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Glitch behavior of the pulsar B1822-09 in the range 0.1 – 2.3 GHz

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Abstract. An analysis of four glitches observed in the pulsar B1822-09 during the period 1994 - 1999 is presented. The main distinguishing feature of these glitches is that the sudden increase in rotational frequency is accompanied by a decrease in the frequency derivative. The largest change of the frequency derivative was measured in the fourth glitch. This glitch occurred around MJD 51054 and was characterized by rather a small increase in rotational frequency of $\Delta\nu/\nu = 7\times10^{-9}$, but a large decrease in the frequency derivative by $\sim 2.4\%$.

The first two glitches were observed practically simultaneously at two frequencies of 0.1 GHz in Pushchino, Russia and 1.6/2.3 GHz at HartRAO, South Africa. An analysis of the high- and low frequency timing data showed that glitches did not affect the pulse arrival times at different frequencies within 2 ms. Glitch signature was identical in the wide frequency range from 0.1 to 2.3 GHz.

In addition, a more exact value of the dispersion measure was measured to be 19.383(3) $\mathrm{pc\,cm^{-3}}$.

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

1. Introduction

In 1994 and 1995 the pulsar B1822-09 underwent two glitches in its spin-down behavior and they had an unusual signature. These glitches were accompanied by a decrease in the magnitude of the frequency derivative, $\dot{\nu}$. Moreover, the frequency derivative after some relaxation time came back to its pre-glitch value. As a consequense, the observed post-glitch relaxation presented a continuous spin-up of the pulsar which lasted ~ 620 days (Shabanova 1998).

In this paper we continue to investigate the glitch behavior of the pulsar B1822-09. Two new glitches were detected on 1998 April 28 and 1998 August 30. Their signature was similar to that of the previous glitches - an increase in rotational frequency was accompanied by a decrease in the magnitude of the frequency derivative.

PSR B1822-09 is the first glitching pulsar to be observed practically simultaneously at widely separated frequencies of 0.1 and 2.3 GHz during seven years since 1991 March to 1998 May. It is shown that glitches did not affect the pulse arrival times at different observing frequencies within 2 ms. Glitch signature was identical in the wide frequency range from 0.1 to 2.3 GHz.

2. Observations and data analysis

Timing observations of PSR B1822-09 at the 26-m HartRAO radiotelescope have been carried out since 1985 October at frequencies around 1644 and 2325 MHz at roughly two week intervals, using the system described by Flanagan (1993). The observing bandwidth was 10 MHz. Each observation usually consisted of three integrations. Pulse arrival times were obtained from 15 min on-line integrations of the pulsed signal sampled at 0.15 ms intervals, using a filter time-constant of 300 microsecs. Time was provided by a hydrogen maser, and referenced to UTC via the global positioning system (GPS) network. The pulse was approximated by a Gaussian and referred to as a Gaussian profile template. Such Gaussian templates have a timing reference point, which was chosen to be the centre of the main component. A total of about 830 pulse arrival times were measured for a 13-yr interval between 1985 October and 1999 February.

The observations of PSR B1822-09 at Pushchino Radio Astronomy Observatory were started in 1991 March using the BSA radiotelescope, making up a linearly polarized transit antenna, which operated at 102.5 MHz until 1998 May and at 111.3 MHz since 1998 November after the BSA reconstruction. Observations were performed 2 or 3 times per month, using 32 channel bank of 20 kHz filter receiver. The technique of observation was described in detail in the early paper (Shabanova 1998). The topocentric arrival pulse times were derived by cross-correlating the mean pulse profile from a single observation with a standard, low-noise template. Timing reference point of the template was taken to be the centre of the mean profile.

Fig. 1 presents examples of the mean pulse profiles for PSR B1822-09 for a single observation at three frequencies of 0.1, 1.6 and 2.3 GHz. The pulse profile shapes are similar to the profiles presented in Arzoumanian et al. (1994) and in Kuzmin et al. (1998). The low signal-to-noise ratio of this source allows us to measure the pulse arrival times with uncertainties between 0.3 and 3 ms, which were approximately the same at the three observing frequencies.

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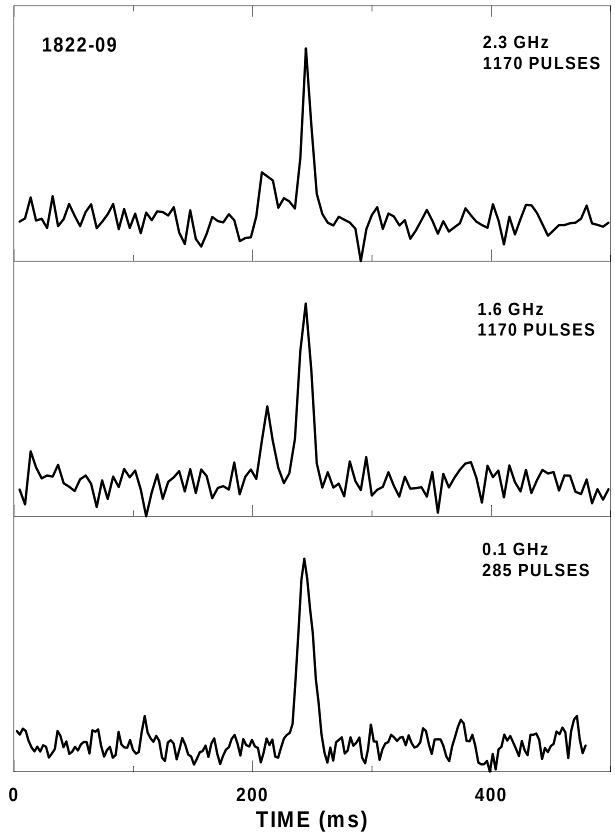

Fig. 1. The mean pulse profile for PSR B1822-09 for a single observation at three observing frequencies of 0.1, 1.6 and 2.3 GHz

The two data sets were analyzed using a standard timing technique (Manchester & Taylor 1977). The topocentric arrival times of the HartRAO and the PRAO data sets were corrected to the barycenter of the Solar System at infinite frequency. Then the two barycentric data sets were combined and a second-order polynomial fit was performed to obtain residuals from a timing model. The JPL ephemeris DE200 was used for the barycentric corrections. Our data analysis procedure is similar to that used in the previous paper (Shabanova 1998). The position of PSR B1822-09 was obtained from Arzoumanian et al. (1994) and the proper motion was taken from Fomalont et al. (1992).

3. Results and discussion

Fig. 2a displays the phase residuals of PSR B1822-09 after removing the second-order polynomial for the 13-yr interval of the HartRAO observations, using the initial values of rotational frequency and the frequency derivative from the interval 1991 - 1994. It is seen, that the pulsar exhibits large phase residuals, the greatest value of which reaches more than one second. Observed residuals should be associated with irregularities such as timing noise and glitches. In the right part of this plot one can see the effects of the glitches observed whose epochs are marked by the arrows. The part of the curve corresponding to simultaneous observations at the HartRAO and the PRAO observatories over a 7-yr interval (1991 March - 1998 May), is marked by

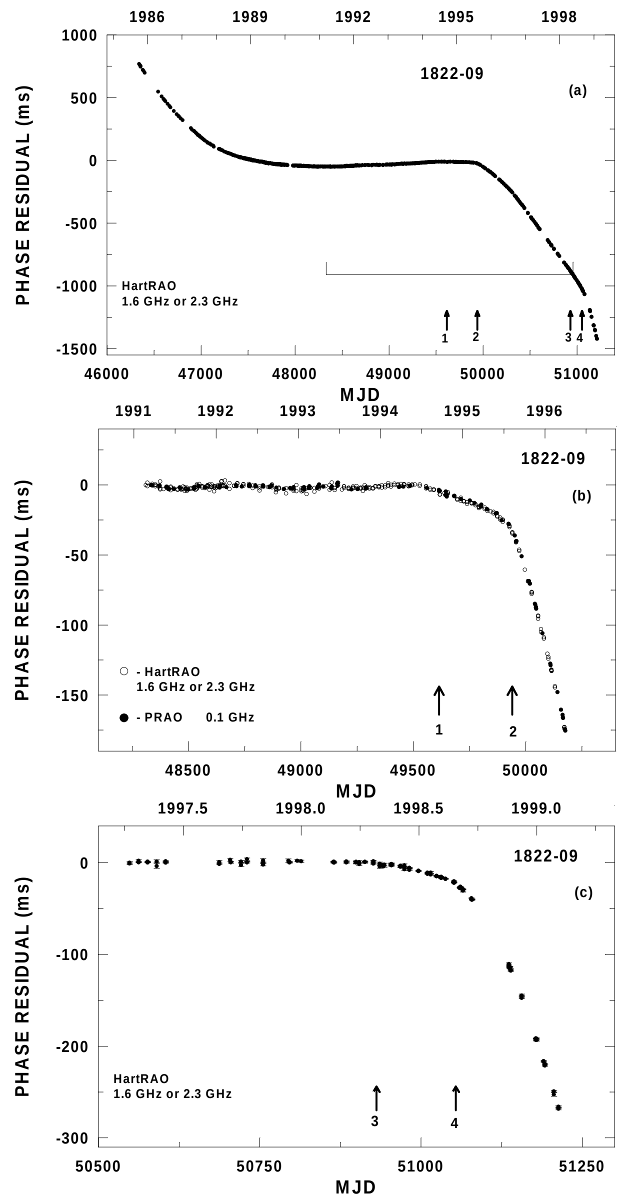

Fig. 2a – c. The phase residuals of PSR B1822-09 obtained after a second-order polynomial fit for the pre-glitch parameters $\nu, \dot{\nu}$: **a** For the HartRAO timing data over a 13-yr time span between 1985 October and 1999 February. The part of the curve corresponding to simultaneous observations at the HartRAO and the PRAO observatories over a 7-yr interval from 1991 March to 1998 May, is marked by a solid line, **b** For simultaneous observations at two observing frequencies of 0.1 GHz (PRAO) and 1.6/2.3 GHz (HartRAO) between 1991 February and 1996 April, where the first and second glitches occurred, **c** For the HartRAO timing data from 1997 April to 1999 February, where the third and fourth glitches occurred. The glitch epochs are marked by arrows

the solid line. Four glitches have been detected in PSR B1822-09 for the latest 4 years. The first two glitches were described earlier by Shabanova (1998) and the third and the fourth ones are presented in this paper. The effects of these glitches in the greater scale are shown in Figs. 2b and 2c.

Table 1. Glitch parameters for the pulsar 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
3	50931(3)	1.30040546510(10)	-88.562(6)	0.7(3)	-3.64(5)	1.30040546600(35)	-88.24(6)	50936–51051	0.5
4	51054(6)	1.30040452394(10)	-88.562(6)	7.1(6)	-23.6(1)	1.30040453314(65)	-86.47(7)	51060–51213	0.6

Simultaneous observations of the pulsar at two widely separated frequencies of 0.1 and 1.6/2.3 GHz permitted to determine the dispersion measure with improved accuracy. The pulse arrival times of PSR B1822-09 were referred to an infinite frequency by removing the interstellar plasma dispersion delay corresponding to the plasma dispersion measure of 19.46 $\mathrm{pc\,cm^{-3}}$ (Arzoumanian et al. 1994). This value of the DM gives an approximately 30-ms delay between the HartRAO and the PRAO data sets – the pulses at 102.7 MHz arrive earlier relative to the pulses at high frequencies. This indicates, that the DM=19.46 $\mathrm{pc\,cm^{-3}}$ is large. The 30.3-ms delay gives the DM correction of 0.077 $\mathrm{pc\,cm^{-3}}$ and a new value of the DM is 19.383(3) $\mathrm{pc\,cm^{-3}}$. A measurement of the dispersion measure done at the Pushchino observatory at low frequencies between 102.5 and 60 MHz gives the value of the DM=19.391(6) $\mathrm{pc\,cm^{-3}}$ (Shitov 1998), which agrees well with our result.

Fig. 2b displays the phase residuals of PSR B1822-09 remaining after removal of the second order polynomial fit from the combined HartRAO and PRAO timing data using the new value of the DM. Here is plotted only the initial part of the full 7-yr residual curve - the interval between 1991 February and 1996 April, where the character of the pre-glitch residuals and the signature of the first and the second glitches are well visible. As seen in this plot, the glitch signature is identical with respect to the frequency. A detailed analysis of the mean time difference between the high- and low frequency phase residual curves shows that glitches do not affect the pulse arrival times at different frequencies within 2 ms. The PSR B1822-09 timing data are too noisy and do not allow to determine the time offset with an accuracy higher than 2 ms. As mentioned by McCulloch et al. (1990), in the case of the Vela glitch 1988 an offset of $\sim$0.1 ms appears between the 635 and 950 MHz data at the time of the glitch.

The effects of the third and the fourth glitches are seen in Fig. 2c, which shows the post-fit residuals only for the HartRAO timing data obtained between 1997 April and 1999 February. The 0.1 GHz data of the PRAO are absent because of the reconstruction of BSA antenna at a new frequency of 111.3 MHz. The phase residuals were obtained from another polynomial fit for the parameters ν and $\dot{\nu}$, derived before the third glitch. The events occurred on 1998 April 28 (MJD 50931) and 1998 August 30 (MJD 51054) and these dates are marked in the figure by arrows 3 and 4.

Table 1 lists the pre-glitch and post-glitch parameters of rotational frequency and the frequency derivative, together with their estimated changes during the glitch. The pre-glitch values of ν_o were extrapolated to the indicated epochs of the glitches 3 and 4 from the epoch MJD 50548.7774 by using the same values of ν and $\dot{\nu}$, which were obtained from the timing data before the third glitch (fit interval 50548–50926): $\nu = 1.30040839359(10)\ s^{-1}$ and $\dot{\nu} = -88.5617(64)\times10^{-15}\ s^{-2}$. These parameters were used to produce Fig. 2c. Quoted errors are twice the formal standard errors and given in units of the last quoted digit. Parameters of the previous two glitches are also included in Table 1 for convenience.

As seen in Figs. 2b and 2c, pulsar glitch behavior is similar in the two figures. In both cases the small glitches of size up to $\Delta\nu/\nu = 2\times10^{-10}$ and 7×10^{-10} (arrows 1 and 3) precede the glitches whose size is larger by an order of magnitude: $\Delta\nu/\nu = 5\times10^{-9}$ and 7×10^{-9} (arrows 2 and 4). It is possible that such a sequence of glitches is not casual and for PSR B1822-09 the glitches occur as pair events. Though the observed glitches are small, they are of great interest because they are accompanied by a negative change in the frequency derivative, i.e. the pulsar after the glitch begins slowing down more slowly than before the glitch. The largest change takes place for the fourth glitch at which a slowdown rate $\Delta\dot{\nu}/\dot{\nu}$ decreased by 2.4$\%$ (Table 1).

A negative change in the frequency derivative causes an unusual post-glitch relaxation of rotational frequency. Fig. 3 shows the variation of the spin-down parameters $\nu, \dot{\nu}$ with time obtained by performing local fits to the timing data over intervals of about 200 days. The upper diagram illustrates a secular slow-down of the pulsar over 13-yr HartRAO 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 (fit interval 1991-1994) values of frequency and the frequency derivative, is given in Fig. 3b. In the right part of this figure the increase of $\Delta\nu$ with time is associated with the observed glitches. Fig. 3c shows variations of the frequency first derivative versus time. As can be seen, a systematic decrease of the frequency first derivative is observed and a magnitude of $\dot{\nu}$ decreases by 0.3% during the period from 1985 to 1994. The systematic decrease of $\dot{\nu}$ indicates the presence of the $\ddot{\nu}$. This plot gives an evident explanation of a discrepancy between the measured values of the period derivative in Arzoumanian et al. (1994) and in Shabanova (1998). The value of the period derivative depends on the epoch of the measurement.

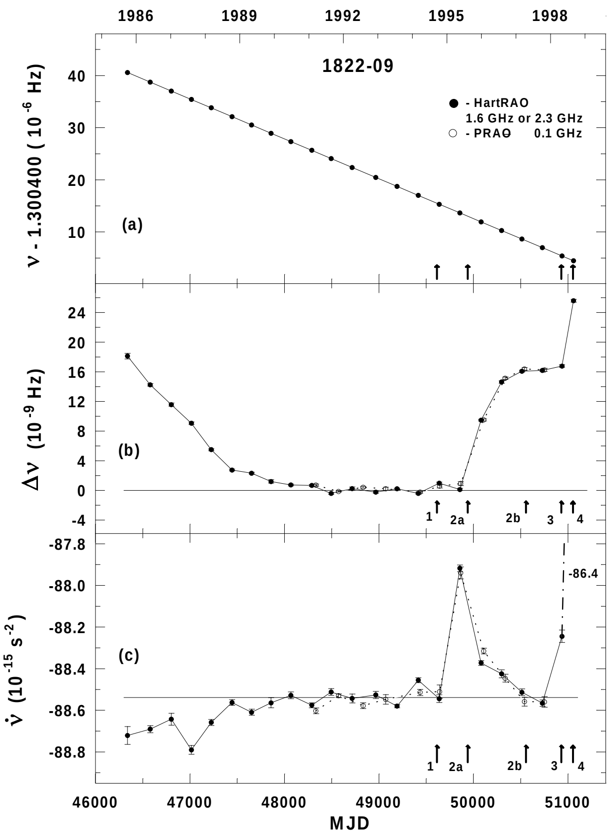

Fig. 3a – c. The variations of the spin-down parameters $\nu, \dot{\nu}$ of the pulsar B1822-09 over a 13-yr time span: **a** The rotation frequency, ν, of the pulsar versus time, **b** The frequency residuals, $\Delta\nu$, remaining after subtracting the initial values of frequency and the frequency derivative derived from the interval 1991 – 1994, **c** The frequency derivative $\dot{\nu}$ versus time. The straight line is the pre-glitch value of $\dot{\nu} = -88.5392 \times 10^{-15}\, s^{-2}$. The value of the last point -86.4 is not shown in this plot, unless the scale be strongly reduced. The glitch epochs are marked by arrows

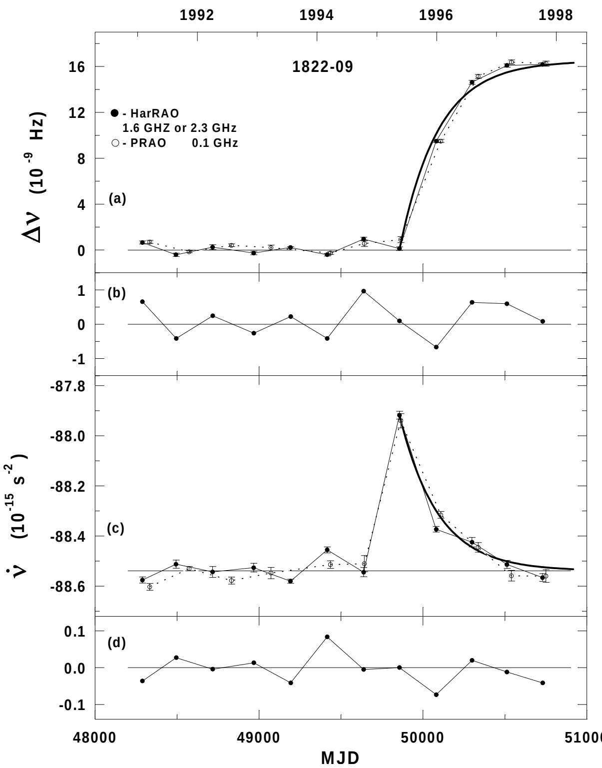

Fig. 4a – d. The behavior of the frequency residuals and the frequency derivative of PSR B1822-09 from the 7-yr simultaneous observations at 0.1 and 1.6/2.3 GHz between 1991 March and 1998 May. The exponentials with 235-day time constant fitted on the glitch data are marked by solid line: **a** Observed frequency residuals, **b** The frequency residuals after subtracting the 235-day asymptotic exponential, **c** Observed values of the frequency derivative, **d** The variations of the frequency derivative after removing the 235-day exponential decay

The large frequency residuals, seen in the left part of Fig. 3b, are also the result of the presence of the $\ddot{\nu}$.

On the background of systematic decrease of $\dot{\nu}$ one can see the changes caused by the glitches. The magnitude of $\dot{\nu}$ decreases by $\sim 0.7\%$ at the time of the second glitch (arrow 2a). While the frequency derivative increases back to its initial value, a slow increase in the frequency rate during 620 days is observed (between arrows 2a and 2b). The gradual change in $\Delta\nu$ reflects the change in the $\dot{\nu}$. The glitch data are well fitted by an exponentials with the 235-day time constant as shown in Fig. 4. The rotation rate residuals after the glitch are fitted by an asymptotic exponential with the 235-day time constant (Fig. 4a), and the frequency derivative is fitted by exponential decay with the same 235-day constant (Fig. 4c). Delayed increases in rotation rate on a timescale of 265 days were previously observed in the 1989 glitch of the Crab pulsar (Lyne et al. 1992). It is possible that we observed a similar glitch event in PSR B1822-09. Because of a large time interval between our observations (two-three weeks) the rapid phase of the glitch could be missed and the slow increase in rotational frequency associated with the second glitch in PSR B1822-09 could be a delayed increase in frequency associated with the first glitch.

As seen in Figs. 4a and 4c, both the frequency residuals, $\Delta\nu$, and the frequency derivative, $\dot{\nu}$, have identical behavior at two observing frequencies and hence in the wide frequency range from 0.1 to 2.3 GHz during a 7-yr interval of simultaneous observations.

In addition to the glitches, the pulsar B1822-09 exhibits a high level of timing noise and is among the 'noisiest' pulsars (Arzoumanian et al. 1994; Lyne 1996). Phase residuals of this pulsar suggest the existence of a large frequency second derivative. As seen in the left part of Fig. 2a, timing noise contributes roughly one second to the pulse arrival times. Fig. 5 displays the phase residuals after removing the second-order polynomial for a 9-yr HartRAO data span before glitches occurred. This plot shows a large cubic residual and is similar to Fig. 3a of Lyne (1996). The value of the frequency second derivative $\ddot{\nu} = 4.8 \times 10^{-25} Hz\ s^{-2}$ gives the timing noise parameter $\Delta_8 = -1.2$, which is in agreement with Δ_8 given in Arzoumanian et al. (1994). Possibly, the derived second derivative is a result of some short-term variations in the first derivative.

Thus, the main effect of the observed glitches in PSR B1822-09 is a significant negative change in the frequency derivative

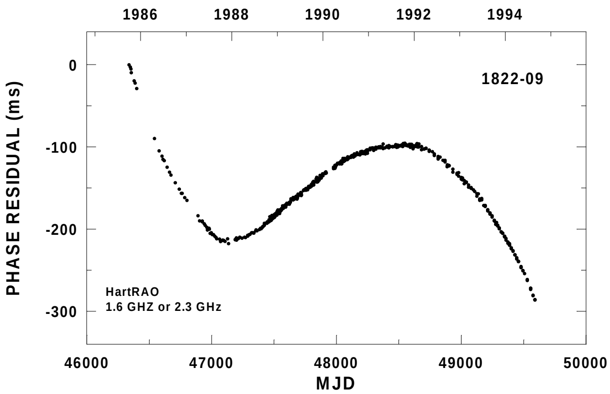

Fig. 5. Timing residuals for PSR B1822-09 from the 9-yr HartRAO observations between October 1985 and 1994 September (before the first glitch) with the mean initial values of frequency and the frequency derivative from the indicated interval. One can see a large cubic residual

(Table 1). After the glitch the slow-down rate is lower than the secular slow-down rate and after some relaxation time it increases back to the pre-glitch value. As a consequence, a gradual increase of rotational rate is observed during this time interval. The exponentials with the 235-day time constant provide good fits to both $\Delta\nu$ and $\dot{\nu}$.

The reason of a gradual glitch may be associated with a thermal instability in a neutron star (Greenstein 1979). A small, gradual glitch may be a response of a neutron star to a sudden local increase of the inner crust temperature (Link & Epstein 1996). The decrease in the slow-down rate is difficult to interpret. All the glitches observed so far were usually accompanied by the increase in the spindown rate (Shemar & Lyne 1996). In the vortex creep theory (Alpar et al. 1984a, 1984b), the increase in $\dot{\nu}$ at the time of glitch is due to a relaxation between the crust superfluid and the rest of the star. The reason of the decrease in the frequency derivative may be attributed to some change in the magnetospheric structure and perhaps in the electromagnetic torque. As discussed by Link & Epstein (1997), changes in the braking torque may be a result of a small variation in the angle between the rotation and magnetic axes.

Another significant feature is that the glitches do not affect the arrival times of pulses at different observing frequencies. As Cheng (1987b) pointed out, the glitches do not change the structure of the surface magnetic field. But glitches may trigger the reconnection of some magnetic field lines near the light cylinder, where the field is much weaker than the surface field. This reconnection may change the alignment of the pulsar magnetic field at the epoch of the glitch. Glitches observed in PSR B1822-09 showed that the time alignment of low and high frequency profiles did not change within 2 ms.

One more interesting feature is that the frequency residuals, $\Delta\nu$, and the frequency derivative, $\dot{\nu}$, have identical signature during the 7-yr observations in the wide frequency range from 0.1 to 2.3 GHz both for the pre-glitch interval and at the time of the glitches (Fig. 4a,c). Identical behavior of ν and $\dot{\nu}$ in the wide frequency range from 0.1 to 2.3 GHz suggests that the magnetospheric noise is the same at high frequencies (glitch noise dominant regime) and at low frequencies (magnetospheric noise dominant regime) (Cheng 1987a, 1987b).

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References

Alpar M.A., Anderson P.W., Pines D., Shaham J., 1984a, ApJ 276, 325
Alpar M.A., Anderson P.W., Pines D., Shaham J., 1984b, ApJ 278, 791
Arzoumanian Z., Nice D.J., Taylor J.H., Thorsett S.E., 1994, ApJ 422, 671
Cheng K.S., 1987a, ApJ 321, 799
Cheng K.S., 1987b, ApJ 321, 805
Flanagan C.S., 1993, MNRAS 260, 643
Fomalont E.B., Goss W.M., Lyne A.G., Manchester R.N., Justtanont K., 1992, MNRAS 258, 497
Greenstein J., 1979, ApJ 231, 880
Kuzmin A.D., Izvekova V.A., Shitov Yu.P., et al., 1998, A&AS 127, 355
Link B., Epstein R.I., 1996, ApJ 457, 844
Link B., Epstein R.I., 1997, ApJ 478, L91
Lyne A.G., 1996, In: Johnston S., Walker M.A., Bailes M. (eds.) Proc. IAU Col. 160, Pulsars: Problems and Progress. San Francisco, p. 73
Lyne A.G., Smith F.G., Pritchard R.S., 1992, Nat 359, 706
Manchester R.N., Taylor J.H., 1977, Pulsars. Freeman, San Francisco
McCulloch P.M., Hamilton P.A., McConnell D., King E.A., 1990, Nat 346, 822
Shabanova T.V., 1998, A&A 337, 723
Shemar S.L., Lyne A.G., 1996, MNRAS 282, 677
Shitov Yu.P., 1998, private communication