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Timing the Young Pulsar at the Centre of SNR 3C 58

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Abstract.

PSR J0205+6449 is a young, rotation-powered pulsar located at the centre of the SNR 3C 58, widely believed to be the remnant of the historical supernova SN 1181. The neutron star is cooler than expected from standard cooling models [1] and the pulsar, though it has a very high spin-down luminosity of $L = 2.6 \times 10^{37}$ ergs/s, has very low radio ($L_{1400} \approx 0.5$ mJy kpc$^2$ [2]) and X-ray luminosities ($L_x = 2.06 \times 10^{32}$ ergs/s [3]). We present 4 yrs of timing data spanning 5 yrs obtained with the Rossi X-ray Timing Explorer, the Jodrell Bank Observatory and the Green Bank Telescope. We present phase-coherent timing analyses showing significant timing noise that prevents a measurement of the ‘braking index’. In addition, we present two glitches observed in the source and discuss implications for the age and temperature of the neutron star.

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INTRODUCTION

Radio pulsars are powered by rotational kinetic energy and emit electromagnetic radiation while spinning down. The spin down can be described by \( \nu = -K\nu^n \), where \( \nu \) is the spin frequency, \( \dot{\nu} \) its derivative, \( K \) a constant related in part to the B-field and \( n \) is the ‘braking index,’ given by \( n = \nu\dot{\nu}/\nu^2 \), and expected to be equal to 3 for a spinning magnetic dipole. However, \( n < 3 \) in all 6 cases where it has been measured [4]. Explanations for \( n < 3 \) include loss of momentum via a particle wind [5], non-dipolar B-field [6] or B-field evolution [7]. Integrating the spin-down law above, gives an estimate of the pulsar age

\[
\tau = \frac{1}{n - 1} \left( 1 - \frac{\nu}{v_0} \right)^{-1},
\]

which reduces to the characteristic age, \( \tau_c = \nu/2\dot{\nu} \), if \( n = 3 \) and the pulsar is spinning rapidly at birth.

The characteristic age of PSR J0205+6449 is \( \sim 5400 \) yrs, roughly 6.5 times larger than its true age if the pulsar is associated with SN 1181. This discrepancy can be reconciled if the pulsar was born spinning near its present spin period of \( \sim 65 \) ms, or, if the pulsar had an unusually large braking index of \( \sim 12 \).

OBSERVATIONS

We report here on timing observations of PSR J0205+6449 obtained to try to measure its braking index and hence age. Observations were taken with the Green Bank Telescope (GBT) from MJD 52327-52776. Data were taken at 820 MHz and 1400 MHz with the BCPM [8]. For details see [2]. Rossi X-ray Timing Explorer (RXTE) observations were taken from MJD 52343-53813 with the proportional counter array [9]; for details, see [10]. Observations began at the Jodrell Bank Observatory (JBO) on MJD 53725 and continue on a regular basis. Data are taken at 1400 MHz with a 2 × 64 × 1-MHz filterbank and an on-line hardware dedisperser (see [11] for details).

PHASE-COHERENT TIMING

The most accurate method to determine spin parameters is phase-coherent timing, that is, accounting for each turn of the pulsar. This is achieved by fitting a Taylor expansion of phase to pulse arrival times. A single phase-coherent timing solution spanning all 5 yrs over which data were taken was impossible to achieve due to a large gap in the data spanning 280 days, and two large glitches. Instead, we present three phase-coherent timing solutions. GBT and RXTE data were fitted together resulting in a timing solution spanning 6 months (MJD 52337-52505). Timing residuals are shown in Fig. 1, with the top panel showing residuals with \( \nu \), \( \dot{\nu} \) and \( \ddot{\nu} \) fitted. Significant timing noise remains in the data and can be fitted with 6 frequency derivatives, shown in the bottom panel of Fig. 1. Phase-coherence was lost after MJD 52505, which we
FIGURE 1. Timing residuals for MJD 52337-52505 from GBT (dots) and RXTE (crosses) observations. Top: residuals with \( \nu \), \( \nu' \) and \( \nu'' \) fitted. Bottom: residuals with an additional 4 frequency derivatives removed.

FIGURE 2. Timing residuals for MJD 52571-52776 from GBT (dots) and RXTE (crosses) observations. Top: residuals with \( \nu \), \( \nu' \) and \( \nu'' \) fitted. Bottom: residuals with an additional 3 frequency derivatives removed.

Interpret as resulting from a large glitch (see Fig. 4).

A second coherent timing solution using GBT and RXTE data spans 7 months (MJD 52571-52776). Timing residuals are shown in Fig. 2, with \( \nu \), \( \nu' \) and \( \nu'' \) fitted in the top panel. Again, significant timing noise remains in the data, which can be fitted with 5 frequency derivatives, shown in the bottom panel of Fig. 2.

Fig. 3 shows residuals for the third timing solution spanning \( \sim 3 \) yrs (MJD 53063-54126), with JBO (dots) and RXTE (crosses) data. The top panel of Fig. 3 shows residuals with \( \nu \) and \( \nu' \) removed; the bottom panel shows residuals with \( \nu'' \) also fitted. The timing noise in this 3 yr period is so large that it cannot be described by 12 polynomials (the maximum currently possible due to machine precision). In addition, \( \nu \) is significantly different from that predicted from the previous timing solution. The difference between the predicted and measured \( \nu \) is too large to be explained by timing noise, indicating that a glitch probably occurred during the 280-day gap in the data.

GLITCHES

In order to analyze the two observed glitches, we measured \( \nu \) over shorter time intervals and plotted these measurements as shown in Fig. 4. We plotted measurements of \( \nu \) before and after each frequency jump to measure the size of each glitch. Fig. 4 shows pre- and post-glitch \( \nu \) measurements with the post-glitch slope subtracted. One sigma uncertainties in the pre- and post-glitch slopes are shown with hatched lines and are indicative of a change in \( \nu \) over the glitch.

We observed a frequency jump between MJD 52505 and 52571 (Fig. 4, left). We interpret this as a glitch with magnitude \( \Delta \nu / \nu = (3.4 \pm 1.1) \times 10^{-7} \) (see also [10]). The change in \( \nu \) over the glitch is not significant. No post-glitch relaxation is detected, which may be due only to the relatively sparse sampling of the data.

We observed a second frequency jump between MJD 52776 and 53063 as shown in the right panel of Fig. 4, which we interpret as a glitch of magnitude \( \Delta \nu / \nu = (3.8 \pm 0.4) \times 10^{-6} \). The frequency derivative also changes significantly with a magnitude of \( \Delta \nu'/\nu = 0.012 \pm 0.001 \). Again, no post-glitch relaxation was detected, though this is not surprising given the large uncertainty in glitch epoch.
DISCUSSION

The initial goal of timing this pulsar was to obtain a measurement of \( n \). However, the value of \( n \) varies significantly among each of the three timing solutions obtained for this source. In addition, the value of \( n \) varies significantly as timing noise is removed from residuals. This indicates that timing noise, and possibly unmodeled glitch recovery, contaminates the measurement of \( n \). Therefore, \( n \) cannot be measured from these data, so an improvement on the characteristic age of the pulsar is not available (as from Eq. (1)).

We believe that two large glitches occurred in 5 yrs of timing PSR J0205+6449. Both the magnitude and frequency of these glitches are typical of a pulsar aged \(~5-10\) kyr (e.g. Vela pulsar), rather than a \(~1\) kyr-old pulsar (e.g. Crab pulsar). This suggests that the pulsar may be older than the historical SN age of 826 yr and that its true age may be closer to its characteristic age of 5400 yr, arguing against the association between the pulsar and historical supernova.

Alternatively, if the pulsar is 826 yrs old, the observed glitches are unusually large. If glitches are related to pulsar age via neutron star temperature [12], these large glitches could be related to the very low measured temperature of PSR J0205+6449 [1], rather than its chronological age. Then we might expect this source to have glitch behaviour similar to that of older, cooler pulsars such as the Vela pulsar. However, large glitches have been observed in the hot surface temperature Anomalous X-ray Pulsars (AXPs, [13]). If the mechanism behind pulsar and magnetar glitches is similar, then neutron star surface temperature may not be the only factor in determining the size of glitches.

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