Gated interferometric imaging of pulsars to detect off-pulse emission

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Abstract

We detected off-pulse emission from two pulsars, B0525+21 and B204516, at 325 MHz using the Giant Metrewave radio telescope. Using the instrument as a high time resolution interferometer and off-line gating we imaged the off-pulse and on-pulse sections of the pulsar period separately to detect off-pulse emission at the level of a few percent of the on-pulse emission. These long period pulsars with low spin-down energies were selected to minimise the detection of emission from pulsar wind nebula. Indeed, interpreting our observation in terms of wind nebulae requires very anomalous interstellar medium particle densities. The alternative explanation of magnetospheric emission poses interesting questions to pulsar emission models. We are in the process of repeating the observations with a larger sample of pulsars and at other frequencies to obtain the spectral index, which is expected to provide further diagnostics for the nature of this emission. These are perhaps the first secure detections of off-pulse emission from pulsar magnetospheres and the first use of GMRT as a gated interferometer to image pulsars.

1 Introduction

In the rotating vector model [1] the pulsed emission from a pulsar is analogous to the sweep of a lighthouse beam — pulsar radiation arises along the open field lines above the magnetic poles. As the pulsar rotates, the misalignment between the magnetic and rotation axes results in an observer detecting a series of pulses at the same period as the rotation of the pulsar. These pulses typically occupy only 5-10% of the pulsar period — the on-pulse region). Barring a small fraction with special geometries most pulsars are not expected to emit any radiation from the off-pulse region. We emphasise that *on-pulse* emission refers to emission from close to the magnetic pole even if it occurs in more than one region in the pulse profile (e.g. inter-pulsars); whereas, off-pulse emission refers to emission far away from the magnetic poles. Indeed, observational efforts during the last 3 decades have not yielded any convincing evidence of off-pulse magnetospheric emission from pulsars. Faint pre- and post-curcor emission have been reported in a few pulsars with emission from as far as 60^o from the main pulse in B0943+10 [2, 3]. However, even in these cases the geometric evidence is consistent with emission along the edge of the open field lines region.

We describe here the detection of off-pulse magnetospheric emission from several pulsars at 325 MHz [4], and ongoing efforts expand the work to additional targets and frequencies.

2 Target Selection, Observations andd Analysis

To investigate this phenomenon further we selected two pulsars, B0525+21 and B2045-16, with long periods (3.75s and 1.96s, respectively) and low spin down energies ($\sim 10^{31}$ erg.s^{-1}) to reduce the probability of detecting the pulsar wind nebular emission. All the PWNe known are associated with young pulsars ($\leq 10^5$ years) and high spin-down luminosities ($> 10^{35}$ erg.s^{-1}). The selected pulsars were also known to not have emission outside the main pulse (e.g. inter-pulsars).

The standard method of pulsar observation detects only the contrast in the pulse profile above an unknown constant pedestal along the time axis. To detect any possible pedestal we decided to image the pulsars

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in the interferometric mode after gating the data to separate the off-pulse and on-pulse sections of the interferometric visibilities. Pulsars have a very steep spectral index ($\alpha \sim$ -1.5 – 2) and are strongest at low radio frequencies. We used the GMRT to observe the pulsars as it is currently the most sensitive low frequency interferometer available; the 325 MHz band was selected as the best combination of sensitivity and resolution. The data was recorded at 131/262 ms instead of the usual 2 s integration time.

After removing the radio frequency interference, the self data from all the antennas was folded to locate the pulse in the interferometric data (see figure, top-left). The high resolution data, with 14 time bins across the pulse period was split into two regions of 5 bins each, one centred on the pulse (on-pulse region) and the other about half a period away (off-pulse region). The data was then averaged within these two gates to reduce the data volume and improve the noise per visibility. Subsequently, separate images were made separately for the off- and on-pulse data sets using AIPS, the standard radio astronomy imaging package.

3 Results

We detected off-pulse emission of 1-5% of the total flux in both the pulsars (Figure 1) [4].

The high resolution imaging showed positional coincidence of better than 2 arcsec between the on- and off-pulse emission, which yielded a probability of less than 0.0015 for chance coincidence of unrelated background sources. We also confirmed the lack of any drift or jitter in the time stamp which could result in a spurious off-pulse detection due to temporal smearing — a histogram of the time stamps showed a scatter of 7 ms (time bin = 121 ms; gate width = 605 ms). The most serious issue was the possibility of leakage of the signal along the time series of visibilities. In principle, GMRT visibilities separated by 512 μS are independent of each other. We tested for leakage of signal along the time axis by measuring the autocorrelation for every baseline after terminating the front-end of the antenna to make sure that neither RFI nor celestial signal (which would be correlated along the time axis) came through to the receiver. We simulated the expected autocorrelation function of receiver noise in the presence of any leakage along the time series. The upper-right panel of figure 1 shows the measured auto-correlation as well as the required autocorrelation to explain the detected off-pulse as a spurious feature arising from leakage of the on-pulse emission. Actually, the observed autocorrelation is an upper limit to the leakage estimate because any gain variation in the receiver system will also contribute an autocorrelation signal. Clearly, the detected off-pulse is not due to contamination of the off-pulse gate by signal from the on-pulse gate.

4 Discussion

Astronomers have been searching for off-pulse emission for over 3 decades. Previous claims of detections [5] later turned out to be unrelated background sources or emission from pulsars of special geometry [6-8]. Other attempts at detecting off-pulse emission resulted in the discovery of pulsar wind nebulae (PWN) [9-11].

It can be shown [4] that interpreting our detection in terms of PWN requires ISM particle densities many orders of magnitude higher (for static PWN) or lower (bow shock PWN) than typical ISM densities of 0.03 cm^{-3}. This is not surprising since we selected targets in which PWN emission was unlikely to play a major role. The geometry of the on-pulse emission in our targets [12-13] argues against the off-pulse emission being from the magnetic polar region. This raises the possibility that the off-pulse emission is from the magnetosphere, but far from the pole, either from the closed lines or from very far along the open field lines.

We are currently analysing 325 MHz observations of 2 more pulsars for off-pulse emission. We have also obtained 610 MHz observations for the two targets discussed here. The spectral index of the off-pulse emission will conclusively distinguish between wind nebula and magnetospheric origins of the detected emission.

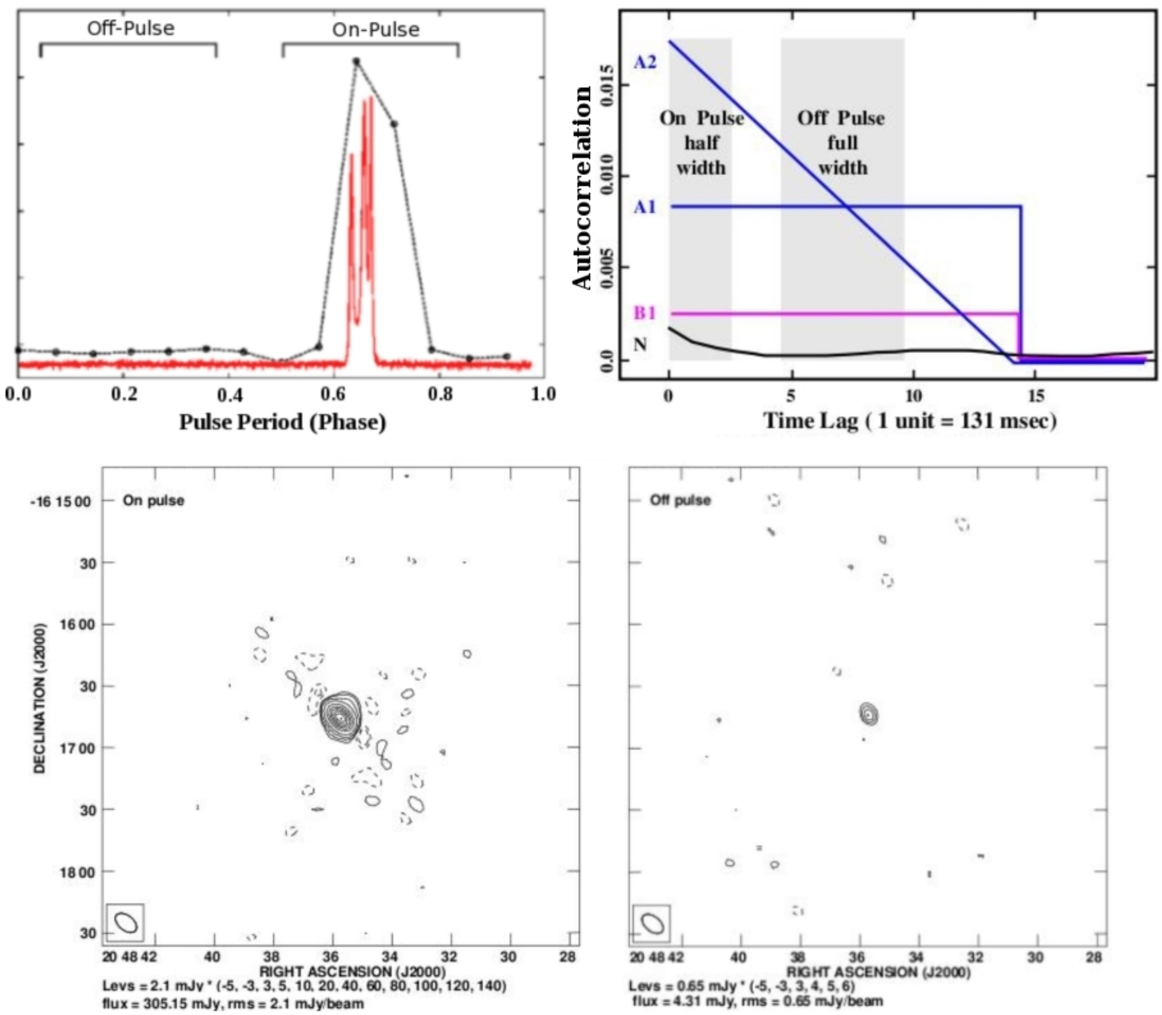

Figure 1: PSR B2045-16: **Upper left:** The pulse profile from the GMRT interferometer self data (upper curve with joined dots) is shown along with the published profile from standard pulsar observations. The on- and off-pulse gates used in this study are also shown. **Lower right:** On-pulse image. **Lower right:** Off-pulse image. **Upper right:** Autocorrelation function of noise in the GMRT receiver system. The lowest curve is the measured noise. The other 3 curves are the required autocorrelation functions to explain the off-pulse emission as spurious signals due to leakage from the on-pulse gate. The figures are adapted from [4].

5 Conclusion

We report the detection of off-pulse emission in several pulsars using the GMRT as a gated interferometer to create off-pulse and on-pulse images of the pulsars. These are perhaps the first secure detections of off-pulse emission. We have shown that the off-pusle detection is very unlikely to be of spurious/instrumental origin or from a pulsar wind nebula. This leaves magnetospheric emission as the most likely source of the detected emission. The presence of magnetospheric emission so far from the magnetic pole imposes challenging constraints on pulsar emission mechanism models. We are currently involved in enlarging the set of targets and obtaining 610 MHz data to obtain the spectral index of the off-pulse emission. This will help in confirming the magnetospheric nature of the off-pulse emission.

6 Acknowledgments

We thank GMRT for allocation of director's discretionary time for this project. GMRT is operated by the National Centre for Radio Astrophysics (TIFR), Pune, India.

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