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MEASUREMENTS OF RADIO PULSAR BRAKING INDICES: A STATISTICAL APPROACH

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Abstract

A statistical technique for measuring the braking index of radio pulsars is presented. Our method employs the recently reported strong correlation (with correlation coefficient $r = 0.95$) between the observed second time derivative of the pulse rotation frequency ($\ddot{\nu}_{\rm obs}$), obtained from fully phase-coherent timing analyses, and a timing noise statistic ($\sigma_{\rm R23}$), used to quantify the amount of pulsar rotational fluctuations absorbed by the cubic term, to estimate the component of the measured braking index originating solely from pulsar timing irregularity ($\ddot{\nu}_{\rm tno}$). The presumed deterministic braking index from electromagnetic torque braking processes ($\ddot{\nu}_{\rm dip}$) is subsequently obtained as the magnitude of the difference between $\ddot{\nu}_{\rm obs}$ and $\ddot{\nu}_{\rm tno}$. Application of this method to a sample of 27 radio pulsars, whose timing data span $\sim 9 - 13$ years, show that (i) for 12 pulsars, the observed timing activity is too weak to allow for unambiguous braking index measurements, (ii) for 5 pulsars, the braking index appears to be significantly measured ($n \lesssim 3$), and (iii) for 10 pulsars, the braking indices have anomalous values. These results are discussed in the context of the prevailing standard model for radio pulsar spin-down.

1 Introduction

Accurate measurements of the braking index (n, which describe how the pulsar spin-down rate varies with its rotation frequency) is fundamental to understanding the pulsar electrodynamics (Yue, Xu & Zhu 2007, and references therein). Currently, the prevailing picture is that pulsars are rapidly rotating highly magnetised neutron stars powered by the rotational kinetic energy of the underlying neutron stars (Goldreich & Julian 1969; Manchester & Taylor 1977; Shapiro & Teukolsky 1983). In the context of the widely acclaimed standard model, the dominant energy loss mechanism is via pure magnetic dipole radiation at the pulsar rotation frequency and acceleration of particle winds (Pacini, 1967; Manchester & Taylor 1977). The model posits that the spin-down of a pulsar should follow a simple power relation of the form (e.g. Manchester & Taylor 1977)

$$\dot{\nu} = -K\nu^n, \tag{1}$$

where ν and $\dot{\nu}$ are, respectively, the pulse rotation frequency and its first time derivative, K is an arbitrary positive constant and $n = 3$ is the torque braking index. Equation (1) can be differentiated to obtain an expression for n in terms of the pulsar rotational parameters

$$n = \frac{\nu\ddot{\nu}}{\dot{\nu}^2}, \tag{2}$$

where $\ddot{\nu}$ is the second derivative of the pulsar spin frequency with respect to time. Eq. (2) suggests that measurements of pulsar braking index, in principle, could follow directly from the standard pulsar timing technique involving a third-order polynomial model.

However, accurate measurements of n have proven extremely difficult. To date, significant measurements have been reported in only 6 out of $\sim$ 1800 known pulsars. All the six measurements were obtained from the phase-coherent timing analysis (hereafter referred to as PCTA), a technique that relies on accounting for every turn of the pulsar (Lyne, Pritchard & Smith 1988; Kaspi, et al. 1994; Lyne et al. 1996; Camilo et al. 2000; Livingstone et al. 2006, 2007). The apparent difficulty in measuring pulsar braking index has been largely attributed to the effects of pulsar rotational irregularity, most pulsars exhibit a wide range of departures from the assumed spin-down law (Lyne & Graham-Smith 1998; Lorimer & Kramer 2005). Broadly speaking, pulsar timing activities can take the form of glitches, spectacular sudden jump in ν and $\dot{\nu}$, (e.g. Zou et al. 2008, and references therein) and the more generic timing noise, observed as structures in the phase residuals after accounting for the pulsar deterministic spin-down (e.g. Hobbs, Lyne & Kramer 2006, and references therein). The presence of pulsar timing activity contaminates the deteriministic spin parameters, making accurate measurement of the parameters almost impossible. Perhaps, $\ddot{\nu}$ is most vulnerable to timing activity effects owing to its extremely small amplitude (Chukwude 2007, and references therein).

Efforts to mitigate the effects of timing activity in braking index measurement have, hitherto, relied on either pre-whitening of barycentric times of pulse arrival (BTOAs) or an outright negation of the second derivative of the pulsar rotation frequency. Simple polynomial whitening, in which

BTOAs are whitened by including mth-order frequency derivatives (where m > 3) in timing model, has yielded accurate n measurements in few pulsars (Manchester, Newton & Durdin 1985; Kaspi et al. 1994; Livingstone et al. 2007). Incidently, all these objects are younger than 3 kyr and are rapidly spinning down pulsars ($|\dot{\nu}| \gtrsim 10^{-11}$ s^{-2}). Recently, Hobbs et al. (2004) developed the harmonic whitening technique, in which BTOAs are first whitened by least-squares fitting of harmonically-related sinewaves. The pre-whitened BTOAs are thereafter fitted with the standard timing models. Application of this technique to a sample of 374 pulsars (Hobbs et al. 2004) failed to produce any realistic measurement of n in the objects. Several authors (e.g. Lyne et al. 1993) have implemented a partially phase-coherent technique, in which pulsar spin-down rates ($\dot{\nu}$) are carefully calculated at different epochs (t) using local fits to relatively shorter spans BTOAs. In this case, $\ddot{\nu}$ is indirectly obtained from the slope of $\dot{\nu}$(t)− t plot. This method presupposes that the resulting cubic term would be minimally contaminated by prevalent pulsar timing activity. It yields $n = 1.4$ and 2.51, respectively, for Vela and Crab pulsars (Lyne et al. 1993, 1996). Similarly, Johnston & Galloway (1999) integrated equation (1) to obtain an expression for n in terms of the presumably more stable spin parameters, ν and $\dot{\nu}$. Inspite of its comparative advantage of negating the highly unstable $\ddot{\nu}$, the technique yielded only anomalous braking indices, when applied to a sample of 20 pulsars (Johnston & Galloway 1999).

In this paper, we present an alternative method of measuring radio pulsar braking indices. The method employs the conventional PCTA to obtain measurements of the rotation parameters (ν, $\dot{\nu}$ and $\ddot{\nu}$) and the difference between the root-mean-square phase residuals from second and third polynomial models. Subsequently, a simple statistical technique is used to remove the contribution of timing activity to the observed frequency second time derivative (presumed to be the sum of the deterimistic and timing fluctuation components).

2 Theory of relationships

Following Chukwude (2003), the frequency second time derivative obtained from a fully phase-coherent timing solution ($\ddot{\nu}_{\rm obs}$) can be modeled in terms of the timing noise and the systematic components as

$$\bar{\ddot{\nu}}_{\rm obs} = \ddot{\nu}_{\rm tno} + \ddot{\nu}_{\rm dip}, \tag{3}$$

where $\ddot{\nu}_{\rm tno}$ is the component that originates from all forms of fluctuations in the pulsar clock (unresolved glitches and timing noise), $\ddot{\nu}_{\rm dip}$ is the deterministic spin-down component and $\bar{\ddot{\nu}}_{\rm obs} \equiv |\ddot{\nu}_{\rm obs}|$ is the magnitude of the observed braking index. This model makes, at least, two elegant predictions. Firstly, the coefficient of the cubic term merely models the deterministic pulsar spin-down, by way of pure dipole magnetic torque braking (Manchester & Taylor 1977). This requires that $\ddot{\nu}_{\rm tno} \ll \ddot{\nu}_{\rm dip}$ and $\ddot{\nu}_{\rm obs} \simeq \ddot{\nu}_{\rm dip}$. In this context, $\ddot{\nu}_{\rm obs}$ is expected to yield $n \simeq 3$. This is, most probably, the case for the five young pulsars whose braking indices have been significantly measured via PCTA technique (e.g. Livingstone et al. 2007).

An alternative scenario is that $\ddot{\nu}_{\rm obs}$ predominantly quantifies the level of the pulsar rotational irregularity. The later scenario will require $\ddot{\nu}_{\rm tno} \gg \ddot{\nu}_{\rm dip}$ and $\ddot{\nu}_{\rm obs} \simeq \ddot{\nu}_{\rm tno}$ (but $\ddot{\nu}_{\rm dip}$ is not necessarily equal to zero). These conditions will result in non-stationary braking indices, with either positive or negative values. In particular, the braking indices obtained from $\ddot{\nu}_{\rm obs}$ will have anomalous values, many orders of magnitude greater than or less than the canonical value of 3 (Johnston & Galloway 1999; Chukwude 2003; Hobbs et al. 2004). Moreover, $\ddot{\nu}_{\rm obs}$ will, almost certainly, correlate with some timing noise statistics. A statistic of interest is the difference between the root-mean-squares phase residuals obtained from 2nd- and 3rd-order polynomial models ($\sigma_{\rm R23}$). Using a sample of 27 radio pulsars, Chukwude (2003) shows that σ_{R23} is 95 % correlated with timing noise dominated $|\ddot{\nu}_{\rm obs}|$. This is perhaps the most plausible scenario in majority of radio pulsars. Following Chukwude (2003), we redefine the timing noise statistic ($\sigma_{\rm R23}$) as

$$\sigma_{\rm R23} = \sqrt{\sigma^2_{\rm R2}(2,T) - \sigma^2_{\rm R3}(3,T)}, \tag{4}$$

where $\sigma_{\rm R2}(2,T)$ and $\sigma_{\rm R3}(3,T)$ are, respectively, the root mean square residuals from second- and third-order polynomial fits to the BTOA data and T is the data timespan length. On the premise that the later scenario is the prevailing case for most known radio pulsars (especially those with $\tau_c \geq 5$ kyr), we posit a simple power-law relation between the observed braking index and the timing irregularity statistic of the form

$$\ddot{\nu}_{\rm tno} = A\sigma^{\beta}_{\rm R23}, \tag{5}$$

where we take A and β (power law index) are constants for a given sample. Theoretically, A represents the smallest value of $\ddot{\nu}$, for the sample, with minimal timing activity contamination. We have used the condition that for the current scenario, $\bar{\ddot{\nu}}_{\rm obs} \simeq \ddot{\nu}_{\rm tno}$, to arrive at equation (5). Once A and β are obtained for a sample of radio pulsars, equation (5) can be used to estimate the timing activity component of the pulsar braking index ($\ddot{\nu}_{\rm tno}$). The deterministic component of the frequency second derivative is given by

$$\ddot{\nu}_{\rm dip} = |\bar{\ddot{\nu}}_{\rm obs} - \ddot{\nu}_{\rm tno}|. \tag{6}$$

The choice of definition of $\ddot{\nu}_{\rm dip}$ in equation (6) is necessitated by the non-stationary character of $\ddot{\nu}_{\rm obs}$.

3 Observations and data analyses

Regular timing observations of all pulsars in the current sample commenced at Hartebeesthoek Radio Astronomy Observatory between 1984 January and 1987 May and is still ongoing. However, a major interruption in HartRAO pulsar timing program occurred between 1999 June and 2000 August during a major hardware upgrade. Save for pulsars B0833−45 and B1641−45, which were on real time glitch monitoring program, no pulsar was observed during this period. Observations were made regularly at intervals of $\lesssim$ 14 days at either 1668 or 2272 MHz using the 26-m HartRAO radio telescope. Pulses were recorded with a single 10 MHz bandwidth receiver at both frequencies and no pre-detection dedispersion hardware was implemented during the period. Detected pulses were smoothed with an appropriate filter-time constant, and integrated over $N_{\rm p}$ consecutive rotation periods, where $N_{\rm p}$ is different for different pulsars. An integration was usually started at a particular second by synchronization to the station clock, which was derived from a hydrogen maser and was referenced to the Universal Coordinated Time (UTC) via a Global Positioning Satellite (GPS) network.

All topocentric arrival times obtained at HartRAO, between 1984 and 1999, were transformed to infinite observing frequency at the Solar System Barycentre (SSB) using the Jet Propulsion Laboratory DE200 solar system ephemeris and the TEMPO software package (http://pulsar.princeton.edu/tempo). Subsequent modelling of the resulting barycentric times of arrival (BTOAs) was accomplished with the HartRAO in-house timing analysis software, which is based on the standard pulsar timing technique of Manchester & Taylor (1977) and is well described in Flanagan (1995). At the solar system barycentre, the time evolution of the rotational phase of a non-binary pulsar is better studied by fitting the BTOAs with a Taylor series expansion of phase of the form (e.g. Manchester & Taylor 1977)

$$\phi(t) = \phi_0 + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \frac{1}{6}\ddot{\nu}(t - t_0)^3, \tag{7}$$

where ϕ_0 is the phase at an arbitrary time t_0. In practice, for sufficiently accurate values of ν, $\dot{\nu}$ and $\ddot{\nu}$, Eq. (7) was used to predict the phase of a given pulsar at any time, t. Usually, the BTOAs and initial pulsar rotation parameters constitute the input to the timing analysis software. The output consists of the refined spin-down parameters and timing residuals (the difference between the observed and model-predicted arrival times). Following Cordes & Downs (1985), the phase residuals, $\Re(t_{\rm j})$ for $1 \leq {\rm j} \leq {\rm N}$ where N is the number of observations, are used to calculate the root-mean-square phase residuals $\sigma_{\rm R(m,T)}$ (where, m = 2 and 3 for 2nd- and 3rd-order polynomial fits, respectively, and T is the observation time span.).

4 Results

The relevant measured and derived parameters of the 27 HartRAO pulsars are summarized in Table 1. Column 1 contains the pulsar name using the B1950.0 naming convention; Cols. 2 and 3 list the spin frequency and the associated formal standard error; the spin-down rate and its formal error are contained in Cols. 4 and 5; Cols. 6, 7 and 8 list, respectively, the observed frequency second derivative, its formal standard error and the timing activity statistic; the calculated timing activity component of the $\ddot{\nu}$ and its formal error are listed in Cols. 9 and 10, respectively; Cols. 11 and 12 contain the pressumed deterministic component of $\ddot{\nu}$ and the associated formal error, respectively, while the resulting braking index ($\rm n_{dip} \equiv \ddot{\nu}_{dip}\nu/\dot{\nu}^2$) and the formal standard error are listed, respectively, in Cols. 13 and 14.

Table 1: The result of the observed and calculated parameters of the 27 HartRAO Pulsars.

Object PSRB (1)	ν s^{-1} (2)	$\Delta\nu$ a (3)	$\dot{\nu}$ $10^{-15}s^{-2}$ (4)	$\Delta\dot{\nu}$ a (5)	$\ddot{\nu}_{obs}$ $10^{-25}s^{-3}$ (6)	$\Delta\ddot{\nu}_{\rm obs}$ a (7)	σ_{R23} mP (8)	$\ddot{\nu}_{\rm tno}$ $10^{-25}s^{-3}$ (9)	$\Delta\ddot{\nu}_{\rm tno}$ b (10)	$\ddot{\nu}_{\rm dip}$ $10^{-25}s^{-3}$ (11)	$\Delta\ddot{\nu}_{\rm dip}$ b (12)	$n_{\rm dip}$ (13)	$\Delta n_{\rm dip}$ (14)
0450-18	1.821696158392	6	-19.091821	18	0.051	12	1.3	0.067	0.200	0.016	0.210	8	105
0736-40	2.66723899983	7	-11.467300	16	-7.674	6	280.6	15.26	0.38	7.59	0.38	15386	760
0740-28	5.99657769025	6	-604.73385	6	-35.54	8	620.9	34.04	0.80	1.504	0.740	2.5	1.2
0835-41	1.330454723903	9	-6.271580	5	0.3795	10	8.5	0.444	0.025	0.065	0.031	219	80
0959-54	0.69609220478	6	-24.994522	12	-13.827	4	260.3	14.15	0.35	0.32	0.35	35	39
1054-62	2.36715607565	7	-20.01190	4	-0.326	6	4.4	0.23	16	0.094	0.158	56	92
1133+16	0.84181190896	12	-2.645946	6	0.0652	8	2.2	0.114	0.016	0.049	0.016	593	196
1221-63	4.619428499992	10	-105.71397	4	-0.1410	10	4.0	0.21	0.10	0.069	0.100	2.9	3.9
1240-64	2.574123963978	5	-29.819964	12	-0.744	4	14.3	0.647	0.057	0.097	0.058	28	17
1323-58	2.09208875280	6	-14.12989	6	4.402	6	39.1	2.082	0.085	2.320	0.087	2430	90
1323-62	1.88709280930	5	-67.258115	14	-1.706	4	33.1	1.764	0.050	0.058	0.050	2.4	2.0
1356-60	7.84290777286	4	-389.86801	7	5.06	7	85.2	4.58	0.13	0.48	0.15	2.5	7
1358-63	1.186530997525	6	-23.58777	5	8.692	8	160.2	8.66	0.23	0.027	0.220	6	48
1426-66	1.273169693773	7	-4.489741	12	-0.190	9	2.4	0.126	0.098	0.064	0.130	401	840
1449-64	5.57148949973	5	-85.23778	6	1.592	10	29.2	1.55	0.14	0.041	0.140	3	10
1451-68	3.796841136660	12	-1.424633	10	-0.037	4	0.5	0.023	0.178	0.014	0.170	2544	33259
1556-44	3.890198835898	7	-15.42827	5	0.212	8	2.6	0.137	0.088	0.075	0.080	123	144
1557-50	5.192073158034	6	-136.46835	6	-0.046	7	2.8	0.145	0.025	0.099	0.025	2.8	6
1641-45	2.197513500235	11	-97.11850	8	4.1687	6	85.7	4.60	0.12	3.43	0.12	80	3
1642-03	2.57938001879	6	-11.85138	5	-0.123	6	8.2	0.428	0.065	0.305	0.065	560	124
1706-16	1.531264844912	8	-14.73178	4	6.341	7	85.8	4.61	0.15	1.73	0.15	1222	106
1727-47	1.205132491642	18	-237.60720	5	3.560	8	43.5	2.268	0.065	1.29	0.10	2.8	2
1749-28	1.777590485696	20	-25.670282	9	-0.099	4	10.7	0.564	0.048	0.465	0.048	125	13
1822-09	1.30042174971	8	-88.36158	10	14.262	6	258.6	14.05	0.35	0.21	0.35	3.5	5.9
1929+10	4.41466176139	15	-22.542298	17	-2.185	7	12.5	0.657	0.076	1.528	0.075	1327	66
1933+16	2.78753800616	14	-46.638826	14	0.145	10	3.3	0.172	0.061	0.027	0.060	3.4	7.5
2045-16	0.509794578169	12	-2.848134	7	0.0086	12	0.1	0.005	0.004	0.003	0.004	21	23

[a] Errors are 2σ formal standard errors and refer to the last significant digit.

[b] is in units of $10^{-25}s^{-3}$.

Figure 1 shows, on $\log - \log$ scale, the plots of the absolute values of the observed frequency second derivative ($|\ddot{\nu}_{\rm obs}|$) against the timing noise statistic, $\sigma_{\rm R23}$ (Fig. 1a) and the measured braking indices ($n_{\rm dip}$) against the presumed deterministic frequency second derivative, $\ddot{\nu}_{\rm pre}$ (Fig. 1b). Fig. 1a shows that the current definition of the pulsar timing activity statistic minimized the scatter in the $\ddot{\nu} - \sigma_{\rm R23}$ plot. A simple linear regression analysis of the data in Fig. 1a yields a correlation coefficient $r = +0.97$, which is a slight improvement over $\sim +0.95$ reported for the two parameter by Chukwude (2003). In particular, we find

$$\log|\ddot{\nu}_{\rm obs}| = -26.29 \pm 0.05 + (1.01 \pm 0.03)\log\sigma_{\rm R23}, \tag{8}$$

The quoted errors are 2-σ formal standard errors and refer to the least significant digits. The strength of the correlation reaffirms earlier results (Chukwude 2003; Hobbs et al. 2004) that the braking indices of most pulsars measured from PCTA are severely contaminated by effects attributable to pulsar timing activity (i.e. $|\ddot{\nu}_{\rm obs}| \simeq \ddot{\nu}_{\rm tno}$). Estimates of $\ddot{\nu}_{\rm tno}$ and $\ddot{\nu}_{\rm dip}$ follow directly from equations (5) and (6), respectively. Fig. 1b shows that our method resulted in $n \sim 3$ for pulsars with $\ddot{\nu}_{\rm pre} \gtrsim 5 \times 10^{-27}$ s^{-3}, irrespective of the size of the error bars. The departure from 3, however, increases sharply below 5×10^{-27} s^{-3}. For a given value of $\ddot{\nu}_{\rm pre} < 5 \times 10^{-27}$ s^{-3}, the amplitude of the departure is relatively smaller for pulsars that exhibit weak timing activity ($\sigma_{\rm R23}/\sigma_{\rm W} < 5$).

The uncertainties listed in Table 1 are 2-σ formal standard errors and refer to the least significant figures. The quoted errors in ν, $\dot{\nu}$ and $\ddot{\nu}_{\rm obs}$ were obtained directly from the HartRAO in-house timing analysis software, others were calculated. The error in $\sigma_{\rm R23}$ is contributed largely by pulse phase jitter and instrumental errors and will, generally, have the character of white noise (Cordes & Downs 1985).

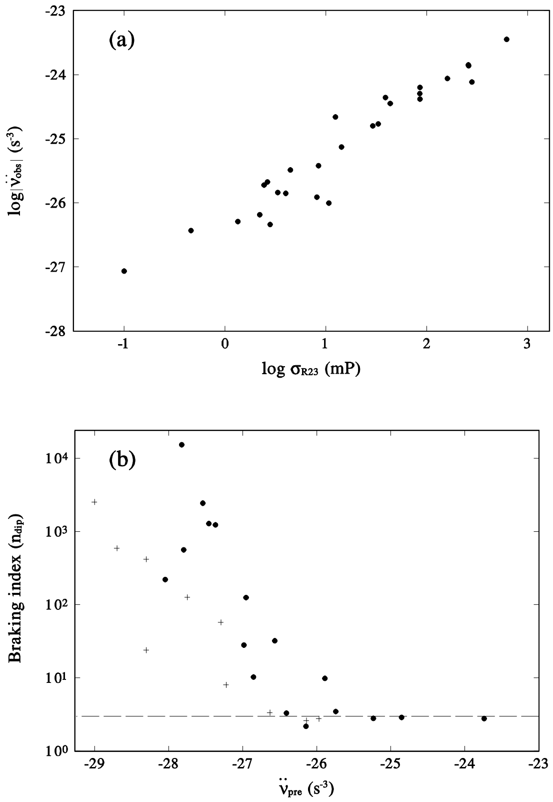

Figure 1: Scatter plots of (a) absolute magnitude of the frequency second time derivative ($\ddot{\nu}_{\rm obs}$), obtained from fully phase-coherent timing analysis against the timing noise activity paramater ($\sigma_{\rm R23}$), obtained as described in the text, and (b) the calculated braking indices ($n_{\rm dip}$), against the deterministic frequency second derivative, expected from the standard vacuum dipole model ($\ddot{\nu}_{\rm pre}$), obtained as described in the text. The long dash horizontal line indicates $n = 3$, the canonical value of the braking index. Key: $\bullet$ = pulsars with pronounced timing activity ($\sigma_{\rm R23} > 5\sigma_{\rm W}$); $+$ = pulsars showing very weak timing activity ($\sigma_{\rm R23} < 5\sigma_{\rm W}$).

The rms white noise ($\sigma_{\rm W}$) was estimated over time intervals of ≤ 1 day using phase residuals from a second-order timing models (Chukwude 2002). The short time scale is necessary to filter out the more slowly varying red noise component from the white noise estimator (Cordes & Downs 1985; Chukwude 2002). Hence, estimates of $\sigma_{\rm W}$ represent the upper limit on the error in $\sigma_{\rm R23}$. Pulsars whose phase residuals display large amplitude intrinsic scatter are characterised by large values of ($\sigma_{\rm W}$). For those objects, the error in $\ddot{\nu}_{\rm tno}$ is dominated by the uncertainty in the rms phase residuals and could be as high as $\sim 700\%$ of the parameter value.

5 Discussion

The dispersions in both the characteristic ages (τ_c) and spin-down rates ($\dot{\nu}$) of the current sample of 27 radio pulsars exceed 2 orders of magnitudes $(78 - 43,000)$ kyr and $(1 - 600)\times10^{-15}$ s^{-2}, respectively, suggesting that they are relatively young and middle-aged pulsars. The results of our analysis can be summarised as follows:

(i) the braking index measurements in 12 pulsars are seemingly ambiguous, with uncertainties in excess of the measured parameters.
(ii) within the limits of quoted errors, significant n measurements (with $n = 2.5 - 2.8$) were possible for 5 pulsars; and
(iii) for the remaining 10 pulsars, our method again produced anomalous braking indices ($28 \lesssim n < 15400$).

The size of the error bars in some of the measured braking indices is somewhat worrisome. There are two major sources of errors in the calculated results. Firstly, small number statistics limits the measurement precision to $\gtrsim 2.5\%$ of the parameter values in all objects in the sample. A more serious limitation on accuracy of our results comes from the signal-to-noise (SNR) of the data. Uncertainties in $\sigma_{\rm R23}$ could introduce errors in the range $\sim 0.2 - 700\%$ of the observed braking index. Generally, the quoted formal errors in the parameters of pulsars with low SNR ($\sigma_{\rm R23}/\sigma_{\rm W} \lesssim 10$) are dominated by uncertainty in the rms phase residuals ($\sigma_{\rm R23}$). For instance, the minimum error in $\ddot{\nu}_{\rm tno}$ for the highest SNR pulsar in the current sample is $\sim 2.7\%$ of $\bar{\ddot{\nu}}_{\rm obs}$. This error, basically, propagates through all subsequent derived parameters ($\Delta\ddot{\nu}^2_{\rm dip} = \Delta\ddot{\nu}^2_{\rm obs} + \Delta\ddot{\nu}^2_{\rm tno}$). Consequently, the uncertainty in the presumed deteriministic frequency second derivative ($\ddot{\nu}_{\rm dip}$) range between $\sim 2.7 - 700\%$ of $\ddot{\nu}_{\rm tno}$. In most cases, this is several orders of magnitude greater than the expected intrinsic pulsar braking index. The formal error in the measured braking index ($\rm n_{dip}$), which scales approximately as $\Delta\ddot{\nu}_{\rm dip}/\ddot{\nu}_{\rm dip}$, is expected to be extremely large for pulsars shown to have $\sim \Delta\ddot{\nu}_{\rm dip} \gg \ddot{\nu}_{\rm dip}$. Minimization of the errors in the measured braking indices would require using larger sample of high SNR pulsars. For instance, an order of magnitude increase in the sample size will yield ~ 1 order of magnitude improvement in formal errors, provided that the SNR > 100.

All the 5 objects (B0740−28, B1323−62, B1356−60, B1557−50 and B1727−47) for which the braking indices appear to be significantly measured are moderately spinning down pulsars, $|\dot{\nu}| \sim (50 - 600) \times 10^{-15} {\rm s}^{-2}$. Save for PSR B0740−28 (with $\tau_c \sim 1500$kyr), all are younger than 600 kyr. The peculiar nature of the pulsar B0740−28 has recently been highlighted (Chukwude 2007). The author shows that the pulsar's spin-down rate of $\sim -605 \times 10^{-15}$ s^{-2} is atypical of objects of similar spin-down age. In addition, the 5 pulsars are characterised by $\ddot{\nu}_{\rm pre} \simeq (0.05 - 1.51) \times 10^{-25}$ s^{-3}, where $\ddot{\nu}_{\rm pre} \equiv 3\dot{\nu}^2/\nu$ is the deterministic frequency second derivative, assuming a standard vacuum dipole model with $n = 3$. Braking indices of these amplitudes will contribute $\sim 60 - 1800$ mP in a pulsar phase over a 13-yr span of data, which apparently could be measurable. The inability of the current technique to yield reliable value of n for the pulsar B1641−45, with comparable spin-down parameters and age, could be attributed to enhanced glitch activity in the object during the period under investigation (Flanagan 1993, 1995). Probably, the observed second frequency derivative for this pulsar is a measure of the slope changes occasioned by these events. Braking index measurements for 12 pulsars are apparently ambiguous, given error bars in excess of the measured parameters. Eight of these pulsars exhibit exceptionally weak timing activity. The corresponding low SNR introduces errors in the range $\sim 40 - 760\%$ in $\ddot{\nu}_{\rm tno}$, which for all the pulsars is well in excess of the measured

$\ddot{\nu}_{\rm dip}$. Athough three of these pulsars (B1221−63, B1449−64 and B1933+16) have $\rm n_{dip}$ = 2.9, 3, and 3.4, respectively, the estimated errors in the parameters are in excess by, at least, a factor. While the size of the errors precludes any definite claim on the measurements, it does not foreclose a possibility that the measured values of $\rm n_{dip}$ could be real.

The traditional phase-coherent technique is believed to be very sensitive to the size of pulsar spin-down rates (e.g. Lyne & Graham-Smith 1998; Lorimer & Kramer 2005; Livingstone et al. 2007). All the five pulsars, for which the technique yielded significant measurements of n, have $|\dot{\nu}| > 2 \times 10^{-11}$ $\rm s^{-2}$, $\tau_c \lesssim 11$ kyr and $\ddot{\nu}_{\rm pre} > 5 \times 10^{-22}$ $\rm s^{-3}$ (Lyne et al. 1993, 1996; Kaspi et al. 1994; Livingstone et al. 2005, 2006, 2007). However, pulsars with such unique characteristics are rare. For instance only $\sim 1\%$ of the about 1800 known pulsars have $|\dot{\nu}| > 1.0 \times 10^{-11}$ s/s (Baiden, private communication). Peharps, the most worrisome aspect of the PCTA method is its high sensitivity to pulsar timing irregularities (Chukwude 2003; Hobbs et al. 2004; Lorimer & Kramer 2005; Livingstone et al. 2007). It is now fairly well established that timing activity, either in form of glitches or the more generic timing noise, correlates strongly with pulsar spin-down rate (Cordes & Downs 1985; D'Alessandro et al. 1993; Chukwude 2003). In view of the rarity of pulsars with unusually large spin-down rates and the prevalence of timing activities amongst most pulsars, the phase-coherent technique, as it is applied currently, has little chance of improving the current statistics of measured braking indices.

The method presented in this paper, which is sensitive to the braking index of pulsars down to $|\dot{\nu}| > 40 \times 10^{-15}$ $\rm s^{-2}$, $\tau_c \lesssim 1500$ kyr and $\ddot{\nu}_{\rm pre} \gtrsim 3 \times 10^{-27}$ $\rm s^{-3}$, apparently appears more attractive. Consequently, our method can be applied more extensively in measuring n among the pulsar population. Current statistics (Baiden, private communication) suggest that about 600 pulsars have spin-down rates in excess of 40×10^{-15} $\rm s^{-2}$. Furthermore, it is the sensitivity of $\ddot{\nu}_{\rm obs}$ to pulsar timing irregularities that is enormously utilized in current technique for braking index measurement. This is remarkable given that timing irregularities (glitches and timing noise) constitute the greatest constraint on the PCTA technique (Cordes & Downs 1985; Lyne & Graham-Smith 1998; Hobbs et al. 2004; Lorimer & Kramer 2005). Objects with $|\dot{\nu}| \gtrsim 50 \times 10^{-15}$ $\rm s^{-2}$, generally classified as young and middle-aged pulsars, are most prone to all sorts of timing activity (Cordes & Helfand 1980; Cordes & Downs 1985; D'Alessandro et al. 1995; Wang et al. 2000; Chukwude 2002; Hobbs et al. 2006) and constitute about 30% of the known pulsar population.

6 Conclusion

A statistical method of measuring the braking index of radio pulsars has been developed and applied to a sample of 27 radio pulsars. The method yielded significant measurements of braking index in five pulsars. These objects have intermediate characteristic ages ($79 < \tau_c < 1500$ kyr) and spin-down rates ($50 \times 10^{-15} < |\dot{\nu}| < 605 \times 10^{-15}$ s/s). Extraordinarily low signal-to-noise ratio precluded unambiguous measurements of n in 12 pulsars, while anomalous braking indices characterised the measurements in the remaining 10 pulsars having relatively smaller spin-down rates.

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