Radiation properties of extreme nulling pulsar J1502−5653

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ABSTRACT

We report on radiation properties of extreme nulling pulsar J1502−5653 by analysing the data acquired from the Parkes 64-m telescope at 1374 MHz. The radio emission from this pulsar exhibits sequences of several tens to several hundred consecutive burst pulses, separated by null pulses, and the appearance of the emission seems quasi-periodic. The null fraction from the data is estimated to be 93.6 per cent. No emission is detected in the integrated profile of all null pulses. Systematic modulations of pulse intensity and phase are found at the beginning of burst pulse sequences just after null. The intensity usually rises to a maximum for the first few pulses, then declines exponentially afterwards, and becomes stable after a few tens of pulse periods. The peak phase appears at later longitudes for the first pulse, then drifts to earlier longitudes rapidly, and then systematic drifting gradually vanishes, while the intensity becomes stable. In this pulsar, the intensity variation and phase modulation of pulses are correlated in a short duration after the emission starts following a null. Observed properties of the pulsar are compared with other nulling pulsars published previously, and the possible explanation for phase modulation is discussed.

Key words: stars: neutron – pulsars: individual: PSR J1502−5653.

1 INTRODUCTION

Pulsar nulling, which was first reported by Backer (1970), is a phenomenon in which the pulse emission abruptly turns off for a certain number of pulse periods, then suddenly returns to normal. Early studies showed that the ‘nulling fraction’ (NF), i.e. the fraction of time that a pulsar is in the null state, of most nulling pulsars is less than 10 per cent (Biggs 1992; Vivekanand 1995). Wang, Manchester & Johnston (2007) studied a sample of 23 nulling pulsars, including some extreme nulling pulsars with NF up to 95 per cent. Investigating the emission behaviours of nulling pulsars is important to understand the pulsar emission mechanism. Different patterns of transition between null and burst state have been noted by several authors. For PSR B1749−28 (Ritchings 1976), B0809+74 (Lyne & Ashworth 1983; van Leeuwen et al. 2003), B1944+17 (Ritchings 1976; Deich et al. 1986) and B0818−41 (Bhattacharyya, Gupta & Gil 2010), the onset of burst is abrupt, and the transition from burst to null state shows a gradual decline of pulse emission. However, the pulse intensity increases gradually when emission starts after a null for PSR J0941−39 (Burke-Spolaor & Baines 2010), and the cessation of emission is sudden for PSR B0031−07 (Vivekanand 1995) and B0818−13 (Lyne & Ashworth 1983). Bhattacharyya et al. (2010) investigated the post- and pre-null emission behaviour of PSR B0818−41, and showed that the first few pulses after the nulls outshine the following pulses, whereas the last few pulses before the nulls are less intense than other pulses, and they noted that the phenomenon of null may be associated with some kind of ‘reset’ of the pulsar radio emission engine. Null of most pulsars occurs randomly. However, Kramer et al. (2006) reported the quasi-periodic nulls of B1931+24; furthermore, periodicity in nulling pulsars has been detected in PSR B1133+16 (Herfindal & Rankin 2007), J1819+1305 (Rankin & Wright 2008) and J1738−2330 (Gaijar, Joshi & Kramer 2009).

PSR J1502−5653 was discovered during the Parkes Multibeam Pulsar Survey (Hobbs et al. 2004). The rotation period of the pulsar, $P$, is 0.535 s, and its first derivative $\dot{P}$ is $1.83 \times 10^{-15}$ s s$^{-1}$. Correspondingly, it has a characteristic age of 4.64 $\times$ 10$^6$ yr and surface magnetic field strength of 10$^{12}$ G (Hobbs et al. 2004). Wang et al. (2007) investigated J1502−5653 at 1518 MHz and showed that this pulsar has an NF of 93 per cent, which makes it an extreme nulling pulsar, with active pulses lasting typically a minute at intervals of 10–15 min of null pulses.

In this paper, we carry out a detailed investigation of the emission behaviour of PSR J1502−5653. Data analysis and results are presented in Section 2. The implications of the results are discussed in Section 3. Finally, in Section 4, we summarize this work.

2 DATA ANALYSIS AND RESULTS

The data were obtained on 2002 September 12 using the Parkes 64-m telescope, at a central frequency of 1374 MHz. The data last for 6 h, and contain 40 308 pulse periods. The filter bank system
has a total bandwidth of 288 MHz with 96 × 3 MHz channels of polarization-summed data (for each beam) which are sampled every 1 ms. Details of the observing system are described by Manchester et al. (2001). The single-pulse time sequence is obtained by dedispersing the data at a dispersion measure of 194.0 pc cm$^{-3}$. Pulse intensities were computed by summing samples within an on-pulse window of width 20 ms and subtracting the baseline level determined in an off-pulse window of width 200 ms.

2.1 Time sequence and blocks of successive pulses

As shown in Fig. 1, the time sequence shows many blocks of consecutive strong pulses. In this paper, we considered intervals of more than 10 pulse periods with no detectable emission as null state, and intervals between null states as burst states. In this way, a total of 29 blocks of burst state (3451 pulses) are identified. The duration of these blocks varies from about 32 s (60 pulses) to 2 min (240 pulses), with an average duration of 1 min, while null state lasts from about 16 s (30 pulses) to 25 min (2800 pulses). The Fourier transformation of the autocorrelation function of the whole time sequence shows two relatively broad peaks at periods of 11 and 18 min, implying that the burst appearance of the pulsar may be quasi-periodic.

10 typical blocks of burst are displayed in separate plots of Fig. 2 in the form of a grey-scale diagram (left-hand panel) and an intensity diagram (right-hand panel). The burst blocks in these plots begin from the 11th pulse, and the preceding 10 nulls are reserved for comparison. The first 10 pulses in each block are quite strong, and the first few tens of pulses are uninterrupted by nulls. However, in the middle or late stages of some burst blocks, the pulse sequence is interrupted by a few short nulls, usually less than 10 periods. Just following some burst blocks, one or two sporadic strong pulses are detected occasionally during the null state. These sporadic single pulses are similar to the pulses during burst states in intensity, phase and shape.

As can be seen in Fig. 2, the pulse intensity shoots up to a relatively high magnitude for the first few pulses, and then the pulse intensity drops gradually. After about 10–20 pulses, this relatively steady decrease is replaced by a pattern of random fluctuation in intensity. As shown in the left-hand panel of Fig. 2, the single pulses drift from later to earlier longitudes at the beginning of each block of burst, and then present irregular modulation in pulse phase. These indicate that the variations of pulse intensity and pulse phase modulations may be correlated at the early stage of burst; this is studied further in Section 2.3. All the 29 blocks of burst start with an abrupt rise of the intensity, and at least 23 of them end up with a gradual decline.

2.2 Average profiles and pulse energy distributions

Fig. 3 shows the integrated profiles for the whole data span including both burst and null pulses and for just the null pulses. There is no detectable profile by integrating all pulses in null state, whereas when the 3451 pulses in burst blocks are added in, the profile is prominent showing that the burst pulses are actually very strong. The average profile of the pulsar is narrow, with a 10 per cent width of 9.4 (14 ms) in longitude.

Fig. 4 presents histograms of pulse energy distribution in the pulsar’s on-pulse and off-pulse windows, which are constructed
using the method described by Ritchings (1976). On-pulse and off-pulse energies are determined by integrating within an on-pulse window and in an off-pulse window of the same duration after the same baseline is subtracted, respectively. The histogram formed from off-pulse energies (dotted line) centres around zero, while that from on-pulse energies (solid line) has a 'long tail' component due to burst pulses and a big Gaussian component due to null pulses. The NF of the pulsar is estimated to be 93.6 per cent through the histograms. As shown in this figure, the energy of the strongest pulse is 42 times that of the mean pulse, suggesting the burst pulses are strong and highly modulated. This is the first pulse in the burst which is situated at about 332 min in Fig. 1.

2.3 Single-pulse intensity variation and phase modulation

To further study the emission behaviour of PSR J1502−5653 during the early stage of burst just after null, we construct the mean pulse sequence by superimposing the first 50 detectable burst pulses of all blocks (the shortest burst block contains more than 50 burst pulses) in accordance with the sequence of pulses and the pulse phases, while 10 earlier pulses are also included for comparison. The distinguishable boundaries from null to burst, the abundance of burst blocks in the data and the appearance of no null in the first 50 pulses in all burst blocks make this method feasible and effective in investigating the emission properties of the early stage of burst. The result is plotted in the top-middle panel of Fig. 5. The intensity fluctuation and phase modulation of the first 10 pulses in the burst state look different from those of the following pulses.

As shown in the top-right panel of Fig. 5, the intensity shoots up at the first mean pulse in the burst state, and remains strong for about three pulses, then goes down exponentially for the following sequence of about 20 pulses, and becomes stable at the half-maximum intensity for the next tens of pulses. Using the method described by Bhattacharyya et al. (2010), we calculate that the average intensity of the first three mean pulses in the burst state is 1.4, 1.8, 2.2 and 2.4 times that of the following fourth–ninth, 10th–15th, 31th–40th and 41th–50th mean pulses, respectively.

The top-left panel of Fig. 5 shows that the peak phases of the first few burst pulses appear at later longitudes than those of the following pulses. In about 13 pulse periods, the pulse phase drifts about 0.8 to earlier longitudes, and the phase of the 13th pulse is equal to the peak phase of the average profile; then the apparent drifting stops and is replaced by irregular phase modulation. We note that the intensity fluctuation and phase modulation of the pulsar are correlated in the beginning of burst.

In Fig. 5, there is some evidence for a weak wide pulse at the start of burst. This pulse is the 10th pulse in the mean pulse sequence. We call it the ‘transition pulse’ in this paper. Fig. 6 shows three consecutive pulses selected from the mean pulse sequence, the last null pulse, the transition pulse and the first strong pulse. The transition pulse has a full width at half-maximum (FWHM) of 6.7 and a signal-to-noise ratio (S/N) of 4.34. For comparison, the S/N of the first strong burst pulse is 44.1 and the width is 4.04. The
transition pulse is very weak, so it is only detectable in the mean pulse sequence.

The bottom panel in Fig. 5 displays the average profile (solid line) of the pulsar and three profiles which are obtained from the first three pulses following the transition pulse, the fourth to ninth pulses and the 10th to 15th pulses, respectively. The peaks of these three profiles appear at longitudes 0.72, 0.35 and 0.13, respectively, where the peak phase of the average profile is set as zero. The widths of these three profiles are 3.86, 4.06 and 4.33, respectively, while that of the average profile is 4.53.

Fig. 7 presents the FWHM of 25 mean pulses in burst state, excluding the transition pulse, showing that the FWHM increases with pulse number at the beginning of burst. Around the 13th pulse of the burst, the width reaches that of the average profile. Apart from the wide transition pulse, it is clear that in a short duration after the null the radiation window gradually broadens, while the pulses drift from later to earlier longitudes. The middle and later stages in the burst block are often randomly disrupted by short nulls, and the behaviour is not so systematic as in the early stages.

3 DISCUSSION

The emission of J1502−5653 is characterized by an abrupt transition from null to burst with a time-scale of less than two pulse periods, a gradual decrease of pulse intensity in the early stage of a burst which is accompanied by a shift to earlier longitude in pulse phase and a broadening in pulse width. Gradual cessation of the emission in some bursts before nulls is also noticed. Similar behaviour can be seen in PSR B0818−14. Bhattacharyya et al. (2010) reported that, for this pulsar, the transition from nulls to bursts is abrupt and pulse intensity from bursts to nulls appears to reduce gradually, and the profile shape of the first few pulses differs from that of the average profile. They also mentioned that the behaviour of subpulse drifting at the beginning of burst pulses after null is different from the following pulses. Similarly, in PSR J1502−5653, the pattern of phase modulation of the first few pulses is distinct from that of the later pulses during burst.

Recently, Burke-Spolaor & Bailes (2010) discovered bizarre emission behaviour of PSR J0941−39, i.e. sometimes it only emits sporadic pulses and at other times it behaves just like a nulling pulsar. From fig. 5 of Burke-Spolaor & Bailes (2010), we notice that the post-null pulse phases seem to shift towards earlier longitudes, and this looks similar to the drifting behaviour of PSR J1502−5653. However, unlike PSR J1502−5653, the pulse intensity of PSR J0941−39 appears to increase gradually at the beginning of post-null emission, when it behaves like a nulling pulsar.

The post-null pulse drifting of PSR J1502−5653 may be explained by the vacuum gap model (Ruderman & Sutherland 1975). According to the classical vacuum gap model, the sub-beams of emission circulate around the magnetic axis, as a result of $E \times B$ drift of spark plasma filaments. At the beginning of each burst, the electric field in the accelerating gap is relatively high and consequently the observed $E \times B$ drift rate is also high. Then the sparking process starts, which produces not only strong radio emission but also $e^-e^+$ pairs. A few pulse periods later, the $e^-e^+$ pairs accumulate in the accelerating gap and decrease the electric field to a relatively stable value where sparking and radio emission go on but the drift rate reduces to nearly zero. As the accumulation proceeds the gap electric field strength keeps on weakening until the sparking process breaks down and the radio emission ceases. Gil, Melikidze & Geppert (2003) and Gil et al. (2008) refined the vacuum model by introducing a thermal ion outflow from the hot polar cap surface. However, the intensity variations and their correlation with phase modulation of burst pulses at the beginning of burst blocks need to be further investigated.

Kramer et al. (2006) noted that PSR B1931+24 turns ‘on’ for 5–10 d and ‘off’ for 25–35 d; the switch occurs in a quasi-periodic fashion, and no obvious emission can be found in the integrated profile of the null state. The difference of the slow-down rates in the ‘on’ and ‘off’ states of this pulsar indicates a massive change in magnetospheric currents. The quasi-periodic transition between ‘on’ and ‘off’ state and non-detection of integrated energy by folding many null pulses of PSR J1502−5653 suggest that the emission behaviour of this pulsar is somehow similar to that of the intermittent pulsar B1931+24, but with very different ‘on’ and ‘off’ time-scales. The scenario of two slow-down rates of PSR B1931+24 may be applicable to PSR J1502−5653; however, measuring two slow-down rates is not possible for this pulsar, because of the very short durations of ‘on’ and ‘off’ states. The time-scale of the magnetospheric-current changing is believed to be very short, and it is not yet clear whether and how the pulses emitted at the very beginning of the strong burst state are influenced by the switching process of the magnetospheric currents.

4 CONCLUSION

The bursts of pulses of PSR J1502−5653 have a typical duration of 1 min or about 100 pulse periods, and they are separated by nulls lasting from 30 to 2800 pulse periods. The power spectra of the pulse sequence show two broad peaks at periods of 11 and 18 min, revealing that the appearance of the emission may be quasi-periodical in this pulsar. The NF estimated from the data is 93.6 per cent. The integrated profile of all null pulses shows no emission. Interestingly, by integrating over 29 pulse sequences, a weak and wide pulse is found just before the first detected single pulse in all burst blocks.

At the beginning of burst after null, the intensity usually rises to the maximum immediately, and keeps a high intensity for a few pulses, then the intensity of the next 20 or 30 pulses declines exponentially, and gradually becomes stable at the half-maximum intensity. In most case, the cessation of radiation is gradual. The peak phase of the first pulse in burst usually appears to be at later longitudes than that of the average profile; then the phase drifts quickly to earlier longitudes for next several pulses. The drifting then tends to slow down in the next 20 to 30 pulse periods, and...
then is replaced by irregular phase modulation. As the peak phase drifts to earlier longitudes, the pulse intensity declines; meanwhile, the radiation window broadens gradually until it reaches the width of the average profile. A good correlation can be seen between intensity variation and phase modulation in the early stage of post-null emission.

The phase modulation may be explained by electric field shielding caused by e⁻e⁻ pairs produced by the sparking process. The emission behaviours of individual pulses during the transition between null and burst state may provide a very important clue to understanding the underlying switching mechanism of nulling pulsars.

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