Journal of Physical Sciences,
Vol. 1, No. 1, 7 – 20, April 2010

Timing noise analysis of 27 HartRAO radio pulsars

A. E. Chukwude*
Department of Physics & Astronomy, University of Nigeria, Nsukka, Enugu State
*** E-mail: aus_chukwude@yahoo.com**

Abstract

Timing observations on 27 radio pulsars obtained at Hartebeesthoek Radio Astronomy Observatory (HartRAO) between 1984 and 1999 were analyzed in order to provide an in-depth empirical description of continuous, random rotational fluctuations in radio pulsars. The results of the detailed time-domain analyses, which are based on the strength parameter and structure function techniques, show that (i) the observed rotational fluctuations in five pulsars are apparently too weak to allow for any meaningful timing noise analysis; (ii) the timing activity of most (> 60%) of the remainder of 22 pulsars cannot be explained in terms of simple idealized random walk processes only and (iii) the observed timing activity of three, three, and two objects are characterised by rotational fluctuations whose statistics appear consistent with random walks in pulse phase, pulse frequency and slowing down rate, respectively. We discuss the results in the framework of the current understanding of radio pulsar timing noise phenomenology.

Key words: *methods: statistical – stars: neutron – pulsars: general*

1. Introduction

As highly magnetized and rapidly rotating neutron stars, most radio pulsars are expected to slow down steadily as they lose rotational kinetic energy via electromagnetic radiation and acceleration of particles winds (Goldreich & Julian 1969; Manchester & Taylor 1977). The deterministic spin-down of an isolated radio pulsar is conventionally approximated by a simple power-law relation of the form

$$\dot{\nu} = -K\nu^{n}, \qquad (1)$$

where $\nu = 1/P$ (P is the pulsar rotation period) is the pulse rotation frequency, $\dot{\nu}$ is its first time derivative (widely referred to as the pulsar spin-down rate), K is an arbitrary positive constant and n is the torque braking index. This steady slowing down have been observed in most isolated pulsars (the only deviants are, perhaps, the few pulsars located in Globular clusters) as a gradual increase in the pulse rotation period at rates that vary over a wide range (Manchester & Taylor 1977; Lyne & Graham-Smith 1998).

However, precision timing observations have revealed that most pulsars support a wide range of rotational imperfections, usually superimposed on the theoretical spin-down law (Lorimer & Kramer 2005). Pulsar deviant rotational behavours are broadly of two sorts: glitches and timing noise. During glitch events, the otherwise smoothly decreasing pulsar rotation frequency (ν) experiences sudden increases. The jumps in ν which in most, but not all cases are accompanied by increases in the absolute magnitude of the spin-down rate ($\dot{\nu}$), relax back to their pre-glitch values on a wide range of timescales (Cordes et al. 1988; Lyne, Shemar & Graham Smith 2000; Wang et al. 2001). Glitch observations and dedicated studies of post-glitch behaviours of the pulsar spin parameters have yielded some remarkable results about neutron star internal structure and evolution (e.g. Flanagan 1990; McCulloch et al. 1990). In particular, it has led to the widely accepted view that a neutron star interior contains substantial superfluid components, which play crucial roles in the over all dynamic behaviour of pulsars (Alpar et al.. 1984, 1993; Ruderman, Zhu & Chen 1998).

On the other hand, the phenomenon of timing noise was first observed in the Crab pulsar as random and sustained departures of the pulse arrival times from the predictions of the standard pulsar spin-down model (Boynton et al. 1972). To date, the gross observational signature of timing noise has remained the excess phase residuals (the difference between the observed and model-predicted pulse arrival times) obtained after allowing for the deterministic spin-down and any resolved glitch event (D'Alessandro et al. 1995, hereafter DA95). Unlike glitches, which have been reported in just about 1% of the known pulsar population, timing noise is presumably present, though at widely varying levels, in nearly all pulsars (Cordes & Downs 1985, hereafter CD85; DA95; Chukwude 2002, 2007). Nonetheless, our understanding of these rotational fluctuations remains shamefully poor after over four decades of coordinated pulsar timing observations. For instance, controversies still surround the actual character and origin of the phenomenon (Chukwude 2002 and references therein). Lately, however, a combination of improved timing idiosyncrasies and robust analyses techniques has revealed that a wide range of fundamental physical and astrophysical phenomena can actually be studied through the analyses of radio pulsar timing noise. Some of these exciting phenomena include: classical and relativistic precession (Stairs, Lyne & Shemar 2000; Shabanova, Lyne & Urama 2001; Weisberg & Taylor 2002; Kramer et al. 2003); extrasolar planetary systems (Wolszczan 1994; Arzoumanian et al. 1996); massive stellar companions around neutron stars (Stairs et al 2001; and references therein); persistent adjustment in neutron star magnetic axis (e.g. Chukwude & Buchner 2010 and references therein); Double neutron star binaries (Burgay et al 2003; Faulkner et al. 2004) and enhanced microglitch activity in radio pulsars (Chukwude & Urama 2010).

In spite of these striking discoveries, lack of adequate characterisation of rotational fluctuations in radio pulsars has continued to undermine pragmatic study of the internal structure and spin-down evolution of neutron stars, particular at long timescales. The presence of timing noise has seriously and adversely affected both the sensitivity and effectiveness of the existing pulsar timing analysis techniques (Cordes 1993; Hobbs, Lyne & Kramer 2006). The implication is that only limited details are available from most analyses and in some cases, results are only ambiguously interpreted. For instance, timing noise has resulted in unreliable or, in worst cases, precluded measurements of some key rotational and astrometric parameters of radio pulsars (Chukwude 2003; Hobbs et al 2004; Lorimer & Kramer 2005). Since accurate measurements of these parameters are crucial for improved understanding of a spectrum of pulsar problems (Lorimer & Kramer 2005), it becomes imperative to step up efforts to realistically characterise rotational fluctuations in radio pulsars.

In this paper, an empirical analysis of timing noise in a sample of 27 relatively slow radio pulsars is presented. This largely time-domain analysis involves testing the consistency, or otherwise, of the observed rotation fluctuations with the random walks models.

2. Basic Theory Of Random Walk Processes

A random walk in the k-th derivative of the pulse phase of a radio pulsar is giving (following Boynton et al 1972) by

$$\frac{d^k\phi(t)}{dt^k} = \sum_i \alpha_j H(t-t_j), \tag{2}$$

where α_j is the random amplitudes of the steps, assumed to have a zero mean, H is a unit step function, where steps occur at times t_j. Borrowing the terminology of Boynton et al. (1972) the random walks corresponding to $k = 0$, 1, and 2, are equivalent to phase noise (PN), frequency noise (FN), and slowing-down noise (SN), respectively. It has been shown that the root-mean-squares phase residuals (σ_R) depend strongly on the time span of observations (T). specifically, $\sigma_R \sim T^{\gamma}$, where $\gamma = 0.5$, 1.5 and 2.5 for PN, FN and SN, respectively (Cordes 1980; Cordes & Greestein 1981). This implies that the true origin of commencement of the random walks must be taken into account for meaningful timing noise analyses. However, it has been widely argued (e.g Cordes 1980; CD85, DA95) that it is sufficiently safe to assume that a random walk in question commenced at an arbitrary time t_0, corresponding to the first arrival time in the data set, provided such analysis is augmented by a low-order polynomial fit. Incidentally, such a low-order polynomial is usually fitted to pulsar timing data as part of the standard data reduction technique (Manchester & Taylor 1977).

2.1. Strength parameters

In the framework of pure random walk processes, the observed radio pulsar timing noise is idealized as consisting of a series of random steps in the pulsar rotation phase (ϕ), frequency (ν) or frequency derivative $\dot{\nu}$. We assume that these steps are too small to be resolved individually and that the amplitudes of the steps possess non-zero second moments, whose distribution in time is approximately Poisson. Each noise model is characterised by a strength parameter, defined (following Cordes and Greenstein 1981) by

$$S_0 = R\langle(\Delta\phi)^2\rangle, \qquad S_1 = \langle(\Delta\nu)^2\rangle \quad \text{and}$$

$$S_2 = \left\langle\left(\Delta\dot{\nu}\right)^2\right\rangle \tag{3}$$

for phase noise, frequency noise and slowing down noise respectively. In equation (3), $\langle(\Delta\phi)^2\rangle$, $\langle(\Delta\nu)^2\rangle$ and $\left\langle\left(\Delta\dot{\nu}\right)^2\right\rangle$ are, respectively, the mean-square values of the unresolved steps in the observed phase, frequency and spindown rate and steps are presumed to occur at an average rate R. In practice, strength parameters can be estimated from the root-mean-square residuals, $\sigma_{TN}(m,T)$, after fitting an mth-order polynomial to timing data spanning a time T. In practices, it is adequate to write

$$\sigma_{TN}(m,T) = \sqrt{\left(\sigma_R^2(m,T) - \sigma_W^2\right)}, \tag{4}$$

where $\sigma_R(m,T)$ is the root-mean-square (rms) phase residuals obtained from a polynomial of order m fitted over a time span T and σ_W is the rms white noise, which consists largely of pulse-to-pulse phase jitter and measurement uncertainties (e.g. CD85). Following Cordes (1980), an appropriate strength parameter estimate can be obtained as

$$S_k = C_{k,m}^2\left[\frac{\sigma^2_{TN(m,T)}}{\langle\sigma^2_{RW}(T)\rangle\mu}\right], \tag{5}$$

where $C_{k,m}^2$ are correction factors applied to kth-order random walk to compensate for the timing noise variance ($(\sigma_R^2$) absorbed by the coefficients of mth-order polynomial and $\langle\sigma^2_{RW}(T)\rangle\mu$ denotes the ensemble average phase variance expected from a random walk of unit strength. Cordes (1980) has shown that for an $m = 2$ polynomial, $C_{k,3}$ takes the values of 4.14, 27.3 and 71.1, respectively, for the three random walk models. Ensemble average quantities are not always easily available. However integral estimates of the second moments of the random walk can easily be calculated (Cordes 1980; DA95). In the continuum limit (and loosely for $RT \gg 1$, which is also valid for uniformly sampled data), the phase variance, $\langle\langle\sigma^2_{RW}(T)\rangle\rangle$, produced by each random walk process is given by (e.g. CD85: Cordes 1993; DA95).

$$\langle\sigma^2_{RW}(T)\rangle = \frac{1}{2}S_0T, \frac{1}{12}S_1T^3 \text{ and } \frac{1}{120}S_2T^5 \tag{6}$$

for PN, FN and SN, respectively, where T is the data time span length. We assume that the random walks are characterised by zero mean and a unit strength parameters (Cordes 1980).

Consistency of a pulsar data with one of the random walk models is indicated by the stationarity of the strength parameter estimates. This condition requires that S_k, for a particular noise process to be independent of the data span length T, provided the constraint $R \gg T^{-1}$ is satisfied (CD85). Following Cordes & Downs (1985), this consistency can be measured by a simple statistic (F) defined as

$$F = \frac{S(T_{max})}{S(T_{min})}, \tag{7}$$

where $S(T_{max})$ is the strength parameter estimate from the entire ($T = T_{max}$) data span and $S(T_{min})$ is the mean strength parameter estimate from N_{min} equal blocks having minimum time span T_{min} each. A pulsar data is considered consistent with a particular random walk model if $F \approx 1$, otherwise inconsistent random walks will cause F to be a strongly increasing function of T_{max}/T_{min}. It has been shown (e.g. CD85; DA95) that if $S(T_{min})$ and $S(T_{min})$ are obtained from statistically independent data blocks and $S(T_{min})$ are Gaussianly distributed, with standard deviation $\sigma_{\log S}$, then the distribution of log F will also be normal with a standard deviation given by

$$\sigma_{\log F} = \sigma_{\log S}\left(\frac{N_{min}+1}{N_{min}}\right), \tag{8}$$

where N_{min} is the number of statistically independent estimate of the strength parameters. The probability of obtaining F less than the observed value can be calculated using an error function of x. A probability of about 0.5 suggests that the pulsar data are consistent with the random walk model in question.

2.2 Structure functions

Structure function analysis employs a method of differencing scheme to estimate the variance of structures in a time series. The technique, which was originally used to characterise noise in the frequency-standard community (Lindsey & Chie 1976; Rutman 1978), has lately found substantial applications in the study of radio pulsar timing noise (Cordes & Downs 1985). In addition to providing tests complimentary to the strength parameters analysis, structure function can be used to determine if the observed rotational fluctuations are large enough to be considered real, rather than the mere random walk processes.

Following Rutman (1978), the nth-order increment of the phase given by

$$\Delta_{\phi}^{(n)}(t,\tau) \equiv \sum_{i=0}^{n}(-1)^{i}\binom{n}{i}\phi[t+(n-i)\tau] \tag{9}$$

defines an nth-order structure function of the phase, which is given by (e.g. Cordes & Downs 1985)

$$D_{\phi}^{(n)}(t,\tau) \equiv \left\langle \left[\Delta_{\phi}^{(n)}(t,\tau)\right]^{2} \right\rangle, \tag{10}$$

In equation (10), t corresponds to the epochs of individual phase (ϕ) measurements and τ is the time-scale probed by the differencing scheme. An nth-order random walk process will be characterised by (n+1)th-order structure function which is independent of time t, but has a unique power-law relationship with τ. Theoretically, a structure function plot: which is basically a log – log plot of the variance of the structures, $D_{\phi}^{(n)}(\tau)$ against the time-scale probed for structures, τ will have a logarithmic slope, also called the structure function slope. The structure function slope is equal to 1, 3, and 5 if the underlying noise process is consistent with random walk in pulse phase, frequency and slowing down rate, respectively. Equation (10) defines the structure function in terms of absolute rotation phase, however real pulsar data consist of phase residuals $(\delta\phi(t))$, obtained after removing a low-order polynomial from the pulse times of arrival. Following D'Alessandro et al. (1995), we defined the 1st-, 2nd- and 3rd-order structure functions of the phase residuals as:

$$D_{\delta\omega}^{(1)}(\tau) = N_{\xi}^{-1}\sum_{i,j}\left[\delta\phi(t_{j}) - \delta\varphi(t_{i})\right]^{2} \tag{11}$$

$$D_{\delta\phi}^{(2)}(\tau) = N_{\xi}^{-1}\sum_{i,j,k}\left[\delta\phi(t_{k}) - 2\delta\phi(t_{j}) + \delta\phi(t_{i})\right]^{2} \tag{12}$$

and

$$D_{\delta\phi}^{(3)} = N_{\delta\phi}^{-1}\sum_{i,j,k,l}\left[\delta\phi(t_{l}) - 3\delta\phi(t_{k}) + 3\delta\phi(t_{j}) - \delta\phi(t_{i})\right]^{2}, \tag{13}$$

respectively, where N_{ξ} is the number of data points in the sum.

In practice structure function estimates can be obtained from unevenly sampled data by binning pairs of data whose separations fall within a desired range about some lag τ (CD85, DA95). Usually pairs of data points are binned logarithmically within some desired time-scale such that $\varepsilon\tau \le t_j - t_i \le \tau/\varepsilon$, where is ε is the binning tolerance chosen such that it satisfies the condition 1 - ε << 1. We have obtained structure function estimates using ε = 0.89, corresponding to 10 bins per decade in time scale τ. Cordes & Downs (1985), D'Alessandro et al. (1995) have shown that that ε = 0.89 makes a particularly good tolerance for realistic structure function calculations.

3. Observations

Regular timing observations of all objects in the current sample of 27 radio pulsars commenced at Hartebeesthoek Radio Astronomy Observatory between 1984 January and 1987 May and continued till around 2007. However, regular timing observations of most HartRAO pulsars were interrupted between 1999 June and 2000 August owing to a major hardware upgrade. In view of this, only timing data accumulated up to 1999 June is reported in this paper. In HartRAO, pulse times of arrival (TOAs) were measured regularly at intervals ~ 1 – 14 days using the observatory 26-m parabolic radio telescope. Pulses from radio pulsars were recorded by a single 10 MHz bandwidth receiver centred near 13 or 18 cm and no pre-detection dedispersion hardware was implemented during the period under consideration.

For each pulsar, detected pulses are smoothed with an appropriate filter-time constant, and folded over N_p consecutive rotation periods to beat down the background noise. N_p is different for different pulsars, but generally varies between 500 and 5000 for the current sample, corresponding to an integration time of about 40 s – 30 mins. Integration was usually started at a particular second by synchronization to the station clock, which is derived from a hydrogen maser and is referenced to the Universal Coordinated Time (UTC) via the global Position satellite (GPS). On average, three such on-line integrations were made for each pulsar during an observing session. Details of data acquisition and reduction at HartRAO have been described elsewhere (Flanagan 1995). The resulting topocentric arrival times were transformed to an infinite observing frequency at the Solar System Barycentre (SSB) with the Jet Propulsion Laboratory DE200 solar system ephemeris (Standish 1982) using TEMPO* software package

Table 1: Some rotational and timing noise activity parameters of the 27 HartRAO radio pulsars

Pulsar PSR B (1)	P (s) (2)	$\dot{P}$ (10^{-15} ss^{-1}) (3)	T_{max} (Days) (4)	$\sigma_R(2,T_{max})$ (ms) (5)	σ w (ms) (6)	SNR (7)	Γ % (8)
0450-18	0.549	5.752	5095	3.12	2.35	1.33	0.6
0736-40	0.375	1.628	5290	108.95	0.48	226.98	30
0740-28	0.167	16.813	5095	126.11	0.24	513.72	80
0835-41	0.752	3.542	5095	6.48	0.32	20.50	0.9
0959-54	1.437	51.910	4875	381.96	1.60	239.46	32
1054-62	0.422	3.571	4727	3.60	0.55	6.85	0.8
1133+16	1.188	3.734	5000	1.75	0.25	7.01	0.1
1221-63	0.216	4.954	4988	1.81	0.24	7.54	0.7
1240-64	0.388	0.500	5290	5.58	0.31	18.08	2
1323-58	0.478	3.228	4640	37.27	0.63	59.53	8
1323-62	0.530	18.885	5008	27.96	0.58	48.40	5
1356-60	0.127	6.338	4659	12.29	0.65	18.94	10
1358-63	0.843	16.663	4300	137.04	1.09	126.01	20
1426-66	0.785	2.776	4900	4.98	0.65	7.66	0.6
1449-64	0.179	2.746	5105	5.04	0.71	7.07	3
1451-68	0.263	0.099	4990	1.08	1.02	1.06	0.4
1556-44	0.257	1.019	5100	1.69	0.28	6.05	0.9
1557-50	0.192	5.062	4677	3.26	0.18	18.12	2
1641-45	0.455	20.089	4900	146.22	0.36	401.71	30
1642-03	0.387	1.778	5057	16.239	0.50	32.78	4
1706-16	0.653	6.291	4365	53.419	1.19	44.95	8
1727-47	0.829	163.671	3190	22.627	0.42	53.87	3
1749-28	0.562	8.119	4960	23.816	0.37	64.22	5
1822-09	0.769	52.432	4980	206.399	0.93	221.82	30
1929+10	0.358	6.002	5290	1.809	0.47	3.82	0.5
2045-16	1.961	2.818	4965	0.608	1.26	1.28	0.03

3. Data Analyses and Results

Subsequent modeling of the barycentric times of pulse arrival (hereafter referred to as BTOAs) was accomplished with the HartRAO in-house pulsar timing analysis software (CPHAS), which is based on the standard pulsar timing technique (e.g. Manchester & Taylor 1977) and is well described in Flanagan (1995). The BTOAs were fitted with a simple Taylor series of the form

$$\phi(t) = \phi_0 + \nu(t-t_0) + \tfrac{1}{2}\dot{\nu}(t-t_0)^2 + \left[\frac{1}{6}\ddot{\nu}(t-t_0)^3\right], \quad (14)$$

where ϕ_0 is the phase at an arbitrary time t_0, ν is the pulse rotation frequency, $\dot{\nu}$ and $\ddot{\nu}$ are its first and second time derivatives, respectively. Basically, equation (14) was used to model the BTOAs by accounting for the deterministic pulsar spin down (Lyne & Graham-Smith 1998; Lorimer & Kramer 2005). The difference between the observed BTOAs and the predictions of the best-fit model (the phase residuals) for the 27 HartRAO pulsars, defined in the sense of model-predicted minus observed BTOAs, have been reported elsewhere (Chukwude 2007). The term enclosed in a square bracket in equation (14) is only included if the phase residuals relative to the assumed spin-down model show evidence for dominant cubic term and have statistics that are inconsistent with the random walk models.

Some relevant rotational and timing noise parameters of the current sample of 27 pulsars are summarised in Table 1. Column (1) lists the pulsar name in B1950.0 naming convention; columns (2) and (3) contain the rotation period (P) and its first time derivative ($\dot{P}$), respectively; the data time span length, the rms phase residuals from m = 2 polynomial model and the rms white noise are listed in cols. (4), (5) and (6) respectively; column (8) lists the $\Gamma = \sigma_R(2,T_{max})/P$, a dimensionless constant which define the fraction of the pulsar rotation period submerged by the observed timing noise, in unit of percent.

3.1 Strength parameter analysis and results

Estimates of the strength parameters and their ratios were obtained, for each random walk model, using the phase residuals from a low-order polynomial to the BTOA data. Only a sub-sample of 22 objects with measurable timing noise activity (SNR > 5 milliperiods) was considered suitable for the present analysis. We obtained the root-mean-square timing noise from m = 2 polynomial fits. Our analysis was complemented by third-order fits for few objects, whose phase residuals show significant evidence for a cubic term and are inconsistent with all the three random walk models.

Two methods of analyses (A and B) were employed in order to obtain statistically independent estimates of strength parameters. In method A, strength parameters were calculated from the entire data span available for each pulsar (i.e. for $\beta = 0$, corresponding to $T = T_{max}$). thereafter, the entire BTOA data was divided into N_{min} blocks of length T_{min}, where N_{min} was determined by (i) the level of timing activity in the pulsar data; (ii) the level of intrinsic scatter in the arrival time data; (iii) the time span of data available and (iv) the constraint that $\sigma_R(m,T_{min}) - \sigma w > 0$. These constraints restricted N_{min} values to $\leq$ 16 for the current sub-sample of 22 radio pulsars. The strength parameters were estimated from these independent short segments of data and F was calculated from $S(T_{max})/S(T_{min})$. Method B involved dividing the entire data set into two equal halves of length $T_{1/2}$, where $T_{1/2} = T_{max}/2$. The first half was divided into n_{min} blocks (where in this case $n_{min}=T_{1/2}/T_{min}$). Strength parameter estimates were obtained from one half of the data, with length $T_{1/2}$ and then from the n_{min} independent blocks of length T_{min}, but obtained from the other half of the data. Again, the average strength parameter $S_I(T_{min})$ was calculated, as described above, while F was obtained from $S(T_{1/2})/S_I(T_{min})$.

In principle, the results from the two methods could be considered to be statistically independent. Although the estimates of the strength parameters obtained from method A are not strictly independent. However, several authors (Cordes & Helfand 1980; CD85; DA95) have argued that statistical independence can be assumed if $T_{max} >> T_{min}$. However, the estimates from method B are statistically independent, since estimates were obtained from non-overlapping data blocks. Following similar previous independent analyses (CD85; DA95), we placed greater weight on the results obtained from method B.

The results of the strength parameter analyses for the sub-sample of 22 HartRAO pulsars are summarized in Table 2. The first and second entries for each object correspond to estimates obtained, respectively, from methods A and B. Column 1 lists the pulsar name, the number of blocks (N_{min} and n_{min}) used to calculate $S(T_{min})$ and $S_f(T_{min})$, respectively, are given in Col. 2; the standard deviations $\sigma_{\log S,}$ obtained from the set of N_{min} and n_{min} strength parameter estimates are given in Col. 3; strength parameter ratios (F) for phase noise, frequency noise and slowing-down noise are listed in Cols. 5, 7, and 9 respectively, while the probabilities of obtaining values of F less than the calculated values for PN, FN, and SN are given in Cols. 6, 8, and 10 respectively.

Table 2: Results of the strength parameters analyses of a sample of 22 HartRAO pulsars.

Pulsar	N_{min}	β	$\sigma_{\log s}$	Strength parameter ratios and the probabilities					
PSR B				F_{PN}	P_{PN}	F_{FN}	P_{FN}	F_{SN}	P_{SN}
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
0736-40	7	3	0.28	2519.42	1.000	37.24	0.999	0.549	0.189
	4	2	0.14	9.98	0.975	0.54	0.109	0.031	0.006
0740-28	8	3	0.32	3316.48	1.000	11.80	0.998	0.042	0.016
	4	2	0.35	96.62	1.000	1.75	0.654	0.019	0.008
0835-41	8	3	0.38	164.56	0.998	0.91	0.460	0.123	0.059
	4	2	0.40	16.45	0.995	1.01	0.520	0.062	0.031
0959-59	8	3	0.41	2952.82	1.000	51.34	0.998	0.672	0.341
	4	2	0.47	4.93	0.995	3.36	0.992	0.018	0.012
1054.62	8	3	0.52	1.14	0.601	0.019	0.013	0.00028	$<10^{-4}$
	4	2	0.40	0.95	0.496	0.054	0.031	0.0034	0.002
1221-63	5	3	0.37	1.57	0.642	0.028	0.014	0.00039	$<10^{-4}$
	3	2	0.38	0.88	0.518	0.042	0.023	0.0023	0.001
1240-64	7	3	0.40	105.47	0.998	1.62	0.682	0.0246	0.012
	4	2	0.35	19.70	0.992	1.13	0.513	0.0650	0.032
1323-58	7	3	0.65	334.81	1.000	4.98	0.997	0.0742	0.006
	3	2	0.71	197.64	1.000	11.74	0.998	0.597	0.601
1323-62	13	4	0.47	113.57	0.998	0.37	0.202	0.0011	$<10^{-4}$
	8	3	0.50	10.20	0.990	0.14	0.089	0.0019	0.002
1356-60	11	4	0.25	101.31	1.000	0.36	0.112	0.0013	0.005
	6	3	0.29	5.86	0.993	0.085	0.032	0.0012	0.001
1358-63	11	4	0.20	3292.11	1.000	11.37	0.997	0.0391	0.020
	6	3	0.22	270.95	1.000	3.65	0.745	0.0488	0.014
1426-66	6	3	0.40	4.02	0.990	0.061	0.032	0.0009	$<10^{-4}$
	4	2	0.31	0.38	0.171	0.029	0.013	0.0017	0.001
1449-64	7	3	0.22	18073.1	1.000	267.34	0.998	2.62	0.580
	4	2	0.37	30.76	0.995	17.19	0.991	0.981	0.488

1556-44	6	3	0.28	2.32	0.598	0.059	0.023	0.0009	$<10^{-4}$
	3	2	0.31	1.14	0.495	0.070	0.032	0.0043	0.002
1557-50	8	4	0.41	22.92	0.998	0.35	0.179	0.0052	0.003
	4	2	0.49	31.74	1.000	1.92	0.876	0.115	0.077
1641-45	16	4	0.48	3197.66	1.000	12.25	0.998	0.0387	0.021
	8	2	0.30	3791.18	1.000	24.46	0.999	0.365	0.139
1642-03	14	4	0.32	171.51	0.997	0.639	0.241	0.0024	0.001
	8	3	0.18	210.93	1.000	3.04	0.605	0.0435	0.011
1706-16	7	3	0.20	3591.41	1.000	7.10	0.966	0.0905	0.022
	3	2	0.15	34.19	0.995	0.37	0.083	0.0212	0.005
1706-16	7	2	0.45	317.93	1.000	0.75	0.465	0.0096	0.006
	3	2	0.38	98.14	1.000	1.01	0.521	0.058	0.008
1727-47	5	3	0.42	79.58	0.999	1.04	0.517	0.016	0.008
	4	2	0.35	19.60	0.992	1.03	0.450	0.065	0.025
1749-28	13	4	0.45	128.22	0.998	0.44	0.236	0.0014	$<10^{-4}$
	7	3	0.25	42.45	0.995	0.63	0.200	0.0093	0.003
1822-09	7	3	0.28	231.72	1.000	3.38	0.838	0.0492	0.018
	4	2	0.20	35.84	0.993	2.14	0.537	0.127	0.036
1929+10	14	4	0.51	28.08	0.998	0.11	0.069	0.0005	0.0003
	8	3	0.46	5.14	0.996	0.08	0.046	0.0012	0.0006

[a]Results from 3rd-order polynomial fits

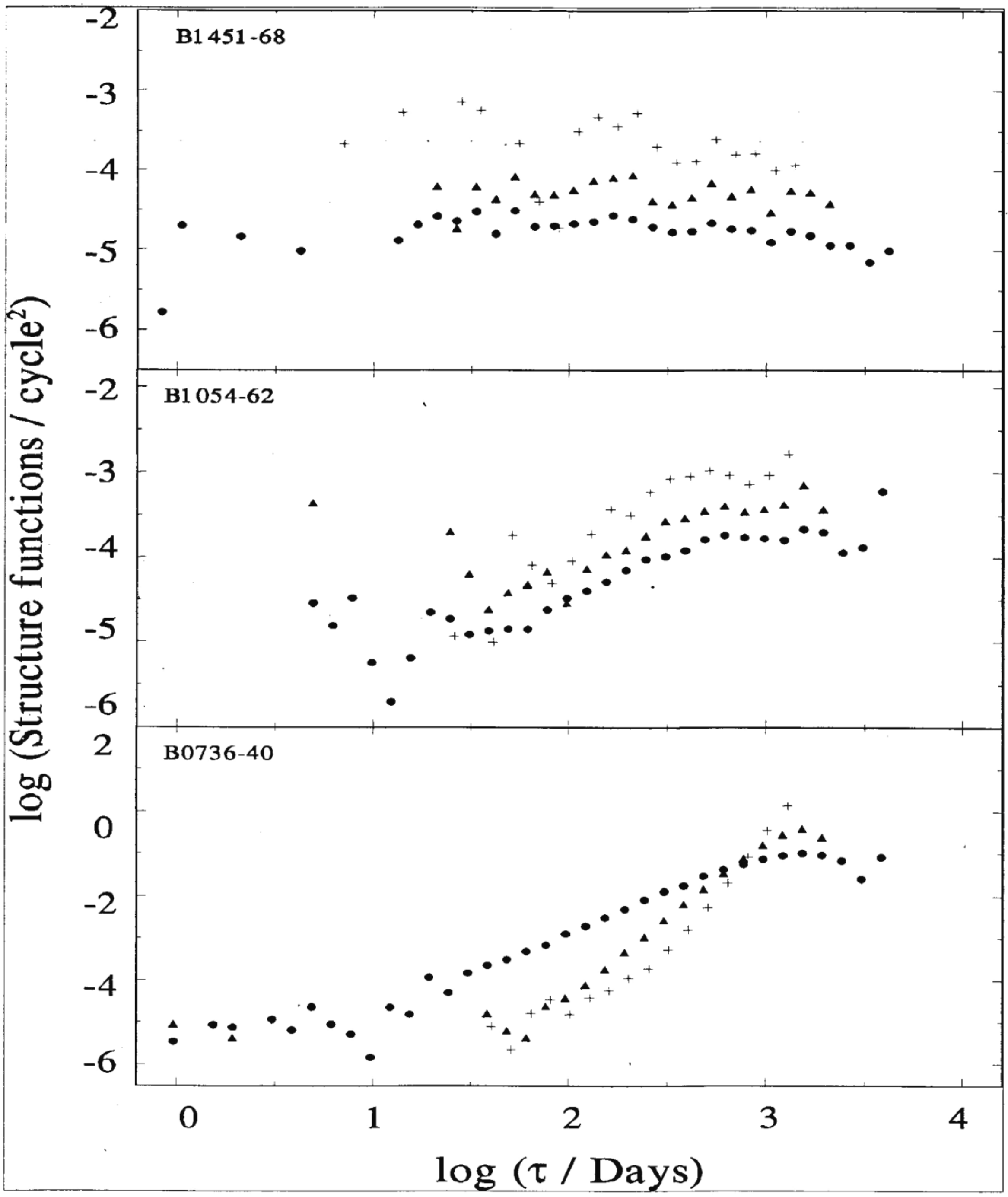

Figure 1: Scatter plots of the variance of the first-, second- and third-order structure functions of the observed timing noise against the time lag (τ) for a selection of 3 HartRAO radio pulsars – B1451-68, B0736-40 and B1054-62, respectively. These pulsars are representatives of objects whose rotational fluctuation over ~ 13 years are apparently very weak, moderate and extremely strong, respectively. Key: • = $D^{(1)}_{\delta\phi}(\tau)$ ▲= $D^{(2)}_{\delta\phi}(\tau)$ and + = $D^{(3)}_{\delta\phi}(\tau)$.

3.2 Structure Function Analysis and Results

We obtained phase residuals for each of the 22 pulsars by removing a 2nd-order model from the entire data. For the few pulsars, whose data showed intrinsic cubic term and were not consistent with any of the random walk models after removing a 2nd-order model, a third-order model was also removed from the observations before calculating the structure functions. Structure function slopes were estimated from a simple linear least-squares regression analysis over time lags bounded by $\tau_{min} \le \tau \le \tau_{max}$. This restriction is necessary to minimize the edge effects and the influence of the stationary measurement uncertainties. It has been argued that at small lags ($\tau < \tau_{min}$), the effect of the additive noise dominates the structure function estimates, while at large lags ($\tau > \tau_{max}$), the effects of the polynomial fits (edge effects) become more pronounced (CD85; DA95).

Figure 1 shows the structure functions plots for a selection of three HartRAO pulsars. The observed timing noise of PSR 1451-68 is very nearly white, without any discernable pattern in the structure function plots over the ~ 13 yrs period. The structure function plots of PSR 1054-62, a moderately active pulsar, are characterised by both dominant effects of measurement error at small lags (τ < 40 d) and flat slopes, which are nearly the same for the three noise models. On the other hand, the plots for PSR 0736-40 have relatively steep slopes for the three structure functions. The results of the structure function analysis of the 22 HartRAO pulsars are summarised in Table 3. Column 1 lists the pulsar name in B1950.0 naming convention; the minimum and maximum time-scales over which the structure function slopes were calculated are listed in Cols. 2 and 2 respectively, where a single value of τ_{min} or τ_{max} refers to all the three structure functions while Cols. 4, 6 and 8 list the 1st-, 2nd-, and 3rd-order structure function slopes. The errors are 1-σ formal errors in the slopes and refer to the last digit quoted.

In summary, we find that: (i) three pulsars (B1054-62, B1221-63 and B1556-44) are characterised by 1st-order structure function slopes of about 1, consistent with PN; (ii) the timing activity of four pulsars (B0835-41, B1641-45, B1727-47) show consistency with FN, and are characterised by 2nd-order structure function slope of about 3; (iii) only one pulsar (B1449-64) is characterised by a 3rd-order structure function slope of ~ 5, suggesting that the observed rotational fluctuations are consistent with SN; (iv) the observed timing noise activities of the remainder of 14 pulsars are largely inconsistent with pure idealized random walk models.

Table 3: Results of the structure functions analysis of a sub-sample of 22 HartRAO pulsars

Pulsars	τ_{min}	τ_{max}	structure function slopes					
PSR B	(days)	(days)	$D^{(1)}_{\delta\phi}$	ERR	$D^{(2)}_{\delta\phi}$	ERR	$D^{(3)}_{\delta\phi}$	ERR
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
0736-40	30,75,200	1000,1530,1285	1.89	3	3.49	7	5.27	2
0740-40[a]	20,50,100	1000,1000,1000	1.54	4	2.60	1	3.01	1
0740-28	20,40,104	1240,1556,1300	1.94	3	3.42	7	4.10	8
0740-28[a]	20,25,125	1250,1250,1000	1.83	5	3.35	7	3.89	8
0835-41	25,150,260	985,1300,1600	1.80	5	2.95	5	4.40	2
0959-54	12,40,60	1210,1210,1280	2.02	3	3.71	5	4.70	2
1054-62	40,40,65	618,620,520	1.04	4	1.04	9	1.50	2
1221-63	60,98,260	620,630,650	1.10	1	1.60	2	3.10	2
1240-64	25,61,30	778,776,655	1.64	4	2.49	8	2.90	1
1323-58	29,58,77	1164,1160,1000	1.82	4	3.32	8	4.40	2
1323-62	25,25,30	1580,1230,1300	1.81	3	2.44	7	2.80	2
1356-60	23,37,98	1850,1840,1230	1.65	4	2.10	5	2.20	2
1358-63	17,68,60	1079,1076,1430	1.83	4	3.70	2	3.73	7
1426-66	77,122,205	977,975,819	1.50	4	1.90	1	3.01	2

1449-64	27,43,350	1390,1380,1465	1.40	4	1.81	1	4.96	5
1556-44	100,150,450	1000,1000,1600	1.04	4	1.20	1	3.01	2
1557-50	29,50,62	750,760,800	1.75	4	2.30	2	3.30	2
1641-45	10,40,50	1000,1510,1600	1.63	2	3.02	8	4.08	9
1642-03	25,38,65	1000,1000,1028	1.65	5	2.74	9	3.40	1
1706-16	13,40,176	1330,1328,1122	1 74	3	2.90	1	6.20	3
1706-16[a]	50,100,200	830,830,870	1.77	8	3.10	1	4.52	3
1727-47	14,70,95	900,895,895	1.66	7	3.10	1	3.30	3
1749-28	12,25.104	1244,1242,1312	1.74	4	2.53	8	3.20	1
1822-09	12,47,78	1000,1189,1250	1.94	5	3.65	9	4.61	1
1822-09[a]	14,63,100	920,890,790	1.45	3	2.32	9	2.50	2
1929+10	17,100,72	870,1100,920	1.32	5	1.61	7	2.20	1

[a]Results obtained after removing a cubic polynomial model from the data.

Quoted errors are 1-σ standard formal errors and refer to the least significant digit.

5. Discussion

The rotation periods of the current sample of 27 radio pulsars are in the range of ~ 0.2 – 2 s, suggesting that they are relatively slow rotating objects. Five pulsars show extremely low timing activity level, with $\sigma_R(2,T)$ < 4 ms over ~ 13 years. For these objects, the uncertainties introduced by the observed rotational fluctuations (timing noise) do not exceed 0.5% of the rotation period. On the other hand, 16 pulsars are moderately timing active, they are characterized by 6 < $\sigma_R(2, T_{max})$ < 100 ms and Γ < 0.2. The remainder of six radio pulsars (B0736-40, B0740-28, B0959-54 and B1822-09) apparently exhibit extraordinarily high level of rotational fluctuations. For these objects, the cumulative rotational fluctuations ($\sigma_R(2,T_{max})$) over a period of ~ 13 years, are in excess of 100 ms. This translates to Γ > 20, implying that over 20% of the pulsar rotation periods could be effectively buried in the timing noise. These values of T are quite significant and, most probably, suggest that the observed timing noise of these pulsars might not be dominated by the mere random walks. Detailed time-domain descriptions of the long-term rotational history of one these pulsars (B0959-54) are presented elsewhere (Chukwude & Buchner 2010).

Our analysis reveal that the post-fit phase residuals of 14 of the current pulsars (from both 2nd- and 3rd– order polynomial models) are characterised by timing activities whose statistics are seemingly inconsistent with the idealized random walk models. Almost all these objects have Γ > 2, with seven of them having Γ in excess of 10. This suggests that rotational fluctuations are significantly enhanced in this sub-sample of HartRAO pulsars. Structure function studies show that the structure function slopes for about 10 pulsars changed only marginally (~ 1) for the three random walk models, over 4 decades of lags. These consist of objects with both marginal and significant timing activity levels. For pulsars, with appreciable rotational fluctuations, this result suggests the presence of other dominant forms of rotational irregularity. Some of these pulsars have been linked with high incidence of microglitch activity (Chukwude & Urama 2010). Few other pulsars (e.g. B0736-40, B0959-54, B1641-45, B170-16 and B1822-09) have steep structure function slopes. Specifically for these objects, we find structure function slopes to be ~ 2, > 3 and > 4 for the 1st-, 2nd- and 3rd-order structure functions, respectively.

In all likelihood, the unusually steep (> 4) 3rd-order structure function slopes of some of the current pulsars may be attributed to random walks in the slowing-down rate. Alternatively, it could mean that the timing activity of these objects receive significant contributions from a systematic frequency second derivative, micro jump activity, and/or other non-random forms of timing noise activity. While systematic frequency second derivative will yield a third-order structure function slope of about 6 (CD85), it cannot sufficiently account for the current data Chukwude (2003). As a consequence, micro jumps and other, probably, non-random forms of timing noise suffice as a more plausible explanation of the large $D_{\delta\omega}^{(3)}$ slope. In particular, the structure functions plots for PSR B1356-60 reveal an interesting change in the logarithmic slope of $D_{\delta\omega}^{(3)}$ from ~ 3 to 5 with a turning point τ_B at ~ 500 days. This result may be interpreted to mean that the observed timing activity of some pulsars could as well be a superposition of more than one type of random walk processes. A similar result has been reported for PSR B0823+60; a pulsar with comparable level of timing noise activity (CD85). The modest interpretation of this observation is that the timing noise of PSR B1356-60 may consist of non-identifiable events in frequency and frequency derivative. Presumably, the random walk in rotation frequency dominate at $T < 500$ days while at $T > 500$ days, the timing activity is dominated by random walk in slowing-down rate.

Nonetheless, the observed phase residuals of few (at least 7) pulsars show statistics which are apparently consistent with the random walk models. But for three objects (B1240-64, B1706-16 and B1727-47), all these pulsars apparently support marginal level of timing noise activity, with $T < 0.009$, (see also Chukwude 2007). In particular, our analysis shows that the observed timing activity of three pulsars (B1054-62, B1221-63 and B1556-44) is not inconsistent with random walks in pulse phase (phase noise). The pulsars B0835-41, B1727-47 and. possibly, B1240-64 are characterised by rotation frequency (frequency noise). The observed rotational fluctuations in PSR B1706-16 show consistency with frequency noise only after removing a 3rd-order model from the BTOAs. Only the data from PSR B1449-64 were found to be consistent with random walk in the slowing-down rate (SN) rate after a second-order polynomial fit to the data. In general, the structure function results largely confirm those of the strength parameters analysis. Perhaps, the only exception is seen in the timing activity of PSR B1641-45 which was found to be consistent with random walk in frequency, in the structure function analysis, while the strength parameter studies showed the data to be inconsistent with all the random walk models. The reason for this discrepancy is not immediately obvious; however the pulsar had undergone at least two small glitches over this period. These glitch events were not removed from the current data and could have been responsible for the observed discrepancy.

The timing observations on eighteen (18) HartRAO pulsars overlap with the Mt. pleasant observatory (University of Tasmanian) sample of pulsars previously studied by D'Alessandro et al. (1995). While our results are largely in good agreement with those of DA95, there are, nonetheless, few notable disagreements. For instance, with while current analysis reveals that the phase residuals of PSRs B0835-41 and 1727-47 are consistent with frequency noise, they were found to be consistent with phase noise by DA95. Similarly DA95 reported that the observed timing noise in pulsars B0736-40, B0959-54 and B1358-63 are all in agreement with random walk models. Present analysis, however, could not confirm these results. It is also noteworthy that our analyses (both strength parameter and structure function studies) show that the data on PSR B1449-64 are consistent with slowing down noise, in outright disagreement with phase noise reported for the object by DA95. The observed discrepancies in these results could be attributed to both the differences in the time spans of the two data sets (the time span of our data being about twice that of Tasmania) and the enhancement of other forms of timing activity (Alpar et al. 1986; DA95). For instance some of the pulsars whose phase residuals were reported to be consistent with the random walk models have been linked with enhanced microglitch activity (Chukwude & Urama 2010).

6. Conclusion

The strength parameter and structure function analyses have demonstrated that the observed timing activity of most of the 22 HartRAO pulsars, with significant deviant rotational behaviour, cannot be explained in the framework of simple idealized random walk processes. Perhaps, a combination of random walks and one or more other forms of rotational activity might be required to adequately account for the observed timing noise of these objects. Nonetheless, the timing activity of few objects (PSRs B0835-41, B1054-62, B1221-63, B1449-64, B1556-44, B1641-45, B1706-16 and B1727-47) was found to be consistent with simple idealized random walk models. However consistency with a random walk models does not rule out the possibility that the gross timing noise activity of these pulsars also receive appreciable contribution from other types of rotational irregularities.

Acknowledgements

This work was done, in part, while the author was visiting HartRAO as Doctoral student. He is grateful to the Director, staff of the observatory and Dr. C.S. Flanagan for their support and hospitality.

References

Alpar: M.A. Langer, S.A. and Sauls, J.A. (1984). Rapid postglitch spin-up of the superfluid core in pulsars. ApJ, 282, pp.533-541

Alpar, M.A., Chau, H.F., Cheng, K.S. and Pines, D. (193). Postglitch relaxation of VELA pulsar after its first eight large glitches, ApJ, 409, pp.345-349

Arzoumanian, Z., Joshi, K., Rasio, F., Thorsett, S.E. (1996). Orbital parameters of the PSR 1620-26 triple system.In: Johnston, S., Walker, M.A. and Bailes, M (ed) IAU Colloquium Pulsars: problems and Progress. Astronomical society of the Pacific 160, 525

Boynton, P.E., Groth, E.J., Hutchinson, D.P., et al. (1972). Optical timing of the Crab pulsar, NP0532. ApJ, 175, pp.217-242.

Burgay, M. D'Amico, N., Possenti, A., et al. (2003). An increased estimate of the merger rate of double neutron stars from observations of a highly relativistic system. Nature, 426, pp. 531-533

Chukwude, A.E. (2002). A study of timing noise in radio pulsars. PhD thesis, University of Nigeria, Nsukka

Chukwude, A.E. (2003). On the statistical implication of timing noise for pulsar braking index. A&A 406, pp.667-671

Chukwude, A.E. (2007). A statistical analysis of radio pulsar timing noise. ChJAA, 7, pp.521-530

Chukwude, A.E. and Buchner, S. (2010). Evidence for magnetic axis re-orientation in the pulsar B0959-54. MNRAS, in press

Chukwude, A.E., Ubachukwu, A.A. and Okeke, P.N. (2003). Periodicities in rotation and DM of PSR B1557-50. A&A, 399, pp.231-235

Chukwude, A.E. and Urama, J.O. (2010). Observations of microglitches in HartRAO radio pulsars. MNRAS, in press

Cordes, J.M. (1980). Pulsar timing II – Analysis of random walk timing noise – Application to Crab pulsar ApJ, 237, pp.216-226

Cordes, J.M. (1993). The detectability of planetary companions in radio pulsars. In: Phillips, J.A., Thorsett, S.E. and Kulkarni, S.R. (ed) ASP Conf. Ser. 36, Planets Around Pulsars, pp.43-60

Cordes, J.M. and Downs, G.S, (1985). JPL pulsar timing observations III. Pulsar rotation fluctuations. ApJS, 59, pp.343-382

Cordes, J.M., Downs, G.S. and Krauss-Polstorff, J. (1988). JPL pulsar timing observations IV. Macro and microjumps in the VELA pulsar 0833-45. ApJ, 330, pp.847-869

Cordes, J.M. and Greenstein, G. (1981). Pulsar timing IV – Physical models for timing noise processes. ApJ, 245, pp.1060-1079

Cordes, J.M. and Helfand, D.J. (1980). Pulsar timing III – Timing noise of 50 pulsars. ApJ, 239, pp.640-650

D'Alessandro, F., McCulloch, P.M., Hamilton, P.A. and Deshpande, A.A. (1995). The timing noise of 45 southern pulsars. MNRAS, 277, pp.1033-1046

Faulkner, A.J., Kramer, M. and Lyne, A.G. et al (2004). Parkes multibeam pulsar survey V – Finding binary and millisecond pulsars. MNRAS, 355, pp.147-158

Flanagan, C.S. (1990). Rapid recovery of the VELA pulsar from a glitch. Nature, 345, pp.416 –417

Flanagan, C.S. (1995). Glitch observations in pulsars 0833-45 and 1641-45. PhD thesis, Rhodes University Grahamstown, South Africa

Goldreich, P. and Julian, W.H. (1969). Pulsar electrodynamics. ApJ, 157, pp.869-871

Hobbs, G., Lyne, A.G. and Kramer, M. (2006). Pulsar timing noise. ChJAA suppl. 2, pp.169-175

Hobbs, G., Lyne, A.G. and Kramer, M. et al (2004). Long-term timing observations of 374 pulsars. MNRAS, 353, pp.1311-1344

Kramer, M., Bell, J.F. Manchester, R.A. et al. (2003). MNRAS, 342, pp.1299-1305

Lindsey, W.C. and Chie, C.M. (1976). Theory of oscillator instability based upon structure functions. Proc. IEEE, 64, pp.1652-1666

Lorimer, D., Kramer, M. (2005). Handbook of pulsar Astronomy (Cambridge University Press)

Lyne, A.G., Graham-Smith, F. (1998). Pulsar Astronomy (Cambridge University Press)

Lyne, A.G., Shemar, S.L. and Graham-Smith, F. (2000). Statistical studies of pulsar glitches MNRAS, 315, pp.534-542

Manchester, R.N. and Taylor, J.H. (1977). Pulsars (San Francisco: Freeman)

McCulloch, P.M. Hamilton, P.A., McConnell, D. and King, E.A. (1990). The VELA glitch of Christmas 1988. Nature, 346, pp.822-824

Ruderman, M., Zhu, T. and Chen, K. (1998). Neutron star magnetic field evolution, crust movement and glitches. ApJ, 492, pp.267-280

Rutman, J. (1978). Characterization of phase and frequency instabilities in precision frequency sources – fifteen years of progress. Proc IEEE, 66,pp.1048-1075

Shabanova, T.V., Lyne, A.G. and Urama, J.O. (2001). Evidence for free procession in the pulsar B1642-03. ApJ, 552, pp.321-325

Stairs, I.H., Lyne,A.G. and Shemar, L.S. (2000). Evidence for free procession in a pulsar.Nature, 406, pp.484-486

Stairs, I.H., Manchester, R.N., Lyne, A.G. et al. (2001). PSR J1740-3052: A pulsar with a massive companion. Nature, 325, pp.979-988

Wang, N., Wu, X., Manchester, R.N., et al. (2001). A large glitch in the Crab pulsar. ChJAA 3, pp.195-199

Weisberg, J.M. and Taylor, J.H. (2002). General relativistic geodetic spin procession in binary pulsar B1913+16: Mapping the emission beam in two dimensions. ApJ, 576, pp.942-949

Wolszczan, A. (1994). Confirmation of Earth-mass planets orbiting the millisecond pulsar PSR B1257-12. Science, 264, pp.538-542