Unusual glitch behaviours of two young pulsars

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ABSTRACT
In this paper we report unusual glitches in two young pulsars, PSR J1825−0935 (B1822−09) and PSR J1835−1106. For PSR J1825−0935, a slow glitch characterised by a temporary decrease in the slowdown rate occurred between 2000 December 31 to 2001 December 6. This event resulted in a permanent increase in frequency with fractional size $\Delta \nu/\nu \approx 31.2(2) \times 10^{-9}$, however little effect remained in slowdown rate. The glitch in PSR J1835−1106 occurred abruptly in November 2001 (MJD 52220±3) with $\Delta \nu/\nu \approx 14.6(4) \times 10^{-9}$ and little or no change in the slow-down rate. A significant change in $\dot{\nu}$ apparently occurred at the glitch with $\dot{\nu}$ having opposite sign for the pre- and post-glitch data.

Key words: stars:neutron—pulsars:general

1 INTRODUCTION
A pulsar glitch is a phenomenon in which there is an abrupt increase in the rotation frequency $\nu$, often accompanied by an increase in slow-down rate. Typically the fractional increase in pulsar rotation frequency is in the range $\Delta \nu/\nu = 10^{-9} \sim 10^{-6}$, and the relative increment in slowdown rate is $\Delta \dot{\nu}/\dot{\nu} \sim 10^{-3}$, where $\nu$ and $\dot{\nu}$ are pulsar rotation frequency and frequency derivative, respectively. Larger glitches in younger pulsars are usually followed by an exponential recovery or relaxation back toward the pre-glitch frequency, while for older pulsars and small glitches the jump tends to be permanent. Glitch activity, defined as the accumulated pulse frequency change due to glitches divided by the data span, is high in young pulsars with characteristic age of $10^4 - 10^5$ yr, while it is low for very young and very old pulsars (Shemar & Lyne 1996; Wang et al. 2000).

The trigger of the pulsar glitch is not well understood. In the classic starquake model, as a consequence of long-term slow-down in spin rate, deformation stress in the rigid crust builds up to resist the decreasing oblateness (Baym et al. 1969). When the stress exceeds a critical point, the crust cracks suddenly, resulting in a sudden increase in spin rate. In the superfluid vortex unpinning and re-pinning model, triggering of the glitch is due to coupling of crust and the superfluid interior as a consequence of a sudden unpinning of vortex lines and the post-glitch relaxation is due to the vortex gradually re-pinning to the crust lattice (Anderson & Itoh 1975; Alpar, Cheng & Pines 1989). Based on the observed typical glitches, both of the models have a sudden increase in rotation frequency and slowdown rate (i.e. $\Delta \nu/\nu > 0$) at the time of the glitch. The post-glitch relaxation represents a return to equilibrium with a linear response of the interior superfluid, while the lack of relaxation represents a nonlinear response of the superfluid (Alpar, Cheng & Pines 1989; Ruderman, Zhu & Chen 1998). As more glitches were detected, it became clear that glitch behaviour varies in aspects such as glitch rate, amplitude and relaxation. In some cases discrete timing behaviours such as slow glitches were observed, i.e., the pulsar is spun-up over a time scale of days, weeks or even months (Shabanova 1998; Wang et al. 2000; Wong, Backer & Lyne 2001), accompanied by decreased slowdown rate ($\Delta \dot{\nu}/\dot{\nu} < 0$). These diverse features suggest glitches are triggered locally in the superfluid interior.

In addition to glitches, pulsars also suffer another kind of timing irregularity known as timing noise, which is characterised by restless, unpredictable, smaller scale fluctuations in spin rate (Cordes & Downs 1985) with timescales from days to years. The timing noise induced fluctuations of pulse frequency are small, with fractional changes $\delta \nu/\nu < 10^{-9}$. Younger pulsars generally show more timing irregularities (Cordes & Downs 1985; D’Amico et al. 1998).

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In this paper we report two unusual glitch events in PSR J1825−0935 (B1822−09) and PSR J1835−1106 detected by Urumqi 25 m radio telescope. PSR J1825−0935 is well known by its rare properties of interpulse, mode-changing, drifting sub-pulse and microstructure in the pulse emission (Fowler et al. 1981; Gil et al. 1994). Earlier observations have revealed unusual glitch events for PSR J1825−0935 (Shabanova 1998, Shabanova & Urama 2000), in which there was a gradual spin-up or equivalently a decreased slow-down rate over a few hundred days. In this paper we present a new but similar discrete timing event which occurred between 2000 December 31 and 2001 December 6. We interpret this as a slow glitch as suggested by Greenstein (1979) and Cordes (1979).

PSR J1835−1106 is a young pulsar (characteristic age $\sim 10^5$ yr) discovered in Parkes Southern Pulsar Survey (Manchester et al. 1996) which has no previously detected glitch. In Section 2 we introduce the observations and data analysis, Section 3 describes the glitches in detail, and in Section 4 we discuss our results.

2 OBSERVATIONS AND DATA ANALYSIS

Observations for PSR J1825−0935 and PSR J1835−1106 were made regularly at 1540 MHz as part of the Urumqi Observing timing program which commenced in 1999. Currently about 200 pulsars are monitored with an average interval between observations of about nine days (Wang et al. 2001). The data for this work consist of observations spanning $\sim 1$400 days from January 2000 to November 2003. The receiver was a dual-polarisation room-temperature system before July 2000 and was then upgraded to a cryogenic system. The dedispersion is provided by a $2 \times 128 \times 2.5$ MHz filterbank. The 1-bit digitised data were sampled at 1-ms intervals and on-line folded at the topocentric period to form sub-integrations. The offline data reduction includes dedispersing and summing the data in frequency and time to form mean pulse profiles.

The mean pulse profile from each observation was cross-correlated with a high quality template to produce pulse topocentric times of arrival (TOAs), which were then analysed using the timing program TEMPO†. The JPL ephemeris DE200 (Standish 1982) was used to correct TOAs to the Solar-System barycentre. The time-corrected data for a given pulsar were fitted with the standard spin-down model in which the predicted pulse phase $\Phi(t)$ is expressed as:

$$\Phi(t) = \Phi_0 + \nu_0(t - t_0) + \frac{1}{2} \nu_0(t - t_0)^2 + \frac{1}{6} \nu_0(t - t_0)^3,$$

(1)

where $\Phi_0$, $\nu_0$, $\nu_0$ and $\nu_0$ are the pulse phase at time $t_0$, and $\nu_0$, $\nu_0$ and $\nu_0$ are the pulsar rotation frequency, frequency derivative, and frequency second derivative at time $t_0$ respectively.

In a classic glitch, there is a sudden deviation in the observed pulse phase at the time of the glitch due to the jump in frequency and frequency derivative, plus an exponential decay in the frequency jump as a function of time. However as will be described in more detail in Section 3.1, the glitch in PSR B1825−0935 builds up gradually and we describe the glitch effect by comparing the timing solutions away from the spin-up event. For PSR J1835−1106, the analysis shows an abrupt jump in frequency but little change in frequency derivative at the glitch epoch, and no exponential decay.

Table 1 gives the pulsar names and J2000 positions in the first three columns, the remaining columns contain the pulsar dispersion measure (DM) and characteristic age. Uncertainties in the last quoted digit are given in parentheses. Given these parameters and rotation model in Equations 1 we obtained the glitch parameters which will be described in detail in next section. The positions and DMs were held fixed in the fitting process.

3 RESULTS

3.1 PSR J1825−0935 (B1822−09)

Fig. 1(a) shows the timing residuals spanning the whole data set after fitting for $\nu$ and $\dot{\nu}$. The three dashed lines, representing MJDs 51909, 52249 and 52798 respectively, divide the data into four sections. Large residuals arise when fitting data across the dashed lines and a change in $\dot{\nu}$ between the first two dashed lines is evident. The rotation parameters derived from each section are given in Table 2. Fig. 1(b) shows the timing residuals for the whole data set with respect to the timing solution for the first section. The curvature of the residuals between the first two dashed lines (MJD 51909−52249) reveals a gradual spin-up or, more accurately, a decrease in the spin-down rate for PSR J1825−0935.

This decrease in spin-down rate is clearly shown in Fig. 2, which shows the variations of rotation frequency and frequency derivative with respect to timing solution before MJD 51909. The individual values of $\nu$ and $\dot{\nu}$ in the plot are derived from short fits spanning 50−100 d. The plot confirms the gradual increase of pulsar frequency between MJD 51909−52249, and another possible similar but much smaller event near the end of the data, as indicated by the third dashed line. Following Greenstein (1979), we describe these events as slow glitches. As shown in Fig. 2(a), for the first slow glitch, there was a continuous increase in frequency for about 300 d followed by a return to the initial state for the next 500 d. Associated with the spin-up process is a decreasing slow-down rate (increasing $\dot{\nu}$) which lasted $\sim 120$ d with maximum $\Delta \nu \sim 3 \times 10^{-15} s^{-2}$. The slow-down rate then decayed to approximately the pre-glitch level within $\sim 220$ d. The fractional changes in frequency and frequency derivative before and after the slow glitch are $\Delta \nu/\nu = 31.2(2) \times 10^{-9}$ and $\Delta \dot{\nu}/\dot{\nu} = 1.9(1) \times 10^{-8}$ respectively. These values and the approximate size of the second possible slow glitch are given in Table 3.

3.2 PSR J1835−1106

Fig. 3(a) shows the pre-fit residuals spanning the whole data set with respect to the timing solution before MJD 52220. The sudden change in residual slope after MJD 52220 indicates a clear glitch at this time. The residuals after fitting for a glitch model with jumps in frequency and frequency derivative at MJD 52220 as well as the pulse frequency and its first two derivatives are shown in Fig. 3(b). Significant cubic terms with opposite signs are present in the pre- and

† see http://www.atnf.csiro.au/research/pulsar/tempo/
Table 1. The parameters of PSR J1825−0935 and PSR J1835−1106.

| PSR J       | PSR B   | RA(J2000) (h m s) | DEC(J2000) (d m s) | DM (cm⁻³ pc) | Age (10⁵ yr) |
|-------------|---------|------------------|-------------------|--------------|--------------|
| 1825−0935   | 1822−09 | 18:25:30.596(6)  | −09:35:22.8(4)    | 19.39(4)     | 2.33         |
| 1835−1106   |         | 18:35:18.287(2)  | −11:06:15.1(2)    | 132.679(3)   | 1.28         |

a Arzoumanian et al., 1994  b Hobbs et al. 2003  c D'Amico et al., 1998

Table 2. The rotation parameters for PSR J1825−0935 and PSR J1835−1106. The errors are at 2σ level.

| PSR J       | ν (s⁻¹) | ˙ν (10⁻¹²s⁻²) | ˙ν (10⁻²⁴s⁻³) | Epoch (MJD) | Fit Span (MJD) | Residual (ms) | No. of TOAs |
|-------------|---------|--------------|--------------|-------------|---------------|---------------|-------------|
| 1825−0935   | 1.30039948201(3) | −0.088487(8) | − | 51718.0 | 51549-51886 | 0.73 | 49 |
|             | 1.3003967479(2) | −0.08684(2) | −9.0(7) | 52079.0 | 51909-52249 | 1.46 | 40 |
|             | 1.3003933152(3) | −0.088657(5) | − | 52529.0 | 52287-52769 | 0.87 | 44 |
|             | 1.3003906000(2) | −0.08850(7) | − | 52884.0 | 52798-52969 | 0.93 | 14 |
| 1835−1106   | 6.02731418467(3) | −0.74902(2) | 96(4) | 51909.0 | 51600-52218 | 1.34 | 68 |
|             | 6.0272702839(4) | −0.74807(2) | −74(4) | 52595.0 | 52221-53021 | 2.12 | 70 |

Figure 1. Timing residuals for PSR J1825−0935 spanning the whole data set (a) after fitting for ν and ˙ν and (b) with respect to the model before the slow glitch. The slow glitch occurred between MJD 51909–52249 as indicated by the first two dashed lines. Another possible slow glitch with smaller amplitude occurred near the end of the data set as indicated by the third dashed line.

Figure 2. Variation of ν and ˙ν for PSR J1825−0935. (a) Frequency residuals Δν relative to the pre-glitch solution. (b) Observed variations of ˙ν.

4 DISCUSSION

Shabanova & Urana (2000) discussed four glitches in PSR J1825−0935 between 1994 September to 1999 February. However we interpret them as two slow glitches, with the first occured during MJD 49940 to 50557 (glitches 2a to 2b of Shabanova & Urana, 2000), and the second slow glitch
beginning at 51054 but still not completed at the end of their data set (glitch 4 in Shabanova & Urama, 2000). Shabanova & Urama (2000) state that each slow glitch was preceded by a small glitch (glitches 1 and 3 in their paper) with fractional size $10^{-10}$, however we did not detect such an event before the third slow glitch we report in this paper. In the first slow glitch, the continuous increase in pulsar frequency lasted for 620 d, leaving a permanent increase in frequency with amplitude 16 nHz. The second slow glitch lasted at least 120 d, with frequency increase $\geq 9$ nHz. The third event reported here lasted $\sim 340$ days and is similar to the previous two but with a much larger amplitude of 46 nHz. The possible fourth slow glitch lasted at least 170 d with frequency increase $\geq 3$ nHz. These spin-up events are separated by 1114 d, 909 d and 549 d respectively.

It appears that PSR J1825−0935 switches between normal steady slow-down and intervals of decreased slow-down rate. Timing noise in pulsars is usually attributed to fluctuations in the interior neutron superfluid and its pinning to the neutron-star crust (Alpar, Nandkumar & Pines 1986; Ruderman 1991). These two phases may represent different states of the interior superfluid or, less likely, of the magnetospheric configuration.

The glitch detected in PSR J1835−1106 has the normal abrupt increase in pulsar rotation frequency but little change in $\dot{\nu}$ at the glitch epoch, similar to small glitches detected in other pulsars. A more interesting feature is the apparent reversal of the sign of $\ddot{\nu}$ at the time of the glitch. Again, this most likely originates from a change in the properties of the interior superfluid at the time of the glitch.

5 SUMMARY

In this paper we present two unusual glitches observed recently in PSR J1825−0935 and PSR J1835−1106 at Urumqi Astronomical Observatory. These two glitches are both different to glitches in most other pulsars, demonstrating the great diversity of glitch behaviours.

The main aspects for PSR J1825−0935 glitches are as follows. They are slow glitches, with the pulsar frequency continuously increasing for several hundred days, similar to the glitch events reported by Shabanova & Urama (2000). The persistent increases in frequency result from a temporarily decreased slow-down rate lasting several hundred days, after which the slow-down rate returns to its stable value. The main event reported here results in a permanent frequency increase of 46 nHz, several times larger than the previously reported events.

For J1835−1106 there was a clear glitch of relative size $\sim 10^{-8}$ at MJD 52220, the first glitch observed in this pulsar. Unlike glitches observed in most other pulsars, there was no increase in slow-down rate at the time of the glitch. There was however a reversal in sign of $\dot{\nu}$ apparently associated with the glitch, indicating a change in the properties of the process(es) responsible for timing noise in this pulsar.

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