International Journal of Astrophysics and Space Science
2018; 6(4): 62-72
http://www.sciencepublishinggroup.com/j/ijass
doi: 10.11648/j.ijass.20180604.11
ISSN: 2376-7014 (Print); ISSN: 2376-7022 (Online)

Statistical Study of Glitch Behaviours of Glitching Pulsars

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To cite this article:
Christian Ikechukwu Eze, Evaristus Uzochukwu Iyida, Finbarr Chidi Odo, Johnson Ozoemena Urama. Statistical Study of Glitch Behaviours of Glitching Pulsars. *International Journal of Astrophysics and Space Science*. Vol. 6, No. 4, 2018, pp. 62-72.
doi: 10.11648/j.ijass.20180604.11

Received: September 12, 2018; **Accepted**: September 28, 2018; **Published**: October 25, 2018

Abstract: Detailed long-term timing observations have revealed that the expected smooth spin- down of many pulsars is prone to a variety of discrete disruptions often referred to as glitches. Although the nature and behaviour of small glitches are still poorly understood compared to large glitches, it is widely believed that both originate from some complex dynamical changes within the neutron star interior and their study could provide valuable information about the internal structure and dynamics of the neutron stars. In this paper, the distribution of glitch sizes, glitch patterns and possible relationships between glitch parameters and pulsar rotational parameters were statistically investigated using 482 glitches reported in 168 pulsars. The distribution of glitch sizes showed predominance of large glitches for J0537-6910, J0835-4510, J1341-6220 and J18001-2304; small glitches for J0534+2200, J0631+1036 and J1740-3015 and continuous glitch size distribution for J0534+2200, J1341-6220, J1740-3015 and J1801-2304. PSRs J0537-6910 and J0835-4510 showed specific regular pattern with J1740-3015 showing a quasi-regular pattern. The mean glitch size of these pulsars relates considerably with rotational frequency (ν) and spin down rate ($\dot{\nu}$) in simple power laws. Similarly, variation of glitch activity with the characteristic age (τ) traces a curve that peaks at $\tau = 10^4$ yr and decays with age for older pulsars with $\tau \geq 10^4$yr. The angular momentum transfer resulting to glitches appears to be maximum at youthful age ($\approx 10^4$-10^6yr) of pulsars when certain rotational properties as well as temperature of the star best supports vortex pinning and unpinning of the superfluid of the star interior.

Keywords: Pulsar, General- Stars, Neutron-Methods, Statistical

1. Introduction

Pulsars are highly magnetized rapidly rotating neutron stars that generate regular pulses of broad electromagnetic radiations that are modulated by their rotation period [1]. Rotation period of most pulsars are stable over a long period of time due to huge moment of inertia they posses. However, long term observation have shown that some pulsars spin down regularly as they emit radiation and particles [2]. The spin down rate ($\dot{\nu}$) is related to the rotational frequency (ν) by the standard spin down law expressed as:

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

where K(I, μ, α) is a positive constant and n is a braking index [3]. I is the moment of inertia, μ is the dipole moment and α is the angle between the spin axis and μ. The braking index can be obtained through a direct measurement of the spin frequency and its time derivatives [1, 3]. From Equation 1, it can be shown that the characteristic age (τ) of a pulsar can be expressed [eg1, 3, 4] as:

$$\tau = -\frac{\nu}{2\dot{\nu}} \tag{2}$$

Nevertheless, scientists have also observed timing irregularities which serve as windows into the neutron star interior. These are of two types: timing noise and glitches. Timing noise are generally regarded as random, sustained fluctuations of pulse arrival time [5], lasting from days to years and resulting in excess timing phase residuals [6]. Glitches on the other hand are characterized by sudden increase or jump in pulsar rotation frequency, ν, but not always accompanied by an increase in magnitude of the spin down rate ($\dot{\nu}$) [7]. They are thought to be triggered either by the neutron star crust quakes [8] or some form of dynamical changes within neutron star, such as a sudden transfer of angular momentum from the more rapidly inner superfluid components to the slowly spinning crust [9] or both [10].

Glitch sizes span several orders of magnitudes, $10^{-12} \leq \frac{\Delta\nu}{\nu} \leq 10^{-5}$ [11], and with majority of the glitches having magnitude ($\Delta\nu / \nu$) of between 10^{-8} – 10^{-6} [12]. Glitches are grouped into two, namely: microglitches and macroglitches [13]. Microglitches are regarded as a class of small amplitude jumps observed in pulsar rotation frequency and/or its first time derivative [13, 14]. On the other hand, macroglitches are regarded as a class of large magnitude of jumps in pulsar rotational frequency, ν , usually accompanied by an increase in magnitude of the spin down rate, $\dot{\nu}$ [14]. They are believed to have magnitudes, $\frac{\Delta\nu}{\nu} > 10^{-7}$ [11, 14]

The distribution of glitches showed a close connection to the characteristic age of pulsars (τ) [11]. There is a predominance of small glitches according to the authors for $\tau > 10^5$ yr and τ<103 yr; and no large glitch has been reported for $\tau > 10^7$yr. This was corroborated by the report that large glitches are mostly exhibited by pulsars with characteristic age between 10^3 to 10^5 yr [12]. The glitch size distributions are consistent with power laws with the index varying from pulsar to pulsar [15].

The glitch sizes are also seen to be affected by magnetic field of the pulsar [7], spin down rate [11], rotational periods [16]. The glitch size distribution of the most glitched pulsars that may have statistical significance will be conducted to ascertain their specific patterns and possibly infer the behaviour of the individual glitching pulsars.

The time to the next glitch (waiting time) for individual pulsars with many glitches is sometimes proportional to the fractional glitch amplitude [17]. It was shown that Vela pulsar, J0537–6910 and J1341–6220 show a quasiperiodic glitch pattern [15]. Vela alone was reported to have quasi-regularly pattern [18], and a linear glitch pattern was also reported for Vela and J0537–6910 depicting also strong elasticity of the objects [12]. This corroborated the report that Vela and J0537–6910 have particular glitching behaviours or pattern and that such pattern may be shared by most Vela-like pulsars [11]. However, they did not give any precise description of the pattern. In view of all these, there are still slight discrepancies in the findings about the glitch patterns of the most frequently glitching pulsars. As a result, the glitch pattern of these pulsars will be re-investigated. It is also necessary for one to identify the Vela-like pulsars and the Crab-like pulsar among the seven most glitched frequently glitching pulsars.

Besides glitch sizes, the glitch activity is of paramount interest in study of glitches of glitching pulsars. Glitch activity A_g is the mean fractional change in the rotation frequency, ν , per year due to glitch and can be expressed as [2]:

$$A_g = \frac{1}{t_g} \sum \frac{\Delta\nu}{\nu} \tag{3}$$

Where $\sum\frac{\Delta\nu}{\nu}$ is the sum of all glitches occurring in the observed time span t_g which is measured in years. Glitch activity is driven by electromagnetic spin down [19]. It was shown quantitatively that glitch activity decreases linearly with decreasing rate of slow down [7]. This was in line with several works [eg. 20, 21], that glitch activity is higher for pulsars with higher spin down rates. For pulsars older than 10^4 yr, the glitch activity is proportional to the spin down rate [20].

Several other authors still calculated the glitch activity for some pulsars. Similar glitch activity values were obtainedfor some pulsars (eg. B0740-28) but for some other pulsars (eg. B0355+54), the discrepancies in the glitch activity values obtained were much due to the number of glitches in their data samples [20, 22]. Several authors [e.g. 12] who investigated glitch activity did it when the number of glitches were fewer than the available number at the time of this work. Since statistics improves with number and having obtained more glitch data, it is still necessary to re-evaluate and reinvestigate the glitch activities for the pulsars.

Finally, glitch activity also seems to be dependent on age [7, 11, 12, 19]. There also appears to be correlation between glitch activity and the spin down rate [11]. In addition, a number of other pulsars and glitch parameters have been correlated in the past. However, similar challenge of not stating the confidence level in the correlation was also noticed. This makes the correlation partially inefficient for making or drawing substantial inference. Such correlations therefore need to be evaluated, and the nature of dependence on some pulsar parameters investigated.

This work sets to carry out the statistical study of 482 glitches in 168 pulsars with a view to investigating the distribution of glitch sizes, glitch patterns and possible relationship between glitch parameters and pulsar rotational parameters of glitching pulsars.

2. Sample Descriptionand Methods

A total of 482 glitches from 168 pulsars were studied. The glitch parameters were all taken from the Jodrell Bank glitch catalogue 1 [11], while the pulsar rotational parameters were taken from Australia Telescope National Facility (ATNF) pulsar catalogue 2.

From our population, we sampled the frequently glitching pulsars and gave a more detailed attention to the seven most glitched frequently glitching pulsars. These pulsars were given due attention owing to the number of glitches they have and the implication of number to the statistical method we adopted in this study. They have glitched more than 10 times each and accounted for over 30% of the entire glitches in the population.

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1 http://www.jb.man.ac.uk.pulsar/glitches.html

2 www.atnf.csiro.au

The sample was not treated in isolation. It was considered most when the individual behaviours of pulsars were needed. When the behaviours of the entire pulsars were required, the entire population of 168 pulsars were used or in several occasions, pulsars that meet some defined conditions necessary for the research work. We applied distributive and correlation statistics in the course of this work. The measures of central tendency of the distributions made were obtained and skewness was used to ascertain the degree of departure of these distributions from normality. The correlations obtained were calculated at 95% confidence.

3. Analysisand Results

3.1. Glitch Sizes

Figure 1 is the distribution of glitch sizes of the 482 known glitches in 168 pulsars. The result approximates to a bimodal lognormal distribution for the entire glitches. The bimodal nature with one mode in the large glitch range and the other in the small glitch range suggests a possible dual glitch mechanism [eg. 11, 21]. The modal glitch sizes occurred at $3.16 \times 10^{-6}$and 3.16×10^{-9} respectively and the skewness of the distribution is -0.06. On the contrary, it was suggested that only angular momentum transfer model can still give a bimodal glitch distribution, so, a single glitch mechanism was proposed [23]. They however did not explain satisfactorily the gap they observed in the plot of FMI against FGS they made, from which they deduced the single glitch mechanism. Different mechanisms may have contributed to the transfer of angular momentum of certain magnitude to the crust leading to the two compartments of glitch sizes.

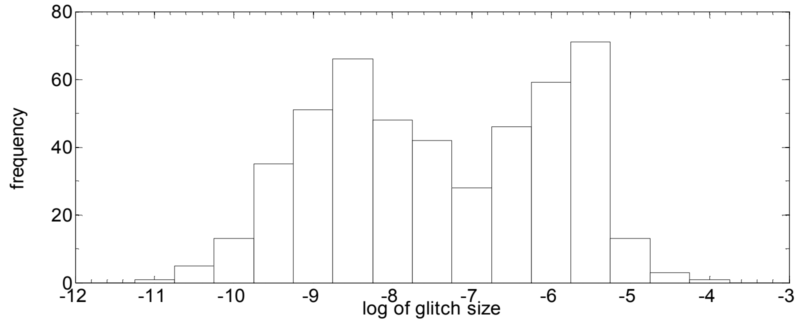
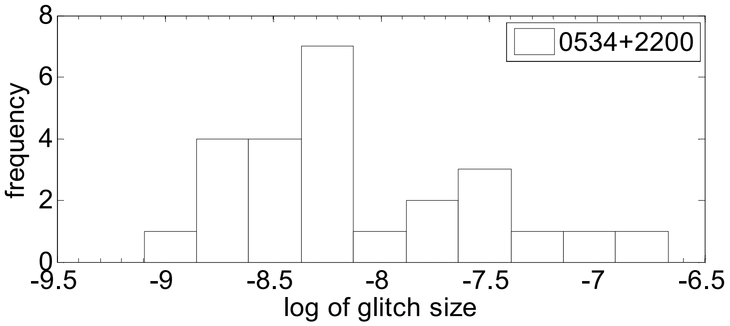
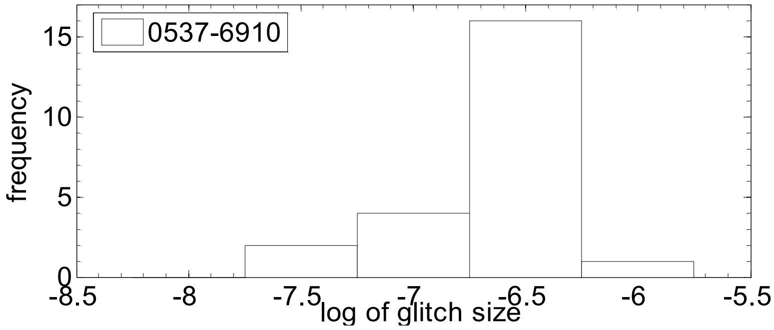
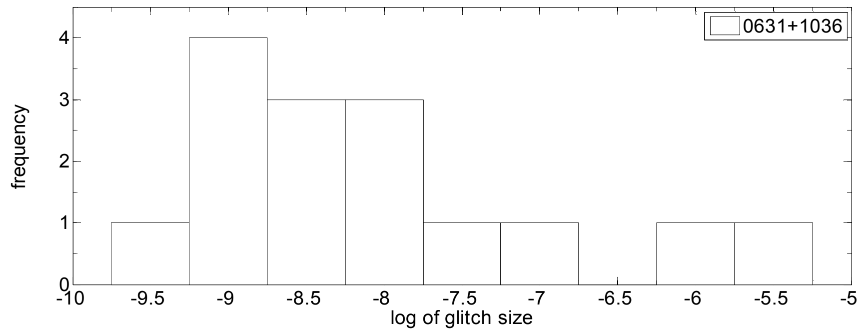


Figure 1. The distribution of glitch sizes of 482 glitches in 168 pulsars.

Moreover, the fluctuations of pulse frequency induced by timing noise are small, with fractional changes $\frac{\Delta\nu}{\nu} < 10^{-9}$ [24] and so some of the events recorded as glitches could possibly be timing noise. This was corroborated by the report that the minimum size of the Crab's size spectrum, $\frac{\Delta\nu}{\nu} \sim 10^{-9}$ is significantly above the resolvable event [19]. These authors further stated that the lower end of the size distribution is contaminated by a different population of timing noise events which are possibly of magnetospheric origin.






0631+1036
frequency
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1
2
3
4
-10
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-6.5
-6
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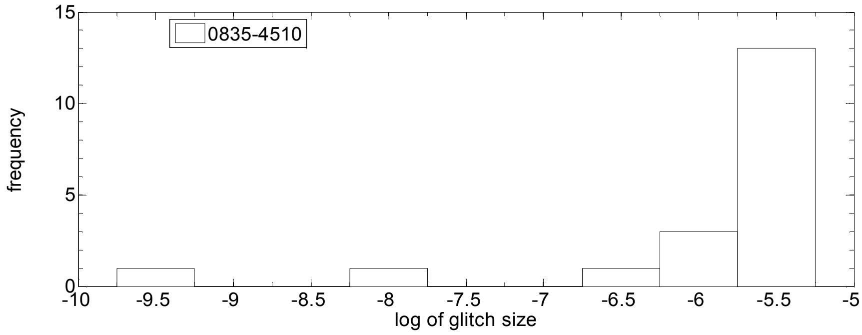
-5
log of glitch size


0835-4510
frequency
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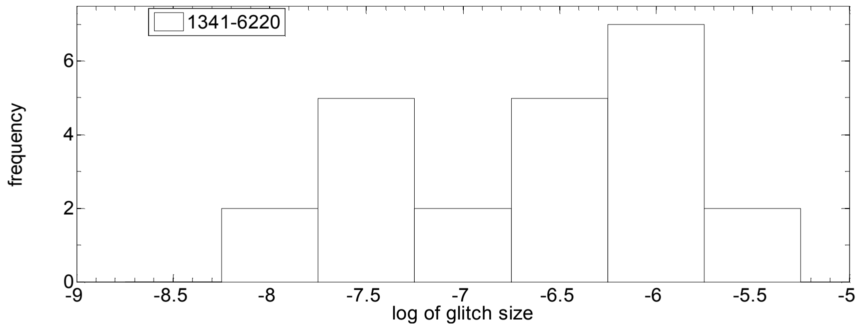
log of glitch size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-6
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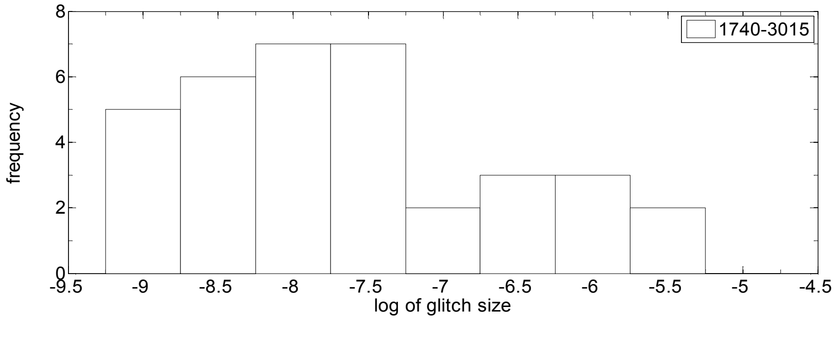
-5
log of glitch size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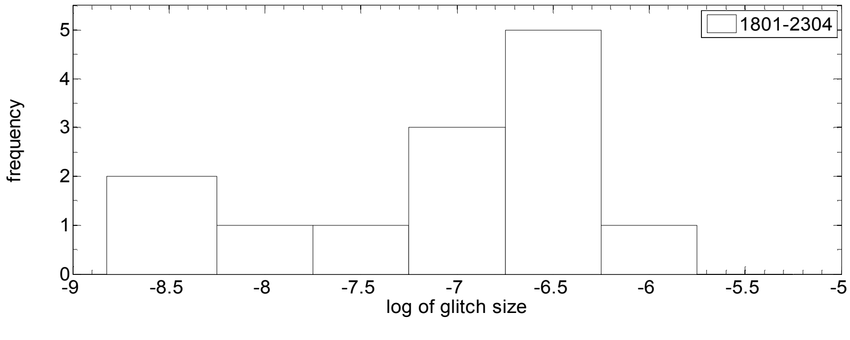
-5
-4.5
log of glitch size


1801-2304
frequency
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-5
log of glitch size

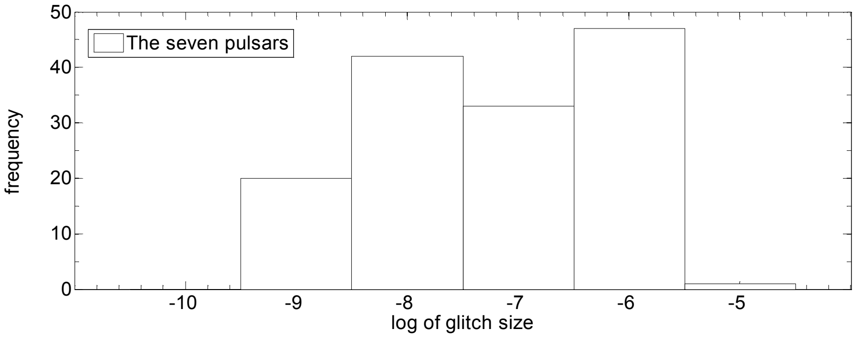
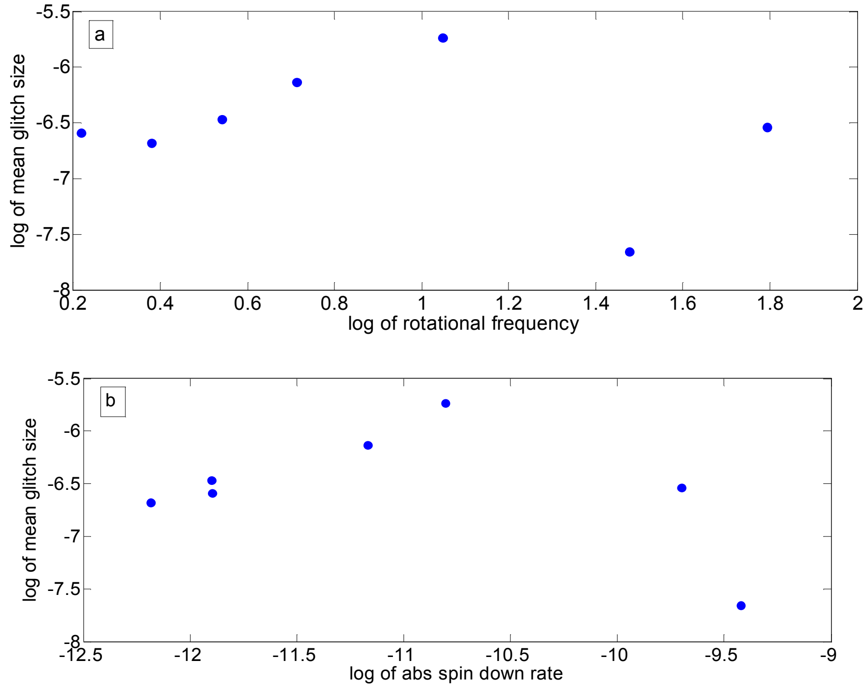


Figure 2. *The distribution of glitch sizes, on logarithmic scales of pulsars that have glitched more than 10 times.*

For the seven frequently glitching pulsars that have glitched more than ten times, the distribution is shown in Figure 2 and the result is summarized in Table 1. As shown in the Figure 2, the pulsars, J0537-6910, J0835-4510, J1341-6220 and J1801-2304 had more of large glitches. PSRs J0534+2200, J0631+1036 and J1740-3015 on the other hand had more of small glitches with J0534+2200, J1341-6220, J1740-3015 and J1801-2304 having also a continuous glitch size distribution. PSR1740-3015 appears to be in more chaotic state than Vela even though both have almost similar characteristic age [11]. This may be the reason for the continuous distribution of J1740-3015 glitch sizes as suggested by these authors who later attributed the chaotic state to the inhomogeneous distribution of pinning zones with different pinning capacities. When the glitch size of the seven were combined, we obtained a continuous bimodal distribution which had more of large glitches. This possibly resulted from the combined effect of glitches of the constituting pulsars and also suggests possible dual glitch mechanisms. They also could possibly have got few timing noise events mistakenly recorded as glitches.

Table 1. *Distribution of glitch sizes of the frequently glitching pulsars.*

Pulsar Jname	**Mode×10^{-7}**	**Mean×10^{-7}**	**Median×10^{-7}**	**Skewness**
0534+2200	0.056	0.222	0.080	0.59
0537-6910	3.160	2.880	2.590	-1.84
0631+1036	0.010	3.400	0.047	1.11
0835-4510	31.600	18.300	20.500	-2.54
1341-6220	10.000	7.310	2.770	-0.26
1740+3015	0.178	2.560	0.169	0.41
180 1-2304	3.160	2.100	0.986	-0.73



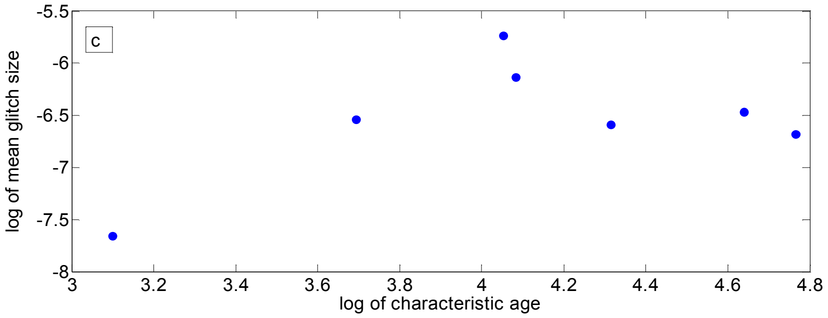
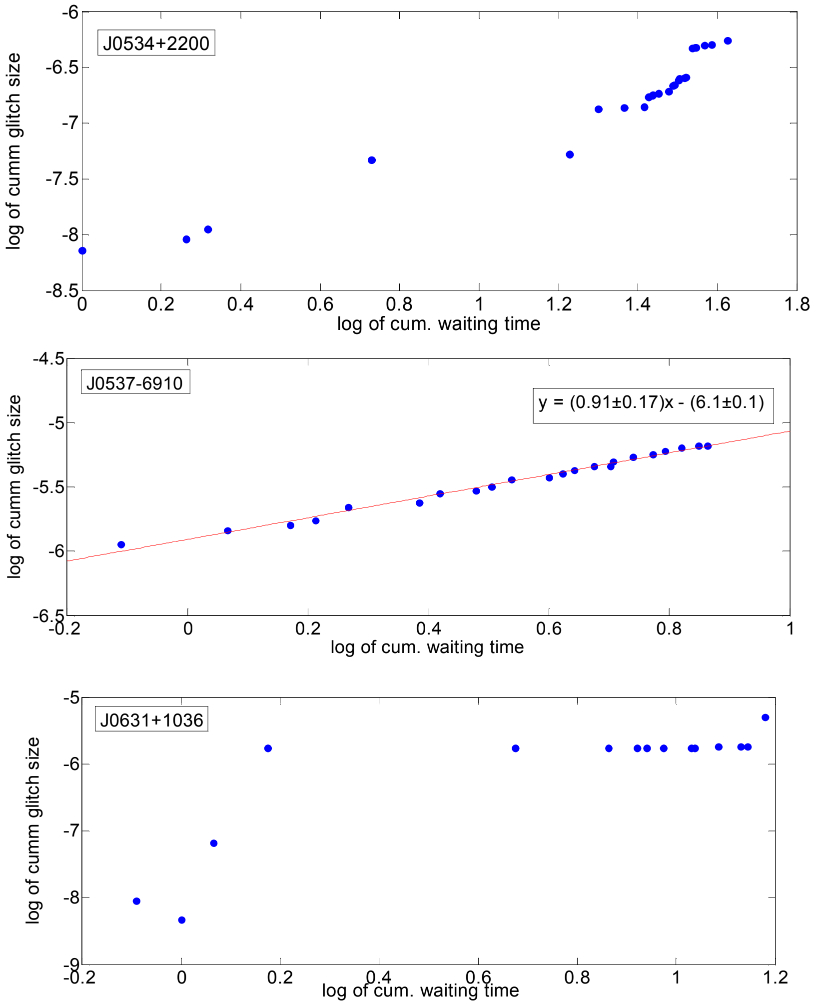


Figure 3. *Scatter plots of mean glitch size against (a) rotational frequency (b) absolute spin down rate (c) characteristic age.*

The mean glitch size was plotted against the pulsar rotational parameters for the seven frequently glitching pulsars as shown in Figure 3. Besides J0534+2200 and J0537-6910 which are young pulsars, the mean glitch size increases with pulsars' rotational frequency and absolute spin down rate as shown in Figures 3a and b. Figure 3c shows that mean glitch size peaks for youthful pulsars ($\tau \approx$ 10kyr). In general, mean glitch size for youthful pulsars has power law relation with rotational frequency and absolute spin down rate.

Moreover, a plot of cumulative glitch size verse the cumulative waiting time is shown in Figure 4 for the seven pulsars with at least 10 glitches. The correlation coefficient and the chance probability (p) are shown in Table 2. For p ≤ 0.05, we shall accept a non- zero correlation. We noticed from the Table 2 that the cumulative glitch size correlated with the cumulative waiting time for the seven pulsars [17]. The cumulative nature of the plot may have contributed to the very high correlation obtained. It was observed from the Figure 4 that J0537–6910, J0835–4510 showed specific regular patterns with J1740–3015 showing a quasi-regularly pattern. J0537–6910 and J0835–4510 were already reported to have regular patterns by several authors [e.g. 12]. The pattern of J1740-3015 was approximated to a quasi-regular one owing to the dispersion and the manner in which several data points aggregated themselves at some points.



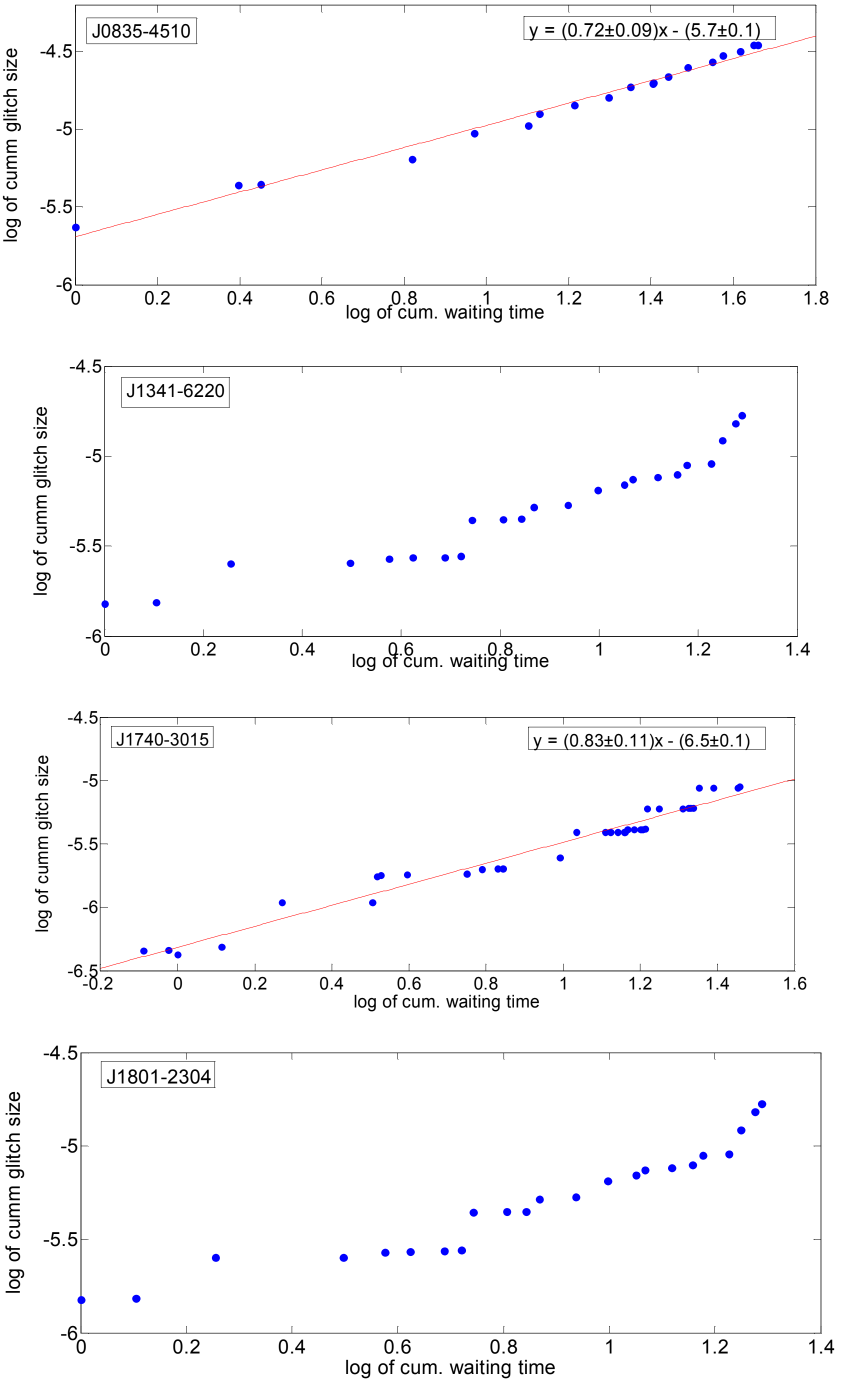


Figure 4. *Plots of cumulative glitches size against cumulative waiting time for the seven frequently glitching pulsars with more than 10 glitches.*

Table 2. *The correlations and p-values of the frequently glitching pulsars.*

PSRs	Correlation	$P \times 10^{-6}$
J0534+2200	0.96	0.30
J0537-6910	0.99	1.43
J0631+1036	0.84	100.00
J0835-4510	0.99	8.37
J1341-6220	0.95	1.39
J1740+3015	0.98	1.51
J1801-2304	0.98	500.00

Figure 5 shows the plots of glitch size against pulsar rotational parameters. Figure 5a is a scatter plot of log of glitch size against log of rotational frequency. The result shows no significant correlation (r = 0.18) and thus suggests no linear relationship. A correlation of -0.39 was also obtained from a scatter plot of log of glitch size against log of characteristic age shown in Figure 5b. At the range of 3kyr to 100kyr, there appears to be a dominance of large glitches. Above 100kyr, we noticed a dominance of small glitches and pulsars with characteristic age greater than 10^7yr had only small glitches in line with [12]. We also noticed some giant glitches among the very young pulsars with characteristic age, 1-3kyr. These glitches could be from magnetars whose glitch sizes could be enhanced by magnetospheric activities of the star [25]. Glitch sizes increase for pulsars with characteristic age between 3kyr to 40kyr where there appears to be a peak. It traces a curve for the seven frequently glitching pulsars.

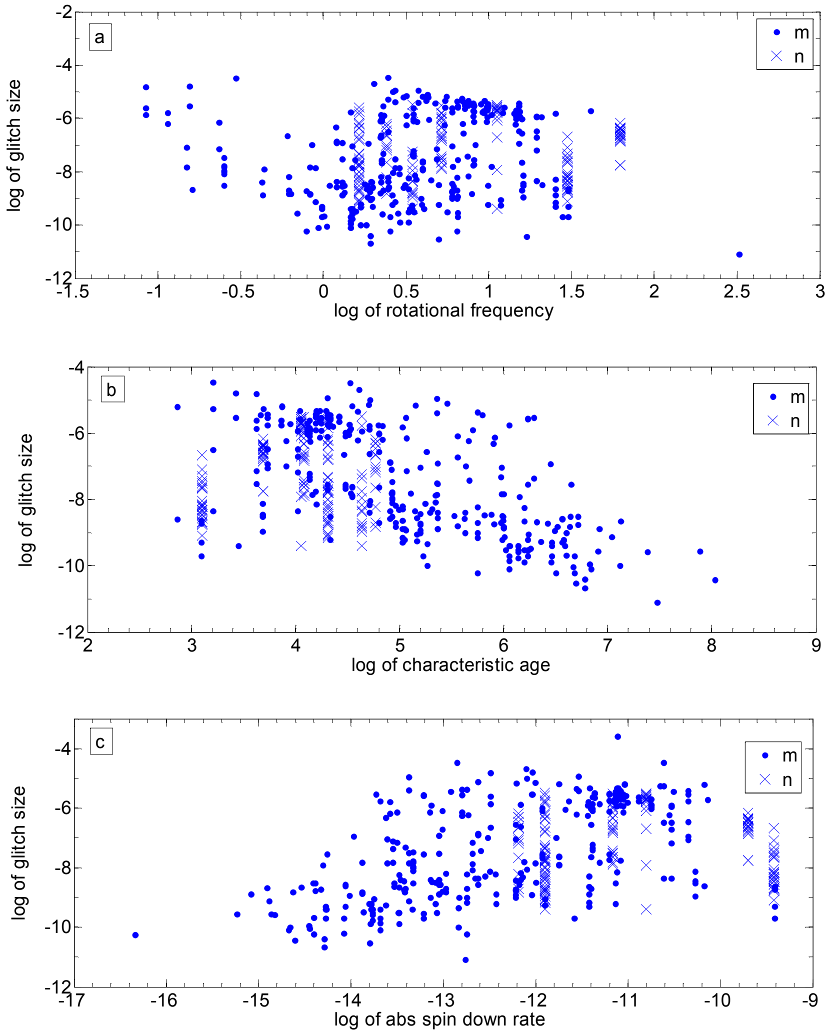


Figure 5. *Scatter plots on logarithmic scales of glitch size against (a) rotational frequency (b) characteristic age (c) absolute spin down rate (note: 'm' represents pulsars with less than 10 glitches, 'n' represent frequently gliching pulsars).*

Figure 5c is a plot of log of glitch size against log of absolute spin down rate. A correlation of 0.45 was obtained and this shows moderate but no significant correlation between glitch sizes and absolute spin down rate. However, the glitch sizes seem to increase with increase in spin down rate. This is evident in the plot as pulsars with $|\dot{\nu}| \leq 10^{-14}$ Hzs^{-1} had majorly small glitches with very few large glitches. For $|\dot{\nu}| \geq 10^{-13}$ Hzs^{-1}, very few small glitches were observed. Moreover, about 2/3 of the glitches occurred in pulsars having $|\dot{\nu}| \geq 10^{-13}$ Hzs^{-1}. This partly corroborates the works of several authors that glitches occur more frequently in youthful pulsars with large spin down rate [7, 11, 20].

3.2. Glitch Activity

The glitch activities of all the known pulsars that have glitched more than five times were calculated and plots of glitch activity against some pulsar rotational parameters conducted as shown in Figure 6. In Figure 6a, log of glitch activity was plotted against log of rotational frequency and the result shows no significant relationship between the two parameters (r = 0.28). Figure 6b is a scatter plot of log of glitch activity against log of absolute spin down rate. This resulted to a correlation of 0.59 with a chance probability of 4.61 x 10^{-8} suggesting that a relationship exists between glitch activity and spin down rate. Glitch activity increases with increase in $|\dot{\nu}|$ for pulsars within the range $10^{-14} \leq |\dot{\nu}| \leq 10^{-11}$ Hzs^{-1} [11, 20]. The two young pulsars with $|\dot{\nu}| \geq 10^{-11}$ Hzs^{-1} depart from this relation. They do not seem to follow a specific pattern. This could be as a result of the inhomogeneity and chaotic nature of their interior as a result of the internal temperature which reduces the vortex pinning capacity. For the seven frequently glitching pulsars with absolute spin down rate $10^{-14} \leq |\dot{\nu}| \leq 10^{-10}$ Hzs^{-1}, the glitch activity traces a curve.

In Figure 6c, a correlation of -0.66 and a P- value of 4.27 x 10^{-10} were obtained from the plot of log of glitch activity against log of characteristic age. This suggests that activity decays with age. It corroborates several authors [eg.11;20;26]. However, over the entire pulsar population, activity increases and peaks for pulsars with $\tau \approx$ 10kyrs and then decreases [11]. For pulsars with $\tau \geq$ 10kyr, an A_g- τ relation was obtained as:

$$\mathrm{Log}A_g = (-0.98\pm0.27)\log\tau - (2.52\pm 1.31) \qquad (4)$$

with a correlation coefficient, r = -0.76 at 95% confidence. The equation suggests an inverse power law relation of A_g and τ. The very young pulsars with high glitch activity are possibly magnetars whose glitch sizes are enhanced by magnetospheric activities [25].

Moreover, careful observation of the frequently glitching pulsars reveals a curve while moving from Crab, the youngest to the oldest pulsar among them. This perhaps may be as a result of their spans of characteristic age and spin down rate.

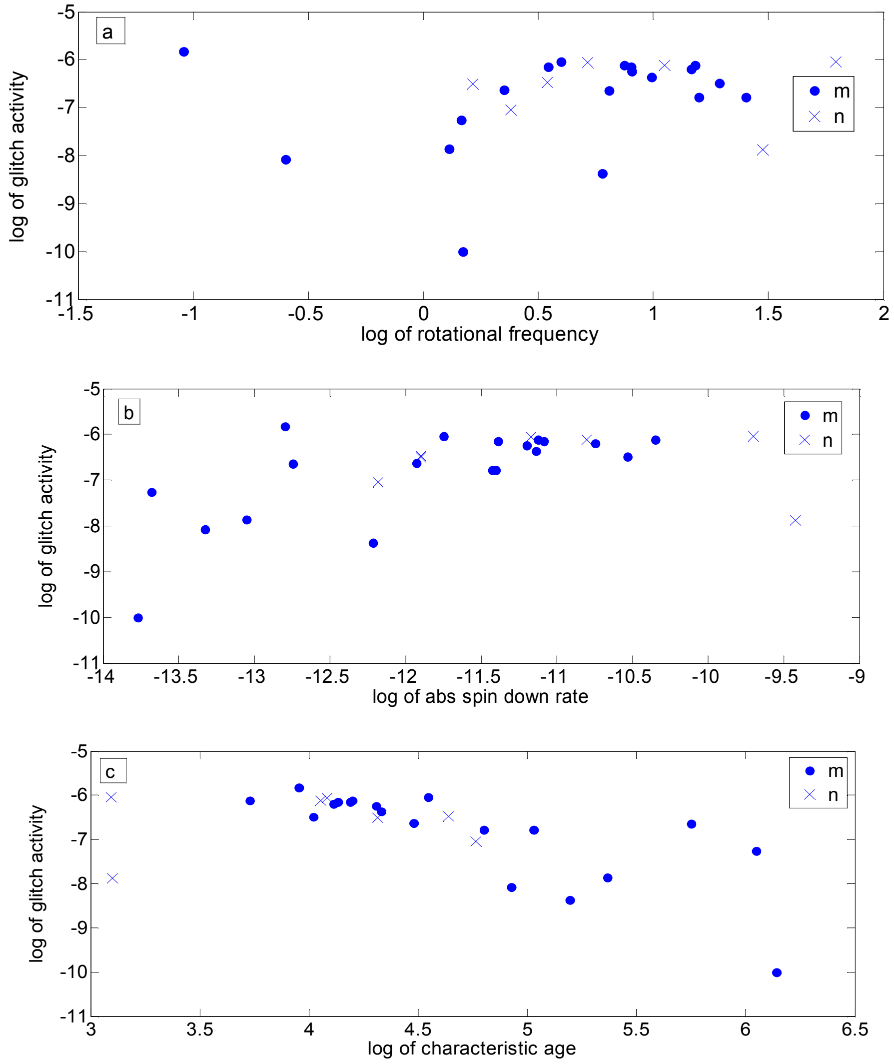


Figure 6. *Scatter plots, on logarithmic scales of glitch activity against(a) rotational frequency (b) absolute spin down rate (c) characteristic age(note: 'm' represents the other pulsars that have glitched more than five times each and 'n' represents the most glitched frequently glitching pulsars)*

4. Discussion

The mechanism that leads to glitch in glitching pulsars has been a subject of several investigations in the past. While it was argued that all glitches are manifestation of a single glitch mechanism [23], several other authors suggested a dual glitch mechanism [eg. 11].

The bimodal distribution obtained for the entire glitches supports the dual glitch mechanism earlier reported by several authors [eg. 11, 21]. This is as a result of the earlier proposal made that small glitches may be generated by star quakes while large glitches may be as a result of the transfer of angular momentum from the superfluid interior to the outer crust.

Moreover, more glitches were observed for pulsars with intermediate $\dot{\nu}$ of $10^{-14} \leq \dot{\nu} \leq 10^{-11}$ Hzs^{-1}, intermediate characteristic age of $10^4 < \tau < 10^5$yr and low rotational frequency of $1 < \nu \leq 30$Hz. The seven frequently glitching pulsars are within this range except for the X-ray pulsar, J0537- 6910 with $\nu \approx 60$Hz. We also observed that for pulsars with $\tau \geq 10^4$yr, the glitch size decays with age and $\tau < 10^3$yr shows small glitches. This corroborates the works of several authors in this subject [eg. 11, 12].

Nevertheless, it was noticed among the seven frequently glitching pulsars that the glitch size dependence on characteristic age may be as a result of some primary factors upon which the age depends such as K (I, μ,α) as shown in Equations 2 and 1.

The mean glitch size for the seven pulsars increased with rotational frequency and absolute spin down rate besides those of Crab and J0537-6910. It peaks for pulsars with $\tau \approx$ 10kyr. The angular momentum transfer becomes maximum at youthful age of the pulsars when certain rotational properties as well as temperature of the star best supports vortex pinning and unpinning of the superfluid of the star interior. In general, mean glitch size for youthful pulsars has power law relation with rotational frequency and absolute spin down rate as earlier stated.

Moreover, from Figure 4, we observed that J0537–6910, J0835–4510 showed specific regular patterns with J1740–3015 showing a quasi-regularly pattern. This suggests homogeneity and certain degree of elasticity of the neutron star interior [12]. The observation of the regular pattern for some of these pulsars were partly in line with literature. The regular patterns of Vela (J0835-4510) and J0537-6910 were recognized by a number of authors [eg. 11, 12, 15, 19, 23]. Alpar reported only that of Vela [18], and PSR1341-6220 was reported to have quasi-regular pattern [15, 19].

In addition, glitch activity correlates significantly with spin down rate and characteristic age with correlation coefficients of 0.59 and -0.66 respectively suggesting that activity increases with spin down rate but decreases as the characteristic age increases. These were in line with several results [eg. 2, 7, 11, 20, 21]. This A_g- τ relation is more significant for pulsars with $\tau \geq 10^4$yr. The very young pulsars seem to deviate from this as their activities increase with age. This increase continues, though not uniformly, until it attains a peak at $10^4 < \tau < 10^5$ yr [11].

This perhaps may be the reason we noticed a turning point in the glitch activity among frequently glitching radio pulsars moving from the Crab (J0534+2200) pulsar, the youngest to 1801–2304, the oldest among them. These frequently glitching pulsars have characteristic age in the range 1kyr$\leq \tau \leq$ 100kyr which suggests that they are a combination of young and youthful pulsars.

Such turning point was also noticed among the frequently glitching radio pulsar to be caused by rotational frequency and spin down rate. This may suggest that the dependence of glitch activity on spin down rate and characteristic age may be primarily as a result of some intrinsic properties of the pulsars such as the moment of inertia, rotational frequency, etc. The contribution of moment of inertia of the pinned superfluid at the time of glitch and during the post-glitch recovery was reported [7].

5. Conclusion

We have carried out some statistical analyses of 482 glitches observed in 168 pulsars. The results have revealed some interesting glitch behaviours of these glitching pulsars. The distribution of glitch sizes showed predominance of large glitches for J0537–6910, J0835–4510, J1341–6220 and J1801–2304; small glitches for J0534+2200, J0631+1036 and J1740–3015 as well as continuous glitch size distributions for J0534–2200, J1341–6220, J1740–3015 and J1801-2304. All these reflect the degree of homogeneity and stability of the pulsar interior arising from certain intrinsic pulsar properties which allow glitches of certain sizes. For the entire glitching pulsars, a bimodal glitch size distribution was observed suggesting possible dual glitch mechanisms. PSRs J0537–6910 and J0835–4510 showed regular pattern, while J1740–3015 shows a quasi-regular pattern. This may be attributed to the homogeneity and certain degree of elasticity of the neutron star interior.

The frequently glitching pulsars all have $\dot{\nu}$ ranging from $\approx 10^{-13}$ to 10^{-10} Hzs^{-1}. (ie intermediate spin down rate) and τ in the range, 1kyr $\leq \tau \leq$ 100kyr. This suggests that very young and very old pulsars which have high and very low spin down rate respectively do not glitch often. Moreover, they all have glitch activity in the range of $\approx 10^{-8}$ yr $^{-1}$ to 10^{-7} yr $^{-1}$ and mean glitch size of $\approx 10^{-8} - 10^{-6}$ with Crab and Vela pulsars at the either boundaries of the latter. The mean glitch size for pulsars with $\tau \geq$ 10kyr has power law relation with rotational frequency and spin down rate and inverse power law relation with characteristic age. The glitch activity relates considerably with characteristic age for the entire pulsars with $\tau \geq$ 10kyr. It traces a curve with the characteristic age and spin down rate for the frequently glitching pulsars.

The angular momentum transfer resulting to glitches appears to be maximum at youthful age ($\approx 10^4$-10^6yr) of pulsars when certain rotational properties as well as temperature of the star best supports vortex pinning and unpinning of the superfluid of the star interior.

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