Timing noise of 133 pulsars in the southern hemisphere

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Abstract. Pulsars are small, dense stars which rotate up to 1500 times per second and emit radio waves in a directed beam along their magnetic axis. Pulsars are remarkably stable rotators, and by measuring the arrival times of the radio beam the pulsar can be used as a clock in space. Applications of pulsar timing have led to the first exoplanet system, stringent tests of theories of gravity and have the potential to detect gravitational waves. Yet, the pulsars spin is not perfect, and understanding the imperfections (timing noise) is important to the aforementioned applications. Here, we present the analyses of timing noise of 133 pulsars observed with the Parkes radio telescope in Australia over the period of 4 years. The results show that as consistent with pulsar toy model equations the measured breaking index, representing the magnitude of timing noise, has an anti-correlation with the spin-down rate, spin-down energy and characteristics magnetic fields, and it also has a positive correlation with the characteristics age at significant of 10σ. The error in the slope values of those relationships are in the order of 9 percent, which may imply imperfections of the pulsar toy model.

1. Introduction
At the end of life of main-sequence stars, matter of the stars collapses to the center by its gravity. If the stars have masses more than approximately 25 solar masses, they will develop into black holes. Neutron stars evolve from massive stars that have masses between 8 to 25 solar masses. These massive stars explode as supernova and leave behind remnants known as neutron stars [1]. Some neutron stars produce radio pulses every rotation. The assumption that pulsars are regular rotator that follow a simple slow-down model forms the basis of a powerful technique, known as ”Pulsar Timing”, that is used for many applications in astronomy and physics [2-4]. Pulsar timing can also provide information on the pulsar itself, such as the spin evolution, sky position, the masses, orbital period and inclination. However, the precision of this technique is often limited by the existence of ”Timing Noise”, which arises from our limited understanding of the nature of pulsars [5].
According to classical electrodynamics, a rotating magnetic dipole with moment $|m|$ radiates an electromagnetic wave which has the rate of energy loss as

$$
\dot{E}_{\text{dipole}} = \frac{2}{3c^2} |m|^2 \Omega^4 \sin^2 \alpha,
$$

where $\alpha$ is the angle between the spin axis and the magnetic moment, $c$ is the speed of light and $\Omega = 2\pi f$ is the rotational angular frequency. The spin-down luminosity affects the evolution of the rotation frequency as [1],

$$
\dot{\Omega} = - \left( \frac{2|m|^2 \sin^2 \alpha}{3Ic^3} \right) \Omega^3,
$$

where $I = 10^{45} \text{g cm}^2$ is the canonical moment of inertia. Illustrating this equation more generally by a power law as a function of the rotational frequency ($\nu = 1/P$),

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

where braking index, $n$, of 3 corresponding to magnetic dipole rotating in the vacuum. Differentiating the above equation and eliminate $K$, we obtain

$$
n = \nu \ddot{\nu} / \dot{\nu}^2.
$$

Therefore, $n$, which reflects the nature of spin-down behaviour, can be determined if we can measure $\dot{\nu}$ (where $\dot{\nu}$ is first derivative of frequency) and a second spin frequency derivative ($\ddot{\nu}$).

However, it is very difficult to directly measure braking index. For old pulsars, $\nu \approx 1 \text{ Hz}$ and $\dot{\nu} \approx 10^{-15} \text{ Hz s}^{-1}$, we would need $10^9 \text{ s}$ or $\approx 100 \text{ years}$ [6]. It has been reported that timing noise can dominate the intrinsic $\dot{\nu}$ value by a factor of 100 [7]. Only a few pulsars have their $n$ measured to be between 1.4 to 2.9 [8]. The only one kind of the effect that dominate the value of $\ddot{\nu}$, and consequently $n$, have been proposed for timing noise.

2. Observation and data analysis

We investigate the relationships between $\nu$ and $\dot{\nu}$, $n$ and the rate of loss of rotational energy ($\dot{E}$), the characteristic age ($\tau$) and the surface magnetic field ($B_s$), which can be calculated as follows [1]:

$$
\dot{E} \approx 3.95 \times 10^{31} \text{ erg/s} \left( \frac{-\dot{\nu}}{10^{-15}} \right) \left( \frac{\nu}{s} \right),
$$

$$
\tau \equiv 15.8 \text{ Myr} \left( \frac{\nu}{s} \right) \left( \frac{-\dot{\nu}}{10^{-15}} \right)^{-1},
$$

and

$$
B_s \approx 10^{12} G \left( \frac{-\dot{\nu}}{10^{-15}} \right)^{1/2} \left( \frac{\nu^3}{s} \right)^{-1/2}.
$$

We use the Parkes radio telescope to observe 133 pulsars in the southern hemisphere and 3 pulsars in the northern hemisphere. Our data was observed by the telescope at a center frequency of 1.4 GHz.

We find a correlation between $n$ and $\dot{\nu}$, $\dot{E}$, $\tau$, and $B_s$ by rid a $\dot{\nu}$

$$
\log n = - \log \dot{\nu} + \frac{1}{2} (\log 2 - \log \nu),
$$

$$
\log n = - \log \dot{E} + \frac{1}{2} (\log 2 + \log \nu) - \log 4\pi^2 I,
$$

where $I$ is the canonical moment of inertia of the pulsar.
\[
\log n = \log \tau_c + \frac{1}{2} \log \nu + \frac{3}{2} \log 2, \quad (10)
\]

and

\[
\log n = -\log B + \log \nu + \frac{1}{2} \log 2 + \log \left(3.2 \times 10^{19}\right). \quad (11)
\]

TEMPO2 package was developed at the ATNF mainly by Hobbs, Edwards and Manchester [9]. TEMPO2 is a software package that allows us to analyse the time of arrival, ToA, from observations, together with a timing model, a solar system ephemeris, and clock information from the observatory. Tempo2 package provides the difference between the ToA and the timing model that known as residuals and uncertainty of residual. In this work, we fit for \( \dot{\nu} \) necessary for computations of equations (5)-(7).

3. Results and discussion

There are significant of \( \dot{\nu} \) at 2\( \sigma \) that only have 38 pulsars from 133 pulsars of our data. In this numbers, 18 have positive values and 20 have negative values. In this work, we used a significant of \( \dot{\nu} \) at 2\( \sigma \), 5\( \sigma \), 7\( \sigma \) and 10\( \sigma \). Figure 1 braking index, \( n \), versus \( \dot{\nu} \), \( \dot{E} \), \( \tau_c \) and \( B \) has anti-correlations with \( \dot{\nu} \), \( \dot{E} \), \( \tau_c \) and \( B \) at slope are -1.09, -0.92 and -1.08 that has an error are 9\%, 8\% and 2\% respectively. \( n \) have positive correlation with \( \tau_c \) at slope of 1.04 that have an error at 4\%. At significant \( \dot{\nu} \) at 10\( \sigma \) has a slope closer than significant of \( \dot{\nu} \) at 2\( \sigma \) when we compare with our expectation value in equations (8)-(10).

![Figure 1](image)

Figure 1. \( n \) versus \( \dot{\nu} \) (a), \( \dot{E} \) (b), \( \tau_c \) (c) and \( B \) (d) with a straight line from linear fitting with the data.

Table 1 shows value of 2\( \sigma_{\dot{\nu}} \) to 10\( \sigma_{\dot{\nu}} \) for slope of \( n \) with \( \dot{\nu} \), \( \dot{E} \), \( \tau_c \) and \( B \). Slope of \( n \) with \( \dot{\nu} \), \( \tau_c \) and \( B \) converge to -1, +1 and -1 respectively when \( \sigma_{\dot{\nu}} \) up to 10\( \sigma \). \( \sigma_{\dot{\nu}} \) versus slope of \( n \) with \( \dot{E} \) have a slope nearly spread around -1 because \( \dot{E} \) have a great significant since 2\( \sigma \) [10].
Table 1. Results showing slope of $n$ versus $\dot{\nu}$, $\dot{E}$, $\tau_c$ and $B$ at $2\sigma$, $\sigma$, $7\sigma$ and $10\sigma$.

|         | $2\sigma_{\dot{\nu}}$ | $5\sigma_{\dot{\nu}}$ | $7\sigma_{\dot{\nu}}$ | $10\sigma_{\dot{\nu}}$ |
|---------|------------------------|------------------------|------------------------|------------------------|
| $n$ versus $\dot{\nu}$ | -1.32 | -1.13 | -1.11 | -1.09 |
| $n$ versus $\dot{E}$ | -1.04 | -0.94 | -0.93 | -0.95 |
| $n$ versus $\tau_c$ | 1.33   | 1.06  | 1.08  | 1.04  |
| $n$ versus $B$ | -1.42 | -1.11 | -1.15 | -1.08 |

4. Conclusion
We have used regular observations of a group of 133 pulsars with the Parkes radio telescopes to examine the timing noise properties. Braking index, $n$, rely on the measurement of $\dot{\nu}$ by using Tempo2 package. The results at $10\sigma_{\dot{\nu}}$ that highest converge to expected slope, show timing noise has an anti-correlation with the spin-down rate, $\dot{\nu}$, spin-down energy, $\dot{E}$, and magnetic field, $B$, that has error in the slope of 9%, 5% and 8% respectively. Timing noise have a positive correlation with the characteristic age of pulsars, $\tau_c$, that have error in the slope of 4%.

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