ON THE NATURE OF OFF-PULSE EMISSION FROM PULSARS

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Received 2012 August 5; accepted 2012 August 23; published 2012 October 3

ABSTRACT

In our earlier studies, we reported the detection of off-pulse emission from two long-period pulsars B0525+21 and B2045–16. The pulsars were observed at a single epoch using the 325 MHz frequency band of the Giant Meterwave Radio Telescope (GMRT). In this paper, we report a detailed study of the off-pulse emission from these two pulsars using multiple observations at two different frequencies, 325 MHz and 610 MHz bands of GMRT. We report detection of off-pulse emission during each observation and based on the scintillation effects and spectral index of off-pulse emission we conclude a magnetospheric origin. The magnetospheric origin of off-pulse emission gives rise to various interesting possibilities about its emission mechanism and raises questions about the structure of the magnetosphere.

Key words: pulsars: general – pulsars: individual (B0525+21, B2045–16) – techniques: interferometric

1. INTRODUCTION

The basic pulsar phenomenon where a series of highly regular narrow pulses is observed has been explained from the very outset by invoking the lighthouse model. In this model, the highly magnetized, rotating neutron star has a charge filled magnetosphere. The magnetic field surrounding the central star is characterized by a dipolar field with open and closed field line regions. The locus of the foot prints of the open field lines on the neutron star surface constitute the polar cap. It is believed that plasma is accelerated to relativistic velocities at the polar cap, which streams out along the open field lines, giving rise to the observed coherent radio emission. This originates a few hundred kilometers above the stellar surface, and appears as narrow pulses due to the rotation of the neutron star. The plasma remains trapped in the closed field line regions thereby abating from the emission process.

The known cases of emission from pulsars outside the main pulse are the interpulse, pre/post-cursor emission and the pulsar wind nebulae (PWNe). The interpulse and pre/post-cursors emission appear as temporal structures in the time series data. The interpulse emission (located 180° away from main pulse) are usually associated with orthogonal rotators, the radio emission in the interpulse believed to originate from the opposite magnetic pole. The pre/post-cursor emission are located closer to the main pulse and connected via a bridge emission. They are highly polarized and their location in the magnetosphere is uncertain. The time series observations of pulsars are insensitive to any temporally constant background emission. The technique of gated interferometry, where the main pulse emission is blocked, can probe a constant background emission by mapping the off-pulse region. In the past, gated interferometric studies have been employed to detect PWNe from very energetic young pulsars with spin-down energies $E \geq 10^{44}$ erg s$^{-1}$ (Frail & Scharringhausen 1997).

In recent studies, we reported the detection of off-pulse emission from two long-period pulsars based on gated interferometric observations with the Giant Meterwave Radio Telescope (GMRT) at 325 MHz (Basu et al. 2011, hereafter Paper I). Our detection of off-pulse emission is a “unique” and surprising result because the two long-period pulsars are relatively old and less energetic unlike the pulsars known to harbor PWN. Also, the pulse profiles do not show any temporal structures outside the main pulse. We concluded on heuristic grounds that the detected off-pulse emission is magnetospheric in origin based on outlandish expectations of interstellar medium (ISM) densities to sustain a PWN for these pulsar energetics.

In this paper we continue our previous investigations of off-pulse emission. In Section 2 we report the detection of off-pulse emission at widely separated times and frequencies (see Section 2.1) and also account for the authenticity of these detections by carrying out a detailed test of the instrument to weed out possibility of the detected emission being a result of smearing of the pulsed signal across time (see Section 2.2). In Section 3 we study the flux variations which lead us to an upper limit of the size of the off-pulse emission region (see Section 3.1) and we also obtain secure estimates of its spectral index $\alpha$ (see Section 3.2). Based on our estimates of these properties, we conclude that off-pulse emission have a magnetospheric origin. Finally, we discuss the results and their implications in Section 4.

2. OBSERVATIONS AND ANALYSIS

2.1. Multi-epoch/Multi-frequency Observations

We reported detection of off-pulse emission in Paper I from two pulsars, PSR B0525+21 and B2045–16, based on single epoch observations at 325 MHz with the GMRT. We have now observed these two pulsars at 325 MHz and 610 MHz multiple times. The observations were carried out between 2010 January and 2011 August (see Table 1). The specialized interferometric high time resolutions of 128/256 ms supported by the GMRT correlator system were used for these observations. We observed the pulsars at both 325 MHz and 610 MHz frequency bands. During the early months of 2011, the GMRT correlator system was upgraded from the previously existing hardware backend (GHB) to a software backend (GSB) which is currently being used. The GHB was used with the lowest available time resolution of 131 ms and a bandwidth of 16 MHz split into 128 channels. The GSB initially operated at a lowest time resolution of 251 ms over a 16 MHz bandwidth spread across 32 channels. The GSB was extended to operate at 125 ms time resolution over 16 MHz bandwidth split into 256 channels. All these modes were used for our observations as documented in Columns 1–6 of Table 1.
We used the technique of “offline-gating” discussed in Paper I to image the on- and off-pulse regions. To summarize briefly, the interferometric time series data were folded with the periodicity of the pulsar to determine the on- and off-pulse phases; a phase was assigned to each time record and two “gates” were put in to separate the on- and off-phase data, which were then imaged and the flux of the point source coincident with the pulsar position in each image measured. To check for the consistency of measured pulsar flux over different epochs of observations, we compared the flux of the other point sources in the field which were within 10% (within calibration errors) for all observations. This indicates that any large variations in the on- and off-pulse flux were intrinsic effects.

Table 1 gives the details of the experimental setup and also summarizes the results of the analysis. Column 7 shows the angular resolution in the images. During each of these observations a point source was detected at the location of the pulsars in both the on- and off-pulse maps. The on-pulse flux, averaged over the pulse period (all on-pulse flux reported in this paper is averaged over the entire period), is reported in Column 8 while Column 9 reports the measured off-pulse flux. The ratio of the off-pulse flux and period averaged on-pulse flux is shown in Column 10. An example of off-pulse and on-pulse image for a single epoch at 610 MHz is shown in Figures 1 and 2.

Thus in summary, in each of the multi-epoch and multi-frequency interferometric observations we have detected off-pulse emission from PSR B0525+21 and B2045–16. In our studies we used two different correlator systems, the GHB and GSB, and two different frequency bands, 325 MHz and 610 MHz, which make it extremely unlikely for the off-pulse to be a spurious detection.

2.2. Pulsed Noise Source: Smearing of Signal across Time

In Paper I, we discussed the possibility that off-pulse emission was a result of temporal leakage of the pulsed signal. To investigate this we recorded front end terminated 131 ms interferometric data and estimated the autocorrelation of the noise signal for each baseline. We found that the observed autocorrelations were significantly lower (0.04%) than the levels required (around 1%) to explain the observed off-pulse emission (see Paper I for details).

However, the above experiment did not account for temporal leakages due to a strong pulsed signal as seen in pulsars. In order to investigate this effect a series of narrow single pulses with no off-pulse emission was required to be introduced in the receiver system. A broadband pulsed noise source with a period of 4 s and a duty cycle of 32 ms was developed for this purpose. The power of the on-pulse signal was −5 dbm and the signal was down by 30 db in the off-state, which was significantly below the detected off-pulse emission. The noise source was radiated from an antenna in the central square of the GMRT. Interferometric data were recorded with a time resolution of 251 ms for about half an hour with the noise source switched on. Since the noise source was in the near field, the geometrical delay calculations were vastly complicated (it is a function of the distance of the individual antennas from the pulsed noise source). We did not correct for any geometrical delay in the correlator chain. This implied that only for a handful of cases (10 baselines) were the antennas close enough for the coherence condition to hold, and these baselines were used for the subsequent analysis as discussed below.

If there were no leakage of the pulsed signal in time, the folded profile with increasing number of periods averaged together, for any baseline, would show a decrease in the off-pulse noise and an increase in the signal-to-noise ratio (S/N) by a factor $\sqrt{N}$, where $N$ is the number of folded periods.

The interferometer measures the correlation between the voltages recorded by the individual elements (Thompson et al. 1986):

$$ r(\tau) = \frac{1}{2T} \int_{-T}^{T} V_1(t) \times V_2(t - \tau)dt, $$

where the quantity $r(\tau)$ is related to the intensity of the incident signal and $2T$ is the temporal resolution (251 ms).

We assume that the system introduces a constant fractional leakage $\epsilon$ into the adjacent time bin (this is the most likely situation, besides any other situation will lead to a lower S/N). The correlation in the adjacent bin in such a scenario is given as

$$ r'(\tau) = \epsilon^2 \frac{1}{2T} \int_{-T}^{T} V_1(t) \times V_2(t - \tau)dt, \quad \epsilon < 1. $$

The statistics of the bins adjacent to the pulsed source is characterized by a mean ($\mu$) and rms ($\sigma$) given as

$$ \mu = \epsilon^{2n} \frac{1 - \epsilon^{2N}}{N(1 - \epsilon^2)} \times r(\tau) \quad (1) $$

$$ \sigma \sim \frac{\epsilon^{2n}}{(1 - \epsilon^2)^{3/2}} \sqrt{\frac{1 - \epsilon^{2N}}{N(1 + \epsilon^2)}} \times r(\tau). \quad (2) $$

Here the first bin is the nth bin from the pulsed source with $N$ bins used for statistics; $r(\tau)$ is the correlation in the pulsed source bin. The statistics of the adjacent bins will be governed by a combination of Gaussian statistics due to random noise and
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Figure 1. Folded profile (top) of B0525+21 representing the on- and off-pulse gates. The corresponding contour maps of the on-pulse (bottom left) and off-pulse (bottom right) emission from the pulsar. The data were recorded on 2011 February 15 at 610 MHz.

the constant leakage into adjacent bins. However, for sufficiently long averaging, the effect of random noise will be overshadowed by the leakage term and the S/N for the pulsed source would saturate at a constant level.

The interferometric data from the pulsed noise source were folded with a periodicity of 4 s to determine the profile (see Figure 3). A large number of profiles of the noise source were generated by folding an increasing number of periods. The S/N for each of these profiles were calculated by dividing the total signal in the noise bin with the rms fluctuation in the adjacent bins. In Figure 3 we plot the S/N as a function of the square root of the number of periods (points) along with the best fit (dark solid line).

We have detected off-pulse emission in pulsars at a level of 0.5%–1% of the on-pulse flux. The off-pulse region in our studies are five bins (n = 5) from the on-pulse and we can calculate the leakage (ε) required using Equations (1) and (2) to explain the detected off-pulse. This would lead to an S/N ~ 500, as represented by the dot dashed horizontal line in Figure 3. However, the bins adjacent to the noise source continue to follow Gaussian statistics at S/N ~ 8000 as seen in Figure 3. This implies that the temporal leakage can only lead to an off-pulse emission which is less than 0.03% of the on-pulse flux. Hence, the detected off-pulse emission cannot originate as a result of temporal leakage of the on-pulse signal into adjacent time bins.

The unprecedented detection of off-pulse emission makes it imperative to exhaust all possibilities of spurious detection. In this section we report repeated detections of off-pulse emission in multiple epochs and frequencies using different correlator systems and also rule out spurious detection that can result due to temporal leakage. We have established that the off-pulse emission is genuine and not a result of systematic anomaly. We now look ahead to determining the nature of off-pulse emission.

3. MAGNETOSPHERIC ORIGIN OF OFF-PULSE EMISSION: FLUX VARIATION AND SPECTRAL INDEX STUDY

In Paper I we argued that low energetic (E ~ 10^{31} erg s^{-1}) long-period pulsars B0525+21 and B2045–16, were unlikely to harbor PWNe around them. The ISM particle densities required to drive either a static or a bow shock nebula turns out to be grossly unrealistic. We concluded that the off-pulse emission must have a magnetospheric origin.

The radio emission in PWNe is due to relativistic charged particles producing synchrotron emission in the ambient ISM magnetic field. The typical size of PWNe is between 0.1 and 1 pc due to expansion of the pulsar wind in the surrounding ISM (Gaensler & Slane 2006). If the off-pulse emission can be constrained to several orders of magnitude lower than the typical PWN sizes, a PWN origin can be discounted. Further,
Figure 2. Folded profile (top) of B2045−16 representing the on- and off-pulse gates. The corresponding contour maps of the on-pulse (bottom left) and off-pulse (bottom right) emission from the pulsar. The data were recorded on 2011 August 25 at 610 MHz.

Figure 3. Pulsed noise source as observed with the interferometer (left), with 565 folded periods of 4 s and a time resolution of 250 ms. The change in signal-to-noise ratio of the pulsed signal with increasing number of folded periods (N) from 10 periods to 565 periods (right). The dark solid lines represent a linear increase of S/N with √N indicating the baseline to be noise like. The dot-dashed horizontal line is the level at which the S/N was expected to saturate if temporal leakage was the source of off-pulse emission.

a wide range of studies (Weiler & Sramek 1988) suggests that PWNe observed in the radio frequencies between 100 MHz and 10 GHz are usually characterized by a flat radio spectral index α in the range 0 > α > −0.5 (where $S \sim \nu^\alpha$). The spectrum presumably reflects the energy spectrum of the injected particles from the pulsar. In some older PWNe the spectrum might steepen somewhat, as in PWNe DA495 (Kothes et al. 2008) where the spectrum steepen to α = −0.87 above 1.3 GHz as a result of synchrotron aging. In contrast to PWNe, the pulsed emission is the coherent radio emission arising due to relativistically streaming charged particles in strong magnetic field with the observed average α ≈ −1.8 (Maron et al. 2000). Although in some examples the spectra might show breaks where α is flatter for certain frequency range (like PSR B1952+29 which has α = −0.6 between 400 MHz and 1.4 GHz; also see the spectra of B2045–16 in Figure 6), mostly they are consistent with a steep
The long-term averaging results in reduced contribution of RISS and DISS to the pulsar flux. Stinebring et al. (2000) quote the pulsar flux is also affected by pulsar obtained averaging 2500–3000 pulses is relatively stable due to both intrinsic and extraneous effects. The intrinsic variations occur on timescales of microseconds to several minutes manifesting as microstructures in single pulses, drifting subpulses, nulling, mode changing, etc. However, the profile of a pulsar is time variant its flux has been monitored at different frequencies for several years as reported in Lorimer et al. (1995) and Stinebring et al. (1990). In order to determine the spectral index of the off-pulse emission it is imperative we understand its short- and long-term flux variations at each frequency.

PSR B0525+21 has a dispersion measure of 50.9 pc cm\(^{-3}\) and its flux has been monitored at different frequencies for several years as reported in Lorimer et al. (1995) and Stinebring et al. (2000) (see Figure 6 for the average flux at low frequencies). The long-term averaging results in reduced contribution of RISS and DISS to the pulsar flux. Stinebring et al. (2000) quote the scintillation parameters at our observing frequency of 610 MHz as \(T_d \sim 70 \text{ s}, \Delta \nu_d \sim 230 \text{ KHz}, m_r \sim 0.32, \text{ and } T_r \sim 4 \text{ days}.\) Using the scaling relations the equivalent quantities at 325 MHz are \(T_d \sim 33 \text{ s}, \Delta \nu_d \sim 15 \text{ KHz}, m_r \sim 0.22, \text{ and } T_r \sim 16 \text{ days}.\)

Each of the GMRT observations for B0525+21 extends for about 6–8 hr and 16 MHz bandwidth at both 325 and 610 MHz. Any flux variations due to DISS will be greatly reduced over these scales. Based on our current understanding, any DISS will be greatly reduced over these scales. Due to RISS, one expects 5% and 10% variation in flux over a single observing run at 325 MHz and 610 MHz, respectively (these are comparable to the error in flux measurements and hence undetectable). In Table 1 the average on- and off-pulse flux and the off-pulse to on-pulse flux ratio during each observing session is reported. The long-term flux change (about 55%) seen at 325 MHz (Figure 4, first panel on left) is due to RISS; however, the off-pulse to on-pulse flux ratio remains constant both at 325 and 610 MHz (see Figure 4, second panel on the left). The short-term flux variations were determined by dividing a single observing session into shorter intervals (0.5–1 hr) and making images for each case. The on- and off-pulse flux was measured for each interval and the off-pulse to on-pulse flux ratio was calculated (see Figure 5, panels on the left). The short timescale flux variations were within the errors of measurement, as expected, and the off-pulse to on-pulse flux ratio was also constant.

B2045–16 has a dispersion measure of 11.5 pc cm\(^{-3}\) and its long-term flux has been monitored at multiple frequencies by Stinebring & Condon (1990) and Lorimer et al. (1995). Based on daily flux measurements for 43 days, Stinebring & Condon (1990) quote the scintillation parameters at 310 MHz (near our observing frequency of 325 MHz) as \(T_d \sim 63 \text{ s}, \Delta \nu_d \sim 288 \text{ KHz}, m_r \sim 0.60, \text{ and } T_r \sim 1.5 \text{ days}.\) Using the scaling relations the equivalent quantities at 610 MHz are \(T_d \sim 134 \text{ s}, \Delta \nu_d \sim 4 \text{ MHz}, m_r \sim 0.85, \text{ and } T_r \sim 0.5 \text{ days}.\)

The observations extended for 3–5 hr over 16 MHz bandwidth at both 325 and 610 MHz for each observing run. Any DISS...
related flux variations are expected to be reduced due to averaging over time and frequency. However, due to RISS, we expect large flux variations of 110% and 40% over a single observing run at 610 and 325 MHz, respectively. In Table 1 the average on- and off-pulse flux measurements and the off-pulse to on-pulse flux ratios for each observation are quoted. The long-term flux variations and off-pulse to on-pulse flux ratio are shown in Figure 4, right panel. The pulsar flux shows variation in the flux values which are expected due to RISS; however, the off-pulse to on-pulse flux ratio also showed large variations at long

*Figure 5.* Plots show the variation of the on-pulse flux and the off-pulse to on-pulse flux ratio at shorter timescales. The duration of a single observation spans several hours and the on- and off-pulse fluxes were determined averaging 0.5–1 hr at a time within a single observation. For the pulsar B0525+21 (left), the on-pulse flux varied at short timescales (several hours) within errors of measurements and the on-pulse to off-pulse ratio remained constant at these timescales. In the case of B2045–16 (right) the on-pulse flux variations were once again within errors at 325 MHz with the off-pulse to on-pulse flux ratio remaining constant. At 610 MHz the on-pulse flux showed large variations; however, the off-pulse to on-pulse flux ratio once again remained constant at short timescales for both observations even though they sometimes go below detection level (arrows pointing downward show upper limit of detection). This demonstrated both the long and short timescale constancy of the off-pulse to on-pulse flux ratio for B2045–16 at 610 MHz.
The spectra were determined between 300 MHz and 1.6 GHz by fitting a power law to the archival data (Maron et al. 2000; Lorimer et al. 1995). In the case of B2045–16 (right) the on-pulse spectrum was obtained between 300 MHz and 10 GHz. There is a break in the spectrum around 750 MHz and two separate spectral indices were calculated with values of $-2.3$ above 750 MHz which flattened to $-0.95$ at low frequencies.

### Table 2

| Pulsar   | Period (s) | Dist (kpc) | $V_{\text{trans}}$ (km s$^{-1}$) | $T_{325}^\text{off}$ (day) | $T_{610}^\text{off}$ (day) | $P_c/2\pi$ (km) | $D_{325}^\text{OFF}$ (km) | $D_{610}^\text{OFF}$ (km) | $\theta_{325}^\text{max}$ ($^\circ$) | $\theta_{610}^\text{max}$ ($^\circ$) | $R_{325}^\text{max}$ (km) | $R_{610}^\text{max}$ (km) |
|----------|------------|------------|----------------------------------|-----------------------------|-----------------------------|----------------------|-----------------------------|-----------------------------|---------------------------------|-------------------------------|-----------------------------|-----------------------------|
| B0525+21 | 3.746      | 2.28       | 229                              | 16                          | 4                           | $1.8 \times 10^5$     | $1.6 \times 10^8$     | $4.0 \times 10^7$     | $1.2 \times 10^{-6}$         | $2.5 \times 10^{-6}$         | $4.1 \times 10^5$             | $8.6 \times 10^5$             |
| B2045–16 | 1.962      | 0.95       | 511                              | 1.5                         | 0.5                         | $0.9 \times 10^5$     | $3.3 \times 10^7$     | $1.1 \times 10^7$     | $5.7 \times 10^{-6}$         | $9.3 \times 10^{-6}$         | $8.2 \times 10^5$             | $13.2 \times 10^5$            |

The off-pulse to on-pulse flux ratio as demonstrated above remains constant at all timescales for both pulsars. This signifies that the timescales of refractive scintillations for the off-pulse are similar to that of the main pulse, which readily puts a constraint on the size of the emitting region of the off-pulse with respect to the on-pulse. If we assume a thin screen approximation for refractive scintillation, i.e., the refractive scintillations are due to a thin lens (0.001–0.005 fraction of the thickness of intervening medium) placed a fractional distance $\beta$ ($\beta = D_\ell/D$, where $D_\ell$ is the separation between pulsar and lens and $D$ is the distance of pulsar from observer) from the pulsar, the refractive timescale is given as

$$T_r = \frac{D_\ell}{V_{\text{trans}}(1 - \beta)}, \quad (3)$$

where $D_\ell$ is the diameter of the lens and $V_{\text{trans}}$ is the transverse velocity of the pulsar in the sky plane with respect to observer. The similar refractive timescales imply that the on-pulse and off-pulse emission is unresolved with respect to the lens putting an upper limit to emitting regions for the on- and off-pulse with the maximum angular separation given as $\theta_{\text{max}} \sim \lambda/D_\ell$.

Using the known properties of the pulsars (Table 2) and assuming the refractive lens lies midway between the pulsar and observer ($\beta = 0.5$), we calculate the diameter of the lens ($D_\ell$) in each case using Equation (3). This is further used to determine the upper limits to the angular size of the emitting region ($\theta_{\text{max}}$). Finally, the physical size of the maximum emitting region ($R_{\text{max}}$) is calculated using $\theta_{\text{max}}$ and distance to the pulsars (see Table 2). The maximum emitting region (which is also the maximum separation between the on-pulse and off-pulse emitting regions) is constrained to be a few microarcsec ($\theta_{\text{max}}$). This further implies that the off-pulse emission is constrained by the refractive scintillations to originate within an order of magnitude of the light cylinder radius ($P_c/2\pi$). As discussed previously, this is several orders of magnitude lower than the typical size of a PWN and thereby rules out the PWN origin of off-pulse emission.

### 3.2. Spectral Index of On- and Off-Pulse Emission

We have established that the off-pulse to on-pulse flux ratios remain constant at all timescales. This enables us to determine the off-pulse spectral index between 325 MHz and 610 MHz provided the on-pulse spectral index is known and both the emissions follow a power-law spectrum. The off-pulse spectral index is given as

$$\alpha_{\text{OFF}} = \alpha_{\text{ON}} + \frac{\log(\rho_1/\rho_2)}{\log(v_1/v_2)}, \quad (4)$$

The short timescale flux values were determined once again by dividing a single observing session into shorter intervals (0.5–1 hr) and making images for each case. The on-pulse flux at 610 MHz showed large variations in excess of 100% (see Figure 5, third panel on the right); however, the off-pulse to on-pulse flux ratio, when detected, remained at constant level for the two observations separated by months (see Figure 5, fourth panel on the right). The apparent variation of the off-pulse to on-pulse flux ratio at large timescales can be attributed to the fact that the off-pulse was below detection limit for a large fraction of the observing run resulting in an underestimation of the average off-pulse flux over the entire observing run. At 325 MHz the short timescale measurements once again showed a constant level of off-pulse to on-pulse flux ratio at short timescales for the observation on 2011 August 3 (see Figure 5, second panel on right). The observation on 2011 January 16 was affected by the telescope pointing 34′ away from the pulsar resulting in increased noise levels at pulsar position thereby making the short interval studies impossible (the off-pulse was undetected in increased noise levels at pulsar position thereby making the short interval studies impossible). We conclude that despite the large variation of the on-pulse flux and the apparent variation of the off-pulse to on-pulse flux ratio at large timescales, the off-pulse to on-pulse flux ratios remain constant at all timescales for this pulsar.
2. The next important step was to establish through observational arguments the nature of off-pulse emission. In Section 3 we demonstrate that for PSR B0525+21 the off-pulse to on-pulse flux ratio is constant at both 325 and 610 MHz, which in turn gives a spectral index \( \alpha_{\text{OFF}} \sim -1.4 \). We have also demonstrated that despite apparent variations in the long-term off-pulse to on-pulse flux ratio for the pulsar B2045–16, it actually remains constant at all timescales when the off-pulse flux variations are taken into account. This once again allowed us to determine the spectral index of \( \alpha_{\text{OFF}} \sim -1.1 \). Based on the observed properties of refractive scintillation, we derived the radio emission region of the off-pulse emission to have a maximum size of magnetospheric scale (see Section 3.1). The steep spectral index coupled with a highly compact emission region makes it highly unlikely for the off-pulse emission to be a PWNe.

The off-pulse emission appears to be a completely new and hitherto undetected magnetospheric emission from pulsars. The estimated brightness temperature of the off-pulse emission is greater than \( 10^{18} \) K, assuming the emission originates at the light cylinder. This strongly suggests a coherent radio emission process as the mechanism for explaining the off-pulse emission which leads to the next important question: Where and how does this off-pulse coherent emission originate in the pulsar magnetosphere? Currently, we do not have any good answers to these questions but there are a few likely possibilities that can be considered. The basic pulsar models suggest that the power from the rotational energy in a neutron star is tapped and converted into the observed radiation. The rotating magnetic field of the neutron star acts like a unipolar inductor, creating high electric fields around the neutron star where charged particles are accelerated to relativistic velocities along the open field lines. This eventually leads to the pulsar radiation. A large number of models exist that try to establish the location of the charge accelerating regions and suggest physical mechanisms that can excite the coherent radio emission in pulsars. However, here we will not go into the details of any of these models, but would like to point out why finding the location of the emission region in the pulsar magnetosphere is central in unraveling the origin of the off-pulse emission.

In most pulsar theories the radio emission is excited due to development of plasma instabilities in the outflowing plasma. The main pulse emission arises around 500 km above the neutron star surface (Blaskiewicz et al. 1991; Rankin 1993; Kijak & Gil 1998; Krzeszowski et al. 2009). At these heights the magnetic field is very strong, and the relativistic charged plasma particles are forced to move along the curved magnetic field lines. Here the well-known two-stream plasma instability naturally generates Langmuir plasma waves. If the plasma is subjected to a non-stationary flow, it then leads to the modulational instability of Langmuir waves, which results in the formation of relativistic charged solitons capable of emitting coherent curvature radiation (Melikidze et al. 2000; Gil et al. 2004; Mitra et al. 2009). The off-pulse emission on the other hand lies in the region outside the main pulse, and currently we are not certain about its exact location. For the emission to originate from open field lines, the location needs to be above the main pulse in regions where the open dipolar magnetic field lines diverge. As the pulsar rotates, this divergent region above the main pulse is sampled by the observer as the off-pulse emission. The other well-known maser-type plasma instability that can give rise to the coherent emission is the cyclotron–Cherenkov or Cherenkov drift instability (Kazbegi et al. 1987, 1991). The instabilities are

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3 A more sensitive phase resolved study is currently underway where we aim to image each phase resolved bin to localize the off-pulse emission region.
due to the interaction of the fast particles of the primary beam with the normal modes of the electron–positron plasma. These instabilities are known to operate close to the light cylinder and could be a viable source of off-pulse emission.

There might be other possible origins of the off-pulse emission which we will need to evaluate and understand in the future; however, it is clear that this newly found off-pulse emission from low energetic slowly rotating neutron stars provide important clues in understanding the physical phenomenon operating in the pulsar magnetosphere.

We thank Jayanta Roy for developing the 128 ms interferometric mode of the GMRT software backend (GSB) which were used as a part of these observations. We thank Navnath Shinde, Sweta Gupta, Ajay Vishwakarm, Ajit Kumar, and other members of the GMRT engineering team for developing the pulsed noise source used in our studies. We thank the staff of the GMRT that made these observations possible. GMRT is run by the National Centre for Radio Astrophysics of the Tata Institute of Fundamental Research.

Facility: GMRT

REFERENCES

Basu, R., Athreya, R., & Mitra, D. 2011, ApJ, 728, 157
Blaskiewicz, M., Cordes, J. M., & Wasserman, I. 1991, ApJ, 370, 643
Frail, D. A., & Scharrtinghausen, B. R. 1997, ApJ, 480, 364
Gaensler, B. M., & Slane, P. O. 2006, ARA&A, 44, 17
Gil, J., Lyubarsky, Y., & Melikidze, G. I. 2004, ApJ, 600, 872
Kazbegi, A. Z., Machabeli, G. Z., & Melikidze, G. I. 1987, Aust. J. Phys., 40, 755
Kazbegi, A. Z., Machabeli, G. Z., & Melikidze, G. I. 1991, MNRAS, 253, 377
Kijak, J., & Gil, J. 1998, MNRAS, 299, 855
Kothes, R., Landecker, T. L., Reich, W., Safi-Harb, S., & Arzoumanian, Z. 2008, ApJ, 687, 516
Krzeszowski, K., Mitra, D., Gupta, Y., et al. 2009, MNRAS, 393, 1617
Lorimer, D. R., Yates, J. A., Lyne, A. G., & Gould, D. M. 1995, MNRAS, 273, 411
Maron, O., Kijak, J., Kramer, M., & Wielebinski, R. 2000, A&AS, 147, 195
Melikidze, G. I., Gil, J. A., & Pataraya, A. D. 2000, ApJ, 544, 1081
Mitra, D., Gil, J., & Melikidze, G. I. 2009, ApJ, 696, 141
Rankin, J. M. 1993, ApJ, 405, 285
Rathnasree, N., & Rankin, J. M. 1995, ApJ, 452, 814
Stinebring, D. R., & Condon, J. J. 1990, ApJ, 352, 207
Stinebring, D. R., Smirnova, T. V., Hankins, T. H., et al. 2000, ApJ, 539, 309
Thomson, A. R., Moran, J. M., & Swenson, G. W. 1986, Interferometry and Synthesis in Radio Astronomy (New York: Wiley Interscience)
Weiler, K. W., & Sramek, R. A. 1988, ARA&A, 26, 295