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The timing noise of PSR 0823+26, 1706−16, 1749−28, 2021+51 and the anomalous braking indices

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ABSTRACT

We have investigated the stability of the pulse frequency second derivatives ($\ddot{\nu}$) of PSR 0823+26, 1706−16, 1749−28 and 2021+51 that show significant quadratic trends in their pulse-frequency histories in order to determine whether the observed second derivatives are secular or if they arise as part of noise processes. We have used time-of-arrival (TOA) data extending to more than three decades, which are the longest time-spans ever taken into account in pulse-timing analyses. We investigated the stability of the pulse-frequency second derivative in the framework of low-resolution noise power spectra estimated from the residuals of pulse frequency and TOA data. We have found that the $\ddot{\nu}$ terms of these sources arise from the red torque noise in the fluctuations of pulse-frequency derivatives, which may originate from the external torques from the magnetosphere of the pulsar.

Key words: stars: neutron – pulsars: general – pulsars: individual: PSR 0823+26 – pulsars: individual: PSR 1706−16 – pulsars: individual: PSR 1749−28 – pulsars: individual: PSR 2021+51.

1 INTRODUCTION

Rotation-powered pulsars emit energy by electromagnetic radiation ('pulsar braking'). The spin-down is occasionally interrupted by sudden period discontinuities ('glitches'). In addition, pulse arrival time measurements display irregularities in the rotation rate known as 'timing noise'. The timing noise above the measurement errors could be the result of a noisy component of the secular torque involving fluctuations in the magnetosphere of the neutron star (Cheng 1987a,b, 1989). Alternatively, timing noise could arise from internal torques coupling different components of the neutron star, for example the de/recoupling of the crust superfluid (Alpar, Nandkumar & Pines 1986; Jones 1990). Timing noise for pulsars has been studied over the last three decades (Boynton et al. 1972; Groth 1975; Cordes 1980; Cordes & Helfand 1980; Cordes & Downs 1985; D'Alessandro et al. 1995, 1997; Deshpande, D'Alessandro & McCulloch 1996). Boynton et al. (1972) proposed that the timing noise in the times of arrival (TOA) of pulses might arise from 'random walk' processes, which are rth order (r=1,2,3) time integrals of a 'white noise' time series (or time series of unresolved delta functions). The random walks in phase ϕ, pulse frequency ν and pulse-frequency derivative $\dot{\nu}$ are called 'phase noise', 'frequency noise' and 'slowing down noise', respectively (Cordes 1980). The timing noise of the Crab pulsar was found to be consistent with the 'frequency noise' (or random walk in pulse frequency) (Boynton et al. 1972; Groth 1975). The timing analyses of other pulsars' time series showed that they are also consistent with random walk processes, which are superposed on identifiable microjumps in the timing parameters (Cordes 1980; Cordes & Downs 1985).

The cross talk between the timing noise and secular slowing down is very important. Many of the middle-aged pulsars with spin-down age $\tau = P/2\dot{P}$ greater than about 10^6 yr have shown anomalous trends in their secular frequency second derivative ($\ddot{\nu}$) (Cordes & Downs 1985). These trends make it impossible to recover the braking law $\dot{\nu} \sim \nu^n$ of the pulsar (for pure magnetic dipole radiation n=3). Nominal values of $\ddot{\nu}$ from timing fits gave anomalous braking indices ranging from -10^4 to 10^4 in various pulsars. Recent observations of some young/middle-aged pulsars with glitches also showed anomalous positive braking indices of the order ~20–200 (Shemar & Lyne 1996). Interglitch recovery between successive glitches can effect the pulsar's dynamical parameters such as $\dot{\nu}$ and $\ddot{\nu}$. For the glitching pulsars, the high values of the second derivative of the rotation rate, $\ddot{\nu}$, and associated braking indices of order 20–200 are characteristic of interglitch recovery (Alpar 1998), which extends from one glitch to the next one, as studied in detail between the glitches of the Vela pulsar (Alpar et al. 1993). For all middle-aged pulsars the expected intervals between glitch events are of the order of a few hundred years (Alpar & Baykal 1994). Thus, a pulsar is most likely to be observed during the interglitch recovery phase. This raises the question of whether other middle-aged pulsars also exhibit typical interglitch recovery or whether timing noise dominates the observed timing of these pulsars.

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We have investigated the time series of pulsars on the longest available time-scales by combining the earlier observations of 24 pulsars (Downs & Reichley 1983) and recent observations (Siegman, Manchester & Durdin 1993; Arzoumanian, Nice & Taylor 1994). In this way, we have available timing data for time-spans of the order of 30 yr for several pulsars. Several of these pulsars are automatically eliminated as candidates for secular timing behaviour, as their frequency time series are not consistent with secular quadratic trends (constant $\ddot{\nu}$). Alternatively, polynomial fits to the TOA of these pulsars can require higher order polynomials rather than a cubic polynomial. For these pulsars the time series is dominated by complicated noise processes rather than interglitch recovery. For four pulsars, PSR 0823+26, 1706−16, 1749−28 and 2021+51, there are significant quadratic trends in the frequency histories (cubics in TOA). In this work, we evaluate these quadratic trends to decide whether they are secular trends or just part of the timing-noise process.

In Section 2, we describe the TOA of the pulses and present pulse-frequency histories of the four pulsars. In Section 3, we construct the power-density spectra in the fluctuations of derivatives of pulse frequencies using the mean-squared residuals technique developed by Deeter (1984) and compare the slowing- down parameters of the pulsars with the same parameters deduced from noise strengths.

2 THE DATA BASES

The TOA of pulses used in this work are drawn from the observations of Downs & Reichley (1983) from 1968 to 1982 using the Goldstone telescope in California; Siegman, Manchester & Durdin (1993) from 1986 February to 1988 July, using the Molonglo Observatory Synthesis Telescope; and Arzoumanian et al. (1994), from 1989 August to 1990 February, using the National Radio Astronomy Observatory in Green Bank West Virgina. The TOA of pulses that were transformed by Downs & Reichley (1983) and Siegman et al. (1993) to geocentre and Arzoumanian et al. (1994) to topocentre, were transformed to the solar system barycentre.

Pulse-cycle counts were assigned to the recorded TOA of pulses. In this procedure, data sets separated by gaps that are of the order of several years were not combined into single ephemerides, to avoid possible cycle-count ambiguities (note that we estimated the power spectra in low frequency by using the pulse-frequency time series). The local pulse frequencies are estimated by fitting the cycle counts with a Taylor series

$$\phi = \phi_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2, \tag{1}$$

where t_0, ϕ_0, ν_0 and $\dot{\nu}$ are the time ephemeris, phase, frequency and derivative of the frequency. Typically, these fits are determined on data sets of $\sim 10^2$ d. This time-scale is relatively short for the appearance of red-noise components and possible braking indices in the residuals of TOA of pulses $[\ddot{\nu}/6(t - t_0)^3 \ll 1]$. We therefore did not include the cubic terms in our fits. Table 1 presents the timing solution of PSR 0823+26, 1706-16, 1749-28 and 2021+51, from the pulse-frequency history records. In Fig. 1, the long-term history of pulse-frequency residuals is represented by removing the long-term spin-down trend ($\dot{\nu}$).

3 POWER SPECTRA

The technique applied in this work for the estimation of red-noise power density and associated random walk noise strengths is discussed in detail by Deeter & Boynton (1982) and Deeter (1984). Some aspects are also summarized here. In the case of rth-order red noise with strength S_r, the mean-square residual for data spanning an interval with length T is proportional to $S_r T^{2r-1}$. The proportionality factor depends on the degree m of the polynomial removed prior to computing the mean-square residual; this factor can be obtained by determining the expected mean-square residual for unit strength red noise $S_{(r=1)}$ over unit interval (T=1), either by Monte Carlo methods (Cordes 1980) or by direct mathematical evaluation (Deeter 1984). The expected mean-square residual, after removing a polynomial of degree m over an interval of length T, is given by

$$< \sigma_R^2(m, T) >= S_r T^{2r-1} < \sigma_R^2(m, 1) >_{\rm u}, \tag{2}$$

where the subscript u indicates that the expectation has been derived for a unit-strength noise process. We estimated the noise strengths at the longest time-scale $T_{\rm max}$ or at lowest frequency; f=1/$T_{\rm max}$, where $T_{\rm max}$ is the maximum time-span of the data, from the residuals of pulse frequencies by removing their linear trends. For the shorter intervals or higher frequencies, f_n=n/$T_{\rm max}$, where n is a positive integer, we removed quadratic trends from the TOA data. In order to see whether the noise strengths are stable or not and to see whether the quadratic trends in pulse frequency and cubic trends in TOA absorb the noise, we estimate alternative sets of noise strengths by removing quadratic polynomials from the pulse-frequency data for the longest time-span of data and cubic polynomials from the TOA data for the shorter intervals. In Fig. 2, noise strengths (or power-spectra estimates) are plotted against the reciprocal of the time-scale (or sampling frequency $f = n/T$). It is found that for each source these two power spectra are consistent with each other in terms of average noise strength S_r and slope of the power spectra. This shows that our original noise estimates were robust (consistent with each other in terms of the noise strength parameter, S_r) and were not dominated by either of the two particular polynomial trends. If there were a secular polynomial trend in the data, we could expect that particular trend to produce a significantly better fit, i.e. a

Table 1. Timing solution of PSR 0823+26, 1706−16, 1749−28, 2021+51 from pulse-frequency histories.

PSR 0823+26	
Epoch(JD)	2 443 754.5472134(6)
Pulse frequency (Hz)	1.88444538582(4)
Pulse-frequency derivative (Hz s^{-1})	$-0.60494(2)\times10^{-14}$
Second derivative of pulse frequency (Hz s^{-2})	$-0.208(3)\times10^{-24}$
PSR 1706-16	
Epoch(JD)	2 444 455.1161243(5)
Pulse frequency (Hz)	1.53127025825(9)
Pulse-frequency derivative (Hz s^{-1})	$-0.14888(2)\times10^{-13}$
Second derivative of pulse frequency (Hz s^{-2})	$0.2517(7)\times10^{-24}$
PSR 1749-28	
Epoch(JD)	2 442 622.66650772(9)
Pulse frequency (Hz)	1.77760420787(4)
Pulse-frequency derivative (Hz s^{-1})	$-0.25714(5)\times10^{-13}$
Second derivative of pulse frequency (Hz s^{-2})	$0.112(1)\times10^{-24}$
PSR 2021+51	
Epoch(JD)	2 443 488.7150164(5)
Pulse frequency (Hz)	1.88965873165(7)
Pulse-frequency derivative (Hz s^{-1})	$-0.109195(3)\times10^{-13}$
Second derivative of pulse frequency (Hz s^{-2})	$-0.56(3)\times10^{-25}$

() denotes 1σ error according to least-square fitting (red-noise contribution in the error estimates are not included).

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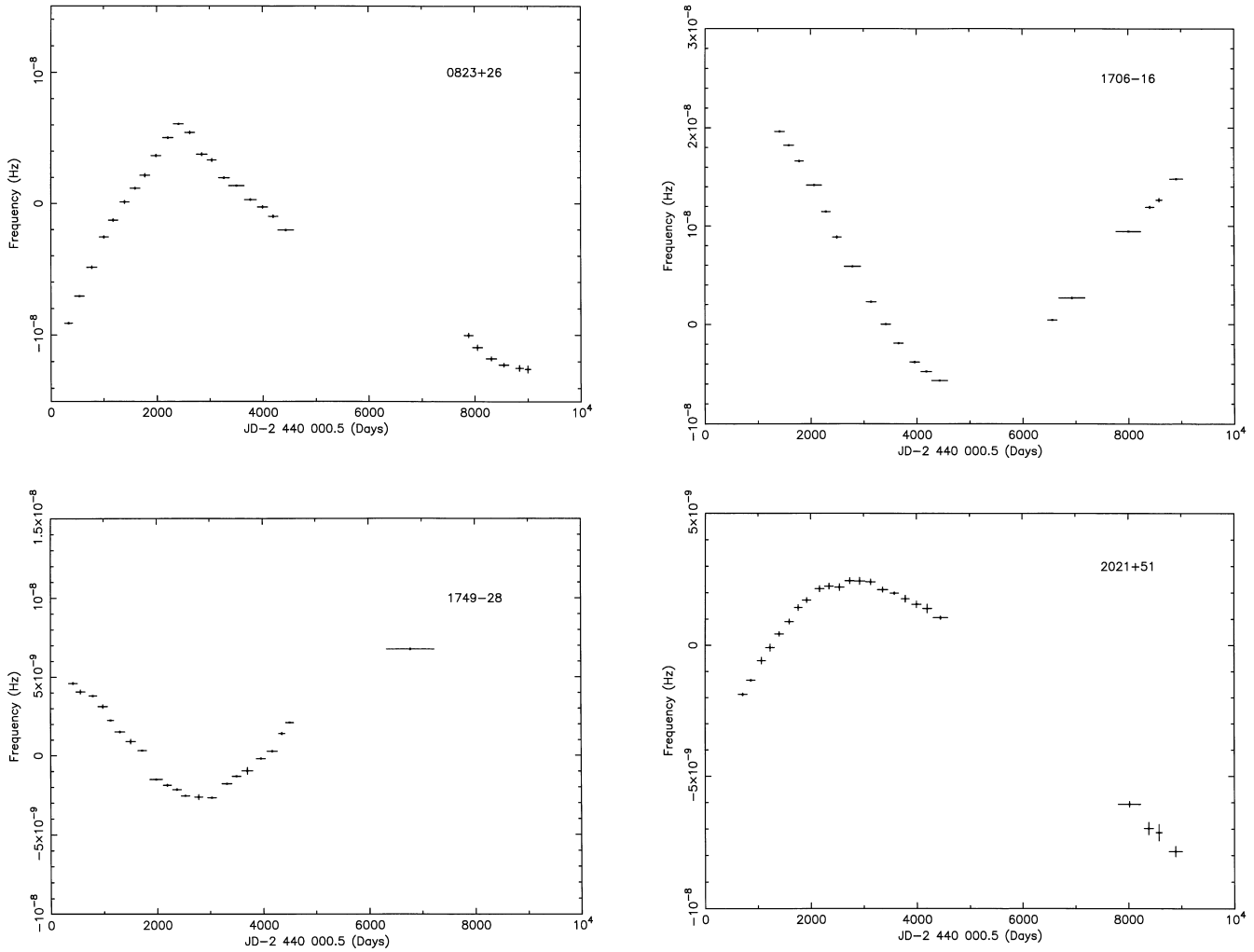


Figure 1. Pulse-frequency residuals of PSR 0823+26, 1706−16, 1749−28, 2021+51 after removing secular spin-down trend of the data.

significantly lower and different power spectrum, compared with the other polynomial models.

3.1 Diagnostic of power spectra

In the estimation of noise strengths, we adopted r=1 for pulse-frequency data and r=2 for the TOA data. If the noise-strength measurements are constant, independent of observing frequency or equivalently, the power spectra have zero slope, then pulse-frequency fluctuations can be explained in terms of a stationary random walk model and fluctuations of the pulse-frequency derivatives can be explained as a stationary white noise model; at all time-scales, the same noise process prevails. For the data from the four pulsars at hand, the power-density estimates (or noise strengths) have higher values at low frequency. In the power spectra, power-density estimates in the derivative of the pulse frequencies (see Fig. 2 and Table 2) behave approximately as $P_{\dot{\nu}} \sim f^{-\alpha}$, where $\alpha\sim$ 0.5-2.4, indicating the presence of strong red noise. As seen from Table 2 two of the sources PSR 0823+26 and 1749−28 have non-even integer power-law indices with large error bars in the power spectra of their pulse-frequency derivatives. On the other hand, PSR 2021+51 and 1706−16 have power-law indices ~ -2, which implies that pure random walk in the pulse-frequency derivatives (or $P_{\dot{\nu}} \sim f^{-2}$) (Boynton & Deeter 1982) is possible. This suggests that either some of these pulsars experience unresolved step-like perturbations that are superposed on the white-noise process in their pulse-frequency-derivative histories (mixed process) or they are making pure random walks in their pulse-frequency derivatives. The deviation from white noise to red noise in the pulse-frequency derivatives may arise from both arguments.

4 CONCLUSION

We have investigated the stability of the pulse-frequency second derivatives ($\ddot{\nu}$) of four pulsars that show significant quadratic trends in their pulse-frequency histories in order to determine whether the observed second derivatives are secular or if they arise as part of noise processes. We have used TOA data extending to more than three decades. These are the longest time-spans ever taken into account in pulse-timing analyses. We investigated the stability of the pulse-frequency second derivative in the framework of low-resolution noise power spectra (Deeter 1984) estimated from the residuals of pulse frequency and TOA data. Two independent noise strengths were estimated for each source, by removing the $\dot{\nu}$ and $\ddot{\nu}$ from the longest time-span of data sets and their independent subsets of data. We found that the power spectra obtained from

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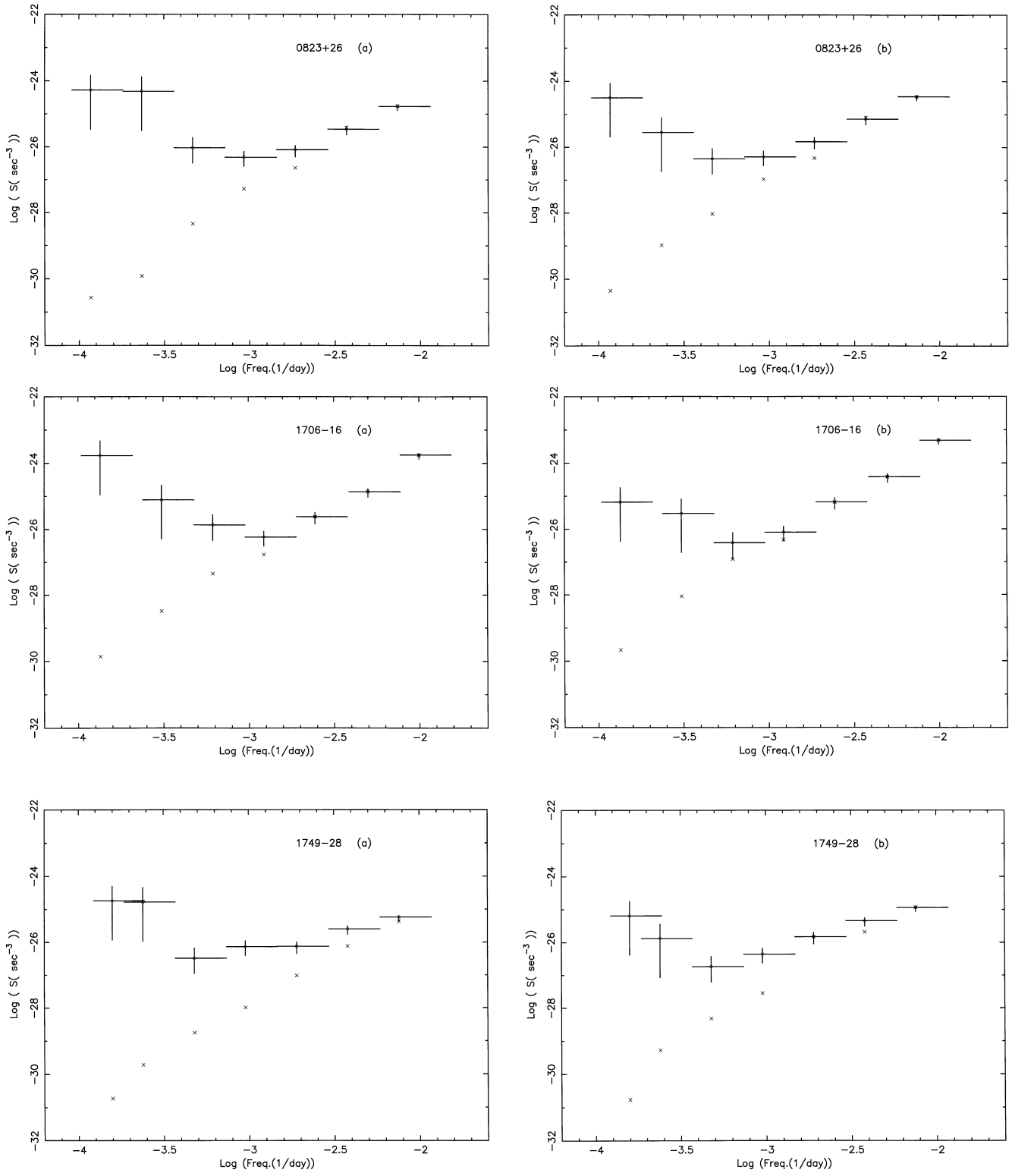


Figure 2. Power-density spectra of the fluctuations in the pulse frequency derivatives ($P_{\dot{\nu}}$) of PSR 0823+26(a,b), 1706−16(a,b), 1749−28(a,b), 2021+51(a,b). The power- density estimates are indicated by error bars. Vertical error bars indicate the stability of each power estimate (approximately $\pm 1\sigma$ error bars) as obtained by Monte Carlo simulations including the uncertainties in the pulse frequency and TOA data. Horizontal error bars indicate approximate $\pm 1\sigma$ error bars of the distribution of analysis frequencies sampled by each power- density estimate, as specified by Deeter (1984). The contributions to the noise strengths owing to uncertainties in the pulse frequency and TOA data are plotted as crosses. The notation (a) denotes that power- density estimates are obtained by removing linear trends from pulse-frequency data and quadratic trends from the TOA data and (b) denotes that one-degree higher polynomials are removed in each power-density estimate.

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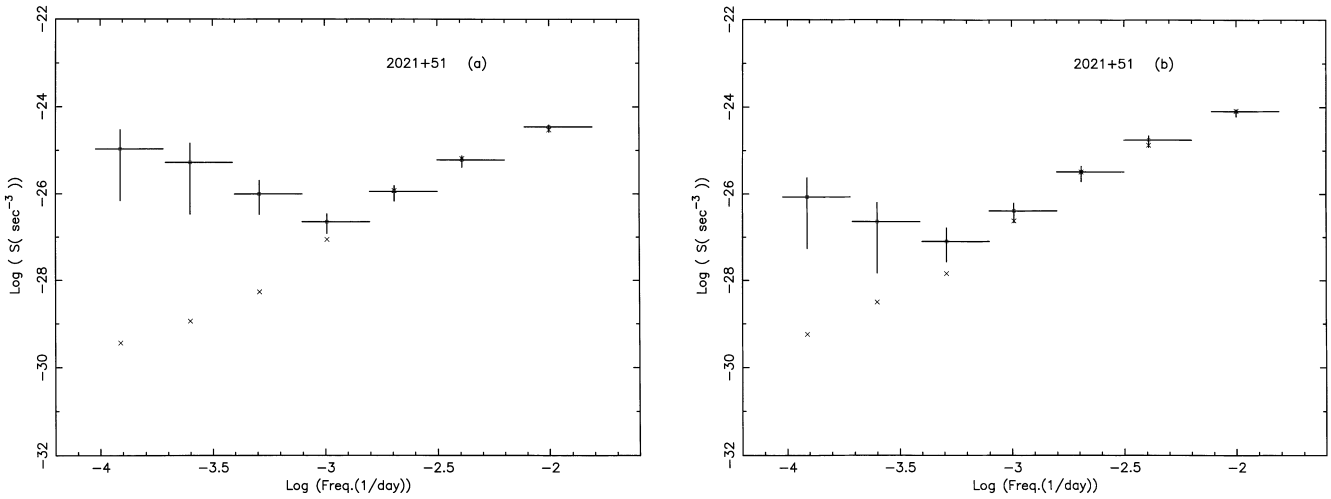


Figure 2 – *continued*

the residuals after removing $\dot{\nu}$ or an additional secular $\ddot{\nu}$ term were consistent with each other at the 1σ confidence level. This shows that the quadratic trends ($\ddot{\nu}$) in pulse-frequency time series were not secular: in the sense that including a $\ddot{\nu}$ term in the fits does not provide a significant improvement over the fits with $\dot{\nu}$ alone. What are the possible sources of the noise process in these systems? Using the vortex creep theory, Alpar et al. (1986) developed model noise power spectra for three different types of events that might affect the observed timing noise. These events were: (i) pure vortex unpinning events (microglitches), (ii) breaking of the crustal lattice by pinned vortices, (iii) external events that do not involve vortex unpinning. They predict the form of the power spectrum of timing noise in the derivative of pulse frequency ($\dot{\nu}$) to be

$$P_{\dot{\nu}}(f) = 4\pi^2 R < \Delta\Omega^2 > \frac{(1-Q)^2 + f^2\tau^2}{4\pi^2 + f^2\tau^2} (\mathrm{rad^2 s^{-3}}), \qquad (3)$$

where R is the microglitch or breaking of the crust rate (event rate), $< \Delta\Omega^2 >$ is the root mean square of the pulse-frequency fluctuations (step size of the fluctuations), $Q = [\int_0^{\inf} \Delta\dot{\nu}(t)\mathrm{d}t]/\Delta\nu$ is the fractional change in the pulse frequency for each relaxed event, τ is the relaxation time for each event.

The above model noise spectra change at around $f{=}\tau^{-1}$. $Q{=}1$ is the pure unpinning case. In this model, logarithmic slope of the spectrum changes from +2 (blue) to 0 (white) noise at $f{=}\tau^{-1}$. If $(1-Q)^2 \gg 1$ or $(1-Q)^2 \ll 1$ the events are dominated by crust breaking. The initial pulse-frequency jump can relax to any value owing to the initial crust quake. Therefore, Q can take any value different from 1. The power spectrum of the noise resulting from unpinning events from the initial crust quake (or mixed events) have slopes of 0 at low frequency, ± 2 at $f \sim \tau^{-1}$ and 0 at high frequency. Therefore, white noise in the $\dot{\nu}$ time series is expected at very low and high frequencies. Change in the noise level is expected at time-scales τ owing to the coupling of superfluid layers. Naturally, events that do not involve vortex unpinning should show almost null coupling (or infinite coupling time), therefore flat-noise spectra in the fluctuations of $\dot{\nu}$ time series are expected. However, the power spectra at hand favour red noise in $\dot{\nu}$ fluctuations at all frequencies, especially at low frequency.

Table 2. Parameters of power spectra.

Pulsar		Mean noise strength log(s^{-3})	Power-law index
PSR 0823+26	(a)	−25.93	−1.16 ± 0.48
	(b)	−25.93	−0.39 ± 0.36
PSR 2021+51	(a)	−26.21	−1.95 ± 0.74
	(b)	−26.72	−1.64 ± 1.40
PSR 1706−16	(a)	−25.65	−2.41 ± 0.79
	(b)	−25.88	−1.94 ±1.33
PSR 1749−28	(a)	−26.03	−0.88 ± 0.50
	(b)	−26.27	−1.05 ± 0.83

(a) estimates the noise strengths from the residuals of the linear trend of the pulse-frequency data and the quadratic trend of TOA data. (b) uses one order higher degree of polynomial in the estimation of noise strengths (see the text).

Cheng (1987a,b) has suggested that red noise in pulse-frequency derivatives may arise from external torques from the magnetosphere of pulsar. In this model, pair production processes in the outer gap of the magnetosphere can give rapid variation in the current braking torque $\delta N_{\delta J \times B}$, where δJ is a perturbed current on the magnetosphere of the pulsar and B is the external magnetic field. If the current braking torque perturbs the rotation rate of the neutron star by microglitches this torque will remain unchanged until the next microglitch and hence, step-like changes in the torque will give rise to a random walk in $\dot{\nu}$. The rate of the torque variations, naturally, will be the same as the rate of microglitches, which may occur as a result of the internal re/decoupling of crust superfluid and crust or sudden movement of neutron-star crustal plates of the type described by Ruderman (1991). Of course, if the microglitches seldom occur, a quasi-random walk in the power spectra of $\dot{\nu}$ time series is expected. Our measured noise power spectra in the $\dot{\nu}$ time series are consistent with red noise and hence may arise from magnetospheric torque fluctuations.

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