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An unusual glitch signature in the pulsar PSR B1822-09

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Abstract. Two glitches have been detected in the pulsar PSR B1822-09. The first glitch occurred around MJD 49615 and was characterized by a fractional increase in rotational frequency of 2×10^{-10}. The second glitch occurred 325 days after the first one and caused a fractional change in frequency of 5×10^{-9}. Of interest was the post-glitch behaviour. The rotational frequency immediately after the second glitch began slowly, gradually increasing which lasted ∼620 days. As a result of the slow increase a fractional change in rotation frequency for this period of time made up 7×10^{-9}. This event was accompanied by a decrease in the frequency derivative, which having reached minimum magnitude $\sim0.4\%$ less than the original value, returned to its initial value.

Key words: pulsars: general – pulsars: individual: PSR B1822-09 – stars: rotation

1. Introduction

Glitches are rare phenomena and they have been observed so far in only 21 pulsars from more than 700 known ones (Lyne 1996). Pulsar glitches and post-glitch relaxation of the rotation frequency is the main source of information on the structure of neutron stars. Glitches are associated with the irregular transfer of angular momentum between the rigid crust and a more rapidly rotating superfluid neutron interior (Baym et al. 1969; Alpar et al. 1993; Lyne 1996). The glitches are usually characterized by short rise times, which are less than a day, and long post-glitch relaxation times with time scales from a few days to a few years. The changes in the pulsar rotation rate vary in a wide range from $\Delta\nu/\nu = 10^{-6}$ for giant glitches to $\Delta\nu/\nu = 10^{-10}$ for small glitches. Analysis of the observed glitches has shown that the highest glitch activity has been exhibited by the pulsars with characteristic ages between 10^4 and 10^5 year (McKenna & Lyne 1990; Johnston et al. 1995). Very young and older pulsars have low glitch activity. The post-glitch relaxation have been observed rather in the younger pulsars and may be described by two exponential components for most pulsars (Shemar & Lyne 1996).

This paper presents the timing observations for the pulsar PSR B1822-09, which suffered two glitches, the second of which had an unusual signature, and was not observed earlier in any pulsar. The second discrete glitch was immediately followed by a continuous spin-up of the pulsar which lasted ∼620 days. Notice that this slow glitch was accompanied by the decrease in the frequency derivative, which having reached minimum magnitude $\sim0.4\%$ less than the original value, then relaxed back toward to its former value.

The pulsar PSR B1822-09 was discovered in Jodrell Bank search in 1972 (Davies et al. 1972). It has a period of 0.769 s, rather a large spindown rate 52.3×10^{-15} s/s and a characteristic age of $P/2\dot{P}\sim2.5\times10^5$ years.

2. Observations and data analysis

Timing observations of the pulsar PSR B1822-09 present part of the continuing program of pulsar timing measurements at Pushchino Observatory using the radiotelescope BSA, which is the linearly polarized transit antenna array, operating at 102.5 MHz (3 MHz of band). The dimensions of dipole array are $200\times400\,m$ that yield 30000 m^2 of BSA effective area and (3.5/$\cos(\delta)$) min of transit time for observation. Observations of PSR B1822-09 were started in 1991 March and have been performed regularly, 2 or 3 times per month, using 32 channel bank of 20 kHz filter receiver. The receiver time constant was 3 ms, and the signal was sampled at 2.5 ms intervals. The pulse profile in each channel was derived with synchronous accumulation with the apparent pulsar's period of 285 individual pulses, corresponding to 3.7 minutes of transit time at the declination of PSR B1822-09. Then the signals from all channels were summed to obtain the dedispersed mean pulse profile for a single observation.

The topocentric arrival pulse times were derived by cross-correlating the mean pulse profile with a standard, low-noise template. Template was formed by averaging 16 mean profiles with a high signal-to-noise ratio. The PSR B1822-09 was relatively weak at 102.5 MHz, having signal-to-noise ratio between 20 to 5, which determined measured pulse arrival time uncertainties from 0.7 to 3 ms. The full data set for this pulsar included about 200 pulse times. These topocentric arrival times

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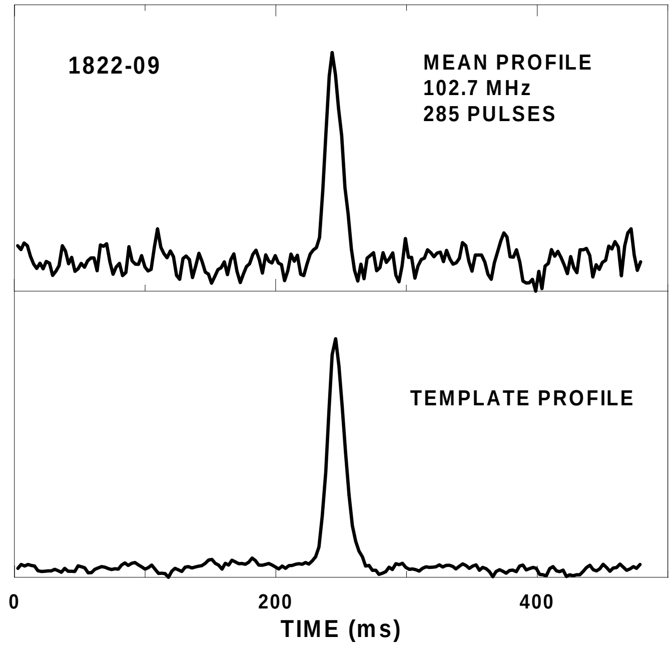

Fig. 1. The mean pulse profile for a single observation and the template profile for PSR B1822-09

were corrected to the barycenter of the Solar System using the JPL ephemeris DE200.

Arrival times were referred to the National time service of Russia using PRAO local frequency and time service, which was accurate to better than 100 ns and provided the precision pulsar timing measurements in Pushchino Observatory (Shabanova 1995; Shitov & Pugachev 1997).

Example of the mean pulse profile for PSR B1822-09 and its template are plotted in Fig. 1. The pulse profile shows one component at 102.5 MHz and its shape is similar to the 400 MHz profile (Fig. 2 of Arzoumanian et al. 1994). Apparently, the mode-changing component of the profile is not seen at low frequencies. Interpulse is not visible in the mean profile for a single observation, being extremely weak at 102.5 MHz.

The data were analyzed using a standard timing technique (Manchester & Taylor 1977). The parameters characterizing a secular spin-down of the pulsar PSR B1822-09 were obtained from a least-squares fit of a second-order polynomial. The pulse phase φ of the pulsar at the time t was calculated as

$$\varphi(t) = \varphi_o + \nu(t - t_o) + \frac{1}{2}\dot{\nu}(t - t_o)^2 \,, \quad (1)$$

where φ_o is the phase at some reference time t_o, and $\nu, \dot{\nu}$ are the rotation frequency and its first derivative at a given epoch t_o. Timing residuals were obtained as the difference between the calculated phase and the nearest integer $R = \varphi - N$ and were used to compute differential corrections to the initial parameter values. Final timing residuals were derived using improved parameters of frequency and the frequency derivative. The position and the proper motion of the PSR B1822-09 were from Arzoumanian et al. (1994) and Fomalont et al. (1992) respectively. The position was not improved from our timing data. Derived coordinates were in good agreement with those published by Arzoumanian et al. (1994).

3. Results and discussion

Fig. 2a shows the phase residuals, obtained after subtraction of a second-order polynomial from timing data, collected over a 6.8-year period between 1991 March and 1997 December. The plotted points represent residuals from a least-squares fit of frequency and the frequency derivative on the pre-glitch arrival time data for 1991 March to 1994 September. Since 1994 September the curve goes sharply downwards and for the subsequent 3 years reaches its greatest negative value of about 820 ms, which is more than one period of the pulsar.

The effects of the glitches are more clearly seen in Fig. 2b, which shows in the greater scale the residuals, punctured on the top plot. The pulsar suffered two small glitches and they determined two changes in the slope of the residuals observed. The precise time of each glitch was estimated as a crossing point of two straight lines, fitted to the intervals of about 100 days of the pre-glitch and post-glitch phase residuals. The events occurred on 1994 September 20 (MJD 49615) and on 1995 August 11 (MJD 49940). These dates are marked in figures by arrows. The first glitch was characterized by a fractional increase in rotational frequency of $\Delta\nu/\nu = 2{\times}10^{-10}$. The second glitch occurred 325 days after the first one and caused a fractional increase of frequency an order of magnitude larger with $\Delta\nu/\nu = 5.2{\times}10^{-9}$.

The main distinguishing feature of these glitches is that the sudden increase in frequency occurred with a decrease in the frequency derivative. After the first glitch a fractional change in the frequency derivative has a negative value of $\Delta\dot{\nu}/\dot{\nu} = -0.6{\times}10^{-3}$. Although this value has rather a large uncertainty which is 33%, nevertheless it indicates a tendency to a decrease in the derivative (Fig. 3c). The second glitch occurred with a fractional decrease in the frequency derivative of $\Delta\dot{\nu}/\dot{\nu} = -2.39{\times}10^{-3}$. The frequency derivative $\dot{\nu}$, obtained from each post-glitch data, is smaller than the pre-glitch value: the pulsar after the glitch began slowing more slowly than before the glitch.

The pre-glitch parameters were obtained from timing data before the first glitch (fit interval 48333–49614) and had the values: period $P = 0.768979181777(19)\ s$ and the period derivative $\dot{P} = 52.3558(4){\times}10^{-15}\ s/s$ at epoch MJD 48333.1738 (respectively $\nu = 1.30042532190(3)\ s^{-1}$ and $\dot{\nu} = -88.5392(6){\times}10^{-15}\ s^{-2}$). The rms timing residuals after the fit was 0.8 ms. There is a discrepancy between the present results and those of Arzoumanian et al. (1994), where they quote a period derivative of $\dot{P} = 52.3636(7){\times}10^{-15}\ s/s$. The NRAO data span (from 1989 August to 1993 April) partly overlap with the Pushchino data span (beginning since 1991 March) and the discrepancy between the results may possibly indicate to the existence of short-term variations in the period derivative. It should be noted that the pulsar PSR B1822-09 is among the 'noisyest' pulsars. Arzoumanian et al. (1994) determined for this pulsar the value of the stability parameter of $\Delta_8 = -1.2$.

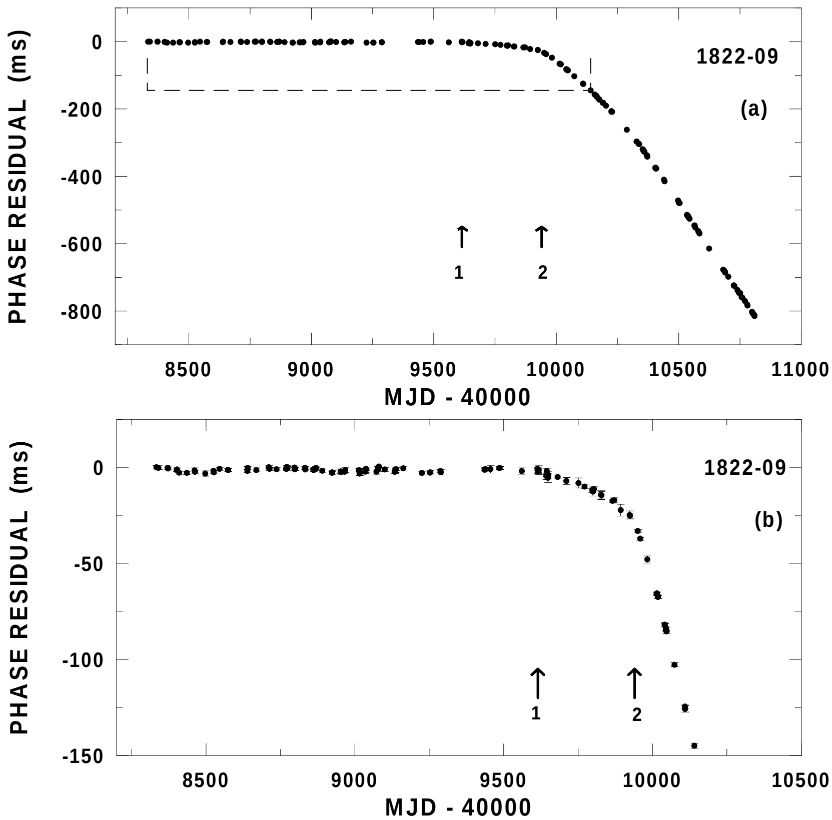

Fig. 2a and b. The phase residuals of PSR B1822-09 obtained after a second-order polynomial fit for the pre-glitch parameters $\nu, \dot{\nu}$: **a** For all timing data collected from the full interval of observation from 1991 March to 1997 December, **b** For the part timing data collected from 1991 March to 1996 February and punctured on the top plot. The dates of two glitches are marked in figures by arrows.

This value indicates a high level of timing noise. The post-fit rms residuals for the deterministic timing solution containing only one timing derivative is 1.75 ms and 0.86 ms for a large number of frequency derivatives fitted to the data (Table 1 of Arzoumanian et al. 1994). These values indicate that timing noise significantly larger than the measurement uncertainties. The presence of timing noise limits the accuracy of measured position and implies that the observed spin-down parameters are nonstationary. The second derivative of the frequency measured in Arzoumanian et al. (1994) indicates that the value of the first derivative is function of time. This point of view provides a very good explanation for a discrepancy between the NRAO and the Pushchino results. Phase residuals of the PSR B1822-09 over about a 10 year period are plotted in Fig. 3a of Lyne (1996), which also shows that this pulsar has much timing noise.

The fitted pre-glitch parameters of rotation frequency and the frequency derivative, glitch parameters and the post-glitch mean parameters together with the epoch of each glitch, fit interval and rms arrival time residuals are given in Table 1. Quoted errors are twice the formal standard errors of the least-squares fit and given in units of the last quoted digit. The pre-glitch values of ν_o given in Table 1 were calculated at the indicated epoch for the first glitch and for the two components of the second glitch by using the same pre-glitch values of $\nu, \dot{\nu}$ at epoch MJD 48333.1738. Notice, that the offset at the time of the second glitch, left by the first glitch, is small enough to be neglected.

For a more detailed analysis of the variation of the spin-down parameters $\nu, \dot{\nu}$ with time, all the timing data were divided into non-overlapping intervals of about 120 days and local fits were performed in each interval (Demianski & Proszynski 1983; Shemar & Lyne 1996). Fig. 3 shows the variations of values $\nu, \Delta\nu, \dot{\nu}$ with time, all of which are referred to the first point of each interval. Fig. 3a illustrates a secular slow-down of the pulsar over 6.8 years of observations. The observed glitches are too small to be seen on the scale of this diagram. A plot of the frequency variations $\Delta\nu$, remaining after subtracting the pre-glitch values of frequency and the frequency derivative, is given in Fig. 3b. This diagram shows two discrete small frequency glitches (marked by the arrows 1 and 2a), which are responsible for two changes in the slope of the residuals observed around MJD 49615 and MJD 49940. Fig. 3c shows variations of the frequency first derivative versus time. The straight line is the pre-glitch frequency derivative $\dot{\nu} = -88.5392 \times 10^{-15}\, s^{-2}$.

The lower two diagrams show that behaviour of rotation rate and the frequency derivative is unusual during the second glitch. Rotational frequency immediately after the second discrete change (arrow 2a) began continuously increasing which lasted $\sim$620 days, from 1995 August to 1997 April. As a result of the slow increase a fractional change in the rotation frequency for this period made up $\Delta\nu/\nu = 7 \times 10^{-9}$. In 1997 April the increase in rotational frequency ceased. The epoch when rotational frequency after the second discrete glitch reaches the maximum amplitude is marked in Fig. 3b with the arrow 2b and corresponds to MJD 50557 (1997 April 19). The resulting amplitude of the full second glitch is rather large with

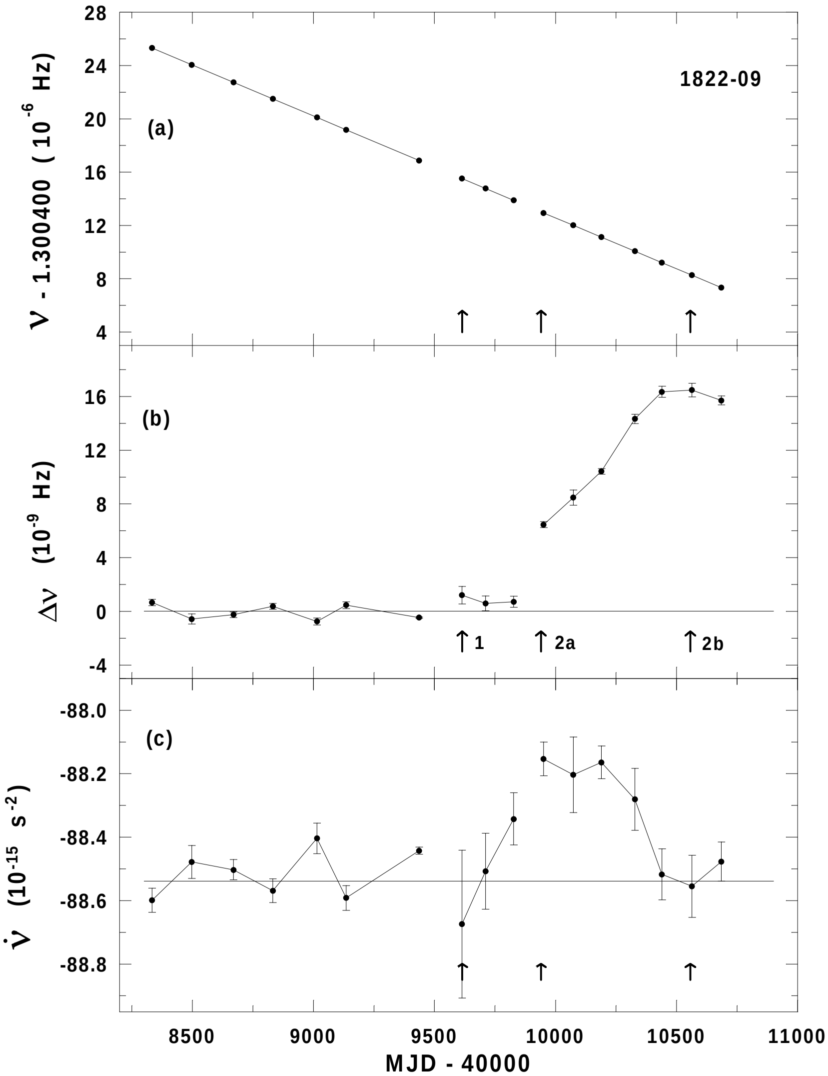

Fig. 3a–c. The variations of the spin-down parameters $\nu, \dot{\nu}$ of the pulsar PSR B1822-09 over 6.8 years of observations: **a** The rotation frequency, ν, of the pulsar versus time, **b** The frequency residuals, $\Delta\nu$, remaining after subtracting the pre-glitch values of frequency and the frequency derivative, **c** The frequency derivative $\dot{\nu}$ versus time. The straight line is the pre-glitch value of $\dot{\nu} = -88.5392 \times 10^{-15}\ s^{-2}$

Table 1. Glitch parameters for the pulsar PSR B1822-09

	Glitch Epoch (MJD)	Pre-glitch Parameters ν_o (s^{-1})	$\dot{\nu}_o$ $(10^{-15}\ s^{-2})$	Glitch Parameters $\Delta\nu/\nu_o$ (10^{-9})	$\Delta\dot{\nu}/\dot{\nu}_o$ (10^{-3})	Post-glitch Parameters ν_p (s^{-1})	$\dot{\nu}_p$ $(10^{-15} s^{-2})$	Fit Interval (MJD)	rms (ms)
1	49615(8)	1.30041551627(3)	-88.5392(6)	0.2(1)	-0.6(2)	1.30041551656(18)	-88.486(15)	49615–49925	0.6
2a	49940(2)	1.30041303013(3)	-88.5392(6)	5.21(7)	-2.39(4)	1.30041303690(9)	-88.3275(36)	49951–50544	0.8
2b	50557(6)	1.30040831031(3)	-88.5392(6)	12.6(2)	0.2(2)	1.30040832671(25)	-88.562(24)	50564–50810	0.6

$\Delta\nu/\nu = 12.6 \times 10^{-9}$. Parameters for the second glitch at epoch MJD 50557 are given in the third row of Table 1.

The observed gradual change in rotational frequency reflects the change in the frequency derivative, which is distinctly seen in Fig. 3c. Else before the second glitch the magnitude of $\dot{\nu}$ began slowly decreasing to the new value of $\dot{\nu} = -88.15 \times 10^{-15}\ s^{-2}$ and fixed on it for about 240 days. Over such time span the frequency derivative was $\sim 0.4\%$ less than the initial value. Then the frequency derivative slowly came back to the initial value during ∼250 days. Note the time interval of the gradual decrease of the pulsar slow-down rate corresponds to the time interval of its relaxation back to the initial derivative. As can be seen from Figs. 3b and 3c, the increase in the rotational frequency ceased, when the frequency derivative came back to the original value. The last point in Fig. 3b lies below the maximum change in the frequency and, possibly, it represents the end of the post-glitch relaxation. It will be seen from further observations.

The observed glitches in the pulsar PSR B1822-09 and the classical glitch of the same magnitude are schematically given in Fig. 4. The classical glitch is characterized by short time rise and associated with a sudden increase in the rotation frequency of neutron star crust, usually followed by an exponential re-

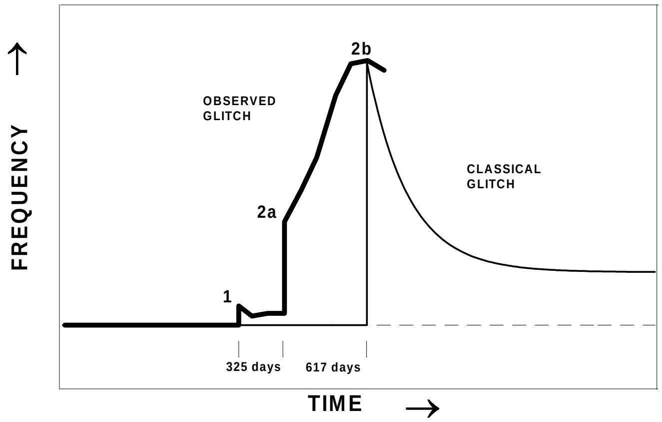

Fig. 4. The signature of the observed glitches and that of a classical glitch with the same amplitude are shown schematically. Secular slowdown effect was removed otherwise the glithes would be invisible if they were plotted in scale. As can be seen, the observed second glitch is not an instantaneous event and its time rise is about 620 days. Seen, that this glitch consists of two parts: the discrete change (2a) in frequency and the gradual change in frequency. The amplitude of the glitch maximum (2b) is $\Delta\nu/\nu = 12.6{\times}10^{-9}$.

laxation to their pre-glitch frequency. The exponent behavior following the glitch can be explained by the presence of a fluid component in the interior of the neutron star (Baym et al. 1969; Alpar et al. 1993). As can be seen, the second glitch observed is not an instantaneous event (compared to the observational resolution) and consists of two parts: the discrete increase in the rotational frequency (2a) with $\Delta\nu/\nu = 5.2{\times}10^{-9}$ and a gradual increase in the frequency with $\Delta\nu/\nu = 7.4{\times}10^{-9}$. The size of the resulting amplitude (2b) is $\Delta\nu/\nu = 12.6{\times}10^{-9}$. More than one half of the final change in the rotational frequency are provided by gradual increase in the frequency during $\sim$620 days. Such long time scale behavior differ significantly from all other glitches observed so far.

It should be noted that the observed glitches in PSR B1822-09 can actually be a result of one glitch event, similar to the glitch observed in the Crab pulsar in 1989 (Lyne et al. 1992). This glitch was characterized by a rapid increase and decrease of the rotation frequency over a timescale of 2-3 weeks and followed by a very slow increase in frequency with a timescale of $\sim$300 days. Suppose, that observations of the first rapid event in the pulsar PSR B1822-09 were missed due to low resolution (Pushchino observations were conducted at time intervals of about 1 month). Then the slow increase in rotation frequency associated with the second glitch in PSR B1822-09 could simply be a delayed increase in frequency associated with the first glitch.

It is now thought that the reason of glitches may be a starquake or catastrophic superfluid vortex unpinning (Baym et al. 1969; Alpar et al. 1993; Lyne 1996). A starquake model cannot account for a gradual glitch behavior, because a glitch in this model is an instantaneous event. In principle, accumulation of several smaller frequency increases with a certain frequency derivative set could account for a slow increase in frequency. However, it seems more probably, that a gradual glitch behavior is associated with changes observed in the frequency derivative. The existence of the slow glitch, as a response of a neutron star to a perturbation in its temperature, have been predicted by a model in which a glitch was associated with a thermal instability in a neutron star (Greenstein 1979).

The reason of the change in the frequency derivative may be attributed to some change in the magnetospheric structure and perhaps in the electromagnetic torque. The observed decrease of slowdown rate requires decreased tor- que on the pulsar. Possible changes in the magnetosheric structure (in case of thermal instability) could cause the changes in the shape of the mean pulse profile. Comparison of the mean profiles obtained during the full period of timing observations shows no significant change in either the mean pulse intensity or the mean pulse shape.

There were some other reports on glitches which did not exhibit the characteristic signature of classical glitch. For example, a glitch with a gradual rise for 40 days was observed early in PSR B1907+00 (Gullahorn et al. 1976). For the case of PSR B1508+55, the frequency derivative relaxed to a new value $\sim 0.5\%$ less than the original value (Manchester & Taylor 1974). A gradual increase frequency for $\sim$60 days was observed in the first glitch in PSR B0355+54 (Shabanova 1990). An unusual signature of the glitch, which was detected in the pulsar PSR B1822-09, provides a valuable tool for investigating the problems of the neutron star structure.

4. Summary

The main observational results of this paper are as follows.

1. Two glitches have been detected in the pulsar PSR B1822-09.
2. The first glitch was small, with $\Delta\nu/\nu = 2{\times}10^{-10}$. It showed usual behavior and was associated with a sudden increase in rotation rate.
3. The second glitch was rather large, with the resulting amplitude of $\Delta\nu/\nu = 12.6{\times}10^{-9}$. It shows complex behavior and consists of two parts: a discrete increase in rotational frequency with $\Delta\nu/\nu = 5.2{\times}10^{-9}$ and continuous increase in frequency which lasted $\sim$620 days. As a result of the gradual increase a fractional change in rotational frequency for this time period made up $\Delta\nu/\nu = 7.4{\times}10^{-9}$, more than one half of the full amplitude of the glitch.
4. A gradual increase in rotation rate results from a decrease in the frequency derivative, which having reached the minimum magnitude $\sim 0.4\%$ less than the original value, returned to its initial value.

Finally, note that the PSR B1822-09 is a very interesting object. It is the only pulsar known which possesses simultaneously such rare properties of the pulsar emission as mode-changing behaviour, interpulse emission, drifting subpulses and microstructure (Fowler et al. 1981; Gil et al. 1994). Detection of two glitches in rotation rate of star, the second of which has an unusual signature, confirms such characteristic of the pulsar.

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