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Effects of Spin Properties on Braking Indices of 208 Glitching Pulsars

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Abstract: Pulsars are stars that emit electromagnetic radiation in a definite time interval. Detailed study of the long-term timing observations of pulsars indicate that the predictable smooth spin- down of pulsars is predisposed to discrete fluctuations known as glitch. The rotation frequency of pulsars decays with time as quantified by the braking index (n). The braking indices have been known to have no consequence on the quantities like obliquity angle evolution or complex high-order multipole structure but on the spin properties of the pulsars. In the canonical model of the theory of braking indices, $n = 3$ for all pulsars, but observational information has shown that $n \neq 3$, indicating that the canonical model requires reconsideration. Using the Australian Telescope National Facility (ATNF) pulsar catalogue, we selected 208 pulsars with 670 glitches and used the distributions of the spin properties to statistically investigate their effects on the braking indices. We computed the braking indices of these pulsars using the theoretical method and observed that the braking index is much smaller for very young pulsars (10^4-10^7) which have been observed to show more glitch activity than their old, stable counterparts. A simple regression analysis of our data show that spin properties of pulsar are more than 65% correlated with the magnitude of pulsar braking index. The implications of the spin properties on braking indices on long timescales are discussed.

Keywords: Pulsars, Braking Index, Glitches: Spin-Properties, Methods: Statistical - Regression Analysis

1. Introduction

Pulsars are extremely magnetized, rapidly rotating neutron stars that are supposedly produced through a supernova explosion of very massive O and B stars (mass is in the range of 8 - 10 solar mass) that are created in the collapse of the stellar core [1, 2]. They have enormous moment of inertia (10^{45}g/cm^2) that leads to outstandingly smooth rotation rate, thus, making it the most precise clocks in the universe [2, 3]. They offer the opportunity to study physics in regimes unattainable in any terrestrial laboratory and provide a powerful probe for exploring the interstellar medium [2, 4]. Their periods of rotation are remarkably stable such that pulsars are extremely good cosmic clocks [5]. This clock-like behavior has different applications, for example, for testing the gravitational theories [6-8] as well as detection of stochastic background of gravitational waves [9, 10].

Although, pulsars are known to have remarkable rotational stability, detailed studies have revealed that they exhibit two distinct types of spin irregularities. These are glitches and timing noise. Glitches are sudden tiny jumps in pulsar rotation rate which are usually accompanied by increase in the magnitude of frequency derivative [11]. Glitches are uncommon spectacular events characterized by recovery of the jumps in frequency and its first time derivatives on a large range of timescales [12, 11]. Currently, it is generally agreed that glitches come from various complex dynamical changes within the interior of neutron star; hence, the study could offer valuable information about the internal structure and dynamics of neutron stars [11-13]. The macroglitch is rare but outstanding event that is frequently characterized by recovery of the pulsar spin down rate on large wide range of timescales [14, 15]. Meanwhile, Microglitches are not known very well, non-attractive and can be defined by flexible signs [16].

On the other hand, braking index (n) is a value that measures how pulsars gradually slow down with time and it theoretically constrains the different pulsar spin-down models. In the standard pulsar model of an unchanging magnetic dipole in a vacuum, the braking index is predicted to have a value of three [17] while in a more realistic model of pulsar magnetosphere, it is assumed to take values between 1.8 and 3 [18]. The values of braking index can be obtained by relaxing the various assumptions of the model for instance, allowing magnetic field evolution [19], momentum loss due to a particle wind [20], or a varying angle between the spin and magnetic poles [21]. Observations show that the rotation frequency of pulsars is slowly decaying with time (the stars are spinning down), implying a gradual decrease of the angular velocity, according to the canonical model [22]. Such decay is quantified by this dimensionless parameter known as braking index. The canonical model predicts that this index has only one value for all pulsars which is equal to 3. However, information from different observations show that actual braking indices are different from 3, indicating that the canonical model requires a second thought.

Several researchers have worked on braking indices of pulsars [23-27]. However, the measurement of the braking indices of pulsars remained a challenge because of the difficulty in measuring the frequency second time derivative. Also, it has been observed that young pulsars which have been observed to exhibit more glitches (τ_c < 100 kyr) are the only pulsars that allows a measurement of their braking indices [28-31]. Deviating from the traditional way of differentiating the spin-down law, the braking indices of selected pulsars have been calculated by some authors using the integration method see, e.g. [23]. Their result showed a deviation from the canonical value of n = 3 and is reportedly anomalous. Though this approach has its limitations such as giving different values for the braking index for different epoch variation, it was useful for calculating braking indices of middle-aged ($10^4 - 10^6$ yrs) pulsars without using the long, phase coherent timing solution. Also, other researchers measured the braking indices for 19 young radio pulsars and argued that braking index is robust against uncertainties in the irregular (stochastic) component of pulsars' timing noise and reflects a regular pulsar evolution at least at the timescales of tens of years [32, 33]. The obtained values for eleven of them which are in the range $\sim$ 10 – 100, two are negative, two are above 100 and only four are compatible with the classical value n = 3 predicted by the magneto-dipole formula for constant field and obliquity angle. Similarly, it has been noted that the braking indices measured in 12 out of 19 radio pulsars have spin-down age less than 120 Kyr which is a fraction of ≈ 60 % [32]. For older pulsars, this fraction is much smaller (≈ 11%). Furthermore, other authors employed the differentiation method to the phase coherent timing solution on 27 HartRAO pulsars to study the braking indices of pulsars [22]. Their result, which mostly gave braking indices with anomalous values ($2.4 \leq n \leq 15386.0$), fails to support the hypothesis that pure magnetic dipole radiations at pulsar rotation frequency and acceleration of particle winds constitute the dominant spin-down mechanism for most radio pulsars. In this paper, we study the spin properties of frequently glitching pulsars by measuring their braking indices. This is in order to test and ascertain the effects of these properties on the braking indices. The paper is organized in this way. Section 2 discusses the simple timescale estimate of pulsars while Section 3 describes the data sample and the results of the relationship between the spin properties and braking index. In Section 4, we gave the discussion. The paper is concluded in Section 5.

2. Simple Timescale Estimate

The braking index (n) is a value that measures how pulsars gradually slow down with time and it theoretically constrains the different pulsar spin-down models. The braking index is a well-known characteristic of pulsars [see, 19]. The rotation period P of pulsars is known to increase with time and the rate of increase is always related to the rate of loss of rotational kinetic energy through the emission of electromagnetic radiation and particles which interact with the magnetic field of the neutron star [34, 35]. As pulsars are powered by their rotational kinetic energy, their spin periods increase according to the spin down law given by [17] as:

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

where the exponent n is the braking index and K is an arbitrary positive constant and is given in its explicit form by [36] as:

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

where B and I are, respectively, the neutron star surface magnetic field and moment of inertia, R is the stellar radius, α is the angle between the magnetic and the spin axes of the neutron star, and c is the speed of light. In its simplest form, the widely used standard vacuum dipole spin-down model, K is taken to be an arbitrary positive constant and n = 3 [17]. However, the braking index can be obtained by a direct measurement of the pulse spin frequency and its first time derivatives and is given [17, 2] as:

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

where $\ddot{\nu}$ is frequency second time derivative. If a pulsar is born at a time $t = 0$ with spin period $P_0 << P$, integrating equation (1) a time when the pulsar is born, from $t = 0$ to the present time $t = T$ yields the spin down age of the pulsar T [37] as:

$$T = \frac{P}{(\text{n-1})\,\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right], \tag{4}$$

where P_0 is the spin period at birth. For spin down due to pure magnetic dipole braking in a vacuum, the braking index $n = 3$. Hence, the characteristic age of the pulsar reduces to

$$\tau_c = \frac{P}{2\dot{P}}. \quad (5)$$

For a canonical pulsar of radius 12 km and moment of inertia of 10^{45}gcm^2, the estimate of the surface magnetic field can be expressed as

$$B_s = 3.2\times10^{19}\sqrt{P\dot{P}} \quad (6)$$

Similarly, the integration of the spin down law as given in equation (1) over time gives another formula of the braking index which is irrespective of the spin frequency second derivative as;

$$n = 1 + \frac{\nu_1\dot{\nu}_2 - \nu_2\dot{\nu}_1}{\nu_1\dot{\nu}_2(t_2 - t_1)} \quad (7)$$

by substituting for $\dot{\nu} = -\frac{\dot{P}}{P^2}$ and $\nu = -\frac{1}{P^2}$ in equation (3), we obtained

$$n = 1 + \frac{P_1\dot{P}_2 - P_2\dot{P}_1}{P_1\dot{P}_2(t_2 - t_1)} \quad (8)$$

where P is the spin period, $\dot{P}$ is the period derivative, t_1 is the epoch of observation, and P_1, ν_1, $\dot{P}_2$, $\dot{\nu}_1$ and P_2, $\dot{\nu}_2$ are values measured at t_1 and t_2 respectively.

3. Sample Description, Analysis and Results

3.1. Sample

The data sample used for this research work are from the Jodrell Bank Observatory (JBO) glitch catalogue on https://www.jb.man.ac.uk/pulsar/glitches/gTable.html. The catalogue contains 670 glitches in rotation of 208 pulsars as at the time of this analysis. A careful inspection of the observed data of the 208 JBO pulsars suggests that the pulsars have undergone glitches for at least once. We selected the 208 pulsars that have been found to exhibit glitches and obtained their pulsar spin properties (spin frequency second time derivative ($\ddot{\nu}$), surface magnetic field (B_s) and characteristic age (τ_c) from the catalogue. The braking indices of the 208 pulsars were computed using equation (3). We then classified the braking indices into two subsets: (n > 0 and n < 0) based on whether the value of the braking index is greater or less than 0. We obtained 112 pulsars with positive braking indices while 96 pulsars have negative braking indices.

3.2. Analysis and Results

The technique used in the analysis of the current sample is distributive and simple regression analysis methods. The basic physical equations that relate the characteristic properties of pulsars were used for the theoretical setting while the braking index of the pulsars was computed. In statistical approach, the conventional measurements of central tendency and dispersion were used to determine the average values of the parameters. The key interest is to understand the distributions of the spin properties parameters and to explore the level of relationships between the parameters and braking indices.

3.2.1. Distribution of the Spin Properties of Our Sample

Here, we plot and examine the distributions of the spin down parameters of our sample. The distributions of these parameters were carefully analysed in order to extract the relevant information about the samples. Figure 1 (a) gives the distribution of the absolute values of the braking indices of the 208 pulsars. The distribution does not appear normal which suggests that the braking index is affected by mutual independent factors. For instance, the canonical value of n = 3, which is characteristic of the magneto dipole braking and occupy a large fraction of the population. Apparently, other factors must be responsible for the departure of n values from the canonical value of 3. It is found that the 112 pulsars with positive values of the braking indices have a mean of n = 398.321 with minimum and maximum values of n are 7.43 and 1584893.87 respectively, which show extreme dispersion in the values of the braking indices. The 96 pulsars with negative values of braking indices have the mean of their absolute values as 860.54 with minimum and maximum values of 5011872 respectively. We obtained significant values of the braking index ($0 < n \leq 4$) for 16 pulsars as shown in Table 1 with their spin properties also listed. The distribution of frequency second time derivative ($\ddot{\nu}$) of the 523 radio pulsars is shown in Figure 1 (b). Clearly, the spread in the parameter covers a wide range 1.032×10^{-22} to $1.132\times10^{-29}\,ss^1$ which corresponds to ~ 8 orders of magnitude dispersion in the parameter with mean and median values of $3.26\times10^{-26}\,ss^1$, $3.506\times10^{-25}\,ss^1$ for n < 0 and $3.67\times10^{-25}\,ss^1$, $6.89\times10^{-26}\,ss^1$ for n > 0 respectively. The distribution is bi-modal with more than half of pulsars having frequency second time derivative below the mean value for both for n < 0 and for n > 0. The distribution is not symmetric as it skews towards the positive direction.

Table 1. *Pulsars with significant values of braking indices and their spin properties.*

Name of pulsar	Braking index (*n*)	frequency second time derivative (log scale)	characteristic age (log scale)
B0531 + 21	1.000 ± 0.008	-24.3872	6.541579
J0537 – 6910	2.080 ± 0.002	-25.1367	6.507427
JJ0631 + 1036	4.010 ± 0.001	-24.7959	5.563481

Name of pulsar	Braking index (*n*)	frequency second time derivative (log scale)	characteristic age (log scale)
B0740 – 28	2.600 ± 0.003	-25.4559	6.788875
B0833 - 45	1.700 ± 0.005	-23.6778	5.545307
J1023 – 5819	1.680 ± 0.003	-23.9208	5.352183
B1338 – 62	3.650 ± 0.002	-23.9086	5.650308
J1413-6141	2.760 ± 0.001	-24.1079	5.193125
B1737 – 30	5.120 ± 0.002	-25.5686	7.047775
B1757 -24	4.320 ± 0.002	-24.5421	6.439333
B1758 -23	3.610 ± 0.004	-23.0506	5.442488
J1814 – 1744	1.780 ± 0.005	-27.5086	7.605305
B18- 22 – 09	1.490 ± 0.006	-23.1079	5.694605
B1823 – 13	3.300 ± 0.004	-26.4711	7.082785
J1841 - 0524	2.540 ± 0.007	-27.3279	7.008600
J2229 + 6114	3.040 ± 0.002	-23.7959	5.276462

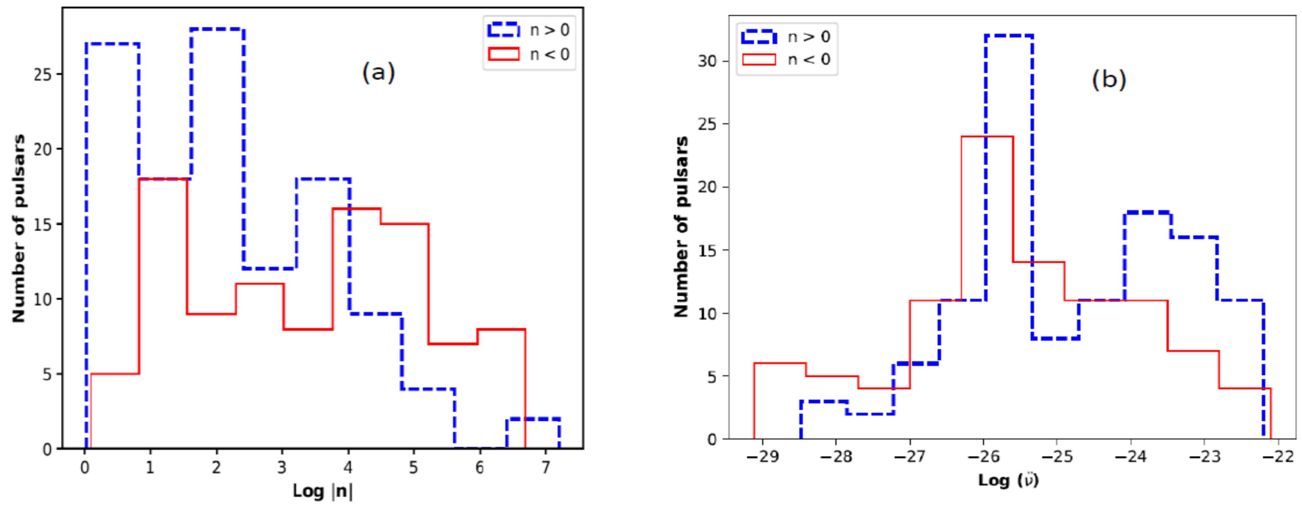


Figure 1. *Distributions of (a) braking indices (b) frequency second time derivative on logarithmic scales for 208 pulsars in our sample.*

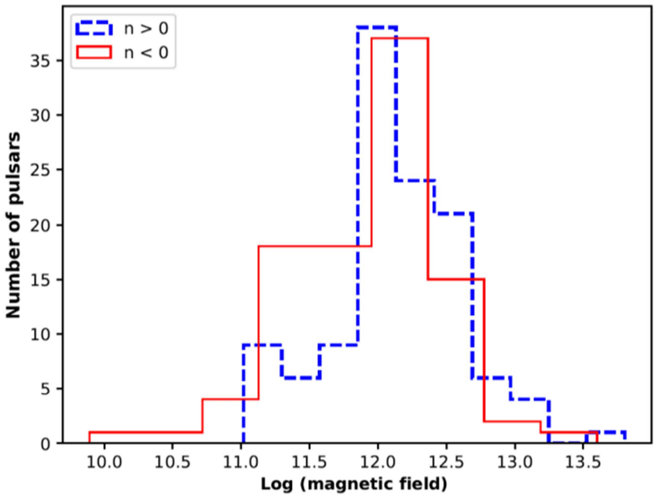
The distribution of characteristic age (τ_c) of 208 glitching pulsars is shown in Figure 2 (a). The characteristic age was grouped based on the intervals of ten years and distributed in order to know the age range of the pulsar with highest value of braking index. The ages range from $\approx 1\times 10^4$ - 6.30×10^9 year which shows that pulsars in our sample are young, energetic pulsars believed to be undergoing glitch phenomenon. The mean value of the pulsars' age is 6.20×10^6yr for n < 0 and 4.67×10^6yr for n > 0 while the median values are 1.80×10^7yr , 5.06×10^7yr for n < 0, n > 0 respectively.. From this measure of dispersion, it suggests that the age of these pulsars are not widely dispersed and does not depart from the normal distribution. This corresponds to the fact that our sample are young, energetic glitching pulsars. Also, the distribution of the surface magnetic field (B_s) of the 523 radio pulsars is shown in Figure 2 (b). The surface magnetic field ranges from $\approx 6.0\times 10^9 - 6.30\times10^{13}$ G. The surface magnetic field is characterized by a narrow spread (up to 7 orders of magnitude) with about 90 % of the pulsars having *B* value in the range of of $\approx 10^{11} - 10^{13} Gauss$ G. Notably, about 90% of these pulsars in current sample have surface magnetic field in the range $10^{11} - 10^{12}$ G which is clearly within the range given by (Lorimer and Kramer 2005) for radio pulsars which are known to show glitches.

3.2.2. Simple Regression Analysis

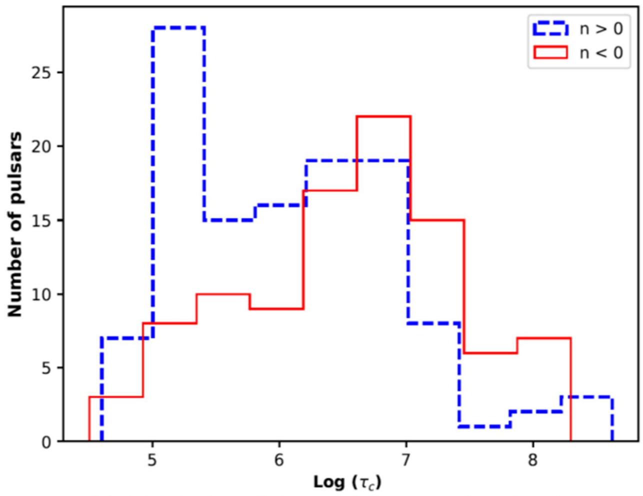
In this subsection, the relationship between the braking indices of our sample and the spin down properties of the glitching pulsars were investigated using the Pearson correlation theory. The study of these correlations can provide valuable information about the relationship between these parameters. In our implementation of the test, the strength of the apparent correlation is quantified by the Pearson product-moment correlation coefficient *r* [38], defined as

$$r = \frac{\sum (a_i - \bar{a})(b_i - \bar{b})}{\sqrt{\sum (a_i - \bar{a})(\sqrt{\sum b_i - b})}} \tag{9}$$

$\bar{a}$ and $\bar{b}$ are the mean values of a_i and b_i respectively with being the two pairs of the pulsars parameters. Figures 3 (a) and (b) show the scatter plots of the frequency first time derivative ($\dot{\nu}$) and frequency second time derivative ($\ddot{\nu}$) as a function of braking indices on logarithmic scales for 208 pulsars. Apparently, the plots show clear and significant negative trend which suggests that pulsars with large $\dot{\nu}$ and $\ddot{\nu}$ on average are found to possess large braking indices. A simple linear regression analysis was performed on our samples for n < 0, n > 0 and on the combined sample). The results are shown in Table 2. The slope *m*, intercept *c*, correlation coefficient *r* with the errors are indicated while *p* is the chance probability. These correlations suggest that spin down properties are a function of the braking indices.

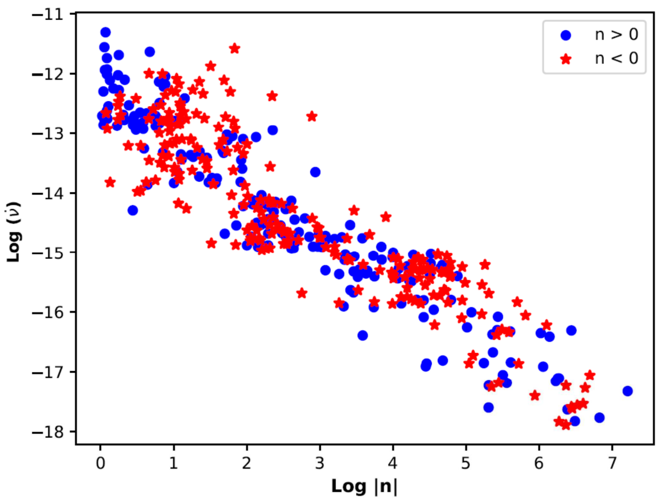


(a). Distributions of surface magnetic field on logarithmic scales for 208 pulsars in our sample.

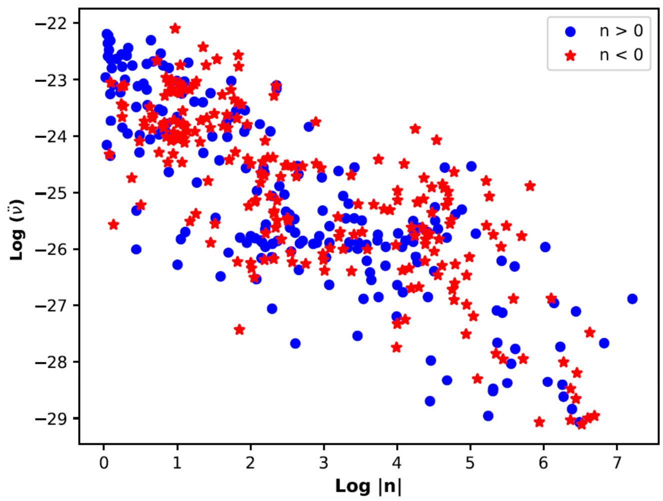


(b). Distribution of characteristic age on logarithmic scales for 208 pulsars in our sample.

Figure 2. *Distributions of (a) surface magnetic field (b) characteristic age on logarithmic scales for 208 pulsars in our sample.*



(a)



(b)

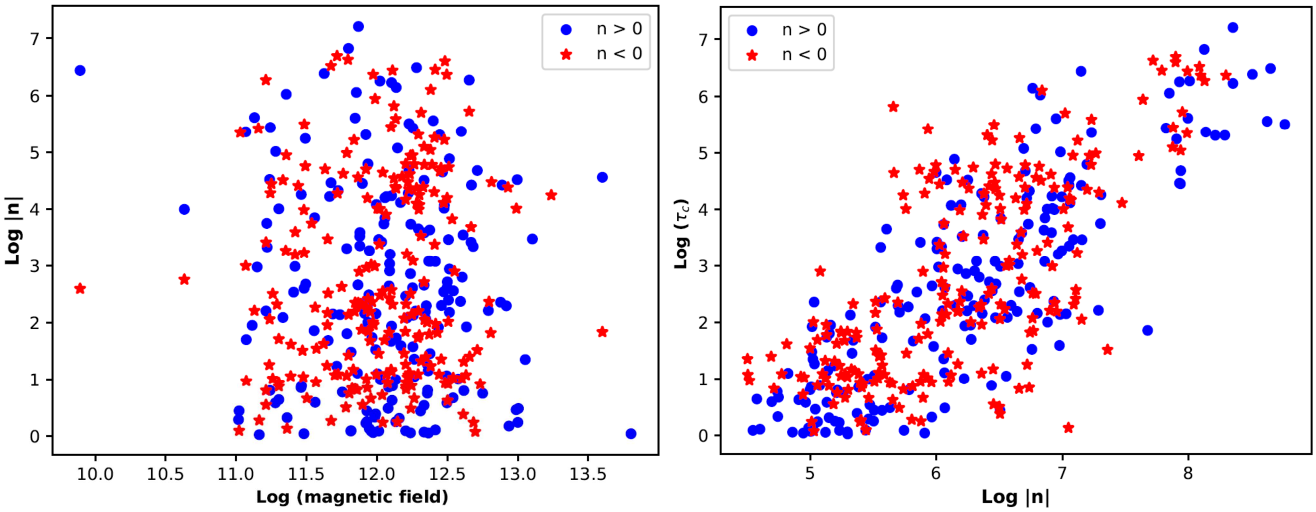
Figure 3. *Plots of frequency first time derivative (b) frequency second time derivative as a function of braking indices on logarithmic scales for 208 pulsars.*

Table 2. *Results of linear regression analysis of the pulsars with n < 0, n> 0 and the combined sample.*

Scatter plot	value of braking index	m	Δm	c	Δc	r	p
	|n| > 0	1.21	0.10	-12.30	0.20	-0.86	~ 10^{-6}
$Log \log \dot{v} - Log\,\|n\|$	|n| < 0	1.17	0.20	-12.70	0.10	-0.83	~ 10^{-5}
	combined sample	1.36	0.10	12.09	0.20	-0.82	~ 10^{-5}
	|n| > 0	0.89	0.20	-22.50	0.30	-0.57	~ 10^{-6}
$Log \log \ddot{v} - Log\,\|n\|$	|n| < 0	0.74	0.10	-22.33	0.10	-0.65	~ 10^{-4}
	combined sample	0.8 4	0.20	-23.33	0.20	-0.62	~ 10^{-4}

The scatter plots of the braking index as a function of the surface magnetic field (*B*) on logarithmic scales is shown in Figure 4 (a). Evidently, the figure is characterized by large amplitude scatter in braking index and surface magnetic field. However, superimposed on this scatter is no obvious trend as most pulsars have magnetic field in the range $6.0\times 10^{11} - 6.30\times10^{13}$ which is characteristic of young, glitching pulsars. A simple linear regression analysis of our data shows very marginal correlation with correlation coefficient r ≈ 0.08.

Figure 4 (b) is the scatter plot of the pulse characteristic age against the braking index for the present sample. The figure is characterized by a strong positive sloping trend implying that young pulsars have canonical values of braking index and thus, exhibit more glitch activity than their old, stable counterparts. A simple linear regression analysis of data shows that $\tau_C - |n|$ on average positively correlated (with correlation coefficients $r \approx 0.76$).



(a) (b)

Figure 4. *Plots of (a) braking indices as a function of surface magnetic field (b) characteristic age as a function of braking indices on logarithmic scales.*

4. Discussion

The result of the statistical analysis of 208 glitching pulsars with observed spin down properties and their effects on the braking indices has been presented. We noticed that those 14 pulsars with significant values i.e. ($0 < n \leq 4$) of the braking indices have periods between 0.04 s and 1.27 s. They have period derivatives within 10^{-12} and 10^{-16} with characteristic age ranging from 10^4 to 10^9yr and they are predominantly young pulsars and have been noted to be glitching pulsars. The obvious implication of our result is that mostly young and a few middle-aged pulsars have significant values of the calculated braking indices. Following the conventional model for pulsar's braking index, we say that the pulsars with $n \neq 3$ have not had their braking indices measured accurately due to some reasons. We suggest the following reasons to be responsible for the deviation from the canonical value of $n = 3$ for the braking index. One of the reasons could be recovery from unseen glitches [39] for middle-aged glitching pulsars ($\tau \sim 10^5 yr$) before the observations of the data we used were made. This is possible since the expected interval between glitch events are of the order of a few hundred years [40]. If this is so, a typical exponential recovery will cause n to be very high [23, 41]. This is only applicable to a few of our samples, so we argue that other reasons such as quadrupole braking could be responsible. This implies that the spin properties of our sample can be said to be dominated by magnetic braking. Hence, for these pulsars braking indices close to ±3 are expected and observed. Another reason could be an unobserved glitch which normally causes a negative value of the braking index for the pulsar [23]. Our results do not fully support this since the plots of the negative values of the braking indices contains glitching pulsars. Therefore, we argue that unobserved glitch (for young pulsars with high spin down rates) and some other factors could be responsible for the negative values of the braking index. For old pulsars, we attribute the high values of the braking indices to high rotation rate as earlier suggested by [42]. Since pulsars with longer periods ($P > 1s$) and low spin-down i.e. $\ddot{\nu} < 10^{-15}$ have low glitch activity [43] which results in a high n values. A change in the braking index value obtained using the integration method is caused by the differences in epochs of observations as we observed from our analysis of 16 sub-samples. As a result, it is a factor affecting the value of the braking index in line with other authors [23, 41, 44]. We suggest that we have accurately measured their braking indices and noted the significant values obtained for the braking indices of the 17 pulsars when compared to the spin-down model.

5. Conclusion

Using a sample of pulsars from the Australian Telescope National facility data catalogue, we compiled and performed a statistical study of the spin properties of 208 glitching pulsars. We computed the braking indices of these pulsars. From the result, we obtained the values of the braking indices of the 208 pulsars with the period range (0.0016 s $\leq P \leq$ 4.30819 s) and period derivative ($7.02 \times 10^{-21} \leq \dot{P} \leq 1.53 \times 10^{-12}$). The values of their characteristic ages were found within the range of (10^3 yr $\leq \tau \leq 10^9$ yr). We also obtained significant values of the braking indices of the 16 sub-sample with frequency (2.4532 Hz $\leq \nu \leq$ 15.8248 Hz) and frequency derivative ($-6.03 \times 10^{-14} \leq \dot{\nu} \leq -2.42 \times 10^{-11}$). The values of their characteristic ages are found within the range of (10^3 yr $\leq \tau \leq 10^6$ yr) with 12 young pulsars and 5 middle-age pulsars. Our results show that the braking indices are observed to be a function of magnetic field of the pulsar, spin down rate, rotational periods.

References

[1] Kaspi, V. M., and Helfand, D. J., Constraining the Birth Events of Neutron Stars. ASP Conference Series, 9999, 2002, P. O. Slane and B. M. Gaensler, ed.

[2] Lorimer, D. R. and Kramar, M. (2005) Handbook of Pulsar Astronomy. Cambridge University Press, Cambridge.

[3] Lyne, A. G., Graham-Smith, F., 2005, Pulsar Astronomy, Cambridge, UK: Cambridge University Press, 2005.

[4] Lyne, A. G., Hobbs, G., Kramer, M. and Stairs, B. (2010) Switched Magnetospheric Regulation of Pulsar Spin-Down. Science, 329, 408-412.

[5] Bell-Burnell, S. J. (1977). Petit Four. Annals of the New York Academy of Sciences, 302, 685 https://doi.org/10.1111/j.1749-6632.1977.tb37085.x.

[6] Kramer, M., Lyne, A. G., O'Brien, J. T., Jordan, C. A. and Lorimer, D. R. (2006). Periodically Active Pulsar Giving Insight into Magnetospheric Physics. Science, 312, 549-551. https://doi.org/10.1126/science.1124060.

[7] Cameron, A. D., Champion, D. J., Kramer, M., Bailes, M., Barr, E. D., Bassa, C. G., et al. (2018) The High Timing Resolution Universe Pulsar Survey-XIII. PSR J1757-1854, the Most Accelerated Binary Pulsar. Mont. Not. of the Royal Astron. Soci. Letters, 475, L57-L61. https://doi.org/10.1093/mnrasl/sly003.

[8] Stovall K., Freire, P, Chatterjee, P., et al., (2018). PALFA discovery of a highly relativistic double neutron star binary. Astrophysical Journal Letters. 854 (2), L22 https://doi.org/10.3847/2041-8213/aaad06.

[9] Shannon, R. M., Ravi, V., Lentati, L. T., Lasky, P. D., Hobbs, G., Kerr, M., et al. (2015). Gravitational Waves from Binary Supermassive Blackhole Missing in Pulsar Observations. Science, 349, 1522-1525. https://doi.org/10.1126/science.aab1910

[10] Arzoumanian, Z., Baker, P. T., Brazier, A., Burke-Spolaor, S., Chamberlin, S. J., Chatterjee, S., et al. (2018) The NANOGrav 11 Year Dataset: Pulsar Timing Constraints on the Stochastic Gravitational Wave Background. Astrophysical Journal. 859, 47. https://doi.org/10.3847/1538-4357/aabd3b

[11] Lyne, A. G., Shemar, S. L., and Graham Smith, F. Statistical Studies of Pulsar glitches. Mon. Not. R. Astron. Soc., 315, 2000, 534–542.

[12] Hobbs, G., Coles, W., Manchester, R. N., Keith, M. J., Shannon, R. M., Chen, D., Bailes, M., Bhat, N. D. R., BurkeSpolaor, S., Champion, D. et al. Development of a Pulsar-based Timescale. Mon. Not. R. Astron. Soc., 427, 2012, 2780.

[13] Espinoza, C. M., Lyne, A. G., Stappers, B. W. and Kramer, M. A study of 315 glitches in the rotation of 102 pulsars. Mon. Not. R. Astron. Soc., 414, 2011, 1679-1704.

[14] Flanagan, C. S. (1995) Unpublished Ph.D Thesis, Rhodes University of Grahamstown, South Africa.

[15] Urama, J. O. (2002) Glitch Monitoring in PSR B1046-58 and B1737-30. Mont. Not. of the Royal Astro. Soc., 330, 58- 62. https://doi.org/10.1046/j.1365-8711.2002.05099.x.

[16] Chukwude, A. E., Urama, S. O. (2010). Observations of Microglitches in Hartebeesthoek Radio Astronomy Observatory Radio Pulsars. Mont. Not. of the Royal Astron. Soci., 406, 1907-1917. https://doi.org/10.1111/j.1365-2966.2010.16789.x.

[17] Manchester, R. N. and Taylor, J. H. (1977). Pulsars. W. H. Freeman and Company, San Francisco.

[18] Melatos, A. (1997). Monthly Notices of Royal Astronomical Society, 288, 1049.

[19] Blandford, R. D., & Romani, R. W. (1988). Monthly Notices of Royal Astronomical Society, 234, 57.

[20] Harding, A. K., Contopoulos, I., & Kazanas, D. (1999). Astrophysical Journal Letters, 525, L125.

[21] Lyne, A., Graham-Smith, F., Weltevrede, P., et al. (2013). Science, 342, 598.

[22] Chukwude, A. E., Baiden, A. A. and Onuchukwu, C. C. (2010). Astronomy & Astrophysics. 515, A21.

[23] Johnston, S., & Galloway, D. (1999). Pulsar braking indices revisited. Monthly Notices of the Royal Astronomical Society, 306, L50–L54. https://doi.org/10.1046/j.1365-8711.1999.02737.x

[24] Livingstone, Margaret A., Kaspi, V. M., Gavriil, F. P., Manchester, R. N., Gotthelf, E. V. G., & Kuiper, L. (2007). New phase-coherent measurements of pulsar braking indices. Astrophysics and Space Science, 308, 317–323. https://doi.org/10.1007/s10509-007- 9320-3

[25] Weltevrede, P., Johnston, S., & Espinoza, C. M. (2011). The glitch-induced identity changes of PSR J1119-6127 (Vol. 1357, pp. 109–112). Presented at the American Institute of Physics Conference Series. https://doi.org/10.1063/1.3615091

[26] Clark, C. J., Pletsch, H. J., Wu, J., Guillemot, L., Camilo, F., Johnson, T. J., Nieder, L. (2016). The Braking Index of a Radio-quiet Gamma-Ray Pulsar. The Astrophysical Journal Letters, 832, L15. https://doi.org/10.3847/2041-8205/832/1/L15

[27] Antonopoulou, D., Espinoza, C. M., Kuiper, L., & Andersson, N. (2017). Pulsar spin-down: the glitch-dominated rotation of PSR J0537−6910. Monthly Notices of the Royal Astronomical Society, 473 (2), 1644–1655. https://doi.org/10.1093/mnras/stx2429

[28] Groth, E. J. (1975). Timing of the Crab Pular II. Method of Analysis. The Astrophysical Journal Supplement Series, 29. https://doi.org/10.1086/190353

[29] Manchester, R. N., & Peterson, B. A. (1989). A braking index for PSR 0540-69. The Astrophysical Journal Letters, 342, L23–L25. https://doi.org/10.1086/185475

[30] Nagase, F., Deeter, J., Lewis, W., Dotani, T., Makino, F., & Mitsuda, K. (1990). GINGA observations of the 50 millisecond pulsar PSR 0540 - 69. The Astrophysical Journal Letters, 351, L13–L16. https://doi.org/10.1086/185668

[31] Lyne, A. G., Pritchard, R. S., & Graham-Smith, F. (1993). Twenty-Three Years of Crab Pulsar Rotational History. Monthly Notices of the Royal Astronomical Society, 265, 1003. https://doi.org/10.1093/mnras/265.4.1003

[32] Parthasarathy A., et al., (2019). Monthly Notices of the Royal Astronomical Society, 489, 3810.

[33] Parthasarathy A., et al., (2020). Monthly Notices of the Royal Astronomical Society, 494, 2012.

[34] Shapiro, S. L., Teukolsky, S. A., & Wasserman, I. (1983). Implications of the millisecond pulsar for neutron star models. Astrophysical Journal, 272, 702–707. https://doi.org/10.1086/161332

[35] McKenna, J., and Lyne, A. G. PSRI737 – 30 and period discontinues in young pulsars. Nature, 343, 1990, 349–350.

[36] Allen, M. P. and Horvath, J. E. (1997) Glitches, Torque Evolution and the Dynamics of Young Pulsars. Monthly Notices of the Royal Astronomical Society, 287, 615-621. https://doi.org/10.1093/mnras/287.3.615

[37] Lyne, A. G., Pritchard, R. S., & Smith, F. G. (1988). Crab pulsar timing 1982-87. Monthly Notices of the Royal Astronomical Society, 233, 667–676. https://doi.org/10.1093/mnras/233.3.667

[38] Press WH, Teukolsky SA, Vetterling WT, Flannery BP, Numerical Recipes in Fortran: The Art of Scientific Computing (Cambridge University Press, Cambridge, UK, 1994).

[39] Espinoza, C. M., Lyne, A. G., & Stappers, B. W. (2017). New long-term braking index measurements for glitching pulsars using a glitch-template method. Monthly Notices of the Royal Astronomical Society, 466, 147–162. https://doi.org/10.1093/mnras/stw3081

[40] Alpar, M. A., & Baykal, A. (1994). Expectancy of Large Pulsar Glitches - a Comparison of Models with the Observed Glitch Sample. Monthly Notices of the Royal Astronomical Society, 269, 849. https://doi.org/10.1093/mnras/269.4.849

[41] Archibald, R. F., Gotthelf, E. V., Ferdman, R. D., Kaspi, V. M., Guillot, S., Harrison, F. A., Tomsick, J. A. (2016). A High Braking Index for a Pulsar. The Astrophysical Journal Letters, 819 (1), L16. https://doi.org/10.3847/2041-8205/819/1/L16

[42] Shannon, R. M., Lentati, L. T., Kerr, M., Johnston, S., Hobbs, G., & Manchester, R. N. (2016). Characterizing the rotational irregularities of the Vela pulsar from 21 yr of phase-coherent timing. Monthly Notices of the Royal Astronomical Society, 459, 3104–3111. https://doi.org/10.109

[43] Espinoza, C. M., Lyne, A. G., Stappers, B. W. and Kramer, M. (2011). A study of 315 glitches in the rotation of 102 pulsars. Mon. Not. R. Astron. Soc., 414, 1679-1704.

[44] Hobbs, G., Lyne, A. G., and Kramar M. An analysis of the timing irregularities for 366 pulsars. Mon. Not. R. Astron. Soc., 402, 2010, 1027-1048.