present one is \(\sim 1.5''\). This could arise due to the proper motion of the pulsar in the sky plane. This is however unlikely because the position of the pulsar reported in radio (Kramer et al. 2003, 1999) and in X-rays (Maitra et al. 2017, 2012) at different epochs are consistent with each other. In the absence of any known high resolution (~1") and high sensitivity observation of the field near 1.4 GHz, we cannot check the positions of other background sources in the \textit{GMRT} 1.35 GHz field of view. Field sources observed at 1.35 GHz could be systematically offset (by \(\sim 1.5''\)) due to the phase change caused by ionospheric effects between the target field and the phase calibrator.

Fig. 1 (left) shows a Red-Blue image of the region with the 1.35 GHz \textit{uGMRT} image in red and the 0.5–8 keV \textit{Chandra} image from Maitra et al. (2017) in blue. The white contours denote the 3, 4 and 5\(\sigma\) contours of the diffuse X-ray PWN from Acero et al. (2013). The extent of the radio feature is much larger than the compact axisymmetric nebula seen with \textit{Chandra}, and is comparable to the diffuse X-ray nebula seen with \textit{XMM-Newton}. The central ring-like radio emission surrounding the pulsar is \(\sim 45''\) in diameter, and is of the same size as the inner nebula seen with \textit{XMM-Newton}. This corresponds to the innermost white contour denoting the emission at 5\(\sigma\) significance. A brightening is observed at the south-eastern region of the ring. Two extended tail-like features extend in the north-west direction making the total nebula about 1.5" (90") in extent. It is worth noting that Acero et al. (2013) reported diffuse X-ray emission up to \(\sim 150''\). However, as can be seen from the over-plotted contours, the 3\(\sigma\) emission extends only up to 90". Further the X-ray emission seen with \textit{XMM-Newton} is contaminated with the Vela SNR at energies \(< 1\) keV, and by the non-thermal emission from the Vela Jr at energies \(> 1\) keV. Therefore, any low significance emission should be treated with caution.

4 DISCUSSION

At the estimated distance of 900 pc, the radio nebula detected around PSR J0855–4644 corresponds to a physical size of 0.44 pc. The inferences on the nature of the radio emission and some derived physical properties of the system are given below.

4.1 Nature of the radio emission

The spatial coincidence of the enhanced radio emission with the diffuse X-ray emission surrounding PSR J0855–4644, is a strong indication that we have discovered the radio counterpart of the PWN. However, in the absence of radio data at two different wave-lengths, the spectral index of the source cannot be determined which would establish the nature of the emission as non-thermal with certainty (as is expected from PWN). In the absence of this, we have investigated the possibility of this emission emerging from two other competing phenomena: a SNR associated with PSR J0855–4644 and an overlapping HII region.

First we assume that the ring-like radio structure surrounding the pulsar is an associated SNR. In this hypothesis, we can fix a lower limit for the age of the SNR to 10 kyr (the characteristic age of the PSR is 140 kyr but this estimate is often an overestimate of the true age of the system). At a distance of 900 pc, the physical radius is 0.1 pc. The Sedov-Taylor equation relates the radius of the forward shock \(R_{sh}\) as a function of time \(t\) for a given supernova explosion energy \(E\), and density \(n_0\) as:

\[
R_{sh} = 5.06 \left(\frac{n_0}{1 \text{ cm}^{-3}}\right)^{1/5} \left(\frac{E}{10^{51} \text{ ergs}}\right)^{1/5} \left(\frac{t}{10^3 \text{ years}}\right)^{2/5} \text{ pc}
\]

Assuming \(E = 10^{53}\) ergs, \(n_0 \sim 10^{10} \text{ cm}^{-3}\) (for \(R_{sh} = 0.1\) pc and age \(\sim 10\) kyr). In the unlikely scenario where the pulsar distance is overestimated by a factor of 10 (i.e. \(R_{sh} = 1\) pc), \(n_0\) would be still be very high \(\sim 10^{12} \text{ cm}^{-3}\). Assuming a cloud of size similar to the partial shell-like source with a density of \(10^{10}\) \text{ cm}^{-3}\), its associated column density \(N_H\) would be \(6 \times 10^{21} \text{ cm}^{-2}\) \((6 \times 10^{22} \text{ cm}^{-2}\)). Comparing this from the 3\(\sigma\) and 12\(\sigma\) CO data along the line of sight to the pulsar (Fig. 6 of Acero et al. 2013), \(N_H \sim 1.5 \times 10^{22} \text{ cm}^{-2}\), when integrated over all velocities. Therefore, we conclude that the association of the ring-like structure with a SNR evolving in a dense molecular cloud is unlikely.

We also consider the possibility of the emission being thermal free-free in nature. This region has been observed by the WISE survey at 22 \(\mu\)m (Wright et al. 2010). Infra-red emission at 24 \(\mu\)m has earlier been shown to be highly correlated with Paschen-\(\alpha\) emission (Calzetti et al. 2005) and is used as a proxy of thermal emission (Murphy et al. 2006) from galaxies. Emission at this band can be used to predict the thermal emission in the radio band (Basu & Roy 2013). Dust emissivity at a very nearby wavelength of 22 \(\mu\)m is expected to be quite close to its 24 \(\mu\)m emission and can be used as a tracer of HII region density. The Model by Gordon et al. (2017) indicate the dust emission at 24 \(\mu\)m to be \(\sim 15\%\) higher than what is measured at 22 \(\mu\)m from WISE data. From the background subtracted images, we did not detect any emission at the position of the source from the WISE map at 22 \(\mu\)m (Fig. 2). The measured upper limit of its flux density at 22 \(\mu\)m is 700 DN (WISE map unit). Using

\(^1\) https://science.nrao.edu/facilities/vla/observing/callist
Furthermore, Basu & Roy (2013) noted that the proper motion for PSR J0855–4644 is 9′′ × 5′′. Its major and minor axis is 9′′ and 5′′ respectively and the beam position angle is 16′ (major axis orientation from North towards East). Basu & Roy (Cheng et al. 2004; Maitra et al. 2007; Kargaltsev et al. 2017). Although the proper motion for PSR J0855–4644 is not yet known, the bow shock structure indicates supersonic motion through the local medium. In this case the termination shock radius \( R_{\text{ts}} \) can be determined from the balance between the relativistic wind of the pulsar and the ram pressure at the head of the shock. This is expressed as (Cheng et al. 2004)

\[
R_{\text{ts}} \sim 3 \times 10^{16} \frac{E_{\text{p}} n_{1}}{\nu_{\text{p,100}}} \frac{v_{\text{p,100}}}{100 \text{ cm}}.
\]

Here \( n_{1} \) is the number density in units of particles cm\(^{-3} \) and \( \nu_{\text{p,100}} \) is the space velocity of the pulsar in units of 100 km/s. Assuming the partial-ring to be the termination surface \( R_{\text{ts}} \), the distance between the pulsar and the tip of the bow shock is \( \sim 20′′ \) \(( \sim 0.1 \text{ pc at a distance of 900 pc})\). Given an \( E \) of 10\(^{36} \) erg/s and a typical ambient density of 1 cm\(^{-3} \), the velocity of the pulsar is \( \sim 100 \) km/s. Further assuming that the transverse velocity of the pulsar is comparable to the velocity estimated as above, a shift of \( \sim 0.5′′ \) is expected between the radio and the X-ray observation separated by 13 years. Given the uncertainty in the determination of the positions, such a shift would not be noticeable and is consistent with our results. Future deeper and more sensitive observations separated by a large time gap will ascertain this.

### 4.2 Comparison between the radio and X-ray emission

The difference between the size of the radio and X-ray PWNe mainly depends on whether synchrotron cooling has set in. This can often lead to a difference in size between the radio and X-ray PWNe. Since the higher energy X-ray electrons cool faster, the number of X-ray emitting particles decrease rapidly with increasing distance from the pulsar leading to a smaller size of the X-ray nebula compared to the radio counterpart. For the same reason a steepening in the power-law spectral index of the synchrotron emission is also observed frequently. The break frequency \( \nu_{\text{break}} \) is a function of the age of the pulsar and the magnetic field of the nebula, \( \dot{\nu}' \). Lower values of \( \nu_{\text{break}} \) are expected for higher magnetic fields \( B_{\text{neb}} \). Therefore systems which have comparable sizes of the X-ray and radio nebulae may have either weak \( B_{\text{neb}} \) or are intrinsically young PWNe where the process of cooling has not yet set in (e.g. 3C 58, G130.7+3.1: Gaensler & Slane 2006). Furthermore,
the radio and the X-ray emission are not always spatially correlated and even anti-correlation has been observed, e.g., for Vela (Dodson et al. 2003); and G319.9-0.97 (Ng et al. 2010).

Comparison between the radio and X-ray emission around PSR J0855–4644 (Fig. 1) indicates that the radio nebula is comparable in size with the X-ray nebula. The faint tail-like features of the radio emission in the north-west however extend beyond the X-ray emission. This indicates that the size of the X-ray PWN \( \lesssim \) to the radio counterpart. The \( E \) and the morphology of the compact X-ray PWN around PSR J0855–4644 point to a Vela-like pulsar, generally categorized as fast-spinning pulsars with characteristic ages 10 kyr \( \lesssim \tau_c \lesssim 100 \) kyr and \( E \gtrsim 10^{38} \text{erg/s} \) (Kramer et al. 2003). Although the characteristic age of the system is measured to be 140 kyr, it is to be noted that this is often an overestimation of the age of the system (e.g. Migliazzo et al. 2002). Therefore PSR J0855–4644 is not a young PWN (Crab-like) where synchrotron cooling might not have set in. This indicates that the system has a weak \( B_{\text{amb}} \) which renders the cooling time-scales to be longer.

4.3 Inferred properties of the system

From the integrated flux density, the radio luminosity of the PWN (\( L_{\text{rg}} \)) can be estimated assuming a typical spectral index of -0.3 between 10³ and 10¹¹ Hz, and using equation (4) in Frail & Scharringhausen (1997). The estimated \( L_{\text{rg}} \) is \( \sim 1 \times 10^{30} \) erg/s and the radio efficiency \( L_{\text{rg}}/E = \eta_{\text{rg}} \sim 1 \times 10^{-6} \). Given that the flux is measured only at one frequency and not integrated over the entire frequency range of emission of the radio nebula, this is a lower limit. Both \( L_{\text{rg}} \) and \( \eta_{\text{rg}} \) are however very similar to that obtained for the Vela pulsar (Dodson et al. 2003).

5 SUMMARY

From radio observations using the \( uGMRT \) at 1.35 GHz, we have discovered diffuse radio emission surrounding the Vela-like pulsar PSR J0855–4644, for the first time. A central ring-like radio feature surrounds the pulsar, which is brightened at the south-east region. Two tail-like features extend in the north-west direction. A faint diffuse emission fills the whole feature. The structure corresponds to a physical size of 0.44 pc. This is much larger than the compact axisymmetric X-ray nebula (0.06 pc) seen with Chandra but is similar in extent to the diffuse X-ray nebula seen with XMM-Newton.

The spatial coincidence of the radio emission with the diffuse X-ray emission is in strong favour of it being the radio counterpart of the PWN. We have also ruled out its origin as an overlapping SNR on a HH region along the line of sight, given the size of the structure, its comparison with HI and \(^{12}\)CO data along the line of sight to the pulsar, and the \( WISE \) images. The PWN morphology strongly resembles a bow shock nebula and the radius of the termination shock indicates a velocity of 100 km/s through the ambient medium.

The integrated flux density at 1.35 GHz provides an estimate of \( L_{\text{rg}} \sim 1 \times 10^{30} \) erg/s and \( \eta_{\text{rg}} \sim 1 \times 10^{-6} \). These are similar to that observed in the Vela PWN.

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