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On the Effects of Spin Properties on Timing Noise Parameters of Rotation-Powered Pulsars

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Abstract: Detailed investigation of improved timing observations has shown that the spin properties of a large population of rotation-powered pulsars on a varied range of timescales are strongly dominated by random fluctuations. Even though, there is no widely accepted way to characterize timing noise in these pulsars mainly due to the enormous complexity in their structure and true dynamical behavior, the measurements of these pulsar spin properties are essential for extracting important information about their spin down evolution. In this paper, a statistical analysis of a large sample of Jodrell Bank Observatory (JBO) radio pulsars with improved and published data on stability parameters (Δ_8) and other quantities that are used to parameterize pulsar rotational fluctuations on observation timescales [timing noise activity parameter A, timing noise statistic (σ_{23}) and pulsar clock stability parameter σ_Z (T)] was compiled for an in-depth characterization of the spin-down evolution of rotation-powered pulsars. The existence of any relationship will go a long way in helping us probe the properties and dynamics of a neutron star. The results of our analysis reveal that radio pulsar spin-down parameters are reasonably coupled to timing noise activity. A simple regression analysis of our data show that timing irregularities in pulsar is more than 75% correlated with the magnitude of pulsar spin-down variables. The implications of the result of the improved measurements of the key parameters characterizing the spin-down of pulsars on long timescales are discussed.

Keywords: Methods: Statistical, Stars: Neutron, Pulsars: General

1. Introduction

Radio Pulsars (extremely magnetized, rapidly spiraling neutron star) are presumably born in supernova explosion of massive ($\geq 8\,M_\odot$) O and B stars that are created in the collapse of the stellar core [1]. Their enormous moment of inertia (of the order of 10^{45}g/cm^2) leads to exceptionally smooth rotation rates and provides us with some of the most precise clocks in the universe [2]. Though, it is not for all time conventional, the unending timing observations of pulsars have exposed rotational anomalies in their spin periods. This irregular behavior falls into two classes: discrete discontinuities (glitches) and non-discrete discontinuities (timing noise). Glitches are characterized by uneven increase in pulse rotation frequency accompanied by a change in the spin-down rate $\dot{P}$ and sometimes followed by exponential reduction towards the earlier rotation state [3]. A typical glitch magnitude ranges from 10^{-10} to 10^{-6} and steps in slow-down rate are of the order of 10^{-3} [4]. On the contrary, Timing Noise (TN) is the arbitrary, continued fluctuations in the pulse rotation parameters lasting from days to years and resulting in excess timing phase residuals [5]. It is seen to occur more in isolated radio pulsars in which the pulse arrival times wander endlessly about the fitted ephemeris [6, 7]. Even though, the dominance of TN activity (as unmodeled structures in pulsar timing residuals in excess of what is projected from measurement error) among the pulsar population appears objectively well established, still, the knowledge of the phenomenon is still basically poor [5]. This may perhaps be because of the intricacy of the core structure and magnetosphere of the neutron star [7]. Several concepts for the basis and cause of timing noise have been investigated within the past forty years [8, 6, 9, 5, 10]. The proposed mechanisms include interaction with the interstellar medium [11], accretion [12], fluctuations in the pulsar spin down torque [13], internal processes due to the superfluid component [14, 15] and their combination with magnetospheric instabilities [16]. In addition, previous statistical assessments of timing noise activity in radio pulsars involving the spin properties have not fittingly examined the details of the upshots of these properties on the observed timing irregularities. Though some of the earlier works presumed that the experiential pulsar timing irregularity is strongly subjugated by spin properties [18, 19], others were restricted to only pulsars whose observed timing activity appears to show predominant character of timing noise [5]. In this paper, a large sample of Jodrell Bank Observatory (JBO) radio pulsars were amassed in order to statistically revisit the dependence of pulsar timing instability on their intrinsic spin-down evolution.

2 Theoretical Concepts

2.1. Pulsar Spin-down Evolution

Studying the rotational dynamics of rotation-powered pulsars is of utmost importance for the advance of our global understanding of neutron stars (NSs). These pulsars slowly brake as they lose energy through electromagnetic torques in their magnetospheres [20]. In the simplest approximation, the spin-down is described by the dipole radiation of a misaligned rotator in vacuum. However, it is conventionally presumed that a generalised spin-down law is given [21] as

$$\dot{P} = KP^{2-n} \tag{1}$$

where the exponent n is the braking index and K is an arbitrary positive constant and for the widely used standard vacuum dipole spin-down mode, it can be expressed explicitly [22] as:

$$K = \frac{B^2 R^6 \sin\alpha}{6c^3 I} \tag{2}$$

B and I are respectively, the pulsar surface magnetic field and moment of inertia, R is the radius, α is the angle between the magnetic and the spin axes of pulsar and c is the speed of light. Conversely, direct measurements of pulsar braking index can be accomplished through the measurements of the spin period and its first and second time derivatives respectively given [21, 23] as:

$$n = 2 - \frac{P\ddot{P}}{\dot{P}^2} \tag{3}$$

Assuming that the spin period at birth is much smaller than its present value (i.e. $P_0 << P$) and that pulsar spin-down is due to magnetic dipole radiation (i.e. $n = 3$), the characteristic age can be simplified [21] as:

$$\tau_c = \frac{P}{2\dot{P}}. \tag{4}$$

However, for a radio pulsar (radius of 12 km and moment of inertia of 10^{45}g/cm^2), the rate of loss of rotational kinetic energy is given [21] as

$$\dot{E} = 4\pi^2 I\dot{P}P^{-3}. \tag{5}$$

This quantity $\dot{E}$ is called the spin-down luminosity and it represents the total output power of the pulsar. It follows, therefore, that the spin-down age depends on the spin-down parameters which characterize the intrinsic spin-down evolution of pulsars.

2.2. Parameters Used for Quantifying Timing Noise

The ongoing observations of timing activity in radio pulsars have shown massive complications in the true statistical behavior of most pulsars. Earlier on, a number of parameters were introduced to quantify and exemplify the expanse of timing noise in pulsars. Theoretically, a qualitative measurement of the level of timing noise activity in pulsars can be obtained from the surplus phase residuals remaining after accounting for their deterministic spin-down [24]. To that effect, the observed rotational phase of each pulsar can be fit with a function of the Taylor series expansion of the form [9]

$$\phi_{(t)} = \phi_0 + \nu(t-t_0) + \tfrac{1}{2}\dot{\nu}(t-t_0)^2 + \tfrac{1}{6}\ddot{\nu}(t-t_0)^3 + ..., \tag{6}$$

where the terms ν, $\dot{\nu}$ and $\ddot{\nu}$ are the frequency and its first and second time derivatives respectively and $\phi_{(t)}$ is the phase at a time t. The timing noise activity parameter A is defined as the logarithm of the ratio of the root mean square deviation over a 12 *ms* observation for a given pulsar to the same quantity in the Crab pulsar and can be explicitly expressed following [25] as

$$A = \log\left[\frac{\sigma_{TN}(m,T)}{\sigma_{TN}(m,T)crab}\right], \tag{7}$$

where m is the order of the polynomial fit to the data, T is the time span of the fit in days. $\sigma_{TN}(m,T)$ is the timing noise contribution to the gross root mean square phase residuals obtained by subtracting quadratically the root-mean square timing residuals from the second and third order polynomial fits to the arrival time data (in *ms*) while $\sigma_{TN}(m,T)crab$ is the timing noise of the crab pulsar (in *ms*). In order to characterize the intensity of the fluctuations observed in pulsars based on the amplitude of the observed spin frequency second time derivative $\dot{\nu}$, the stability parameter introduced by [9] can be expressed as

$$\Delta_8 = \log\left(\frac{|\ddot{\nu}|}{6\nu} T_8^3\right), \quad (8)$$

where the frequency second time derivative is observed and measured over a time span of $T_8 = 10^8$ s while the cubic term dictates the variance for a timing noise in the group of average of any red process with a monotonically decaying spectrum. The direct measurement of the quantity of contamination gotten in frequency second time derivative from the standard timing activity by all forms of timing fluctuations. Thus, Timing Noise Statistic (σ_{23}) introduced by [26] is defined as

$$\sigma_{23} = \sigma_R(2,T) - \sigma_R(3,T) \quad (9)$$

where $\sigma_R(2,T)$ and $\sigma_R(3,T)$ are the the root-mean-square (*rms)* phase residuals obtained respectively from the second and third order polynomial models fits to the timing data over a time span *T*. Pulsar clock stability parameter $\sigma_Z(T)$ is a dimensionless Allan variance-like parameter introduced by [27] to quantify the degree of rotational stability in radio pulsars. The authors defined the Parameter $\sigma_Z(T)$ as:

$$\sigma_Z(T) = \frac{1}{2\sqrt{5}}\left[\frac{\sigma_{\ddot{\nu}}\ (T)}{\nu}\right] T^2 \quad (10)$$

where $\sigma_{\ddot{\nu}}$ is *rms* of the measured $\ddot{\nu}$ over the observing spans of length $T = 10$ years [5].

3. Data Sample and Results

3.1. Sample

The data set employed in this paper is a large database of Jodrell Bank Observatory (JBO) radio pulsars with significantly measured spin-down and timing noise activity parameters estimated from radio timing data with time span length of over four decades [5]. The primary dataset which contains 523 objects with complete information on radio pulsar stability parameter Δ_8 was compiled from literature [5, 28, 9]. For cases where sources overlap, the values of Δ_8 obtained from more recent and precision timing were taken. A total of 456 of the radio pulsars in the primary sample (~ 87%) has complete activity parameter (A). This is made up measurements of A for 90 radio pulsars taken from previous published works [26, 29, 12, 6] while the values for 366 radio pulsars were computed from [5] using equation (7) with the supposition that the method used by [5] effectively whitened the timing residuals of the pulsars in the sample. Similarly, 366 radio pulsars have published measurements of the pulsar clock stability parameter $\sigma_Z(T)$ taken from [5]. The timing noise Statistic (σ_{23}) was obtainable for only 313 out of the 523 radio pulsars (~ 60%) and were calculated from the information published in [5] using equation (9). The corresponding period derivative $\dot{P}$, spin-down luminosity $\dot{E}$ and characteristic age (τ_c) were all extracted from the Australian Telescope National Facility (ATNF) Pulsar catalogue[1].

3.2. Analysis and Results

The technique employed in the analysis of the current sample is essentially statistical and analytical method with much emphasis on the Pearson's correlation theory. The statistical method was used to determine the strength of relationships between pairs of variables and understand how the independent variables are related to the dependent variable and to explore the forms of their relationships. The correlation theory calculates the correlation coefficient which provides the strength of correlation between parameters The scatter plots of the timing noise parameters against the logarithm of pulsar period derivative for the sample of the pulsars which have finite and non-zero period derivative in the range -20 $ss^{-1} \leq \log\dot{P} \leq$ -13 ss^{-1} are shown in Figures 1 (a)–(d). Apparently, there is a large amplitude scatter and superimposed on the scatter is a trend which suggests that pulsars with large spin-down rates support higher level of rotational instability. We obtained linear regression equations of

$$A = (0.82 \pm 0.04)\ \log\dot{P} + (-1.40 \pm 0.03) \quad (11)$$

$$\sigma_z = (0.48 \pm 0.34)\ \log\dot{P} + (-1.10 \pm 0.23) \quad (12)$$

$$\Delta_8 = (0.42 \pm 0.14)\ \log\dot{P} + (-1.90 \pm 0.43) \quad (13)$$

$$\log\sigma_{23} = (1.02 \pm 0.14)\ \log\dot{P} + (-1.24 \pm 0.33) \quad (14)$$

A simple linear regression analysis of the averaged data shows a very strong correlation ($r \geq 0.76$) between the timing noise parameters and the pulsar spin-down rate. The correlations are found to be statistically significant at 98% confidence level.

Scatter plots of the timing noise parameters against the radio pulsar characteristic age are shown in Figure 2 (a)–(d). The plots are characterized by significant anti-correlations (-0.89 $\leq r \leq$ -0.75) which are super imposed on large amplitude scatter in the timing noise parameters for a given pulsar spin-down age. Most of the pulsars in our sample have characteristic age in the range ($10^4 \leq \tau_c \leq 10^{10}$) yr implying that they are young, energetic fast rotating radio pulsars. We obtained linear regression equations of

$$A = (0.98 \pm 0.11)\ \log\tau_c - (2.40 \pm 0.13) \quad (15)$$

$$\sigma_z = (0.788 \pm 0.30)\ \log\tau_c - (0.10 \pm 0.03) \quad (16)$$

$$\Delta_8 = (0.42 \pm 0.14)\ \log\tau_c - (1.99 \pm 0.23) \quad (17)$$

$$\log\sigma_{23} = (1.02 \pm 0.14)\ \log\tau_c - (3.24 \pm 0.35) \quad (18)$$

1 www.atnf.csiro.au(/research/pulsar/psrcat)

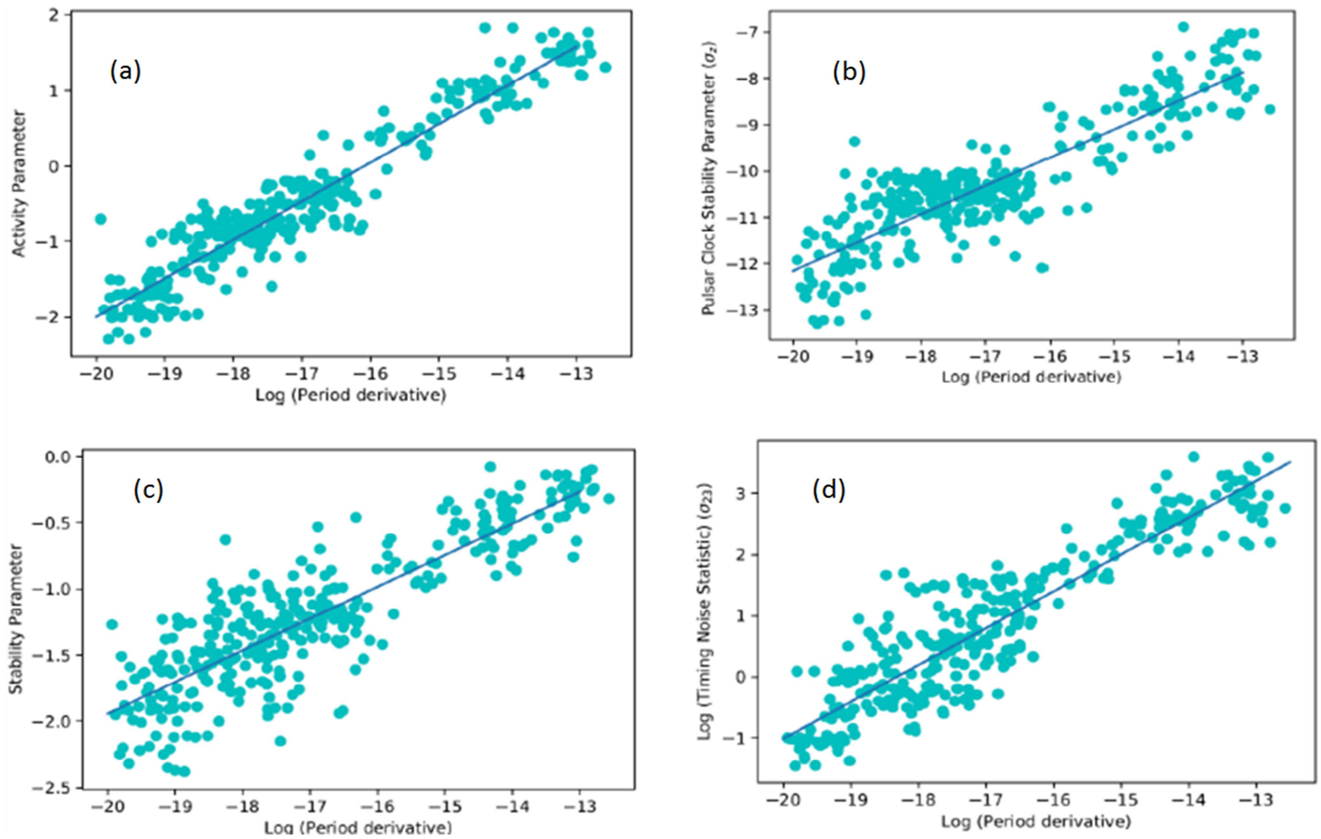

Figure 1. *Scatter plots of (a) activity parameter (b) pulsar clock stability parameter (c) stability parameter (d) logarithm of Timing Noise Statistic against the logarithm of pulsar spin-down-rate.*

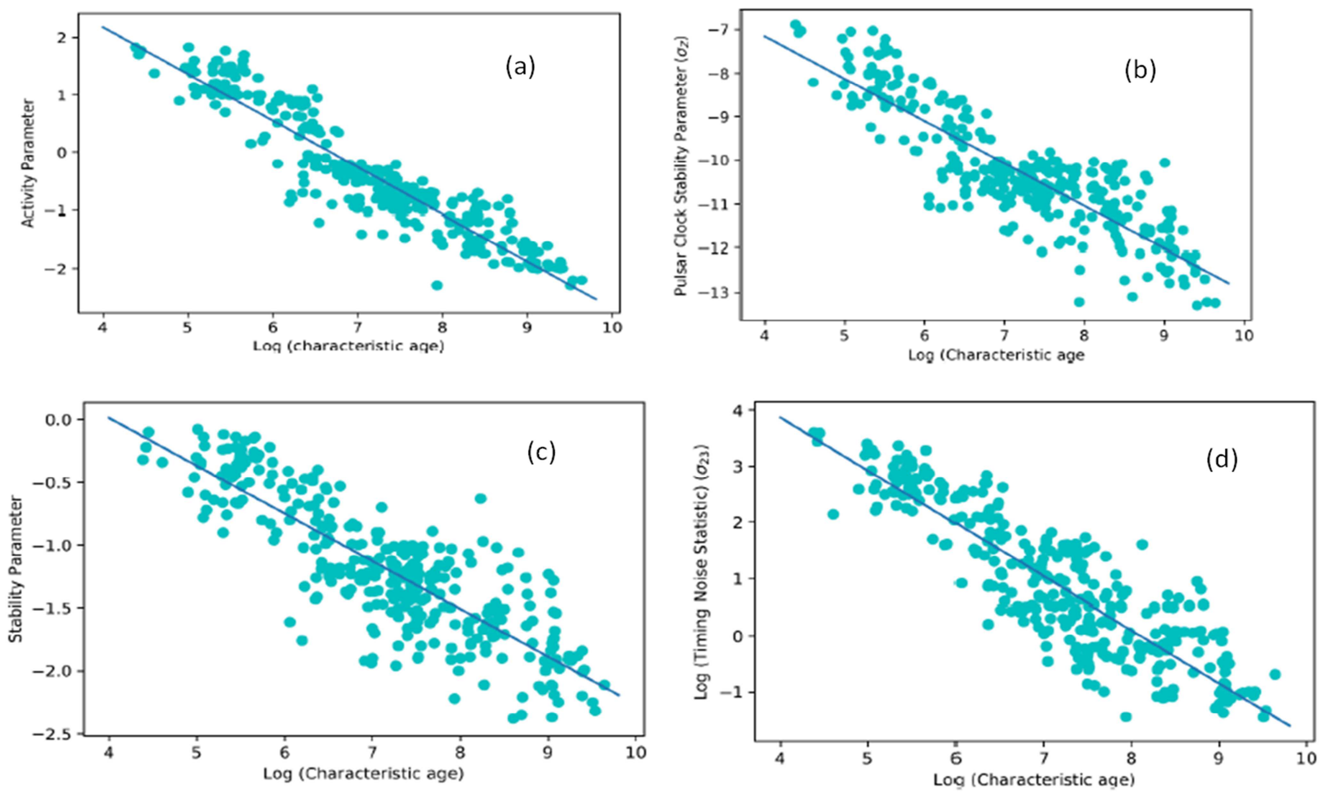

Figure 2. *Scatter plots of (a) activity parameter (b) pulsar clock stability parameter (c) stability parameter (d) logarithm of Timing Noise Statistic against the*

logarithm of radio pulsar characteristic age.

Similarly, we investigated the relationships between the timing noise parameters and the pulsar spin down luminosity. The scatter plots are shown in Figures 3 (a)–(d). Evidently, there is a continuous trend going from the lower left corner of the plot to the upper right corner. We obtained linear regression equations of the forms

$$A = (1.38 \pm 0.21)\ \log \dot{E} + (-3.1 \pm 0.11) \quad (19)$$

$$\sigma_z = (0.28 \pm 0.37)\ \log \dot{E} + (0.12 \pm 0.09) \quad (20)$$

$$\Delta_8 = (0.2 \pm 0.14)\ \log \dot{E} + (1.99 \pm 0.23) \quad (21)$$

$$\log \sigma_{23} = (0.82 \pm 0.22)\ \log \dot{E} + (1.04 \pm 0.15) \quad (22)$$

A simple linear regression analysis of the averaged data shows a very strong correlation ($r > 0.75$) between the timing noise parameters and the pulsar spin-down luminosity with 95% confidence level

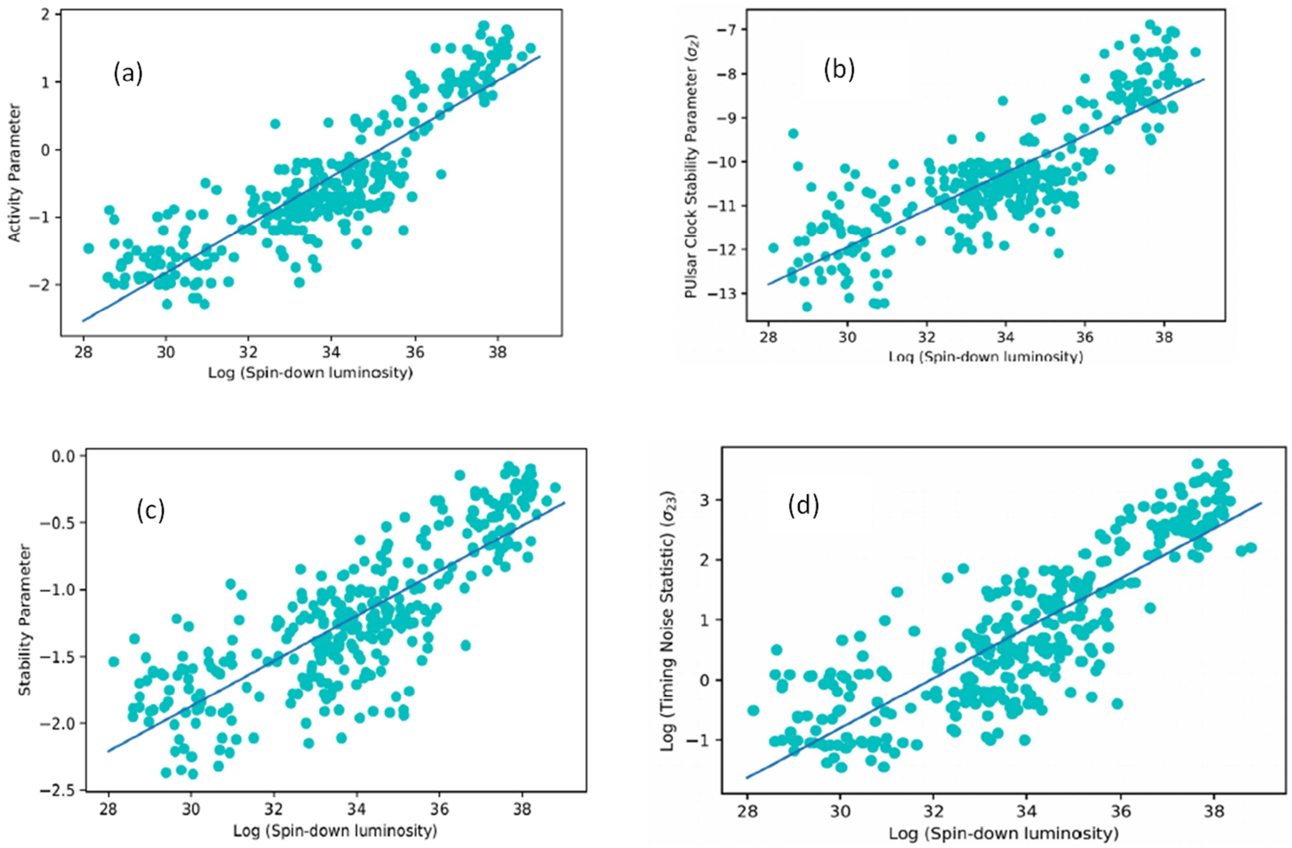

Figure 3. *Scatter plots of (a) activity parameter (b) pulsar clock stability parameter (c) stability parameter (d) logarithm of Timing Noise Statistic against the logarithm of radio pulsar spin-down luminosity.*

4. Discussion

The result of the statistical analysis of a large data base of rotation powered pulsars with improved measurements of timing noise activity parameters and their effects on the intrinsic spin-down parameters has been presented. The pulsar spin-down rate is a rotational parameter and intrinsic property of radio pulsar and consequently, it is expected to show positive relationship with the timing noise parameters. The radio pulsars' spin period and its time derivatives depend on this spin-down rate (Lorimer and Kramer 2005). The large amplitude scatter observed in both the timing noise parameters and spin-down parameters of pulsars in current sample is not entirely unexpected given the large-scale inhomogeneity in their rotational irregularities. The strong correlations (r >+ 0.80) found between activity parameter and the spin-down parameters [the spin-down rate $\dot{P}$] can be described as an intrinsic process interconnected directly with the spin-down of the underlying neutron stars. Some prior studies (27, 5) have substantiated that pulsars that speedily spin-down are well-thought-out to have large values of timing noise activity as well as spin properties. This indicates that radio pulsars' spin-down evolution is reliant on the observed large persistent increases (or offsets) in magnitudes of the spin-down rate. It is also believed that TN is a direct consequence of some form of intrinsic stochastic fluctuations in pulsars spin-down torque (7, 26). In addition, it can also be emphasized that the phase fluctuations over decades may also probably be as a result of the change in the pulsars spin down rate characterized by the intrinsic rotational evolution of the pulsars and variations in the spin down torque. Pulsars are born with different rotational periods and young pulsars might have less periods and are, therefore, found to exhibit more timing noise than timeworn pulsars. Also, the very strong ($r \geq$ - 0.87) correlations which characterize the relationships between timing noise parameters and the characteristic age is a clear indication that young, active pulsars on the average display more rotational instability than their puny, old counterparts. This infers that timing noise depends on the pulse rotational variables with aged and frail radio pulsars with small spin-down rate showing much less timing noise than youthful, energetic ones. The positive relationship showed by the timing noise activity parameter and the spin down luminosity shows that pulsars with large values spin down energy loss rate show much more timing noise. As pulsars get old, their spin energy lessens and they become more stable. Consequently, the strong relationship may be attributed to the periodic changes and irregular loss in the radio pulsar rotational kinetic energy.

5. Conclusion

The observed spin parameters of the radio pulsars have been expansively studied for characterization with the pulsar timing irregularities. Our results have revealed that the strength of timing noise parameters have pronounced significant effects on the radio pulsars spin down evolution. There is a reasonable correlation between stochastic timing noise parameters and spin-down rate, with young pulsars tending to be noisier. Therefore, young pulsars are the best candidates for probing the properties and dynamics of neutron stars. It is also found that the effects of timing noise on spin-down luminosity are on average less severe for pulsars with relatively small values of timing noise parameters but large spin-down evolution. The observed large amplitude and spread in the values of the timing noise parameters highlight the fact that as pulsars age, their spin energy and dynamics lessens and consequently, old pulsars show much less timing noise than young ones.

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