Search for Off-pulse Emission in Long-period Pulsars

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Abstract

We have revisited the problem of off-pulse emission in pulsars, where a detailed search for the presence of low-level radio emission outside the pulse window is carried out. The presence of off-pulse emission was earlier reported in two long-period pulsars, PSR B0525+21 and B2046–16, at frequencies below 1 GHz using the Giant Metrewave Radio Telescope (GMRT). However, subsequent studies did not detect off-pulse emission from these pulsars at higher radio frequencies (>1 GHz). We have carefully inspected the analysis scheme used in the earlier detections and found an anomaly with data editing routines used, which resulted in leakage of signal from the on-pulse to the off-pulse region. We show that the earlier detections from PSR B0525+21 and B2046–16 were a result of this leakage. The above analysis scheme has been modified and offline gating has been used to search for off-pulse emission in 21 long-period pulsars (P > 1.2 s) at different observing frequencies of GMRT. The presence of low-level off-pulse emission of the peak flux 0.5 mJy was detected in the brightest pulsar in this list, PSR 0B0628–28, with an off-pulse to average pulsar flux ratio of 0.25%. We suggest that coherent radio emission resulting due to cyclotron resonance near the light cylinder can be a possible source for the off-pulse emission in this pulsar.

Unified Astronomy Thesaurus concepts: Radio pulsars (1353)

Supporting material: figure sets

1. Introduction

The radio emission from pulsars originates around heights of ~500 km from the stellar surface, which is less than 10% of the light cylinder radius (Kijak & Gil 1998; Mitra & Rankin 2002; Kijak & Gil 2003; Mitra & Li 2004; Krzeszowski et al. 2009; Mitra 2017). As a result the observed radio emission is primarily seen as narrow pulses, which usually occupy a small fraction (~10%) of the period. In rare cases, when the rotation axis is either very close to the dipolar magnetic axis or they are orthogonal to each other, the main pulse is either seen over a large fraction of the pulsar period or interpulse emission from the opposite pole is visible. The other pulsed emission originating outside the main pulse includes the precursor/postcursor emission (Basu et al. 2015), whose origin in the outflowing relativistic plasma is particularly challenging to understand.

There has been a number of works dedicated to searching for and studying the presence of unpulsed emission from pulsars (Bartel et al. 1985; Perry & Lyne 1985; Strom & Van Someren Greve 1990; Hankins et al. 1993; Stappers et al. 1999; Basu et al. 2011, 2012; Marcote et al. 2019). In these works by Bartel et al. 1985 the primary interferometric techniques were employed to detect low-level emission in the profile baseline region (off-pulse), where the main pulse (on-pulse) was masked or “gated.” A scintillation based search for off-pulse emission has also been proposed by Ravi & Deshpande (2018). The motivation for off-pulse emission studies either involve investigation of extended nebulae around pulsars (Weiler et al. 1974; Gaensler et al. 1998, 2000; Dzib et al. 2018; Ruan et al. 2020) or the presence of coherent emission higher up the pulsar magnetosphere (Basu et al. 2013). Other motivation for off-pulse studies involves the recent search for axions, which are a dark matter candidate, toward pulsars (Darling 2020a, 2020b). The spectral line searches for these particles will have improved detection sensitivity in the off-pulse window and reduce the effects of scintillation on continuum baselines.

The presence of off-pulse emission from two long-period pulsars B0525+21 (P = 3.746 s) and B2046–16 (P = 1.961 s) was reported by Basu et al. (2011, 2012) using the 325 MHz and 610 MHz frequency bands of the Giant Metrewave Radio Telescope (GMRT). These studies used the technique of offline gating, where high-time-resolution interferometric data were recorded and subsequently divided into on-pulse and off-pulse parts that were imaged separately. The on-pulse and off-pulse emission showed contemporaneous variations in intensity due to interstellar scintillation that suggested the off-pulse emission emerges close to the on-pulse emission, and thereby has a magnetospheric origin. Marcote et al. (2019) have carried out high spatial resolution observations of the two pulsars B0525+21 and B2046–16 using the European Very Large Baseline Network (EVN) at 1.39 GHz frequencies, with phase-resolved visibilities across the pulsar period. They did not detect any significant off-pulse emission in either pulsar. This prompted us to reexamine the analysis scheme used for the previous detections of off-pulse emission in Basu et al. (2011, 2012). It was found that the data editing technique used in these studies led to leakage of signal from the on-pulse to the off-pulse window. As a result spurious emission appeared in the off-pulse images in the location of the pulsar. We have modified the analysis scheme to remove the source of leakage and extended the offline-gating studies to a larger sample of long-period pulsars. In Section 2 we describe the source of leakage signal from the on-pulse to the off-pulse window and the corrective measures applied to the analysis scheme. In Section 3 we present the details of the observations of
21 long-period pulsars and the offline gating used to probe the presence of off-pulse emission in them. Section 4 shows the results where low-level emission is seen in the off-pulse window of the brightest pulsar (B0628–28) in the sample, and we discuss the implications of the results in Section 5.

2. Investigating Previous Detection of Off-pulse Emission

Basu et al. (2011) developed the offline-gating technique to investigate the presence of off-pulse emission using the GMRT (Swarup et al. 1991). This requires high-time-resolution interferometric observations such that the pulsar period can be divided into sufficient number of bins to separate the on- and off-pulse regions and image them individually. Before the gating process an automatic editing software was used to remove radio frequency interference (RFI) by Basu et al. (2011, 2012). It was found that the data editing software caused leakage of on-pulse signal into the off-pulse region. This resulted in spurious detection of off-pulse emission in these earlier works. An example of this leakage leading to off-pulse emission in PSR B0525+21 is shown in Figure 1. The left panel corresponds to an image of the off-pulse region where they are overwritten. This leakage has caused the detection of off-pulse emission reported by Basu et al. (2011, 2012), as shown in the left panel of Figure 1, which are spurious detections. Around 5%–10% of the observing durations were statistical outliers, which are comparable to the ratio between the on-pulse and off-pulse flux levels in these studies. The off-pulse signal followed the scintillation behavior of the on-pulse signal as they were low-level on-pulse emission.

Astronomical observations are generally recorded in Flexible Image Transport System (FITS) format. In case of radio interferometry the FITS comprises of Header Data Units (HDUs), which record observing details, like the time of observation, the baseline pair identifier, source identifier, etc. The visibility measurements by the interferometer are recorded as a binary sequence following the HDUs. In case of standard GMRT observations, spanning a certain frequency range separated by equispaced channels and more than one polarization, the visibility for each time-baseline-channel-polarization unit is stored as a set of three numbers, real, imaginary measurements, and a specific weighting for each measurement. When the weight is “1” the visibilities are read unchanged, while they are ignored when the weight is “0,” and any other value scales them accordingly. A continuous series of such three element sets are recorded for all measurements. The manipulation of FITS files can be carried out using standard software like the cfitsio package in the c programming language.

In the data editing process a subset of the entire observation is initially read in a buffer array and the statistics is estimated. If any particular visibility is found to be a statistical outlier, it is considered to be affected by RFI and not used in the subsequent analysis by changing their weights to “0” in the buffer. Finally, the visibilities identified as outliers are copied from the buffer to the FITS data set, where the exchange happens only if any statistical outliers are found. However, we have found a bug in the editing software where the data are copied into a different location in the initial FITS file from the buffer. This results in leakage of the on-pulse signal into the off-pulse region where they are overwritten. This leakage has caused the detection of off-pulse emission reported by Basu et al. (2011, 2012), as shown in the left panel of Figure 1, which are spurious detections. Around 5%–10% of the observing durations were statistical outliers, which are comparable to the ratio between the on-pulse and off-pulse flux levels in these studies. The off-pulse signal followed the scintillation behavior of the on-pulse signal as they were low-level on-pulse emission. We have modified our analysis scheme to ensure all data editing is carried out after the gating stage, where the original file is separated into two, corresponding to the on-pulse and off-pulse windows. The data editing software have been updated to ensure that the location of all visibilities are correctly identified in both the buffer and the FITS data sets. An example of the result of new analysis is show in the right panel of Figure 1, where no clear emission at the location of the pulsar is visible in the off-pulse image. The analysis was extended to the previous observations of the pulsars B0525+21 and B2045–16 reported in Basu et al. (2011, 2012), where no clear off-pulse emission was seen. The remaining measurements, including the on-pulse flux and the noise levels in the on-pulse and off-pulse images, were unchanged.
3. Observation and Analysis

We have carried out extended observations to search for off-pulse emission in pulsars using GMRT, which consists of 30 separate antennas arranged in a Y-shaped array with a maximum distance of 27 km between antenna pairs. The observations were carried out using the GMRT software correlator (GSB; Roy et al. 2010), which is currently decommissioned and replaced with a wide-band back end. Interferometric observations generally measure visibilities, which are correlated signals from antenna pairs, after averaging over several seconds and hence are not suitable for most pulsar studies, where the radio emission is seen as narrow bursts of emission repeating at regular periods ranging from a few milliseconds to several seconds. A special mode of the GSB allowed observations with high time resolutions of 128/256 ms that were used for these studies. It is also possible to record the self-data, which are the autocorrelated signals from each antenna, measuring the absolute intensity of the incoming signals. Offline-gating technique was used for these studies, where self-data from pulsars were initially folded at their rotating period to obtain an average profile with well-defined on-pulse and off-pulse regions (see Figure 2). Each recorded time was subsequently assigned a phase related to the profile, and the observation was separated into two parts, corresponding to the on-pulse and off-pulse regions (see Basu et al. 2011 for additional details). Standard imaging techniques using the classic AIPS package was utilized to image the on-pulse and off-pulse parts and search for off-pulse emission in the location of the on-pulse source. The observations were conducted between 2013 and 2014, when the GSB was still operational, at two frequencies centered around 610 MHz and 1280 MHz with 33 MHz bandwidth.

The 128 ms time resolution of GMRT interferometric observations limited the number of pulsars suitable for exploring the presence of off-pulse emission. At least 8–9 phase bins in the profile window are essential to clearly separate the on-pulse and off-pulse regions of the profile (see the discussion in Basu et al. 2011, 2012). As a result long-period pulsars with \( P > 1.2 \text{ s} \) were considered for this work. In addition, we considered nearby bright pulsars with 400 MHz flux >20 mJy, and a dispersion measure <150 pc cm\(^{-3}\), to increase the probability of detection as well as minimize the possibility of scattering tails at the lower observing frequency. This left around 20 pulsars within the GMRT declination range that satisfied these conditions. In addition we also included PSR J2144–3933, which was the longest-period pulsar \( (P = 8.510 \text{ s}) \) known at the time of these observations. In Table 1 we report the details of the 21 pulsars used in this work. The table shows the widths \( (W_{10}; Mitra et al. 2016) \) of the profiles, measured at 10% of the peak intensity level, which shows the on-pulse emission to be restricted to less than 20% of the period in all cases. Table 1 also lists the observing frequency, the period of the pulsar, and the total phase bins in the folded profile \( (N_{\text{bin}}) \), as well as the number of bins averaged for the on-pulse \( (N_{\text{on}}) \) and off-pulse \( (N_{\text{off}}) \) images in each case.

An example of the folded profile from the interferometric observations of PSR B0628–28 is shown in Figure 2 that highlights the on-pulse and off-pulse regions. Detailed images corresponding to both the on-pulse and off-pulse windows were produced, and the region around each pulsar is shown as intensity contours (see Figure 3). The pulsar signal is affected due to interstellar scintillation that causes quasi-periodic variations of the flux within the observing duration. The imaging technique inherently assumes the flux of the sources to be constant for the duration of the observations. Any inherent flux variations causes phase errors around the source resulting in increased noise levels. In some cases the scintillation was prominently present as indicated by phase structures around the pulsar in the on-pulse images. The estimated average on-pulse flux \( (S_{\text{on}}) \) for the observing duration of each pulsar is shown in Table 1, along with the period averaged flux, \( S_{\text{avg}} = S_{\text{on}}N_{\text{on}}/P \), where \( t_{\text{res}} (=0.128/0.256 \text{ s}) \) is the time resolution of observations. In the table the noise levels near the location of the pulsar is shown for both the on-pulse \( (\sigma_{\text{on}}) \) and off-pulse \( (\sigma_{\text{off}}) \) maps. The off-pulse noise varied between 60 \( \mu \text{Jy} \) and 260 \( \mu \text{Jy} \), and was less than 100 \( \mu \text{Jy} \) for majority of pulsars. The on-pulse noise was higher due to the presence of the strong nearby pulsar that also had phase errors due to scintillation.

4. Results

Basu et al. (2011, 2012) reported detection of off-pulse emission from PSR B0525+21 and PSR B2045–16; however, as discussed in Section 2, we found that this earlier detection was caused due to leakage from the on-pulse signal into the off-pulse window. We have corrected the source of leakage and searched for off-pulse emission in 21 pulsars. No clear point-source structure was seen in the off-pulse images at the location of the pulsar in most cases with the exception of PSR B0630–28. Thus, we confirm the results of Marcote et al. (2019), who have also reported the absence of off-pulse emission from PSR B0525+21 and PSR B2045–16. Their study used the European VLBI Network at 1.39 GHz observing frequency. The noise levels in the off-pulse maps were 14 \( \mu \text{Jy} \) for PSR B0525+21 and 32 \( \mu \text{Jy} \) in case of PSR B2045–16. These are significantly lower than the the noise levels obtained in this work at 1.28 GHz, with 77 \( \mu \text{Jy} \) for PSR B0525+21 and 61 \( \mu \text{Jy} \) for PSR B2045–16. In case of PSR B0525+21 the 5\( \sigma \) detection limit at 1.39 GHz was 70 \( \mu \text{Jy} \), which was around 0.7% of the average pulsar flux. In the case of PSR B2045–16 the corresponding limit was 160 \( \mu \text{Jy} \), which was around 0.5%
of the average flux. In addition we have also verified the nondetection of off-pulse emission in these two pulsars at 325 MHz with noise levels around 200–500 μJy and 610 MHz where the noise levels were between 100–200 μJy.

In PSR B0628–28 a weak point-source structure was seen in the off-pulse window with a peak flux of 0.502 mJy, which is 6.5σ of the noise level. The images corresponding to the on-pulse and off-pulse windows of PSR B0628–28 are shown in Figure 3, where the presence of a point source in the off-pulse window coincident with the pulsar in the on-pulse image is seen. We have estimated the relative strength of off-pulse emission compared to the average flux ($S_{\text{off}}/S_{\text{avg}}$), which is around 0.25% (see Table 1, last column). PSR B0628–28 is the brightest source in our sample with $S_{\text{avg}} = 196.5 ± 14.5$, which is between 3 and 80 times higher than the other pulsars observed at 610 MHz. The flux of the five pulsars observed at 1280 MHz is expected to be much lower compared to their 610 MHz values due to steep inverse power-law nature of pulsar spectra (Maron et al. 2000). In Table 1 (final column) the estimates of the ratio between the detection limit, defined as $5 \times \sigma_{\text{off}}$, and $S_{\text{avg}}$ are calculated. The minimum ratio is several times higher than 0.25%, which indicates that if the off-pulse emission is present in the other pulsars at a level similar to B0628–28, it will be well below the detection limit of the instrument.

The low-level off-pulse emission from PSR B0628–28 requires verification from independent telescope systems. Future studies of off-pulse emission in a significant number of pulsars will require higher sensitive observations with at least an order of magnitude lower levels of noise in the images. More significant detections of off-pulse emission, if present, will allow further detailed characterization of their emission behavior, like temporal variability, spectral nature, etc., which can be used to constrain the location of the emission.

5. Discussion

The off-pulse emission seen in pulsars can arise due to a variety of reasons, which we explore below.

5.1. Effect of Line-of-sight Geometry

The on-pulse emission corresponds to the region of the open dipolar magnetic field line, and the duty cycle of the emission depends on the geometry of the pulsar. In certain geometrical configurations, particularly for an almost aligned rotator, there are instances where the pulsed emission can have an almost 100% duty cycle. In the case of PSR B0628–28 the pulsed emission has a duty cycle of about 15%. However, the possibility remains that due to some favorable alignment the observers’ line of sight (LOS) cuts across emission beam over a wide longitude range, but the emission is at a significantly lower level in the majority of period and hence cannot be detected as a pulsed emission. In such a scenario the low-level signal will be detected as off-pulse emission. The on-pulse emission height is constrained to be well within the pulsar magnetosphere at less than 10% of the light cylinder radius (Kijak & Gil 1998; Mitra & Rankin 2002; Kijak & Gil 2003; Mitra & Li 2004; Krzeszowski et al. 2009; Mitra 2017). Hence, in order to have the LOS be within the emission beam for a large fraction of the pulsar period the magnetic inclination angle ($\alpha$), i.e., the angle between the rotation and magnetic axis, has to be small.

A possible way to resolve this issue is to understand the emission geometry of PSR B0628–28. Rankin (1990, 1993)
developed the empirical theory of pulsar emission, where pulse width and polarization properties have been used to derive the pulsar geometry. Rankin (1993) classified the pulsar PSR B0628–28 as a conal single and found $\alpha \sim 13^\circ 5$ and the angle between the rotation axis and the observer LOS to be $\beta \sim 3^\circ 2$. To verify the geometry at our observing frequency of 610 MHz we used the observations of PSR B0628–28 at 618 MHz obtained from the MSPES survey (Mitra et al. 2016). Figure 4 shows the profile of PSR B0628–28 along with the polarization position angle (PPA) across the profile. The PPA traverse shows an S-shaped curve that is dependent on the geometrical angles $\alpha$ and $\beta$, as explained by the rotating vector model (RVM; Radhakrishnan & Cooke 1969). According to RVM the change in the PPA ($\psi$) traverse reflects the change in projection of the magnetic field vector in the emission region as a function of pulse rotational phase ($\phi$) and can be expressed as

$$\psi = \tan^{-1} \left( \frac{\sin \alpha \sin \phi}{\sin(\alpha + \beta)\cos \alpha - \sin \alpha \cos(\alpha + \beta)\cos \phi} \right).$$

(1)

In Figure 4 the RVM fits to the PPA that accurately reproduce the observed S-shaped curve are shown (also see Becker et al. 2005). However, a number of studies (Everett & Weisberg 2001; Mitra & Li 2004) have shown that the RVM fits are not sufficient to estimate $\alpha$ and $\beta$, which are highly correlated in these fits as seen in the $\chi^2$ contour (see Figure 4, bottom panel). We found the best-fit geometry to be $\alpha = 13^\circ$ and $\beta = -3^\circ 1$, which is consistent with the estimates of Rankin (1993). We used the smallest possible value of $\alpha$ that was within the 1$\sigma$ envelope of the $\chi^2$ distribution, to ensure maximum LOS traverse of the emission beam. Note that our PPA fit is able to distinguish the LOS to be an outer LOS, i.e., $\beta$ having a negative value since the PPA traverse has a wider span and the characteristic flaring of the PPA in the profile wings is evident.

With the above estimates of $\alpha$ and $\beta$ and assuming the emission arises from constant height across the pulse, we can find the radius of the beam opening angle ($\rho$) using the expression

$$\sin^2 \rho/2 = \sin(\alpha + \beta)\sin \alpha \sin^2 W/4 + \sin^2 \beta/2,$$

(2)

where $W$ is the width of the pulse profile. Since our concern is to see how far detectable pulse emission is present, we choose the profile edges at the level of 5 times the off-region rms and find $W = 51^\circ 3$. Thus, using $\alpha = 13^\circ$ and $\beta = -3^\circ 1$ we find $\rho = 5^\circ 8$. We thus confirm that the single-component profile in this pulsar, which has been classified as a conal single ($S_1$) type (Rankin 1993), is consistent with the relatively shallow PPA traverse and comparatively high $|\beta/\rho| = 0.53$. In a dipolar case the magnetic field lines diverge with emission height ($h_{em}$), such that

$$h_{em} = 10(\rho/1.23)^2(P/1 s) \text{ km},$$

(3)

where the beam opening angle at the stellar surface, with radius = 10 km, is equal to the radius of the opening angle of the polar cap, $\rho_c = 1.23P^{-0.5}$. Using $\rho = 5^\circ 8$ and $P = 1.24$ s, we obtain $h_{em} = 284$ km.

The implications of the pulsar geometry on the off-pulse emission is represented in Figure 5, where we have shown the emission beam at 618 MHz within the pulsar magnetosphere. The figure also shows the LOS traverse within the emission beam as specified by the estimated geometric angles. Although, the inclination angle between the rotation and magnetic axis is relatively low, it is still not sufficient for the LOS to be consistently within the emission beam throughout the rotation period. This is further highlighted in the figure, where we also
show the part of the LOS traverse corresponding to the on- and off-pulse windows. The only way which regions of the off-pulse window can be included in the open field line region is to decrease $\alpha$ and/or increase $h_{\text{tot}}$. The observed off-pulse emission is outside the on-pulse emission beam, and thus is likely to have a different physical origin.

5.2. Diffuse Nebulae around B0628–28

The low-level off-pulse emission in PSR B0628–28 can also arise due to the presence of a diffuse nebula around the pulsar. Basu et al. (2011) presented simple arguments to show it is unlikely for an older long-period pulsar to sustain an extended nebulae around it. A pulsar wind nebula (PWN) is generated when the relativistic wind from pulsars is confined by the surrounding medium resulting in shock waves that are luminous across the electromagnetic spectrum in synchrotron, inverse Compton, and optical line emission from the shocked regions. In case of isolated pulsars like B0628–28 there are two possibilities for the PWN to arise, either in the form of a “static” PWN or a “bow-shock” PWN. The static PWN corresponds to the case when the pulsar is at relative rest with respect to the surrounding medium (Blandford et al. 1973), while the bow-shock PWN is usually seen when the pulsar velocity is faster than the velocity of the shock front (Gaensler et al. 2000).

In the case of the static PWN the radius of the shock front is given as $R_S = \left(\frac{E}{4\pi \rho_o r_L^3}\right)^{1/7}$, where $E$ is the spin-down energy loss, $t$ the pulsar age, $\rho_o = m_p n_o$ is proton mass, and $n$ is the particle density of the ambient medium. The above expression can be used to estimate the required density of the surrounding interstellar medium (ISM) to harbor a static PWN that can be seen as off-pulse emission. The distance of PSR B0628–28 has been estimated to be around 0.3 kpc (Deller et al. 2009; Yao et al. 2017), and using the telescope resolution as $\sim 5''$, the upper limit for the size of the possible unresolved nebula is around 0.006 pc. The density of the ambient medium using the size limit is given as $n = \frac{5.35 \times 10^{12}E_{32}n_0 r_{100}^2}{R_2} \text{ cm}^{-3}$ (Basu et al. 2011), where $E_{32}$ is in units of $10^{32}$ erg s$^{-1}$, $t$ is in units of $10^6$ yr, and $R_{0.01}$ is in 0.01 pc. Using $E = 1.5 \times 10^{32}$ erg s$^{-1}$ and $t = 2.77 \times 10^6$ yr, the required ISM density for the Static PWN around B0628–28 is $\sim 10^{15}$ cm$^{-3}$. The typical densities of ISM are around 0.03 cm$^{-3}$, which makes it highly improbable to find such high-density regions around the pulsar to sustain a static PWN.

The bow-shock PWN is seen in young, highly energetic pulsars with $E > 10^{35}$ erg s$^{-1}$ (Gaensler & Slane 2006). These pulsars generally have high velocities $V_{\text{PSR}} > 500$–1000 km s$^{-1}$, with respect to the surrounding medium, which results in the formation of a bow-shock instability with radius $R_{\text{BS}} \sim 0.1$–1 pc. The pulsar B0628–28 is older, less energetic, and has velocity of 77.29 km s$^{-1}$ that is not suitable for the formation of a bow-shock nebula. This is further highlighted by the estimates of the the radius of the bow shock that is given as $R_{\text{BS}} = \left(\frac{E}{4\pi c \rho_o V_{\text{PSR}}^2}\right)^{0.5}$, where $c$ is the speed of light. The above expression can be simplified as $R_{\text{BS}} = 1.3 \times 10^{-3}(E_{32}/n_{0.01}V_{100}^2)^{0.5}$ pc, where $V_{100}$ is in units of 100 km s$^{-1}$ and $n_{0.01}$ is in units of 0.01 cm$^{-3}$. Using $V_{\text{PSR}} = 77.29$ km s$^{-1}$ and $n = 0.03$ cm$^{-2}$, the estimated size of bow-shock PWN around B0628–28 is $R_{\text{BS}} = 1.2 \times 10^{-3}$ pc, showing that the radius of the possible bow shock is very small and hence unlikely to form a bow-shock PWN.

5.3. Cyclotron Resonance Instability in the Outer Magnetosphere

Another possible location of the off-pulse emission can be the outer magnetosphere (closer to the light cylinder) along the pulsar open field lines. Kazbegi et al. (1987, 1991) showed the possibility of cyclotron resonance instability to develop in the outflowing relativistic plasma near the outer magnetosphere, leading to coherent radio emission. This mechanism was considered to be a likely candidate for off-pulse emission by Basu et al. (2013), where detailed calculations were carried out to explore the required plasma characteristics. The outflowing plasma along the open field lines of the pulsar magnetosphere plasma consists of an ultrarelativistic beam of primary particles ($\gamma_p \sim 10^6$) and a secondary cloud of electron–positron pair plasma that is less energetic ($\gamma_e \sim 10$–1000). The plasma is generated near the polar cap region of the pulsar and is constrained to move along the field lines due to the high value of magnetic field. However, the magnetic field becomes weaker near the outer magnetosphere ($B_0 \sim 1/r^3$), and the particles can gyrate and move across the field lines. Within the dense secondary plasma clouds a number of electromagnetic modes
Typical values of the physical parameters in pulsars are $\gamma_{\text{res}} = 2 \times 10^6$ (primary resonant particles), $\gamma_T = 10^3$ (the thermal spread in primary particle distribution), $\gamma_p = 10$ (secondary plasma), $\chi = 10^4$, and $\eta = 0.1$. The pulsar B0628–28 has $P = 1.244$ s and $\dot{P} = 7.12 \times 10^{-15}$ s$^{-1}$. Using the above values the growth factor for cyclotron resonance instability in B0628–28 is $\Gamma_T \approx 2.5$, while the resonance frequency is $\nu_0 = \omega_0/2\pi \approx 800$ MHz and the cutoff frequency is $\nu_1 = \omega_1/2\pi \approx 1.6$ GHz, respectively. This shows that the cyclotron resonance instability can develop in the outer magnetosphere of B0628–28, leading to coherent radio emission that can be seen as off-pulse emission. However, a detailed characterization of the off-pulse emission at multiple radio frequencies is needed to establish a detailed model that can explain the observed flux level of the off-pulse emission.

6. Summary

We report on a search for off-pulse emission from 21 long-period pulsars using observations from the GMRT. Off-pulse emission was earlier reported in PSR B0525+21 and PSR B2045–16 by Basu et al. (2011, 2012). In a subsequent study using the EVN, Marcote et al. (2019) showed the absence of off-pulse emission from these two pulsars. We have uncovered that the earlier detection of off-pulse emission was a result of leakage from the on-pulse to the off-pulse window, and thereby confirm the results of Marcote et al. (2019). Low-level off-pulse emission, with a peak flux of 0.5 mJy, was detected in PSR B0628–28. More sensitive observations are required to confirm this detection and further characterize the off-pulse emission behavior. The estimates of LOS geometry make it unlikely for the off-pulse emission to be a low-level emission feature within the main pulse emission beam. The presence of diffuse wind nebulae around the pulsar resulting in the observed off-pulse emission is also unlikely. On the other hand, it is possible for the cyclotron resonance instability to develop in the outer magnetosphere of PSR B0628–28, which is a likely candidate for off-pulse emission.

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