CYCLICAL CHANGES IN THE TIMING RESIDUALS FROM THE PULSAR B0919+06

TATIANA V. SHABANOVA

Pushchino Radio Astronomy Observatory, Astro Space Center, P. N. Lebedev Physical Institute, Russian Academy of Sciences, 142290 Pushchino, Russia; tvsh@prao.ru

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ABSTRACT

We report the detection of a large glitch in the pulsar B0919+06 (J0922+0638). The glitch occurred in 2009 November 5 (MJD 55140) and was characterized by a fractional increase in the rotation frequency of \( \Delta \nu / \nu \sim 1.3 \times 10^{-6} \). A large glitch happens in the pulsar whose rotation has an unstable character. We present the results of the analysis of the rotation behavior of this pulsar over the 30 year time span from 1979 to 2009. These results show that the pulsar’s rotation frequency underwent continuous, slow oscillations that resembled glitch-like events. During the 1991–2009 interval, the pulsar experienced a continuous sequence of 12 slow glitches with a fractional increase in the rotation frequency of \( \Delta \nu / \nu \sim 1.5 \times 10^{-9} \). All the slow glitches observed have similar signatures related to a slow increase in the rotation frequency for \( \sim 200 \) days and to the subsequent relaxation back to the pre-glitch value for \( \sim 400 \) days. We show that a continuous sequence of such slow glitches is characterized by practically identical amplitudes of \( \Delta \nu \sim 3.5 \times 10^{-9} \) Hz and identical time intervals between glitches of \( \sim 600 \) days and is well described by a periodic sawtooth-like function. The detection of two different phenomena, such as a large glitch and a sequence of slow glitches, indicate the presence of two types of discontinuities in the rotation frequency of the pulsar B0919+06. These discontinuities can be classified as normal and slow glitches.

Key words: pulsars: general – pulsars: individual (PSR B0919+06) – stars: neutron – stars: rotation

1. INTRODUCTION

The pulsar B0919+06 was discovered in the second Molonglo pulsar survey (Manchester et al. 1978). It has a period of 0.430 s, a period derivative of \( 13.72 \times 10^{-15} \) s yr\(^{-1} \), and a characteristic age of \( \tau = P / 2 \dot{P} \sim 5 \times 10^5 \) yr. A pulsar distance of 1200 pc and a transverse speed of 505 km s\(^{-1} \) were derived from the measurements of astrometric parameters (Chatterjee et al. 2001).

The data set analyzed includes the archival Jet Propulsion Laboratory (JPL) data and the Pushchino Radio Astronomy Observatory (PRAO) data. The early timing observations of PSR B0919+06 were carried out at the JPL at a frequency of 2388 MHz between 1979 December and 1983 March and covered a span of 3.2 yr (Downs & Krause-Polstorf 1986). At the PRAO, timing observations of the pulsar were made between 1983 August and 2010 February. Together, both data sets cover the 30 year span from 1979 to 2009 with a four-year gap between 1987 and 1990. An analysis of these experimental data showed that PSR B0919+06 had unstable rotation over the entire data span. The timing residuals after the removal of deterministic pulsar spin-down from the arrival times are characterized by a large second derivative that indicates a high level of timing noise.

Two types of unpredictable variations may occur in the spin rate of pulsars—timing noise and glitches (Shemar & Lyne 1996). Timing noise is the manifestation of the random, continuous wandering of the pulse phase that may produce long-term polynomial trends in the timing residuals. Glitches represent sudden, discrete jumps in the pulsar’s rotation frequency, followed by an exponential recovery to the pre-glitch value. Glitches are characterized by short rise times of less than 1 day and reveal themselves as sudden discontinuities in the timing residuals.

A study of the timing behavior of the pulsars B1822–09 and B1642–03 has shown that there is another type of glitch that can be classified as a peculiar or slow glitch (Shabanova 1998, 2005, 2007, 2009a; Shabanova 2009b, hereafter SH09; Shabanova & Urama 2000; Zou et al. 2004). Characteristic features of slow glitches are long rise times of about 200–500 days and small amplitudes of about several parts in \( 10^{-9} \) Hz. Slow glitches produce cyclical changes in the timing residuals. The rotation frequency of these pulsars undergoes continuous, slow oscillations during a long period of time. For the pulsar B1822–09, the oscillatory changes in the rotation frequency were observed over the 1995–2004 interval. In the case of PSR B1642–03, cyclical changes in the timing residuals were observed during the 40 year period from 1969 to 2008. This pulsar demonstrates such striking properties of the slow glitches that allow us to predict the epochs and the amplitudes of new glitches in its rotation frequency (see SH09).

In this paper, we study the rotation history of the pulsar B0919+06 over the 30 year period, report the detection of a large glitch, and show that cyclical changes in the timing residuals from this pulsar are due to the presence of slow glitches. These results indicate that two types of discontinuities, specified as normal and slow glitches, can occur in the rotation frequency of one pulsar.

2. OBSERVATIONS AND TIMING ANALYSIS

Timing observations of the pulsar B0919+06 were carried out at the Pushchino Observatory for more than 26 years from 1983 August to 2010 February with a four-year gap between 1987 and 1990. The observations were made with the Large Phased Array of the Pushchino Observatory, which is a transit telescope, at frequencies near 102 or 112 MHz using a 64-channel radiometer with a channel bandwidth of 20 kHz and a time resolution of 2.56 or 1.28 ms. The duration of one observation of PSR B0919+06 was determined by the width of the antenna beam at the pulsar declination and lasted 3.2 minutes. During this time, 450 individual pulses were summed synchronously with a predicted topocentric pulsar period to produce the mean pulse profile in each 20 kHz channel. After dispersion removal, all
the channel profiles were summed to form an integrated pulse profile for the given observing session. Then, this integrated profile was cross-correlated with a standard low-noise template to give the topocentric pulse arrival times for each observing session.

The topocentric arrival times collected at PRAO and the geocentric arrival times obtained from archival JPL timing data were all referred to as the barycenter of the solar system at infinite frequency using the program TEMPO and the JPL DE200 ephemeris. The position and the proper motion required for this correction were taken from Hobbs et al. (2004) and Chatterjee et al. (2001), respectively. In order to obtain residuals from the timing model, the pulsar’s rotation is modeled by a polynomial including several frequency derivatives. In accordance with a Taylor expansion, the pulse phase $\phi$ at the barycentric arrival time $t$ is expressed as

$$\phi(t) = \phi_0 + \nu(t - t_0) + \dot{\nu}(t - t_0)^2/2 + \ddot{\nu}(t - t_0)^3/6 + \ldots,$$

(1)

where $\phi_0$, $\nu$, $\dot{\nu}$, and $\ddot{\nu}$ are the pulse phase, rotation frequency, and the first and second frequency derivative at some reference time $t_0$, respectively. The timing residuals, obtained as differences between the observed times and the times predicted by a best-fit model, were used for the analysis of the rotation behavior of the pulsar. The pulsar position was held fixed in the fitting procedure.

In order to study variations in the pulsar’s rotation, the parameters $\nu$ and $\dot{\nu}$ were calculated from the local fits, performed to the pulse arrival times over intervals of 150 or 300 days. The frequency residuals ($\Delta \nu$) were obtained at the initial epoch of each interval relative to a third-order polynomial (Equation (1)), including the mean parameters $\nu$, $\dot{\nu}$, and $\ddot{\nu}$ defined over the full interval 1979–2009, 1991–2009, or any other interval.

3. RESULTS

3.1. A Large Glitch of 2009

In 2009 November 5, the pulsar B0919+06 suffered a very large glitch, with a fractional increase in the rotation frequency of $\Delta \nu/\nu = 1.3 \times 10^{-6}$. This glitch is comparable in size to the glitches observed in the Vela pulsar. The glitch was accompanied by a significant decrease in the frequency derivative of $\Delta \dot{\nu}/\nu = -7 \times 10^{-3}$. A glitch was detected during a series of daily observations, so the uncertainty in determining the glitch epoch is within several hours, MJD 55139.8(1). Figure 1 shows the timing residuals relative to a simple $\nu$, $\dot{\nu}$ model fitted to the data before the glitch. The negative growth in the residuals due to this glitch corresponds to a shift of the pulse in the observing window by $\sim 109$ ms day$^{-1}$. The glitch parameters are given in Table 1. Uncertainties in the parentheses represent the formal standard deviation and refer to the last digit quoted.

The large glitch has occurred in a relatively old pulsar with a characteristic age of $\tau \sim 5 \times 10^3$ yr. This age is comparable to the age of PSR B0355+54 ($\tau \sim 5.6 \times 10^3$ yr) which experienced a giant glitch of $\Delta \nu/\nu = 4.4 \times 10^{-6}$ in 1987 (Lyne 1987). The timing observations of PSR B0919+06 over four months after the glitch are not sufficient for detailed research into the post-glitch behavior. Moreover, as will be shown in the following sections, the rotation frequency of this pulsar undergoes continuous, slow oscillations with the spacing of maxima $\sim 600$ days. Further observations are needed to establish a relationship between the large glitch and this oscillatory behavior.

3.2. The Timing Behavior of the Pulsar Between 1979 and 2009

The timing behavior of PSR B0919+06 over the 30 year interval from 1979 December to 2009 November before the large glitch occurred is presented in Figure 2. A four-year data gap seen in the residuals between 1987 and 1990 insignificantly distorts the information about the pulsar’s rotation.

An analysis of the full data set showed that the timing behavior of PSR B0919+06 exhibits significant deviations from a deterministic spin-down low that indicates a presence of large timing noise. So, the pulsar’s rotation was modeled by polynomials that included several frequency derivatives. The timing residuals after subtraction of the third-order polynomial for $\nu$ and the two frequency derivatives $\nu$ and $\dot{\nu}$ are shown in Figure 2(a). The corresponding rotation parameters for model 1979–2009 are given in Table 2. The post-fit residuals display a large quartic term with the amplitude approximately equal to half the pulsar period. This plot shows that the residual curve has a weak but noticeable short-term cyclical structure over the entire time span.

This cyclical structure becomes more discernible in the timing residuals presented in Figure 2(b). The post-fit residuals obtained after subtraction of a polynomial including $\nu$ and three frequency derivatives exhibit the three maxima of a large-scale structure. The timing model with higher-order derivatives, for example, with four or five frequency derivatives, gives similar

| Glitch Parameters | Values |
|-------------------|--------|
| Pre-glitch parameters |       |
| MJD range | 54892–55139 |
| $\nu$ (Hz) | 2.32219343204(6) |
| $\dot{\nu}$ (10$^{-15}$ s$^{-2}$) | $-73.931(6)$ |
| Epoch (MJD) | 54892.8436 |
| rms timing residual (ms) | 0.6 |
| Post-glitch parameters |       |
| MJD range | 55140–55254 |
| $\nu$ (Hz) | 2.3221947716(7) |
| $\dot{\nu}$ (10$^{-15}$ s$^{-2}$) | $-73.43(8)$ |
| Epoch (MJD) | 55140.1604 |
| rms timing residual (ms) | 0.9 |
| Glitch parameters |       |
| $\Delta \nu/\nu (10^{-9})$ | 1257.1(3) |
| $\Delta \dot{\nu}/\nu (10^{-15})$ | $-7(1)$ |
| Epoch (MJD) | 55139.8(1) |

Figure 1. Timing residuals for the large glitch that occurred in the period of PSR B0919+06 in 2009 November 5 (MJD 55140). The dotted line indicates the glitch epoch.
These slow oscillations in the timing residuals. Our purpose is to determine the cause of slow oscillations in the pulsar’s rotation frequency. Because of the paucity of data between 1979 and 1986, the properties of this oscillatory structure will be investigated over the time span from 1991 to 2009 where there is a great deal of experimental data.

### 3.3. Slow Oscillations in the Pulsar’s Rotation Frequency over the Interval 1991–2009

Figure 3 exhibits the timing behavior of the pulsar over the 19 year period between 1991 January and 2009 November. Figure 3(a) displays the timing residuals after the subtraction of a polynomial including \( \nu \) and two frequency derivatives. The rotation parameters measured over this period are given in Table 2. The last point in the residual curve indicates the large glitch that occurred in 2009 November 5. The short-term cyclical structure is clearly seen in the timing residuals.

The timing residuals after subtraction of a polynomial including \( \nu \) and five frequency derivatives are given in Figure 3(b). This plot shows a clear cyclical structure that contains 12 cycles with amplitudes of about 10 ms and maxima spacing of about 600 days. Comparison of the timing residuals presented in Figures 3(a) and 3(b) shows that the epochs and the spacing of the maxima of these cycles are the same in all plots and do not depend on the time span of the data analyzed and the polynomial model fitted. At the same time, the shape and amplitude of these cycles are different in these plots.

The time behavior of the frequency residuals \( \Delta \nu \) and that of the frequency derivative \( \dot{\nu} \) relative to the mean rotation parameters for the model 1991–2009 from Table 2 are presented in Figures 3(c) and 3(d). The plotted values of \( \nu \) and \( \dot{\nu} \) were calculated from the local fits, performed to the arrival time data over intervals of \( \sim 150 \) days which overlapped by \( \sim 75 \) days. Then, the eight points in \( \Delta \nu \) will correspond to a cycle duration of 600 days in the timing residuals.

It is clearly seen from Figure 3(c) that the rotation frequency of the pulsar B0919+06 slowly oscillates during the time interval observed. In each successive cycle, the period of increase in \( \Delta \nu \) is followed by a period of decrease in \( \Delta \nu \). This oscillatory process looks like a continuous sequence of 12 glitch-like events. In contrast to normal glitches, these events can be classified as peculiar or slow glitches because they exhibit long rise times of about a few hundred days. A similar glitch phenomenon was observed earlier in the pulsar B1642−03 (see SH09). Figure 3(d) shows that the time changes in the frequency derivative \( \dot{\nu} \) are the effect of the changes in \( \Delta \nu \). The peaks of \( \Delta \nu \) define the steepness of the front in the \( \Delta \nu \) cycles. In order to study the properties of the slow glitches observed, it is necessary to obtain the shape of the \( \Delta \nu \) cycles that is not distorted by the presence of the timing noise.

![Figure 2](image-url)
the front in





Figure 3. Timing behavior of PSR B0919+06 between 1991 and 2009. (a) The timing residuals after subtraction of the polynomial for \( \nu \) and two frequency derivatives. The last point in the residual curve indicates the large glitch of 2009 November. The slight cyclical structure is clearly seen in the residual curve. (b) The timing residuals after subtraction of the polynomial for \( \nu \) and five frequency derivatives. The clear cyclical structure contains 12 cycles with the amplitudes of \( \sim 10 \) ms and maxima spacing of \( \sim 600 \) days. (c) The frequency residuals relative to the timing model 1991–2009. Slow oscillations in \( \Delta \nu \) look like a continuous sequence of 12 glitch-like events. (d) The changes in the frequency’s first derivative with time. The peaks of \( \Delta \nu \) define the steepness of the front in \( \delta \nu \).

3.4. The Properties of the Observed Slow Glitches

From Figure 3(c), it is seen that the \( \Delta \nu \) curve shows appreciable deviations relative to the timing model 1991–2009. These deviations are a result of the variations in \( \dot{\nu} \) due to higher-order frequency derivatives which are not taken into account by the timing model. In order to obtain the undistorted shape of the \( \Delta \nu \) cycles, we should calculate the frequency residuals \( \Delta \nu \) relative to several timing models that describe the data over the shorter time intervals, including a few slow glitches. A measured magnitude of \( \ddot{\nu} \) is so large that a simple \( \nu, \dot{\nu}, \ddot{\nu} \) spin-down model cannot be used to describe the experimental data even over short intervals. Besides, \( \ddot{\nu} \) changes sign within the interval 1991–2009. The positive value \( \ddot{\nu} = 1.6 \times 10^{-25} \) s\(^{-3}\) measured over the interval 1991–2002 becomes negative \( \ddot{\nu} = -4.1 \times 10^{-25} \) s\(^{-3}\) over the next interval 2002–2009. The maximum length of each chosen short time interval corresponded to such a quantity of the \( \Delta \nu \) cycles that the timing residuals presented relative to the model, including the mean values of \( \nu, \dot{\nu}, \ddot{\nu} \) defined over this short interval, would be symmetrical with respect to the zero line.

We found the three suitable time intervals in which the pulse arrival times, corresponding to a few slow glitches, are well described by the \( \nu, \dot{\nu}, \ddot{\nu} \) model. The timing model 1991–1995 was used to define the frequency residuals \( \Delta \nu \) for glitches 1, 2, 3, and 4; the model 1995–2004 for glitches 5, 6, 7, and 8; and the model 2004–2009 for glitches 9, 10, 11, and 12. The frequency residuals \( \Delta \nu \) defined relative to these three models were then combined into a single data set. This adjusted set of the \( \Delta \nu \) cycles describing the shape of 12 slow glitches is plotted in Figure 4(a). It is seen that the \( \Delta \nu \) curve is nearly symmetrical with respect to the zero line. This indicates that the shapes of the slow glitches were reconstructed rather correctly (compare with Figure 3(c)).

The parameters describing the sequence of 12 slow glitches plotted in Figure 4(a) are given in Table 3. The parameters are presented in the following order: the glitch number; the epoch of the point \( T_{\text{min}} \), which corresponds to the minimum deviation of \( \Delta \nu_{\text{min}} \); the epoch of the point \( T_{\text{max}} \), which corresponds to the maximum deviation of \( \Delta \nu_{\text{max}} \); the glitch amplitude \( \Delta \nu_{g} = \Delta \nu_{\text{max}} + |\Delta \nu_{\text{min}}| \); the time interval to the next glitch \( \Delta T_{\text{max}} \); the time interval between the minimal points of the \( \Delta \nu \) cycles \( \Delta T_{\text{min}} \); the rise time interval \( \Delta T_{\text{ris}} = T_{\text{max}} - T_{\text{min}} \); and the relaxation time interval after the glitch \( \Delta T_{\text{rel}} = T_{\text{min}} - T_{\text{max}} \).

Figure 4(a) and Table 3 allow us to study the properties of the slow glitches that depend on the glitch number. The results are presented in Figure 5. The top panel of Figure 5 shows the relation between the glitch amplitude and the glitch number. It is seen that all the slow glitches approximately have an identical amplitude equal to 3.5(0.5) \times 10^{-5} \) Hz, where the error in the parentheses is the formal standard deviation. The middle panel shows the relation between the time intervals \( \Delta T_{\text{max}} \) (the interval between the successive glitches) and \( \Delta T_{\text{min}} \) (the interval between the minimal points of the \( \Delta \nu \) cycles) and the glitch number. This plot shows that the indicated intervals are approximately equal to 580 and 600 days, respectively. The bottom panel shows the relation between the glitch parameters \( \Delta T_{\text{rel}} \) (the relaxation time interval) and \( \Delta T_{\text{ris}} \) (the rise time interval) and the glitch number,
slow glitches have similar properties. The derived average parameters indicate that all the
presents a relation between the time interval \( \Delta \) and 180 days, respectively. The top panel presents a relation between the glitch amplitude and the
glitch number. All the slow glitches approximately have identical amplitudes. The bottom panel
shows a model sawtooth-like curve with a period of 600 days which is superimposed on the glitch sequence observed. It is seen that the maxima of the model curve coincides well with the maxima of nearly all the slow glitches. Only the maxima of glitches 8 and 9 slightly do not correspond to the model curve. However, as seen from the plot, the slight deviations of the amplitude and phase of these cycles from a model curve do not change the phase of the subsequent cycles of the sequence. The shape of these glitches was probably not precisely restored. The model curve describes the overlapping glitches 2 and 3 very well. It is seen that in this range there was a phase shift for 400 days, exactly equal to \( \Delta T_{\text{rel}} \). After

These three relations indicate that all the slow glitches observed have similar properties that can be described by the following average parameters. The glitches have a small absolute amplitude equal to \( 3 \times 10^{-9} \) Hz. They are characterized by identical inter-glitch intervals \( \Delta T_{\text{max}} \) and approximately the same width of the intervals \( \Delta T_{\text{min}} \), equal to \( \sim 600 \) days. The glitches have similar signatures related to a slow increase in the rotation frequency for \( \sim 200 \) days and the subsequent relaxation back to the pre-glitch value for \( \sim 400 \) days. The relaxations after all the glitches can be described by a linear curve as seen in Figure 4(a). These properties suggest that the sequence of the slow glitches observed can be approximated by a sawtooth-like function.

We created the model sawtooth-like curve using the indicated average parameters. This model curve has the starting point MJD 48350 and includes 10 cycles consisting of two stages—the stage of linear glitch arising with a timescale of 200 days and the stage of linear post-glitch relaxation with a timescale of 400 days. Only two glitches observed, 2 and 3, do not follow this sequence. An analysis of the \( \Delta \nu \) cycles showed that event 2 represents the sum of two partially overlapping glitches, 2 and 3. Glitch 3 defines the starting point of a new phase in the sequence of the slow glitches. Therefore, event 2 should be described by three stages—the stage of a linear glitch arising with a timescale of 200 days, followed by the stage in which the glitch amplitude remains constant for 400 days (the duration of this interval corresponds to the duration of the relaxation time interval \( \Delta T_{\text{rel}} \)) and only then is followed by a linear post-glitch relaxation with a timescale of 400 days. The derived values for this model sawtooth-like curve are given in Table 4.

Figure 4(b) shows a model sawtooth-like curve with a period of 600 days which is superimposed on the glitch sequence observed. It is seen that the maxima of the model curve coincides well with the maxima of nearly all the slow glitches. Only the maxima of glitches 8 and 9 slightly do not correspond to the model curve. However, as seen from the plot, the slight deviations of the amplitude and phase of these cycles from a model curve do not change the phase of the subsequent cycles of the sequence. The shape of these glitches was probably not precisely restored. The model curve describes the overlapping glitches 2 and 3 very well. It is seen that in this range there was a phase shift for 400 days, exactly equal to \( \Delta T_{\text{rel}} \). After

and defines the average values of these parameters equal to 400 and 180 days, respectively.

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**Table 3**

| No. | \( T_{\text{min}} \) (MJD) | \( \Delta T_{\text{min}} \) (10^{-9} Hz) | \( T_{\text{max}} \) (MJD) | \( \Delta T_{\text{max}} \) (10^{-9} Hz) | \( \Delta \nu \) (10^{-9} Hz) | \( \Delta T_{\text{max}} \) (days) | \( \Delta T_{\text{min}} \) (days) | \( \Delta T_{\text{ris}} \) (days) |
|-----|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 1   | 48398           | -1.7            | 48545           | 1.6             | 3.3             | 589             | 524             | 147             | 377             |
| 2   | 48922           | -1.6            | 49134           | 1.5             | 3.1             | 459             | 212             | 30              |
| 3   | 49593           | 2.6             | 50194           | 2.2             | 3.1             | 529             | 675             | 301             | 374             |
| 4   | 50938           | 0.9             | 50723           | 1.7             | 3.3             | 663             | 678             | 155             | 523             |
| 5   | 51246           | 0.8             | 51386           | 2.0             | 3.5             | 606             | 599             | 140             | 459             |
| 6   | 51845           | -0.8            | 51992           | 2.2             | 3.0             | 672             | 604             | 147             | 457             |
| 7   | 52449           | -1.6            | 52664           | 1.6             | 3.2             | 666             | 671             | 215             | 456             |
| 8   | 53120           | -1.4            | 53330           | 1.5             | 2.9             | 396             | 431             | 210             | 221             |
| 9   | 53551           | -1.8            | 53726           | 1.7             | 3.5             | 594             | 617             | 175             | 442             |
| 10  | 54168           | -2.0            | 54320           | 2.6             | 4.6             | 600             | 602             | 152             | 450             |
| 11  | 54770           | -1.7            | 54920           | 2.0             | 3.7             | 30              | 30              | 150             |

Notes. In column order, the table gives the glitch number; epoch of the point \( T_{\text{min}} \), which corresponds to the minimum deviation of \( \Delta T_{\text{min}} \); epoch of the point \( T_{\text{max}} \), which corresponds to the maximum deviation of \( \Delta T_{\text{max}} \); the glitch amplitude \( \Delta \nu = \Delta \nu_{\text{max}} + |\Delta \nu_{\text{min}}| \); the time interval to the next glitch \( \Delta T_{\text{max}} \); the time interval between the minimal points of the \( \Delta \nu \) cycle \( \Delta T_{\text{min}} \); the rise time interval \( \Delta T_{\text{ris}} = T_{\text{max}} - T_{\text{min}} \); the relaxation time interval after the glitch \( \Delta T_{\text{rel}} = T_{\text{min}} - T_{\text{max}} \).
that, point 3 started marking the starting point of a new phase in the sequence of the slow glitches. Despite the phase shift between points 2 and 3, we suppose that the model sawtooth-like function is a periodic function. A comparison of model parameters $T_{\text{min}}$ and $T_{\text{max}}$, given in Table 4, and the same experimental parameters, listed in Table 3, shows that these parameters agree well within a precision limited by the time resolution of ~100 days. We conclude that a model periodic sawtooth-like function approximates a sequence of the observed slow glitches very well. This result indicates a surprising regularity in the occurrence of slow glitches—the time intervals between the slow glitches, equal to 600 days, remain constant for approximately 100 days during ~19 years.

Thus, we found that the cause of slow oscillations in the rotation frequency of PSR B0919+06 over the 1991–2009 interval lies in a continuous generation of slow glitches. The originality of these slow glitches is that they have similar properties and their sequence is described by a periodic sawtooth-like function. Estimates show that the time intervals between the slow glitches observed remain constant for approximately 100 days during this period. In Figure 2(c), curve B suggests that this conclusion can be generalized throughout the observational interval 1979–2009. We may suppose that a sequence of similar slow glitches occurring at regular time intervals produced a sawtooth-like modulation of the rotation frequency, superimposed on the secular spin-down, throughout the whole period 1979–2009. An analysis of the pulse arrival times showed that the process, responsible for the generation of slow glitches over ~30 years, was interrupted by a large glitch of magnitude $\Delta \nu/\nu = 1.3 \times 10^{-6}$ that occurred in 2009 November 5.

5. DISCUSSION

Slow glitches as a unique glitch phenomenon were originally detected for the pulsar B1822−09 in the timing observations that have been carried out at the Pushchino radio telescope since 1991 (Shabanova 1998). Further observations showed that this pulsar experienced a series of five slow glitches and also suffered three glitches of normal signature (Shabanova & Urama 2000; Zou et al. 2004; Shabanova 2005, 2007, 2009a; Yuan et al. 2010). The slow glitches observed were characterized by a gradual increase in the rotation frequency with a long rise time of 100–300 days. It was found that all these slow glitches were the components of one process that acted continuously for ~10 years from 1995 to 2004. These events were then followed by two glitches of normal signature. The glitches of magnitude $\Delta \nu/\nu = 6.7 \times 10^{-9}$ and $\Delta \nu/\nu = 121 \times 10^{-9}$ occurred in 2006 January and 2007 January, respectively (Shabanova 2009a). All these events clearly show the presence of two types of discontinuities in the rotation frequency of the pulsar B1822−09. These discontinuities can be classified as normal and slow glitches.

The pulsar B1642−03 is the second pulsar known, after PSR B1822-09, in the rotation frequency where slow glitches are revealed. As shown in SH09, the rotation frequency of this pulsar undergoes a continuous generation of slow glitches and over the 40 year period of observations, this pulsar suffered eight slow glitches. The amplitude of these glitches and the time interval to the next glitch obey a clear linear relation. This dependence gives strong evidence against the statement that slow glitches can be caused by the same process that causes timing noise in pulsars (Hobbs et al. 2010). The existence of the modulation process that causes the discrete changes of the glitch amplitudes and the post-glitch time intervals that depend on the serial number of the glitch in a given modulation period also confirms that the slow glitches observed are distinct events. The indicated dependences allow us to predict the epochs and sizes of new glitches in this pulsar. These predictions can be verified in the near future, in 2013. This verification will provide the strongest evidence yet that the slow glitches observed are a unique glitch phenomenon.

The pulsar B0919+06 is the third pulsar in our research that experienced slow glitches in its rotation frequency. The main properties of the slow glitches observed are a similarity

| No. | $T_{\text{min}}$ (MJD) | $\Delta \nu_{\text{min}}$ (10^{-9} Hz) | $T_{\text{max}}$ (MJD) | $\Delta \nu_{\text{max}}$ (10^{-9} Hz) |
|-----|-----------------------|--------------------------------------|-----------------------|--------------------------------------|
| 1   | 48350                 | −1.6                                 | 48550                 | 1.9                                  |
| 2   | 48950                 | −1.6                                 | 49150                 | 1.9                                  |
| 3   | 49950                 | −1.6                                 | 50150                 | 1.9                                  |
| 4   | 50550                 | −1.6                                 | 50750                 | 1.9                                  |
| 5   | 51150                 | −1.6                                 | 51350                 | 1.9                                  |
| 6   | 51750                 | −1.6                                 | 51950                 | 1.9                                  |
| 7   | 52350                 | −1.6                                 | 52550                 | 1.9                                  |
| 8   | 52950                 | −1.6                                 | 53150                 | 1.9                                  |
| 9   | 53550                 | −1.6                                 | 53750                 | 1.9                                  |
| 10  | 54150                 | −1.6                                 | 54350                 | 1.9                                  |
| 11  | 54750                 | −1.6                                 | 54950                 | 1.9                                  |

Notes. In column order, the table gives the glitch number; epochs of the points $T_{\text{min}}$, which correspond to the minimum deviations of $\Delta \nu_{\text{min}}$; epochs of the points $T_{\text{max}}$, which correspond to the maximum deviations of $\Delta \nu_{\text{max}}$. The glitch amplitude equals $3.5 \times 10^{-9}$ Hz, $\Delta T_{\text{rel}} = 200$ days, and $\Delta T_{\text{rel}} = 400$ days.
in their signatures and a regularity in their occurrence. The regular occurrence of similar slow glitches produces a periodic sawtooth-like modulation of the rotation frequency with a period of 600 days. As discussed above, the timing residuals do not show strictly periodic cyclical changes because this pulsar possesses a high level of timing noise and the observed amplitude and the shape of the cycles depend on the polynomial model fitted. A derived sawtooth-like modulation of the rotation frequency, shown in Figure 2(c) by curve B, is a result of the reconstruction of cyclical changes that could take place in the pulsar’s rotation frequency if the pulsar rotation is modeled by a simple spin-down model. Curve B reflects the properties of an actual process that generated the slow glitches during the ∼30 years time span. This process was interrupted by a large glitch that occurred in 2009 November. The pulsar B0919+06, as well as B1822−09, clearly exhibits that the pulsar’s rotation frequency underwent two types of discontinuities that can be classified as normal and slow glitches.

Comparison of the rotation parameters for the pulsars showing the slow glitches is presented in Table 5 where the pulsars are listed in order of decreasing age. This table gives the pulsar’s B1950 name, the rotation parameters ν, ν ̇, and ν ̈, the characteristic age τ = P/2 Ẏ, and surface magnetic field B = 3.2 × 10^19(PP) 1/2 G. It is seen that all these pulsars are relatively old pulsars with ages greater than ∼10^5 yr. The oldest pulsar, B1642−03, only has slow glitches. Their amplitude and the time interval between glitches strictly obey a certain law, that is, the glitch sequence in this pulsar possesses the predicted, steady-state properties. The two others, B0919+06 and B1822−09, are substantially younger, have higher frequency derivatives ̇ν and ̈ν, and stronger magnetic fields. They experience large glitches of normal signature that followed the oscillatory process in the rotation frequency identified with slow glitches. A comparison of the pulsar parameters in this table indicates that a tendency to have a sequence of slow glitches with steady-state properties is correlated with the characteristic age of the pulsar. The number of pulsars with slow glitches in their rotation frequency will probably increase considerably in the future. The candidates can be pulsars that exhibit cyclical changes in the timing residuals.

Long sequences of timing residuals were recently published for 366 pulsars observed at the Jodrell Bank between 1968 and 2006 (Hobbs et al. 2010). A detailed analysis of these data shows that the timing residuals of some pulsars have clear cyclical changes during the whole period of observations. According to Hobbs et al. (2010), the quasi-periodic structure in the timing residuals is clearly visible for six pulsars: B1540−06, B1642−03, B1818−04, B1826−17, B1828−11, and B2148+63. It should be noted that all these pulsars are old pulsars with ages varying from 1 × 10^7 to 3.5 × 10^7 yr. Among these pulsars, there are two pulsars, B1642−03 and B1828−11, that were investigated earlier. The results of the spectral analysis of these two pulsars by Hobbs et al. (2010) agree with the results of previous papers (Stairs et al. 2000; Shabanova et al. 2001). It is known that the clear periodic structure in the timing residuals of B1828−11 which is accompanied by correlated pulse shape changes is explained by the free precession of the neutron star (Stairs et al. 2000). In the case of PSR 1642−03, multiple low-frequency components in the power spectrum of timing residuals can be well explained as a result of the continuous generation of slow glitches, the amplitude of which is correlated with the time interval following the glitch (SH09).

As reported by Yuan et al. (2010), the slow glitches have yet to be identified for two pulsars J0631+1036 and B1907+10. The first pulsar is a young pulsar with τ ∼ 4.4 × 10^7 yr, and the second one is substantially older with τ ∼ 1.7 × 10^9 yr. The latter has cyclical timing residuals, as is shown in Figure 3 of Hobbs et al. (2010), which can imply cyclical changes in the rotation frequency.

It is thought that pulsar glitches reflect a variable coupling between the solid crust of a neutron star and the superfluid interior rotating more rapidly than the solid crust. In terms of vortex pinning models, the origin of glitches can be explained by the catastrophic unpinning of superfluid vortices (Anderson & Itoh 1975; Alpar et al. 1984, 1989, 1993; Pines & Alpar 1985). These models provide a satisfactory interpretation of large glitches in pulsars.

The interpretation of the phenomenon of slow glitches is uncertain. According to Hobbs et al. (2010), the slow glitch phenomenon is a quasi-periodic component of the timing noise, unrelated to normal glitches. At the same time, the slow glitches revealed in PSR B1642−03 possess the properties that meet the requirements of the glitch models: (1) all the slow glitches observed have significant exponential decay after the glitch, which is characterized by the same parameter Q ∼ 0.9, and (2) the size of the glitches and the time interval to the following glitch obey a strong linear relation. The third property, the presence of a modulation process which forces the glitch amplitudes and the inter-glitch intervals to change with a discrete step, was not considered yet by any theory of pulsar glitches. In the case of slow glitches, it is necessary to account for the cause of the continuous generation of slow glitches.

For PSR B0919+06, a sawtooth-like modulation of the rotation frequency with a period of 600 days could be interpreted as the free precession of an isolated pulsar if this modulation was accompanied by correlated observable changes in the pulse profile (Shaham 1977; Nelson et al. 1990; Cordes 1993; Stairs et al. 2000). We detected no pulse profile changes during our observations at 112 MHz. A precession model requires a strictly periodic modulation of the pulsar’s rotation frequency. The presence of the phase shift, equal to 400 days, in the modulation curve B between cycles 9 and 10, as is shown in Figure 2(c), contradicts this requirement. These two arguments testify against the interpretation of this sawtooth-like modulation in terms of a free precession model. Besides, this pulsar has experienced a large glitch. As discussed by Link (2007), a slowly precessing neutron star cannot produce a glitch. Useful information for explaining the origin of slow glitches can be obtained from further timing observations of PSR B0919+06. Observations in the next 5–10 years will allow us to find out whether there is a relationship between the different phenomena observed in this pulsar, such as the large glitch and a sequence of slow glitches and whether or not a large glitch has put a stop to the process of generating slow glitches or this process continues after a large glitch in the same mode.

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**Table 5** Parameters for the Pulsars Showing Slow Glitches

| PSR    | ν (s⁻¹) | ̇ν (10⁻¹⁵ s⁻²) | ̈ν (10⁻⁷ s⁻³) | τ (years) | B (G) |
|--------|---------|----------------|---------------|-----------|-------|
| B1642−03 | 2.579   | −11.84         | 0.02          | 3.4 × 10⁶ | 8.3 × 10¹¹ |
| B0919+06 | 2.322   | −74.05         | 1.90          | 5.0 × 10⁵ | 2.5 × 10¹² |
| B1822−09 | 1.300   | −88.59         | 9.00          | 2.3 × 10⁵ | 6.4 × 10¹² |
the many-year observations of this pulsar on the LPA antenna. This work was supported by the European Commission 6th Framework Program, Square Kilometre Array Design Studies (SKADS project, contract No. 011938) and the Russian Foundation for Basic Research (grant 09-02-00473).

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