Meterwavelength Single-pulse Polarimetric Emission Survey. III.  
The Phenomenon of Nulling in Pulsars

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Abstract
A detailed analysis of nulling was conducted for the pulsars studied in the Meterwavelength Single-pulse Polarimetric Emission Survey. We characterized nulling in 36 pulsars including 17 pulsars where the phenomenon was reported for the first time. The most dominant nulls lasted for a short duration, less than five periods. Longer duration nulls extending to hundreds of periods were also seen in some cases. A careful analysis showed the presence of periodicities in the transition from the null to the burst states in 11 pulsars. In our earlier work, fluctuation spectrum analysis showed multiple periodicities in 6 of these 11 pulsars. We demonstrate that the longer periodicity in each case was associated with nulling. The shorter periodicities usually originate from subpulse drifting. The nulling periodicities were more aligned with the periodic amplitude modulation, indicating a possible common origin for both. The most prevalent nulls last for a single period and can be potentially explained using random variations affecting the plasma processes in the pulsar magnetosphere. On the other hand, longer-duration nulls require changes in the pair-production processes, which need an external triggering mechanism for the changes. The presence of periodic nulling puts an added constraint on the triggering mechanism, which also needs to be periodic.

Key words: pulsars: general

Supporting material: figure sets

1. Introduction
Radio emission from pulsars show variability over multiple timescales. These variations can either be due to intrinsic changes in the emission process or the result of external effects, like the interaction of the emission with the intervening medium. The presence of nulling, where the emission ceases within one rotation period, was first reported by Backer (1970). Nulling can manifest over multiple timescales ranging from a few periods to hours at a time, and in the case of intermittent pulsars, from weeks to months. The nulling fractions also show wide variations, ranging from less than a few percent to more than 70% of the time when the emission nulls. Some studies show that pulsars with similar nulling fractions sometimes exhibit very different nulling patterns (Gajjar et al. 2014b).

There are around 75 pulsars where nulling has been reported (Ritchings 1976; Rankin 1986; Biggs 1992; Wang et al. 2007; Gajjar et al. 2012). The physical processes responsible for the transitions between the null to the burst states are still unclear. The long duration nulls in the intermittent pulsar B1931+24 have been identified with large changes in the spin-down energy loss (Kramer et al. 2006). This has motivated the idea of nulling being associated with large-scale magnetospheric changes in pulsars (Cordes 2013; Gajjar et al. 2014a, 2014b). However, it is not clear whether the short and intermediate nulls lasting a few periods (seconds) to hundreds of periods (hours) have the same physical origin as the nulling in intermittent pulsars, which lasts for days at a time. Nulling is largely considered to be a stochastic process switching between two states. But, in some cases, the transition from the null to the burst states have shown periodicity (Herfindal & Rankin 2007, 2009).

The sparking discharges in the Inner Acceleration Region (IAR) of pulsars are believed to generate the plasma necessary for radio emission (Ruderman & Sutherland 1975, hereafter RS75). RS75 considered a system where the rotation and magnetic axes were aligned in opposite directions. The sparks, also called subbeams, were postulated to rotate around the common axis in a steady pattern due to the $E \times B$ drifting. Gil & Sendyk (2000) and Deshpande & Rankin (2001) expanded the RS75 model to the pulsar B0943+10 where the rotation axis is not aligned with the magnetic axis. They considered the subbeam system to rotate around the magnetic axis in order to explain the subpulse drifting seen in this pulsar. This model has now been used in a large number of pulsars to explain the subpulse drifting phenomenon. The periodic nulls are associated with the line of sight passing between the empty regions of the subbeam pattern, although in our recent work (Basu et al. 2016) we found the rotating subbeam system around the magnetic axis to be physically inconsistent in non-aligned pulsars. The sparks are instead expected to move around the rotation axis.

The underlying physical processes responsible for nulling are still unresolved. The longer-duration nulls allude to unknown physical phenomena, which require constraints from observations as well as detailed modeling. In this work, we looked for additional observational clues to characterize nulling. We carried out a detailed analysis of nulling properties in the Meterwavelength Single-pulse Polarimetric Emission Survey (MSPES; Mitra et al. 2016a). This paper is organized as follows: in Section 2, we present the observing details and the analysis schemes used; Section 3 gives the results of our
PSR B1738–08 Freq=618 MHz

Null Length histogram

PSR B1738–08 Freq=618 MHz

Burst Length histogram

PSR B1738–08 Freq=618 MHz

Energy Histogram

PSR B1738–08 Freq=618 MHz

Null Length histogram

Burst Length histogram

PSR B1738–08 Freq=618 MHz

Energy Histogram

PSR B1738–08 Freq=618 MHz

Null Length histogram

Burst Length histogram

PSR B1738–08 Freq=618 MHz

Energy Histogram

2. Observation and Analysis

The observing procedure and initial data processing are detailed in Mitra et al. (2016a) and Basu et al. (2016). We searched for nulling in 123 pulsars observed at 333 and 618 MHz with roughly 2100 pulses in each case. The pulse energy distributions are represented as two histograms corresponding to the on- and off-pulse energies (see Figure 1, bottom-left panel). The off-pulse distributions are centered around zero and reflect the noise characteristics of the baseline level. The off-pulse distributions are expected to exhibit noise-like characteristics resembling a Gaussian function. However, in some cases, low-level wings are seen due to the presence of systematics, which smear the statistical boundary between null and burst pulses.

2.1. Determining Nulling Behavior

Nulling was identified when a bimodal shape was seen in the on-pulse distribution. The null pulses resembled a scaled-down version of the off-pulse distribution and were separated from the burst distribution (see Figure 1, bottom-left panel). In a number of pulsars, the detection sensitivities of the single pulses were insufficient to separate out the two. However, in a few cases, averaging three to five pulses helped to identify the presence of nulling. The nulling behavior is usually...
characterized by the nulling fraction, which signifies the fraction of time the pulsar is in the null state. We have determined the nulling fraction as follows. A Gaussian functional fit was estimated for the off-pulse distribution, which was then scaled appropriately to the nulling part of the on-pulse distribution. The ratio of the two Gaussian peaks gave the measured value of the nulling fraction. In a few cases, the entire nulling durations were too small to form well-constrained distributions. The nulling fraction in these cases were estimated by counting the individual null pulses.

2.2. Resolved Nulls: Estimating Periodicity

We carried out an additional analysis when the null and burst pulses were well-separated. The $3\sigma$ noise level of the off-pulse window was initially considered to be the boundary between the two states. Each single pulse was identified either as the null or the burst pulse based on the above boundary. In the next phase, all single pulses around the boundary were inspected to correct any weak emission identified as nulls. At this stage, the null and the burst pulses were separately averaged to form their respective profiles (see Figure 1, bottom-right panel). Further analysis was carried out if no significant emission was detected in the null profile. The null and burst lengths were determined during each transition along with the total number of transitions between the states. Finally, the null and burst length histograms were estimated (see Figure 1, top panels).

Additionally, given the sequence of null and burst pulses, we examined the presence of periodicity in the transitions between the states. The time series data of 0’s and 1’s were set up corresponding to the null and the burst pulses, respectively. This ensured that all subpulse information were washed away and the only possible periodicity was contained in the transition between the two states. A one-dimensional discrete Fourier transform (DFT) was carried out on the time series data. In general, we used 256 consecutive points to carry out the DFT. If the peak frequency was too close to the edge, the number of points used for the DFT was increased accordingly to resolve the periodicity. The starting position was shifted by 10 pulses, and the process was repeated until the end. Finally, all of the individual DFTs were averaged to produce a more sensitive spectra. This also enabled us to examine any time variations in the periodicity (see Figure 2). In Herfindal & Rankin (2007, 2009), the pulse modulation quelling (PMQ) method was used to estimate the periodicity in nulling. One primary difference in this method is that these authors used the pulses that exhibited “partial nulls.” For example, PSR B1133+16 has a two-component profile where at certain times the emission corresponding to one of the components is missing. This case is called the partial null. The PMQ used scaled-down average profiles for every burst pulse and a similarly scaled half-average profile for the partial nulls (Herfindal & Rankin 2007). In our work, we only considered complete nulls, and the partial nulls were identified as burst emission.

Figure 2. Time-varying Fourier transform of the null/burst (0/1) time series data for the pulsar B1738–08 observed at 618 MHz (left). The longitude-resolved fluctuation spectra (LRFS, right panel) from Basu et al. (2016) is also shown for comparison. The LRFS shows a wide drifting feature at higher frequency and a narrower feature at low frequency. The low-frequency feature is identically reflected in the null/burst spectra where the drifting feature is absent. (The complete figure set (17 images) is available.)
### Table 1
List of Nulling Pulsars

| PSR       | Period (s) | $N_p$ | NF %  | $N_p$ | NF %  | References |
|-----------|------------|-------|-------|-------|-------|------------|
| B0031−07  | 0.943      | 2096  | 31.3±2.3 | 1119  | 22.8±1.8 | 1, 2, 3, 4, 5, 6 |
| B0301−19  | 1.388      | 2115  | 8.7±1.2 | 2115  | 6.1±0.6 | 7          |
| B0525−21  | 3.746      | 400   | 14.4±1.2 | ...   | ...     | 8          |
| B0628−28  | 1.244      | 2112  | 13.6±1.9 | 2111  | N       | 8          |
| B0818−13  | 1.238      | 969   | 9.8±1.2 | 2122  | 0.9     | 9, 10, 11 |
| B0834−06  | 1.274      | 1052  | 3.9±0.3 | 2114  | 4.7±0.7 | 8, 12      |
| B0906−17  | 0.402      | 2078  | 26.8±1.7 | 2234  | 25.7±1.3 | ...        |
| B0942−13  | 0.570      | 2100  | 14.4±0.9 | 2196  | N       | ...        |
| B1114−41  | 0.943      | 2095  | 3.3±0.5 | 1918  | N       | ...        |
| B1133+16  | 1.180      | 753   | 13.7±2.1 | 494   | 11.9±2.3 | 8, 13, 14  |
| B1237+25  | 1.382      | 1081  | 2.0±0.1 | 864   | 3.1±0.4 | 8          |
| B1325−49  | 1.479      | 2100  | 4.0    | 2100  | 4.4     | ...        |
| B1524−39  | 2.418      | 862   | 5.1±1.3 | 1233  | N       | ...        |
| B1556−44  | 0.257      | 2293  | N      | 2484  | 0.24    | ...        |
| B1700−32  | 1.212      | 1716  | 1.6    | 2125  | 0.4     | ...        |
| B1706−16  | 0.653      | 2106  | 3.7±1.3 | 2106  | 4.9±0.3 | 15         |
| J1727−2739| 1.293      | 2126  | 57.0±2.3 | 2127  | 48.3±1.8 | 16, 17     |
| B1730−37  | 0.338      | ...   | ...    | 2110  | 52.4±3.5 | ...        |
| B1738−08  | 2.043      | 1753  | 15.7±1.7 | 2052  | 15.8±1.4 | ...        |
| B1742−30  | 0.676      | 2120  | 40.2±1.9 | 2119  | 24.8±1.0 | 18         |
| B1747−46  | 0.742      | 2017  | 2.4±0.5 | 2084  | 2.4     | ...        |
| B1749−28  | 0.563      | 2129  | 0.2    | 2129  | 1.7±0.4 | 18         |
| B1758−03  | 0.921      | 2145  | 27.7±1.3 | 1944  | 26.1±2.6 | ...        |
| J1808−0813| 0.876      | 2110  | 12.8±1.3 | 1557  | 8.2±1.0 | ...        |
| B1813−36  | 0.387      | 2158  | 16.7±0.7 | ...   | ...     | ...        |
| B1819−22  | 1.874      | 2106  | 4.7±0.9 | 1309  | 5.5±0.7 | ...        |
| B1857−26  | 0.612      | 2152  | 5.1±0.8 | 2152  | 8.1±0.5 | 8, 19      |
| J1901−0906| 1.782      | 2076  | 2.9    | 1068  | 5.6±0.7 | ...        |
| B1918−19  | 0.821      | 2105  | 2.0    | 2180  | N       | 20         |
| B1944−17  | 0.441      | 5566  | 29.7±1.4 | 2174  | 37.9±2.3 | 8, 21, 22  |
| B2003−08  | 0.581      | 2157  | 15.6±1.0 | 2157  | 24.2±1.5 | ...        |
| B2045−16  | 1.962      | 924   | 8.3±1.4 | 1828  | 9.0±0.5 | 8          |
| B2303−30  | 1.576      | 1698  | 5.3±0.5 | ...   | ...     | 23         |
| B2310−42  | 0.349      | 2572  | 3.7±0.5 | ...   | ...     | 24         |
| B2327−20  | 1.644      | 1284  | 9.6±0.9 | 1500  | 13.1±1.5 | 18         |
| J2346−0609| 1.181      | 2130  | 42.5±3.8 | 2128  | 28.7±1.8 | ...        |

### Note
The pulsar name is given in column 1, along with the period from the ATNF database in column 2. Columns 3 and 4 quote the number of single pulses and the nulling fraction at 333 MHz, while columns 5 and 6 present the corresponding values at 618 MHz. In some cases, our criterion for estimating nulling (see the text) implied that nulling could be measured at only one frequency, and the non-detections are represented as “N.” In some cases, the nulling fraction could only be estimated by counting the number of nulls below a pulsar statistical threshold, and no error is calculated for these cases with the numbers serving as an upper limit. Finally, column 7 lists the references for previous nulling studies.

### References:
1. Huguenin et al. (1970); 2. Vivekanand (1995); 3. Vivekanand & Joshi (1997); 4. Joshi & Vivekanand (2000); 5. Smits et al. (2005); 6. Gajjar et al. (2014a); 7. Rankin (1986); 8. Ritchings (1976); 9. Lyne & Ashworth (1983); 10. Janssen & van Leeuwen (2004); 11. Gajjar et al. (2012); 12. Rankin & Wright (2007); 13. Bhat et al. (2007); 14. Herfindal & Rankin (2007); 15. Naidu et al. (2015); 16. Wang et al. (2007); 17. Wen et al. (2016); 18. Biggs (1992); 19. Mitra & Rankin (2008); 20. Rankin et al. (2013); 21. Kloumann & Rankin (2010); 22. Deich et al. (1986); 23. Redman et al. (2005); 24. Wright et al. (2012).

### 3. Results
We have detected nulling in 36 pulsars, including 17 pulsars where it was reported for the first time. Table 1 lists the measured nulling fraction at the two observing frequencies. In some cases, nulling was found to be broadband in nature (Smits et al. 2005; Gajjar et al. 2014a) while other studies have reported excess nulls at certain frequencies (Bhat et al. 2007). Our observations were not simultaneous at the two frequencies where we investigate this effect, but we found the nulling behavior to be similar at both frequencies. In three pulsars, B1114−41, B1524−39, and B1918+19, nulling could only be measured at 333 MHz but not at 618 MHz due to lower sensitivity.

In 19 pulsars, the null and burst pulses were well-separated, and we determined the null length as well as the burst length histograms. The histograms were dominated by the short nulls with duration of a few periods. In five pulsars, B0031−07, B0301+19, B1706−16, J1727−2739, and B1944+17, the average null lengths exceeded five periods. In 11 pulsars, we detected periodicity in the transition between the two states. The average null lengths of the pulsars with periodic nulling were higher than the non-periodic cases.

#### 3.1. Statistical Study
A number of statistical studies exist in the literature to examine randomness in the null/burst sequence. One of the
Table 2
Nulling Statistics of Pulsars Where the Null and Burst Periods Were Resolved

| PSR       | 333 MHz | 618 MHz | 333 MHz | 618 MHz | \( P_N \) | \( Z \) | \( q_{12} \) | \( q_{21} \) | \( \text{NF(F)} \) |
|-----------|---------|---------|---------|---------|----------|------|------|------|---------|
| B0031−07  | 45      | 26.0    | 19.3    | 14      | 42.3     | 34.1 | 75 ± 14 | −52.0 | 0.044  |
| B0301−19  | 43      | 41.9    | 6.3     | 30      | 61.2     | 6.6  | 103 ± 34 | −52.9 | 0.155  |
| B0525−21  | 17      | 16.8    | 4.9     | ...     | ...      | ... | ...   | −14.4 | 0.202  |
| B0818−13  | 58      | 14.6    | 2.1     | 15      | 111.5    | 1.0  | ...   | −22.6 | 0.537  |
| B0834+06  | 64      | 15.5    | 1.0     | 156     | 12.4     | 1.0  | ...   | −1.3  | 0.905  |
| B1133+16  | ...     | ...     | 1.6     | 24      | 33.1     | 1.5  | ...   | −13.5 | 0.657  |
| B1237+25  | 41      | 24.0    | 1.6     | 24      | 33.1     | 1.5  | ...   | −5.9  | 0.766  |
| B1524−39  | 36      | 22.3    | 1.3     | ...     | ...      | ... | ...   | −29.2 | 0.514  |
| B1700−33  | 13      | 127.5   | 2.1     | 5       | 348.4    | 1.0  | 130 ± 70 | −48.9 | 0.220  |
| B1706−16  | 52      | 36.9    | 3.3     | 48      | 37.8     | 5.9  | 206 ± 33 | −41.1 | 0.028  |
| J1727−2379| ...     | ...     | 3.4     | 144     | 10.5     | 3.6  | 34 ± 8 | −37.4 | 0.287  |
| B1738−08  | 152     | 8.1     | 3.4     | 46      | 42.2     | 1.0  | ...   | −1.2  | 0.953  |
| B1747−46  | 75      | 25.2    | 1.0     | 14      | 147.6    | 3.6  | ...   | −44.0 | 0.291  |
| B1749−28  | 2       | 820.0   | 2.0     | 78      | 10.4     | 17.5 | 600 ± 52 | −71.0 | 0.066  |
| B1944+17  | 255     | 7.2     | 14.5    | 109     | 14.3     | 2.4  | 51 ± 20 | −26.8 | 0.417  |
| B2045−16  | 57      | 13.2    | 2.3     | 88      | 17.3     | 1.9  | ...   | −76.8 | 0.518  |
| B2303−30  | 44      | 51.6    | 3.6     | 44      | 51.6     | 3.6  | ...   | −35.2 | 0.274  |
| B2331+42  | 87      | 12.0    | 2.5     | 117     | 10.3     | 2.4  | 19 ± 1  | −26.1 | 0.412  |

Note. Columns 2, 3, and 4 represent the number of transitions between the null and burst states, \( N_T \); the average burst length, \( BL \); and the average null length, \( NL \), respectively at 333 MHz, while columns 5, 6, and 7 present the corresponding values at 618 MHz. Column 8 presents the periodicity \( P_N \) in the transition from the null to the burst states, while column 9 presents the \( Z \) statistics for the runs test. Columns 10 and 11 show the estimated transition probability from the null to burst state and vice versa for a two-state Markov process with the estimated nulling fraction from these transition probabilities, \( \text{NF(E)} \), shown in column 12.

more widely used techniques is the “Wald–Wolfowitz runs test” applied to a two-state system (Redman & Rankin 2009; Gajjar et al. 2012). It is assumed that the transition from a null to a burst state is random, resembling a coin toss experiment. The run \( (R) \) corresponds to the number of transitions between the two states with a total of \( n_1 \) nulls and \( n_2 \) bursts. The statistics pertaining to \( R \) are defined by the mean \( (\mu) \), standard deviation \( (\sigma) \), and the factor \( Z \), which are calculated as

\[
\mu = \frac{2n_1n_2}{n_1 + n_2} + 1, \\
\sigma = \sqrt{\frac{2n_1n_2(2n_1n_2 - n_1 - n_2)}{(n_1 + n_2)^2(n_1 + n_2 - 1)}}, \\
Z = \frac{R - \mu}{\sigma},
\]

Here, \( Z \) is the Gaussian distribution with zero mean and a standard deviation of unity. The randomness of the sequence with 95% confidence level corresponds to \(-1.96 < Z < 1.96\). Table 2 shows the \( Z \) factor calculated assuming that the two frequencies represent different segments of a larger time series configuration. The runs test indicates the null/burst sequence to be nonrandom in the majority of pulsars, with B0834+06 and B1747−46 being the notable exceptions.

The inherent assumption in the runs test is that the transition probabilities from one state to another are identical. In the cases where the transition probabilities differ, the two-state Markov process provides a more appropriate description. The transition probabilities are expressed in a 2 \( \times \) 2 transition matrix \( Q \) as

\[
Q = \begin{pmatrix}
q_{11} & q_{12} \\
q_{21} & q_{22}
\end{pmatrix}.
\]

Here, \( q_{11} \) and \( q_{22} \) are the probabilities of continuing in the null and burst states respectively, while \( q_{12} \) and \( q_{21} \) signify the transition probabilities from the null to burst states and vice versa. These quantities are estimated as (Cordes 2013)

\[
\langle NL \rangle = 1/q_{12}, \quad \langle BL \rangle = 1/q_{21}
\]

along with the normalization condition \( \sum q_j = 1 \). Here, \( \langle NL \rangle \) and \( \langle BL \rangle \) are the average null lengths and burst lengths, respectively. The expected nulling fraction is calculated as

\[
\text{NF} = \frac{q_{21}}{q_{12} + q_{21}}.
\]

The estimated transition probabilities are shown in Table 2 along with the expected nulling fractions. We have once again combined the sequences from the two frequencies for these calculations. The expected nulling fractions from a two-state Markov process, particularly with periodic nulling, were larger than the measured values. This implies that the two-state Markov process is not an appropriate explanation for the transition from the null to the burst state and vice versa.

3.2. The Nulling Periodicity

As mentioned earlier, we measured periodic nulling in 11 pulsars. In six pulsars, B0031−07, B0301+19, J1727−2739, B1738−08, B1944+17, and B2045−16, both nulling and subpulse drifting were seen in the same system as evidenced by the multiple peaks in their fluctuation spectra (see Basu et al. 2016 for a detailed analysis). The nulling periodicities coincided with the low-frequency peaks (see Figure 2), while the high frequency structures were identified with subpulse…
drifting. The nulling periodicities, ranging from $20P$ to $600P$, were larger than the typical subpulse drifting periodicities.

### 3.3. Individual Pulsars

In this section, we describe the single-pulse behavior in individual pulsars. In some cases, nulling was affected by signal-to-noise issues. In others, we noticed peculiar mode changing. The single-pulse plots are available in Mitra et al. (2016a).

**B0628–28** was studied in Ritchings (1976), who did not find any significant nulling. The single-pulse behavior was different at the two frequencies. Nulling was seen only at 333 MHz, with bursts of emission interspersed by longer-duration nulls or very low-level emission. The 618 MHz data showed a continuous but steadily decreasing burst state. Nulling appeared to be periodic or quasi-periodic in nature. The periodicity study could not be conducted due to the presence of weaker burst pulses particularly around the nulls.

**B0942–13** exhibited two types of nulling at 333 MHz within our short window of 2000 pulses. In the beginning, the nulls were of short duration interspersed with the burst state. The mean intensity of the emission started decreasing gradually around the 1000th pulse and completely switched off around the 1500th pulse. A short burst of emission with much lower intensity was seen between the 1800th and 1900th pulse. The 618 MHz emission had weaker signal, and nulling could not be identified in the energy histograms.

**B1556–44** did not show much variation in intensity for the majority of the observations. At the very end of the 618 MHz data, the intensity dropped for 5–10 pulses, leading to possible nulls. The pulsar profile is dominated by a core component, which makes the presence of nulling interesting.

**B1706–16** showed periodic nulling as reported in Table 2. Naidu et al. (2015) also reported longer-duration nulls lasting several thousand periods. The pulsar belongs to a small group that shows extreme nulling.

**J1808–0813** showed the likely presence of periodic or quasi-periodic nulling at both frequencies. Due to the lower sensitivity of the emission, we were not able to separate the null and the burst pulses and carry out a more detailed study of the nulling periodicity.

**B1819–22** exhibits phase-modulated drifting as reported in Basu et al. (2016). The nulling appeared to exhibit a periodic or quasi-periodic nature. We were not able to estimate the nulling periodicity due to the weaker signal. However, a low-frequency feature was seen in the LRFS in addition to subpulse drifting, which may be indicative of nulling periodicity.

**B2003–08** has a multicomponent profile with a likely core emission. The pulsar exhibits amplitude-modulated drifting as reported in Basu et al. (2016). Multiple peaks were seen in the LRFS with the possibility of periodicity due to nulling. The single pulses were once again of too low sensitivity to carry out a more detailed analysis.

**J2346–0609** showed relatively high nulling fractions with bursts of emission. The 333 MHz data were affected by radio frequency interference (RFI). The 618 MHz data had too low sensitivity to carry out the nulling periodicity studies.

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*The single-pulse time series plots can also be accessed from [http://mspes.ia.uz.zgora.pl/](http://mspes.ia.uz.zgora.pl/).*

### 3.4. Non-detections

We were not able to carry out measurements in 10 pulsars where nulling was previously reported. In seven pulsars, B0148$-06$, B0450–18, B0656+14, B0736–40, B1907+03, B1929+10, and B2315+21, the energy histogram analysis was unable to separate the two states due to the lower sensitivity of the signals. Three pulsars, B0740–28, B1727–47, and B1818–04, did not show any nulling despite high sensitivity. In all three cases, the previously reported nulling fractions were upper limits with low values (<0.1%; Biggs 1992). They are relatively high energy, with spin-down energy loss greater than $10^{35}$ erg s$^{-1}$. It is likely that nulling is not present; however, one cannot rule out the possibility of shorter duration, less frequent nulls.

### 4. Comparing Nulling Periodicity and Subpulse Drifting

The nulling periodicities detected in our studies correspond to complete nulls, i.e., no partial nulls have been included, and show periodicities similar to certain drifting cases. However, in contrast to the phase-modulated subpulse drifting in particular, the periodicities associated with nulling show a relative spread as evidenced by the null length and burst length histograms. In an attempt to connect these two phenomena, the periodic nulls have been termed “pseudo-nulls” and interpreted by Herfindal & Rankin (2007, 2009), Rankin & Wright (2008), and Rankin et al. (2013) using the rotating subbeam “carousel” system (Deshpande & Rankin 2001). The pulsar emission beam is believed to consist of a central core component with concentric conal subbeams rotating around the core (Rankin 1990, 1993a). The core components are phase stationary and do not participate in the carousel rotation. If the line of sight cuts the emission beam tangentially, this model predicts that there should be phase-modulated subpulse drifting. In the other case, when the line of sight traverses the beam, the amplitude modulation of the conal components (without any phase variations) is expected. Periodic nulling can show the carousel model in two possible ways. In the first case, nulling occurs for short durations of a few periods when the line of sight passes between two conal subbeams during their rotation cycle. This can also explain the partial nulls where the sight-line nulls only appear on one side of the subbeam system. A typical example of this phenomenon was reported in the pulsar B1133+16 by Herfindal & Rankin (2007). In the second scenario, parts of the rotating subbeam system are postulated to be missing. The longer-duration periodic nulls lasting several tens of periods are seen when the line of sight passes through these empty regions. The longer-duration nulls in PSR J1819+1305 were reported to exhibit this phenomenon by Rankin & Wright (2008). The periodic nulling in the carousel model is associated with conal components (Herfindal & Rankin 2009) and provide an immediate prediction that the nulling should not manifest in the stationary core components. To test this prediction, we collected the 19 pulsars with reported nulling periodicity in Table 3 along with their profile classification. The table shows that in addition to conal components ($S_{o}, D, \gamma$, and $Q$ profile classes), the pulsars with prominent core emission ($S_{c}$ and $M$ classes) also show periodic nulling. The nulling periodicity in the core components is difficult to understand using the carousel model. It seems more likely that the complete nulls correspond to the conditions when the emission completely ceases. Additionally, Basu et al. (2016) reports the presence of
The Astrophysical Journal, 846:109 (10pp), 2017 September 10

Table 3
Details of the Pulsars with Periodic Nulling

| PSR      | Period (s) | E (10^{30} erg s^{-1}) | P_{null} (P) | Class. |
|----------|------------|--------------------------|--------------|--------|
| B0031−07 | 0.943      | 19.2                     | 75 ± 14      | S_1    |
| B0301+19 | 1.388      | 19.1                     | 103 ± 34     | D      |
| B0525+21 | 3.746      | 30.1                     | 46 ± 4       | D      |
| B0751+32 | 1.442      | 14.2                     | 73 ± 10      | D      |
| B0834+06 | 1.274      | 130                      | 16 ± 4       | D      |
| B1133+16 | 1.188      | 87.9                     | 29 ± 2       | D      |
| J1649+2533 | 1.015    | 21.1                     | 27 ± 2       | ...    |
| B1706−16 | 0.653      | 894                      | 130 ± 70     | S_c    |
| J1727−2739 | 1.293    | 20.1                     | 206 ± 33     | ...    |
| B1738−08 | 2.043      | 10.5                     | 34 ± 8       | ,?     |
| J1819+1305 | 1.060    | 11.9                     | 64 ± 8       | ...    |
| B1839+09 | 0.381      | 776                      | 37 ± 3       | S_c    |
| B1918+19 | 0.821      | 63.9                     | 85 ± 14      | ,T     |
| B1944+17 | 0.441      | 11.1                     | 600 ± 52     | ,T     |
| B2034+19 | 2.074      | 9.02                     | 57 ± 6       | ...    |
| B2045−16 | 1.962      | 57.3                     | 51 ± 20      | T      |
| B2303+30 | 1.576      | 29.2                     | 43 ± 8       | S_c    |
| B2310+42 | 0.349      | 104                      | 32 ± 11      | M?     |
| B2327−20 | 1.644      | 41.2                     | 19 ± 1       | T      |

Note. The period and spin-down energy loss are listed in columns 3 and 4, respectively. Column 5 lists the nulling periodicity while column 6 describes the classification of each pulsar. Classifications are from Rankin (1990, 1993b).

periodic amplitude modulation in many pulsars which are core dominated. In a recent work by Mitra & Rankin (2017), highly periodic amplitude modulation was seen in the core component of the pulsar B1946+35. This could also not be explained using the carousel model and was considered as a newly emergent phenomenon.

Basu et al. (2016) showed from theoretical perspectives that there are difficulties in explaining the subpulse drifting phenomenon using a carousel system rotating around the magnetic axis. However, an interesting correlation was seen between the spin-down energy loss (E) and the drifting periodicity (P_{null}). The drifting population can be broadly separated into two groups. The first, corresponding to phase-modulated drifting, showed significant subpulse motion across the pulse window. The periodicities were anti-correlated with E. This phenomenon is correlated with E and discussed in more detail by Basu et al. (2016). On the other hand, the periodic amplitude modulation and periodic nulling, which can be considered as an extreme form of amplitude modulation, are related to an unexplored periodic phenomenon in pulsars.

5. Physical Implications of Nulling

The duration of the most widespread nulling is short, just one or two pulse periods. This is evidenced by the null length histograms, which generally peak at the lowest bin. In some cases, the nulling also lasts for hundreds of periods at a time, with a small but significant population of such pulsars now known (Lewandowski et al. 2004; Wang et al. 2007; Gajjar et al. 2012, 2014b; Kerr et al. 2014; Young et al. 2015). But, even in these cases, the distribution is dominated by short-duration nulls. It has been argued that the processes that cause nulling at different timescales have a different physical origin. The short-duration nulls are associated with stochasticity in the emission process while the longer-duration nulls are large-scale changes in the magnetosphere (see Cordes 2013 and references therein). One obvious way for nulling to occur is the pulse emission beam moving in and out of the observers’ line of sight. Effects like precession or the emission being blocked by an external object orbiting around the neutron star are some likely scenarios for this to happen. This necessitates nulling to be highly periodic with exact null and burst length intervals. However, as is evident in the single pulses, there is no repetitive pattern in the nulling phenomenon even in the cases that show an underlying periodicity. This is also represented in the null length and the burst length histograms, which show a distribution and rule out these mechanisms as the only possible sources of nulling. It is more likely that nulling is related to disruptions in the radio emission process.

The radio emission can be disrupted if the distribution of particles flowing along the dipolar magnetic field lines changes. Goldreich & Julian (1969) demonstrated that the region around a fast spinning neutron star of surface magnetic field 10^{12} G cannot remain a vacuum. They determined a charge-separated force-free magnetosphere with density n_{eq} = \Omega \cdot B / 2\pi c{e}. It has been reported (e.g., most recently by Philippov et al. 2015; Pétri 2016, and references therein) that a sufficient supply of charges from the neutron star surface as well as from pair production results in transition from a charge-separated magnetosphere to a force-free magnetosphere. The charge-separated magnetosphere corresponds to the case where charged particles are trapped in charge-separated zones which co-rotate with the star. On the other hand, the force-free magnetosphere is associated with the electromagnetically dominated pulsar wind and separated into the closed field line region, in which charges co-rotate with the star, and the open field line region, in which charges can flow radially outwards.

The coherent radio emission is excited due to some instabilities in the relativistic plasma outflowing along the open dipolar magnetic field lines. If the fluctuations in the pair-production process are such that the pulsar exists in the transition region between an electrosphere and a force-free magnetosphere, nulling is expected in its electrosphere state when the particle flow is halted. The timescale for which the particle flow can

7 Incidentally, the carousel model of rotating subbeams discussed in the previous section is also a form of geometric nulling.
nulling periodicities. The nulling periodicities line PN pulsars with disruption of the radio emission in the presence of particle periodic nulls. However, a detailed investigation is required to see whether this provides an explanation for the single-period nulls. It is a few hundred milliseconds for a typical one-second pulsar. The stop is comparable to the return current generation time, which is a few hundred milliseconds for a typical one-second pulsar. This provides an explanation for the single-period nulls. However, a detailed investigation is required to see whether the electrosphere can survive for longer durations and the transition between the magnetospheric states can support long-period nulls.

Next, we examine the conditions that may lead to the disruption of the radio emission in the presence of particle flow. Several observational evidence suggest that the radio emission arises around 500 km above the neutron star due to coherent curvature radiation (Mitra & Rankin 2002; Kijak & Gil 2003; Mitra & Li 2004; Krzeszowski et al. 2009; Mitra et al. 2009). These basic observational features can be best explained by the so-called steady-state polar cap models (e.g., Sturrock 1971; Ruderman & Sutherland 1975). In pulsars where $\Omega \cdot B < 0$, the positive ions cannot be extracted from the stellar surface due to high binding energy. This results in the formation of a vacuum gap or IAR above the magnetic poles. Once the IAR is formed, the radio emission process can be broadly divided into three stages occurring at distinct locations. The first stage consists of the breakdown of the IAR by isolated discharges on the polar cap due to magnetic $e^-e^+$ pair production. High-energy gamma-rays ($>1.02$ MeV) can form pairs in the presence of strong magnetic fields (Shukre & Radhakrishnan 1982). The large electric fields separate out the pairs with the backstreaming electrons heating the surface to very high temperatures (up to million degree Kelvin). They further emit soft X-rays due to thermal radiation. The positrons, also called primary particles, accelerate to high Lorentz factors and stream away from the stellar surface. The second stage consists of the primary particles producing further higher energy photons via curvature radiation or inverse Compton scattering, leading to more pairs. This eventually results in a cascade giving rise to a denser but less energetic secondary pair plasma outside the IAR. The outflowing streams of secondary plasma clouds with a specific energy distribution function are formed at the end of this stage. At the final stage, around heights of $\sim500$ km, two-stream instability develops due to the overlapping of fast and slow moving particles of adjacent secondary plasma clouds (Asseo & Melikidze 1998) along a particular set of field lines. This leads to the generation of strong electrostatic Langmuir wave turbulence. The Langmuir waves are modulationally unstable and their nonlinear evolution produces the charged solitons that can excite the radio waves via the curvature radiation mechanism (Melikidze et al. 2000; Gil et al. 2004). The radiation finally emerges as ordinary and extraordinary modes from the secondary plasma (Melikidze et al. 2014; Mitra et al. 2016b).

The emission mechanism is extremely sensitive to the plasma parameters. Any random fluctuations in these parameters are likely to appear between timescales of 100 ns (time to empty the gap after sparking has stopped) to 5 ms (spark formation time), which are much shorter than the typical nulling timescales. The only possibilities that can change the plasma parameters are additional physical processes that alter the nature of the IAR. There are two different mechanisms in the literature that can be used in this context. The first, proposed by Timokhin (2010), suggests changes in the magnetospheric state leading to variations in the spin-down rates. This is brought about by the changes in the current flow and the size of the open field line region, which might be effective in altering the parameters of the outflowing plasma. The second method leads to modifications in the potential drop across the IAR by introducing the concept of a partially screened gap (PSG, Gil et al. 2003; Szary et al. 2015). The surface temperature is considered to be at the critical level for the ions to be emitted and in the process reducing the gap potential. This results in the energy of the primary particle being altered, which can further change the process of
secondary particle production. The secondary pair-production process can switch from being dominated by the curvature radiation mechanism to being dominated by inverse Compton scattering, resulting in a modified energy distribution function. However, the transition between different states would still require an additional triggering mechanism, which is not addressed at present. This triggering mechanism would likely involve an additional source of high-energy photons from outside the IAR. Additionally, the processes generating these photons should be self-regulating in order to switch from the null to the burst states and vice versa. The underlying mechanisms that can lead to such high-energy photons outside the IAR need to be developed with detailed modeling. However, one of our results provides some constraints on this process. The presence of nulling periodicity seen in a number of pulsars suggests that the additional mechanism should be periodic in certain cases.

6. Summary

A detailed study of nulling was conducted for the 123 pulsars observed in the Meterwavelength Single-pulse Polarimetric Emission Survey. Nulling was observed in 36 pulsars, including 11 pulsars showing the presence of nulling periodicity. The nulling periodicity was demonstrated to be different and of longer duration than the phase-modulated subpulse drifting. The presence of nulling requires a triggering mechanism to change the pair-production process within the magnetosphere. The triggering mechanism is not yet known but should be periodic in some pulsars with periodic nulling.

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Appendix

Individual Pulsars in Our Sample

We discuss the previously reported nulling studies for the pulsars, particularly the cases where nulling periodicities are reported, and compare them with our results.

B0031−07 has a conal single profile which exhibits phase-modulated subpulse drifting as well as nulling. The drifting is seen in three different modes, A, B, and C, with $P_3$ values of roughly 12$P$, 7$P$ and 4$P$, respectively (Huguenin et al. 1970). Smits et al. (2005) and Gajjar et al. (2014a) showed the nulling to be broadband in this pulsar. We find the nulling to exhibit a longer periodicity of 75$P$ ± 14$P$, which cannot be connected harmonically to any of the three modes.

B0301+19 has a conal double profile which also shows both nulling and subpulse drifting. The LRFS of this pulsar shows two feature, one associated with drifting with $P_3$ roughly 6$P$ and another corresponding to nulling at 103$P$ ± 34$P$. Herfindal & Rankin (2009) also identified a low-frequency feature in their PMQ analysis. Interestingly, Young & Rankin (2012) showed that the bridge emission between the conal components has a hidden core emission. We find that both the bridge and conal components vanish during the periodic nulls, and it is unlikely to be a result of carousel rotation.

B0525+21 has a conal double profile, where the PMQ analysis of Herfindal & Rankin (2009) showed the presence of a low-frequency double-peaked structure that they identified with nulling. Young & Rankin (2012) report that the bridge emission contains a hidden core component. We recorded only 400 pulses for this pulsar, and the periodicity was not clear in our analysis. However, we found nulling to extend to all of the components, which makes the carousel interpretation unlikely.

B0818−13 has a conal single profile which shows the presence of two distinct emission states (Lyne & Ashworth 1983; Janssen & van Leeuwen 2004). In the brighter phase, the pulsar shows the presence of prominent drift bands with occasional single-period nulls. The weaker emission state shows longer nulling while the drifting continues to exist during the weaker burst states. There is no detectable periodicity in the null to burst transition during either of the two states.

B0834+06 has a conal double profile which shows the presence of drifting as well as nulling. The LRFS in this pulsar shows the presence of a periodicity corresponding to 2.2$P$ (Weltevrede et al. 2006; Basu et al. 2016). This feature corresponds to amplitude modulation. The PMQ analysis of Herfindal & Rankin (2009) found the same feature, although weaker, as well as a low-frequency feature. The periodicity was interpreted as corresponding to nonrandom partial nulls (Rankin & Wright 2007). In our analysis with only the complete nulls, we did not see any periodicity for the null to burst transitions. Nulling is seen for short durations lasting for a few periods in this pulsar. We argued that complete nulls are not geometrical in nature but arise due to changes in the pulsar magnetosphere over short timescales. In Section 5, we discussed possible conditions, such as a transition from a charge-separated magnetosphere to a force-free magnetosphere, etc., where the physical mechanism can change over such short timescales.

B1133+16 has a conal double profile similar to B0301+19 and B0525+21 with the bridge likely once again exhibiting core emission (Young & Rankin 2012). The LRFS shows the presence of a low-frequency feature as reported in Backer (1970) and Weltevrede et al. (2006). The feature becomes more prominent in both the PMQ and our analysis and is clearly related to periodic nulls. Herfindal & Rankin (2007) identified the periodicity as the longer circulation time of the rotating carousel model with sparse and occasional beamlets. They interpreted the shorter nulls as empty sightlines traversing between subbeams. Our analysis uses only the complete nulls and the presence of a hidden core component makes it unlikely to be the result of carousel circulation. Nulling is supposed to be a broadband phenomenon (Smits et al. 2005; Gajjar et al. 2014a) but simultaneous observations by Bhat et al. (2007) report the presence of excess nulls below 1.4 GHz for this pulsar. However, more observations are needed to show whether the periodicity persists across the frequencies.

J1727−2739 has a conal double profile with both nulling and drifting. Wang et al. (2007) reported frequent short bursts separated by null intervals in this pulsar. A more detailed study by Wen et al. (2016) showed the presence of three distinct modes during the burst state with modes A and B showing different drifting properties, while in mode C no subpulse
drifting is detected. We have additionally found nulling to exhibit periodicity.

*B1918+19* shows a three-component conal profile with nulling as well as subpulse drifting. Hanks & Wolszczan (1987) showed the presence of three different drift modes, A, B, and C, with periodicities ~6P, ~4P, and ~3P, respectively, along with a disordered mode (N) without any drifting. Rankin et al. (2013) found the nulls to be confined mainly in the B and N modes with the modes exhibiting specific modular sequences. The three different drift modes have been interpreted in the framework of the carousel model as the number of sparks or subbeams changing in each mode. The PMQ analysis of Herfindal & Rankin (2009) show the presence of two harmonically connected peaks at 85P ± 14P and 43P ± 4P in addition to a wide structure at 12P. The 12P periodicity was detected for the shorter null lengths. However, the results of our periodicity studies show a contrasting nulling behavior for this pulsar. The longer-duration nulls were expected to be true nulls without any periodicity. However, the results of our periodicity studies show a contrasting nulling behavior for this pulsar. The Astroplastic Journal, 2017 September 10

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