A new method to analyse pulsar nulling phenomenon

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Pulsar nulling is a phenomenon of sudden cessation of pulse emission for a number of periods. The nulling fraction was often used to characterize the phenomenon. We propose a new method to analyse pulsar nulling phenomenon, by involving two key parameters, the nulling degree, $\chi$, which is defined as the angle in a rectangular coordinates for the numbers of nulling periods and bursting periods, and the nulling scale, $N$, which is defined as the effective length of the consecutive nulling periods and bursting periods. The nulling degree $\chi$ can be calculated by $\tan \chi = N_{\text{nulling}} / N_{\text{bursting}}$ and the mean is related to the nulling fraction, while the nulling scale, $N$, is also a newly defined fundamental parameter which indicates how often the nulling occurs. We determined the distributions of $\chi$ and $N$ for 10 pulsars by using the data in literature. We found that the nulling degree $\chi$ indicates the relative length of nulling to that of bursting, and the nulling scale $N$ is found to be related to the derivative of rotation frequency and hence the loss rate of rotational energy of pulsars. Their deviations reflect the randomness of the nulling process.

Key words: Pulsars; Radio sources; Radiation mechanisms

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1 Introduction

Pulsar nulling is abrupt cessation in pulsar emission, as first detected in [1], which is still not well understood. It often appears as a broad band phenomenon of pulsar radio emission. Currently, among 2267 known pulsars, nulling phenomenon has been detected for 185 strong pulsars [1-22].

There have been many observations and analyses for the nulling phenomenon for a number of strong pulsars [1-22]. The nulling fraction ($NF$), which is the time fraction for the null emission state, is often used to characterize the nulling properties of pulsars. It is in general less than 10% for most pulsars, but rarely as high as more than 90% for a few pulsars [5,12]. The null duration is a range of one period to hundreds of periods for various pulsars. The Rotating Radio Transient (RRAT) may be the nulling with an extremely high nulling fraction, which emits one pulse in many periods [3].

Observations of individual pulses provide valuable hints for pulsar emission mechanism and propagation process. The switches of pulsar emission modes or magnetosphere states have been observed in many pulsars [4-5], and nulling may regard as being an extreme form of such switches. From a few pulsars, subpulse drifting rate [6-7] and interpulse appearance [8] have been shown to be related to nulling. The subbeam carousel model can be used to explain the quasi-periodicity of nullings detected from some pulsars [9-11]. PSR J0941−39 [3] switches not only between two states for nulling and bursting, but also emits rare pulses during the nulling state as if it is a RRAT.

Previous studies of nulling pulsars have been focused on the correlations between pulsar parameters and the nulling fraction [12,13]. The most often discussed but without consensus is the possible relation between pulsar characteristic age and nulling fraction [22,5,12,13]. However, it is not clear if the nullings occur randomly or periodically [11,14], depending on pulsars. The *Wald-Wolfowitz runs test* was used.
Table 1 Parameters and observational details for 10 nulling pulsars in literature

| PSR Jname | PSR Bname | P (s) | DM (cm⁻³ pc) | Obs. Freq. (MHz) | BW (MHz) | Telescope | Ref. |
|-----------|-----------|------|-------------|-----------------|----------|-----------|------|
| J0820−4114 | B0818−41 | 0.545 | 113.4 | 325/610 | 16 | GMRT | [19] |
| J1049−5833 | - | 2.202 | 446.8 | 1518 | 576 | Parkes | [5] |
| J1502−5653 | - | 0.536 | 194.0 | 1374/1518 | 288/576 | Parkes | [2,5] |
| J1701−3726 | B1658−37 | 2.455 | 303.4 | 1518 | 576 | Parkes | [5] |
| J1703−4851 | - | 1.396 | 150.3 | 1518 | 576 | Parkes | [5] |
| J1727−2739 | - | 1.293 | 147.0 | 1518 | 576 | Parkes | [5] |
| J1752+2359 | - | 0.409 | 36.0 | 430 | 8 | Arecibo | [20] |
| J1819+1305 | - | 1.060 | 64.9 | 327 | 25 | Arecibo | [11] |
| J1820−0509 | - | 0.337 | 104.0 | 1518 | 576 | Parkes | [5] |
| J1946+1805 | B1944+17 | 0.441 | 16.2 | 430 | 8 | Arecibo | [21] |

2 Nulling degree and scale for 10 pulsars

Observations for pulser nulling in general were made for significant detections of single pulses of strong pulsars by using a sensitive radio telescope. In order to get sufficient signal to noise ratio, single-pulse sequences sometimes are integrated to short subintegrations [5,18]. The nulling state is determined by the threshold of three or five times of the rms in the on-pulse window for detection of pulse emission. The nulling length ($N_{\text{nulling}}$) is counted by continuous pulsar periods when the emitted pulse energy is below the threshold, and the bursting length ($N_{\text{bursting}}$) is the number of periods for continuously detected pulse emission above the threshold.

In order to characterize the nulling properties properly, we count the $N_{\text{nulling}}$ and $N_{\text{bursting}}$ from the observed single-pulse sequences, and plot in Fig.1 the numbers for any adjacent states. We then define two parameters $N$ and $\chi$ as

$$N = \sqrt{N_{\text{nulling}}^2 + N_{\text{bursting}}^2}$$

$$\chi = \arctan\left(\frac{N_{\text{nulling}}}{N_{\text{bursting}}}\right)$$

For a sequence of pulses, we obtain a distribution of data points from a set of $N_{\text{nulling}}$ and $N_{\text{bursting}}$. The statistics of these data distribution presumably describe the nulling properties not only for the often-used nulling fraction via $\langle \chi \rangle$, but also the nulling scale via $\langle N \rangle$.

We collect observational nulling data from literature for 10 pulsars, as listed in Table 1, if there are sufficient data of pulse-sequences. The nulling and bursting period numbers of PSR J0820−4114 (B0818−41) are taken from Table 1, 2, 3, 4 in [19], which were observed by using the Giant Metre-wave Radio Telescope (GMRT) at two frequencies (325 MHz and 610 MHz) with bandwidth of 16 MHz. All data of these
Figure 2  Distribution of period numbers of adjacent nulling and bursting (left), and the histogram distribution of nulling degree (middle) and nulling scale (right) and their Gaussian fittings. The black dots in the left plots stand for the nulling periods with the subsequent bursting period, and open circles for the nulling periods with their preceding bursting periods. Most data points in the left panels are measured from pulse sequences in literature. Some data points have similar $N_{nulling}$ and/or $N_{bursting}$, and hence are overlapped in plots in the logarithm-scale.
Figure 2 – continued
Table 2  Nulling degree and nulling scale for 10 pulsars, together with nulling fractions and nulling cycles ($N_c$) taken from literature. The pulsar parameters, the derivative of rotation frequency ($\nu' = \dot{P}/P^2$), the loss rate of rotational energy ($\dot{E} = 4\pi I \dot{P}/P^3$) and the characteristic age ($\tau = P/2\dot{P}$) of pulsars are taken from the ATNF pulsar catalog\[23].

| PSR-Jname   | $\chi$  | $N$   | $NF$  | $N_c(s)$ | $\nu'(10^{-16})$ | $\log \dot{E}$ | $\log \tau$ |
|-------------|---------|-------|-------|----------|------------------|----------------|------------|
| J0820−4114  | $18^\circ \pm 15^\circ$ | $47 \pm 20$ | 30    | 179 $\pm$ 127 | $-0.64$          | 30.66          | 8.66       |
| J1049−5833  | $54^\circ \pm 14^\circ$ | $110 \pm 24$ | $47 \pm 3$ | 179 $\pm$ 127 | $-9.1$           | 31.20          | 6.90       |
| J1052−5653  | $19^\circ \pm 7^\circ$ | $46 \pm 23$ |       |          |                  |                |            |
| J1701−3726  | $81^\circ \pm 6^\circ$ | $1353 \pm 667$ | $93 \pm 4$ | $515 \pm$ 360 | $-63.77$         | 32.67          | 6.67       |
| J1703−4851  | $77^\circ \pm 6^\circ$ | $158 \pm 80$ | $74^*$ |          | $-26.05$         | 31.87          | 6.64       |
| J1727−2739  | $52^\circ \pm 20^\circ$ | $102 \pm 54$ | $52 \pm 3$ | $91 \pm 58$ | $-6.58$          | 31.30          | 7.27       |
| J1752+2359  | $81^\circ \pm 6^\circ$ | $290 \pm 67$ | $81$ |          | $-38.41$         | 32.57          | 7.00       |
| J1819+1305  | $34^\circ \pm 13^\circ$ | $38 \pm 9$ | $41 \pm 6$ |          | $-3.19$          | 31.08          | 7.67       |
| J1820−0509  | $74^\circ \pm 6^\circ$ | $715 \pm 65$ | $67 \pm 3$ | $104 \pm 68$ | $-81.93$         | 32.98          | 6.76       |
| J1946+1805  | $21^\circ \pm 6^\circ$ | $275 \pm 121$ |       |          |                  |                |            |
| J1946+1805  | $55^\circ \pm 26^\circ$ | $14 \pm 7$ | $55 \pm 5$ |          | $-1.24$          | 31.04          | 8.46       |

* Corrected from literature by our measured data.
Figure 3  Left panel: Strong correlation appears between the nulling degree ($\chi$) and the often-used nulling fraction (NF). The nulling degree value of PSR J1049–5833 and PSR J1820–0509 for the peak of the smaller amount of data is plotted as an open circle. Right panel: The null scale ($N$) is also found to be related to the nulling cycle in [5].

Figure 4  Nulling scale ($N$) is obviously correlated to the derivative of rotation frequency ($\nu' = \dot{P}/P^2$) and the loss rate of rotational energy ($\dot{E} = 4\pi I \dot{P}/P^3$), but not the characteristic age ($\tau = P/2\dot{P}$) of pulsars. The correlation parameter $\gamma$ is given in each panel. The values of PSR J1820–0509 and PSR J1049-5833 for the peak of the smaller amount of data are plotted with open circles.

data are used in this work. The data of PSR J1049–5833, and also PSR J1701–3726, J1703–4851, J1727–2739 and J1820–0509, are measured from Fig.2 and Fig.3 in [5], which were observed by using Parkes 64-m telescope at 1518 MHz with a bandwidth of 576 MHz. The data of PSR J1502–5653 are also measured from Fig.1 in [2] which were observed by using the Parkes 64-m telescope at frequency of 1374 MHz with bandwidth of 288 MHz and also Fig.2 in [5] observed at 1518 MHz with a bandwidth of 576 MHz. The pulse sequence data of PSR J1752+2359 are measured from Fig.5 observed with the Arecibo telescope at 430 MHz in [20]. The single-pulse data of PSR J1819+1305 are taken from Fig.4 in [11], observed at 327 MHz by the Arecibo Telescope. The single-pulse sequences of PSR J1946+1805 (B1944+17) are taken from Fig.2 in [21] which were observed using Arecibo at 430 MHz.

The distribution of period numbers of nulling and bursting for these 10 pulsars are plotted in Fig.2, and the histograms for $\chi$ and $N$ are fitted with a Gaussian function. Most of these $\chi$ and $N$ distributions show one peak, some narrow, some extended. The $\chi$ and $N$ distributions of PSR J1049–5833 and J1820–0509 have two peaks. The mean and deviation of the $\chi$ and $N$ distributions of 10 pulsars are listed in Table 2, together with the nulling fractions and nulling cycles ($N_c$) taken from literature and pulsar properties, the derivative of rotation frequency, the loss rate of rotational energy and the characteristic age of pulsars from the pulsar catalog [23].

3 Discussion

The distributions of nulling degree $\chi$ and nulling scale $N$ exhibited a wide range of nulling behaviour, which provide insights for the stability of emission region or the switches of emission modes in pulsar magnetosphere.

As shown in Fig.3, the mean nulling degree $\chi$ is strongly correlated with the often-used nulling fraction (NF) which is the average percentage of nulling time. The larger the mean
nulling degree, the larger the nulling fraction. The distribution of nulling degrees contains more information than the average percentage of time. For example, random nulling length and bursting length should give a very broad distribution of nulling degree, so that the deviation of $\chi$ is large, more than 15 degree for PSR J0820−4114, PSR J1727−2739 and PSR J1946+1805. About half pulsars in our sample show a narrow distribution of a few degree around one (for PSR J1049−5833 and J1820−0509 even two) preferred nulling degree, which indicates the somehow periodical behaviour of nulling.

The other key parameter is the nulling scale, $N$, which indicates how often nulling occurs. The distributions of $N$ for these 10 pulsars show a peak, often with a long tail, except PSR J1049−5833 and J1820−0509 which show two main peaks. The nulling scale of PSR J1502−5653, $N = 1353 \pm 667$ periods (12.46 minutes) is consistent with the quasi-periodicities of 11 minutes and 18 minutes found in [2]. The mean of the nulling scale distribution is closely related to the nulling cycle discussed in [5], as shown in Fig.4. However, the distributions of the nulling scale $N$ show more details of the nulling process, which may be related to the emission process and pulsar radiation pattern. We found in Fig.4 that the nulling scale $N$ is strongly related to the derivative of rotation frequency $\nu'$, the loss rate of rotational energy ($E = 4\pi IP/JP^3$), but not the characteristic age ($\tau = P/2P$) of pulsars.

The standard deviation of the $N$ distributions also indicates the randomness of nulling timescale. A large $\sigma_N$ for broad distributions indicates random or non-periodic nullings. A narrow $N$ distributions can be used to predict the expected timescale of bursting or nulling, which is a clue for understanding pulsar radiation mechanism. For instance, when nulling is caused by the empty passes of our sightline in the carousel-beam system, the distribution of $\chi$ and $N$ can constrain the carousel circulation time and the geometry of carousel-beam system.

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