

**LONG – TERM ROTATIONAL STABILITY OF SOME ISOLATED
RADIO PULSARS**

**A RESEARCH PROJECT SUBMITTED IN FULFILLMENT OF THE
REQUIREMENTS FOR THE AWARD OF A MASTER OF SCIENCE
(M.Sc) DEGREE IN PHYSICS AND ASTRONOMY**

BY

**UGWUANYI, JOSEPH CHINONSO
PG/M.Sc/11/59596**

To

**THE DEPARTMENT OF PHYSICS AND ASTRONOMY
FACULTY OF PHYSICAL SCIENCES
UNIVERSITY OF NIGERIA, NSUKKA**

SUPERVISOR

PROFESSOR A. E. CHUKWUDE

AUGUST, 2016

TITLE PAGE

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CERTIFICATION PAGE

This is to certify that this project work is original and has not been submitted in full or part thereof for any other degree or professional qualification for this or any other University.

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APPROVAL PAGE

Mr. Ugwuanyi Joseph Chinonso, a postgraduate student in the Department of Physics and Astronomy, has satisfactorily completed the requirements in research work for the award of Master of Science Degree in Astrophysics.

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Supervisor

Prof. J. O. Urama
Head of Department

DEDICATION

This work is dedicated to Almighty God without whom this work could not have been a success.

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First and foremost, I thank the almighty God for sustaining me through the period of this research. May all glory and adoration be to his holy name. I cannot thank my project supervisor, Prof. A. E. Chukwude, enough for his fatherly mentoring and untiring scrutiny of this work. His invaluable contributions and encouragements contributed a major drive that led to the completion of this work.

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Ugwuanyi, Joseph Chinonso

TABLE OF CONTENT

Title Page	i
Certification Page	ii
Approval Page	iii
Dedication	iv
Acknowledgment	v
Table of Content	vi
List of Figures	viii
List of Tables	x
Abstract	xi

CHAPTER ONE: INTRODUCTION

1.1 Historical Background	1
1.2 Neutron Star formation and General Description	1
1.3 An Overview of Pulsars	3
1.3.1 Rotational Powered Pulsars (RPPs)	4
1.3.1.1 Radio Pulsars	4
1.3.1.2 X-ray Pulsars	5
1.3.1.3 Rotating Radio Transients (RRTs)	6
1.3.2 Non-rotational Powered Pulsars	7
1.3.2.1 Accretion-powered Pulsars	7
1.3.2.2 Magnetars	8
1.4 Neutron Star Magnetosphere	10
1.5 Pulsar Rotational Irregularities	11
1.5.1 Glitches	12
1.5.2 Timing Noise	15
1.6 Pulsars as Astrophysical Tools	21
1.6.1 Pulsars as High-precision Timing and Time Keeping Devices	21
1.6.2 Laboratory for Testing the Predictions of General Relativity	23

1.6.2.1 The use of Double Neutron Star (DN) Binaries	23
1.6.3 The Study of the Galaxy and the Interstellar Medium	25
1.6.4 The Study of Super ï Dense Matter	26
1.6.5 The Discovery of Extra ï Solar Planets	27
1.6.6 Study of Plasma Physics Under Extreme Conditions	29
1.7 Purpose of Study	29

CHAPTER TWO: LITERATURE REVIEW

2.1 Literature Review	30
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CHAPTER THREE: DATA ANALYSIS & RESULTS

3.1 Sources of Data	36
3.2 Fluctuations in Spindown Parameters of the Pulsar	36
3.3 Error Estimation	38
3.4 Measurement of Braking Indices	39
3.5 Distribution of Observed Parameters	40
3.6 Correlation Studies	43

CHAPTER FOUR: DISCUSSIONS AND CONCLUSION

4.1 Discussion of Results	52
4.2 Conclusion	54
References	56

LIST OF FIGURES

Fig. 1.1	An idealized glitch	2
Fig. 1.2	The change in the rotation of the vela pulsar, PSR 0833-45, over an 11- years period	9
Fig. 1.3	Examples of timing noise in 8 pulsars over about a 10 year period	13
Fig. 1.4	The timing activity plotted as a function of period derivative	14
Fig. 1.5	A graph showing clear pseudo-sinusoidal variations coherent with a model of precessing pulsar	16
Fig. 1.6	Geometric precession of a biaxial neutron star in the inertial frame	17
Fig. 1.7	Showing clear pseudo-sinusoidal variations coherent with a model of precessing pulsars	19
Fig. 1.8	Geometric precession of a biaxial Neutron star in the inertial frame	20
Fig. 1.9	Comparing the stability of PSRs B1855+09 and B1937 +21 with terrestrial atomic clocks	22
Fig.1.10	The shift in the periastron passage of the binary pulsar B1913+16 plotted as function of time	24
Fig. 1.11	Planetary companions that can be detected with pulsar timing observations for different values of timing precision	28
Fig. 3.1	A plot of period $\dot{P}$ against epoch over an interval of time Δt	37
Fig. 3.2(a)	A graph showing the distribution of fractional change in period for 293 pulsars ($\frac{\Delta P}{P}$)	42
Fig. 3.2(b)	A graph showing the distribution of fractional change in period derivative for 293 pulsars ($\frac{\Delta \dot{P}}{\dot{P}}$)	42
Fig 3.3(a)	A graph showing the distribution of $\frac{\Delta P}{P}$ and $\frac{\Delta \dot{P}}{\dot{P}}$ on the same axis for 293 pulsars	43
Fig. 3.3(b)	A graph showing the distribution of $\frac{\Delta P}{P}$, $\frac{\Delta \dot{P}}{\dot{P}}$ and n_3 on the same axis for 293 pulsars	43
Fig. 3.4(a)	A graph showing change in period ΔP against period derivative $\dot{P}$	45
Fig. 3.4(b)	A graph of change in period ΔP against change in period derivative $\Delta \dot{P}$	45

Fig. 3.4(c)	A graph of change in period $\dot{P}$ against pulsar characteristic age τ	45
Fig. 3.4(d)	A graph of change in period derivative $\ddot{P}$ against pulsar characteristic age τ	45
Fig. 3.5(a)	A graph of change in period $\dot{P}$ against surface magnetic field B_{surf}	46
Fig. 3.5(b)	A graph of change in period derivative $\ddot{P}$ against surface magnetic field B_{surf}	46
Fig. 3.6	A graph of change in period derivative $\Delta \dot{P}$ against period derivative $\dot{P}$	47
Fig. 3.7(a)	A graph of the braking index n against the braking index n	48
Fig. 3.7(b)	A graph of the braking index n against period derivative $\dot{P}$	48
Fig. 3.7(c)	A graph of the braking index n against the braking index n	48
Fig. 3.7(d)	A graph of the braking index n against the braking index n	48
Fig. 3.8(a)	A graph of the braking index n against pulsar characteristic age τ	49
Fig. 3.8(b)	A graph of the braking index n against surface magnetic field B_{surf}	49
Fig. 3.9(a)	A graph of spindown rate $\dot{P}$ against epoch for PSR B0740 + 28	50
Fig. 3.9(b)	A graph of spindown rate $\dot{P}$ against epoch for PSR B0355+54	50
Fig. 3.9(c)	A graph of spindown rate $\dot{P}$ against epoch for PSR B1706 + 16	50
Fig. 3.9(d)	A graph of spindown rate $\dot{P}$ against epoch for PSR B0455+55	50
Fig. 3.10(a1)	A graph of spindown rate $\dot{P}$ against epoch for PSR B1742 + 30	51
Fig. 3.10(a2)	A graph of spindown rate $\dot{P}$ against epoch for PSR B1742 + 30 (error point removed)	51
Fig. 3.10(b1)	A graph of spindown rate $\dot{P}$ against epoch for PSR B1718 + 32	51
Fig. 3.10(b2)	A graph of spindown rate $\dot{P}$ against epoch for PSR B1718 + 32 (error point removed)	51
Fig. 3.10(c1)	A graph of spindown rate $\dot{P}$ against epoch for PSR B1822 + 09	51
Fig. 3.10(c2)	A graph of spindown rate $\dot{P}$ against epoch for PSR B1822 + 09 (error point removed)	51

LIST OF TABLES

Table 3.1	A table of correlation coefficient of some of the parameters used in the study	42
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ABSTRACT

We re-examined the phenomenon of rotational instability in radio pulsars on decadal timescales using a sample of 315 radio pulsars whose spin-rates [rotation period (P) and spin-down rate ($\dot{P}$)] have been measured on, at least two different epochs. The first stage of our analysis involves a direct comparison of the measured values of P and $\dot{P}$ at two epochs that are $\sim 10-20$ years apart in order to estimate the fluctuation in the parameters. The results show that the fluctuation in the objects' rotational period (ΔP) is significant in 293 pulsars, while it is at the level of measurement uncertainties in the remaining 22 pulsars. For 293 objects, the fractional change in P ($\frac{\Delta P}{P}$) was found to have absolute values in the range of $\sim 10^{-11}-10^{-1}$. Similarly, the observed fluctuation in spin-down rate ($\Delta \dot{P}$) was considered significant in only 178 pulsars in the sample. In this case, the fractional change in the parameter ($\frac{\Delta \dot{P}}{\dot{P}}$), irrespective of sign, has values in the range of $\sim 10^{-5}-10^2$. Further analysis of our sample reveals a moderate correlation (with $r \sim 0.6$) between ΔP and $\Delta \dot{P}$. On the other hand, only weak correlations (with $|r| < 0.3$) were found between $\Delta P / \Delta \dot{P}$ and the pulsar spindown parameters, which suggests that they are unrelated. For seven radio pulsars, whose spin-rates (P and $\dot{P}$) have been measured at five different epochs, we found strong evidence for non-stationarity of the objects' spin-down rates. The braking indices (n) of the 315 radio pulsars were extensively measured using three different methods that involve: (i) integration of the spin-down law (n_1), differentiation of the spin-down law (n_2) and direct measurement of pulsar period second derivative ($\ddot{P}$) using measurement of $\dot{P}$ at two epochs $\sim 10-20$ years apart (n_3). The three methods produced braking indices of anomalous values with magnitudes in the range of $\sim 0.1-10^{11}$. Irrespective of methods of measurement, the absolute values of n were found to be strongly correlated (with $r \sim 0.7-0.8$) with the pulsar spin-down age (τ) and anti-correlated (with $r \sim 0.6-0.8$) with objects' spin-down rate ($\dot{P}$) and surface magnetic field (B_{surf}).

CHAPTER ONE

INTRODUCTION

1.1 Historical Background

It all began in 1967 when then-graduate student Joycelyn Bell saw it as a simple scratch on a piece of paper made by a chart recorder that was recording radio signals from the outer space. Fortunately, she realized that the scratch was clearly contrasting with known astronomical radio sources such as galaxies and again did not quite look like those produced by Earth-based radio interference. This astonishing discovery was made using an instrument called the "Interplanetary Scintillation Array" built specially to detect short time scale intensity fluctuations and was sensitive to low flux density. The object which was emitting regular pulsations every 1.33 seconds was called LGM-1 (Little Green Man - 1) (Hewish et al., 1968), since it was envisioned that pulsations could come from an intelligent form of extraterrestrial life.

The mystery about the pulsating source took an interesting turn when Bell found three more sources with regular pulsations and periodicity of the order of one second. LGM-1 was then renamed CP 1919, after its right ascension (19h 19m), while the other three were CP 1133, CP 0834 and CP 0950 (Hewish et al., 1968). It was followed by a second paper reporting details about the three other pulsating radio sources and providing further timing results of CP 1919 (Pilkington et al. 1968). The exact nature of pulsar remained unclear, however, until the end of 1968 when neutron star theory and pulsar observation finally converged. The name pulsar was first coined in an article of the Daily Telegraph, 5 March 1968, in an interview with Anthony Hewish about the initial discovery (Hewish, 1968).

1.2 Neutron Star Formation and General Description

Once a massive star ($8 - 40M_{\odot}$) exhausts its nuclear fuel supply, the gravitational force becomes too strong to be supported by degenerate electron pressure. The star collapses violently until, at far higher densities ($\rho_0 \approx 2.8 \times 10^{14} \text{ g cm}^{-3}$), the electrons and protons combine to form neutrons. These neutrons in turn eventually become degenerate. If degenerate neutron pressure can provide sufficient support to halt the collapse, a neutron star is formed. Based on the rotation rate of

neutron star progenitors, conservation of angular momentum suggests that a newly formed neutron star should be spinning very rapidly, with a spin period $P_{spin} \approx 10 - 100 \text{ ms}$ (Hessels, 2007). Likewise, magnetic flux conservation suggests that the star's original magnetic field should be greatly amplified. Theory and observation indicate that the neutron star radius is $R_{NS} \approx 10 - 20 \text{ km}$, with a moment of inertia $I \approx 10^{45} \text{ g cm}^2$. In less than a minute after the birth of a neutron star, its surface temperature is expected to drop below 10^{10} K , mostly via neutrino emission. At such temperatures the crust solidifies, as the nuclei form a body centred cubic lattice [bcc] (Chamel & Haensel, 2008).

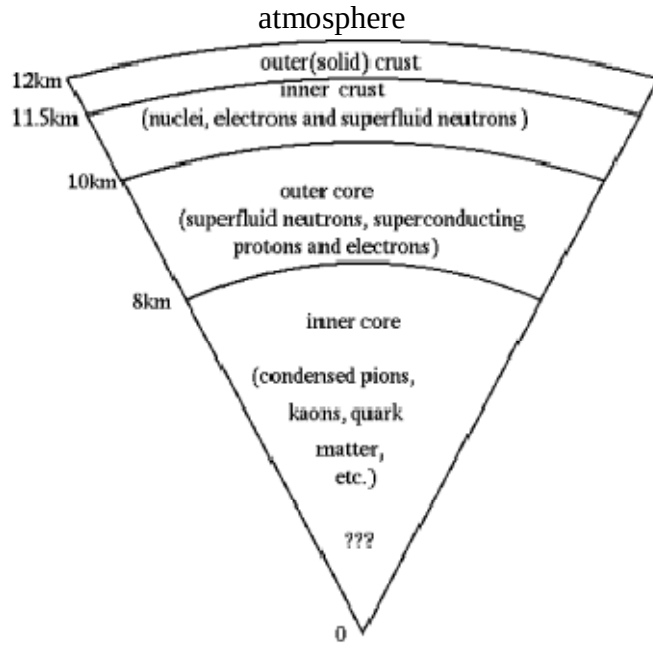


Figure 1.1 A schematic representation of the possible cross-section of a $1.4 M_{\odot}$ neutron star (Urama & Okeke, 1999).

The structure of an isolated neutron star can be separated into five (5) regions: the atmosphere, the outer and inner crust and the outer and inner core as shown in Fig.1.1. The atmosphere is only a few meters thick and mostly composed of Hydrogen H, Helium He, Carbon C and Oxygen O, in abundance that depends (for isolated stars) on the star's age and the conditions of the progenitor supernova explosion (Antonopoulous, 2015). The outer crust is composed of nuclei and electrons. The electrons are degenerate and relativistic everywhere except in an outer

layer, a few metres thick. Near the surface, the nuclei are mostly iron but as the density gets above $\sim 7 \times 10^{10} \text{ g cm}^{-3}$, nuclei richer in neutron appear. The inner crust begins at the neutron drip point, at density $\rho \sim 4.3 \times 10^{11} \text{ g cm}^{-3}$. In this region the neutron-rich nuclei and the electron gas coexist with free neutrons (Antonopoulous, 2015). These neutrons, as well as the nucleons inside the nuclei are expected to be in condensed state at such densities because of their low temperature relative to their Fermi temperature (chamel & Haensel, 2008).

The innermost parts of a neutron star, where densities reach far beyond ρ_0 , are not well understood (Lattimer, 2012). The outer core may contain a neutron superfluid and a proton superconductor. The composition of the inner core, which likely reaches densities a few times larger than the nuclear equilibrium density, is more uncertain, and may host an exotic state of matter such as deconfined quarks, hyperons, or Bose condensates (Lattimer and Prakash, 2004).

1.3 An overview of Pulsars

Pulsars are rapidly rotating highly magnetized neutron stars. Radio pulsars are rapidly spinning highly magnetized neutron stars that emit highly stable pulses of primarily radio waves. Pulsars represent a particular class of rapidly spinning neutron stars that we observe as periodic emitters of electromagnetic radiation. Radio pulsars, i.e. those visible at radio wavelengths, are the canonical type and by far the most common pulsars. Pulsars also have now been observed over the entire spectrum, from radio to high-energy gamma rays, including X-rays, optical and infrared. Although the physical process responsible for the pulsed emission varies across the spectrum, they all share the common behavior of pulsating, which originates from the rotation of the neutron star about its spin axis. Timing the pulsations of a pulsar therefore allows the determination of its spin frequency. Even though pulsars come in different varieties, visible in various parts of the electromagnetic spectrum and possessing a rich set of attributes, we can distinguish two extreme main groups: rotation - powered and non - rotation powered pulsars (Breton, 2008). Here, we shall present a brief overview of the different kinds of pulsars with particular emphasis on radio pulsars, which are the type of neutron stars studied in this work.

1.3.1 Rotation powered pulsars (RPPs)

As their name suggests, rotation powered pulsars (RPPs) owe their energy output to their rotation. Because a time varying magnetic field releases energy, so will a rotating neutron star with a misaligned magnetic axis. This energy comes at the expense of the pulsar's rotational kinetic energy (Gosh, 2007; Lorimer and Kramer, 2004), an effect which is known as magnetic braking. Thus all RPPs are slowing down with time, which is to say they have positive period derivative $\dot{P}$ (Hessels, 2007). The RPPs are the most commonly observed type of pulsars and the vast majority of these are observed as radio pulsars, and thus the term 'radio pulsar' and RPPs are sometimes used interchangeably. This is not strictly correct, as rotation can also power higher energy pulsations (typically X-ray and sometimes γ -ray). Another type of pulsars that is speculated to be in this group (i.e RPPs) is the Rotating Radio Transients (RRATs). Although the nature of these RRATs is still unclear, more research is ongoing to shed more light on the RRATs phenomenon and its connection to the conventional radio pulsars.

1.3.1.1 Radio Pulsars

Radio pulsars are the most common type of pulsars. They are found with spin periods ranging from 1.399 ms for the fastest currently known (Hessels et al., 2006) to 8.51 s for the slowest (Young et al., 1999). Their magnetic fields vary between 10^8 and 10^{14} G and their age between a few hundred years and a few billion years. They are grouped into normal and recycled millisecond pulsars. About 80% of millisecond pulsars belong to a binary system where they are most likely further accelerated by mass accretion from a companion donor star (Bhattacharya & van den Houvel, 1991). Less than 1% of normal pulsars belong to a binary system. Therefore as compared to a millisecond pulsar (spindown rate $\dot{P} \sim 10^{-20}$ ss⁻¹), the normal pulsars has a more rapid spindown (spindown rate $\dot{P} \sim 10^{-15}$ ss⁻¹) (Lorimer and Kramer, 2005). The population of radio pulsars is very diverse and comprises young energetic pulsars such as the Crab and Vela pulsars as well as very old, rapidly rotating pulsars in binary systems.

The radio pulsars are broad band (most are visible between 0.2 – 0.4 Hz) and generally have steep power law spectra:

$$S_\nu = \nu^{-\alpha} \quad (1.1)$$

where S_ν is the flux density at the observing frequency ν . α , which is called the spectral index, can range from $\sim 0.0 - 4.0$, and is on average 1.8 (Maron et al., 2000). Although there is a dearth of pulsar observations below 300 MHz there is evidence that radio luminosity peaks and then turns over somewhere between 100–200 MHz (Malofeev et al., 1994).

The pulsed radio emission that one observes does not result from the time-varying magnetic field (the spinning bar magnet). If it was the case, the observed radio light would be monochromatic and have a frequency corresponding to the spin frequency of the pulsar. Instead, radio emission is created by relativistic electrons accelerated along the open magnetic field lines of the pulsar. They emit synchrotron radiation as they gyrate around the open magnetic field lines under the Lorentz force (Gold, 1968; Pacini, 1968) and this produce an emission cone along the magnetic pole. A pulsation is visible each time the emission cone sweeps across our line of sight just as the fan-beam of a light house illuminates the seashore. Important pieces of puzzle are still missing, however, in order to complete the radio emission model (Lyubarsky, 2008).

1.3.1.2 X-Ray Pulsars

X-ray (rotation powered) pulsars are typically young, energetic pulsars that emit pulsations in X-rays but, sometimes, also in other high energy bands such as γ -rays. Various physical processes (inverse Compton scattering, synchrotron and cyclotron emission and/or curvature radiation) may be responsible for the high-energy emission of these pulsars and produce characteristic spectral components observable in the X-ray both at lower and higher energies as well (Harding, 2007). The exact physical location and the intricate details of particle creation and acceleration are still not perfectly understood. One family of models considers that acceleration occurs close to the surface near the polar caps, a region where the open field lines emerge from the surface (Harding, 2007). In the main competing class models, acceleration occurs further away in the outer gap or the slot gap (Harding, 2007). The former region lies along the transition region between the open and closed field lines where the induced electric field and the local magnetic field cancel out ($\vec{E} \cdot \vec{B} = 0$). The latter region is located on the border of the last open field lines.

Whereas X-ray pulsars tend to be young, rapidly spinning neutron stars with “typical” magnetic fields, some of them were recently found with high magnetic fields ($\sim 10^{13}$ - 10^{14} G) and long spin periods (~ 1 sec) (Safi-Harb, 2008; Gonzalez et al., 2007; Kaspi and McLaughlin, 2005). It is not perfectly clear how these pulsars are related to other X-ray and radio pulsars yet, but it is reasonable to believe that they are slowed down rapidly because of their high magnetic fields. Even though their large energy output can be accounted for by their loss in rotational energy, they lie in the same neighborhood of the $\dot{E} - B^2$ diagram as magnetars. The observation of a magnetar-like burst from one of these X-ray pulsars by Gavril et al. (2008) definitely brought solid evidence bridging the gap between the two families. Additional discoveries will be needed, however, to fully understand their relationship.

Several X-ray pulsars also display pulsed emission at other wavelengths such as radio, infrared and optical. This is the case for the Crab Pulsar (Wilson and Fishman, 1983). In these pulsars, the X-ray and radio pulse profiles sometimes look similar, with aligned phases, but this is not always the case (Wilson and Fishman, 1983; Oosterbroek et al., 2008). Many X-ray pulsars have very sinusoidal pulse profiles. Their spectra generally contain a thermal component as well as non-thermal component, and are often fitted by a black body plus a power-law component. Although the high-energy photons certainly interact in the magnetosphere, it appears that the pulsation might be associated with a hot spot or some thermal inhomogeneity at the surface of the neutron star (Geppert et al., 2006).

1.3.1.3 Rotating Radio Transients (RRATs)

Rotating radio transients (RRATs) were identified for the first time by McLaughlin et al. (2006) in the reprocessing of the Parkes Multibeam Pulsar Survey using a new search technique called a single pulse search. The technique consists of searching raw dedispersed time series by convolving them with a kernel function – typically a top-hat function, but other choices are possible – in order to identify data sequences having values significantly above the noise level. In the original discovery paper, 11 radio transients were found using this technique. For all but one of the sources, it was possible to assess that their regular spin periods are in the range 0.4 – 7 sec. In one case, a significant period derivative was found, thus allowing one to infer its magnetic field strength to be 5×10^{13} G

This discovery considerably changed the approach to searching pulsars as it suggests the existence of a large population of neutron stars emitting radio pulses in an intermittent manner (McLaughlin et al., 2006). In this case, conventional Fourier techniques would generally fail to detect these RRATs because many of them typically have very low burst duty cycles.

1.3.2 Non-Rotation-Powered Pulsars

Among pulsars that are not powered by their rotational energy are the accretion powered pulsars and the magnetars. If a neutron star has a binary companion that has filled its Roche lobe, then it can accrete matter from its companion star. If the neutron star's magnetic field is strong enough, the accreting material is channeled by it and accumulates at the magnetic poles. The material continues to aggregate, eventually reaching a pressure and density at which thermonuclear fusion is possible. The resulting burst is modulated at the neutron star's spin period, a fact that was originally proven for the low mass x-ray binary (LMXB) SAX J1808.4-3658, which also shows transient coherent pulsation from accretion hot spots (Chakrabaty et al., 2003). Theoretical calculations have shown that some neutron stars are powered by the decay of their magnetic field (Thompson & Duncan, 1995, 1996), and there is strong observational evidence supporting this idea (see Woods & Thomson, 2004, and references therein). These neutron stars, termed magnetars, are believed to have surface magnetic fields two or three orders of magnitude larger than RPPs ($B_{surf} \sim 10^{14} - 10^{15} \text{ G}$). Below is a succinct overview of these two sub classes of pulsars.

1.3.2.1 Accretion-Powered Pulsars

Accretion powered pulsars exist in binary systems as x-ray binaries. As their names indicate, these pulsars accrete mass from binary companions, typically via Roche-lobe overflow or wind accretion (Ghosh, 2007). X-ray binaries are classified into two according to the mass of the companion star (the mass losing star) as follows: high mass x-ray binaries (HMXBs) which have the donor star with mass $\geq 10 M_{\odot}$, example Cen X-3, Vela X-1 and low mass x-ray binaries (LMXBs) which have the donor star with mass of about $1 M_{\odot}$ example 4U 1820 + 30, and GX 349 + 2 (ISRO satellite center). Accretion-powered pulsars can show spin-down or spin-up

behaviors depending on whether the accretion mechanism transfers angular momentum to or away from the pulsar. Their spin periods ranges from a few milliseconds to several hundreds seconds (Laycock et al., 2005). Accretion millisecond pulsars in LMXBs are close siblings of millisecond pulsars which are believed to be their descendants (Alpar et al., 1982; Radhakrishnan and Srinivasan, 1982). The pulsations coming from these pulsars, observable in X-rays are produced by the reprocessed thermal emission from their surface, which is heated when the accreted mass, streamed by the magnetic field, lands at the polar caps (Shklovsky, 1967).

1.3.2.2 Magnetars

Magnetar is the generic name for the family of pulsars comprising of Anomalous X-ray Pulsars (AXPs) and Soft Gamma-Ray Repeaters (SGRs). Magnetars are characterized by large period derivatives ($\sim 10^{-12} - 10^{-10} \text{ ss}^{-1}$) and long spin periods (2–12 sec). This implies small characteristic ages ($\sim 10^3 - 10^5$ years) and enormous dipolar magnetic fields ($10^{14} - 10^{15} \text{ G}$). Their observed luminosity in outburst, and even in quiescence (for some of them), is much larger than would be obtained from 100% efficiency conversion of their spin-down energy to X-ray emission and hence they cannot be powered by their rotation (Kaspi, 2007). Two main models originally attempted to explain their nature (Woods and Thompson, 2006). First, it was proposed that magnetar could be powered by accretion from a mass-transferring companion or by a fallback disc left over after the supernova explosion. Very stringent upper limits have been set using timing on the mass of possible companions and shows that all known magnetars are isolated. Also, no trace of disc that would be massive enough to trigger outbursts has been observed. In contrast, the magnetar scenario (Duncan and Thompson, 1992), in which the enormous magnetic field of these neutron stars powers their emission, gained observational evidence over time and is now well established.

A tremendous amount of observational and theoretical progress has been made over recent years, yet no fully self-consistent physical model has been able to explain their properties as a whole, such as their spectrum and timing. Magnetars display a wide variety of properties and more observations will be needed to sort out the exact picture. Quantitatively, however, it is generally believed that magnetic stress accumulated in the crust causes a slow twisting of the magnetic

field outside the neutron star (Thompson et al., 2002; Thompson and Duncan, 1995). When the twisting reaches a critical level, an event similar to a starquake happens and is accompanied by a magnetic reconnection. This deposits an extremely large amount of energy in the magnetar's magnetosphere, maybe as a fireball. Such an event would be followed by a reorganization of the external magnetic field structure.

1.4 Neutron Star Magnetosphere

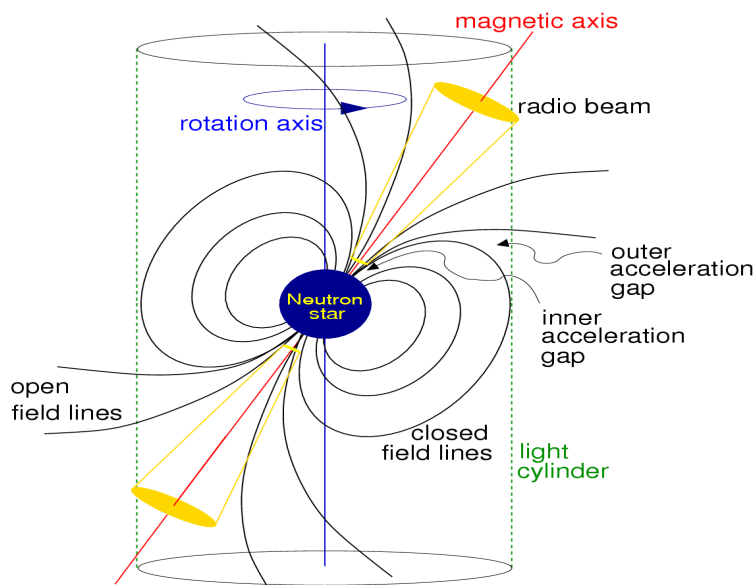


Figure 1.2. *The model of a rotating neutron star and its magnetosphere (not drawn to scale!)*
*Source*¹

The pulsar magnetosphere is a region around the neutron star within which the magnetic (force) field of the star strongly dominates every other force. The magnetosphere is composed of ionized, high-energy plasma which is in rapid co-rotation with the star. Within a radial distance (r_c) of the rotation axis, there is a charge separated, co-rotating magnetosphere (Lyne and Smith, 1998). The magnetosphere consist of the area from the neutron star surface extending up

¹ http://www.cv.nrao.edu/course/ast534/images/PSRs_pulsar_sketch.png

to a distance, r_c , from the spin axis. The radial distance (r_c), given by $\frac{c}{\Omega}$ (where c is the velocity of light and Ω is the angular velocity), is the distance of light cylinder. The velocity of light cylinder is the distance at which a particle with the angular velocity of the pulsar is traveling at the speed of light. The open field line defines the polar cap region on the neutron star surface, centered on the magnetic pole. The polar caps are the radio emitting regions. The particles on the open field lines outside the region can flow out from the magnetosphere. The radio emitting regions are confined to these open polar cap regions (Lyn and Smith, 1998).

The external magnetic field of the neutron star is of great importance in many observable pulsar characteristics. The dipole's misalignment with the rotation axis generates a broad band electromagnetic radiation at the rotation frequency of the pulsar. This accounts for the observed slow down and the main loss of rotational energy of the pulsar. According to Lyne and Smith (1998), for a young pulsar, the outward energy is sufficient to provide high-energy particles in a surrounding nebula. For instance, the rotational energy of the Crab pulsar is the source of energy of the synchrotron and radiation of the surrounding Crab Nebula. The discovery of a Nebula remains one of the strongest evidences that pulsars are formed during supernova explosions. The energy released as the pulsar slows down is enormous and it powers the emission of the synchrotron radiation of the Crab Nebula which has a total luminosity of about 75,000 times in excess of that of the sun (Weiler and Sramel, 1988).

1.4 Pulsar Spindown Model

Pulsar spindown has been studied through the power-law differential equation

$$\dot{\nu} = -K\nu^n, \quad (1.2)$$

where K is a constant and n is called the braking index, determined by the physical mechanisms spinning down the star. For a spinning dipole in vacuum only, equation (1.2) becomes (Gosh, 2007; Lorimer and Kramer, 2005):

$$\dot{\nu} = -K\nu^3, \quad (1.3)$$

with the constant K given by

$$K = \frac{B_{surf}^2 R^6 \sin^2 \alpha}{3Ic^3}, \quad (1.4)$$

where B_{surf} is the surface magnetic field of the star, R is the radius of the star, I is the moment of inertia, α is the angle of inclination of the emission cone with the rotation axis and c is the speed of light. Also by differentiating equation (1.2), n can be obtained in terms of pulsar rotational observables (Manchester & Taylor 1977) in the form:

$$n = \frac{\nu \dot{\nu}}{\nu^2}. \quad (1.5)$$

However, expressing the spindown model of equation (1.2) in terms of pulse period gives

$$\dot{P} = -KP^{2-n} \quad (1.6)$$

and integrating equation (1.6), one can determine the the age of the pulsar (Lorimer and Kramer, 2004) in the form:

$$T = \frac{P}{(n-1) \dot{P}} \left[1 - \left(\frac{P_0}{P} \right)^{n-1} \right] \quad (1.7)$$

where P and P_0 are the current and initial spin periods, respectively. Under the assumption that

$P_0 \ll P$, the spindown time of a perfect dipole ($n = 3$) becomes (Lorimer and Kramer, 2004)

$$\tau_c = \frac{P}{2 \dot{P}}. \quad (1.8)$$

Equation (1.8) is called the characteristic age of the pulsar. Finally, one can derive a relationship between the dipolar magnetic field strength at the surface of the pulsar and its period and period derivative (Lorimer and Kramer, 2004) as

$$B_{surf} = \sqrt{\frac{3c^3}{8\pi^2} \frac{I}{R^6 \sin^2 \alpha} \dot{P} P}. \quad (1.9)$$

1.5 Pulsar Rotational Irregularities

Pulsars are known for their stability as the best clock of the Universe, however long term monitoring projects and the increasing precision of timing measurement has revealed significant deviations from the predicted secular spindown. Pulsar timing is the process of measuring the

arrival time of pulses emitted by a rotating neutron star and therefore tracking its rotation (Lorimer and Kramer 2005). A pulsar timing model is used to predict the pulse phase ϕ . It is usually expressed as Taylor expansion around an epoch t_0 :

$$\phi(t) = \phi_0 + \nu_0(t - t_0) + \frac{1}{2}\dot{\nu}_0(t - t_0)^2 + \frac{1}{6}\ddot{\nu}_0(t - t_0)^3 + \dots \quad (1.10)$$

where ν_0 , $\dot{\nu}_0$ and $\ddot{\nu}_0$ are the spin frequency and its time derivatives at $t = t_0$, t_0 is the initial time when the timing just started and t is the time of arrival of the pulse. Improved rotational parameters are obtained from the new time of arrivals (TOAs) by minimizing the differences between the predicted phase and the observed pulse phase (timing residuals). The irregularities seen in the pulse residuals after subtracting a polynomial fit, as in equation (1.10), are of two sorts: glitches, which are abrupt increases in frequency and timing noise, an umbrella term used to describe all other rotational features (Antonopoulou, 2015). Both these rotational phenomenon are intrinsic to the pulsar and thus of great interest for the physical models of neutron stars and their magnetospheres.

1.5.1 Glitches

Glitches can be defined as discrete discontinuities in the rotation of pulsars. They are readily identifiable in timing residuals as a sudden jump in period (e.g. Radhakrishnan & Manchester, 1969, Reichley & Downs, 1969), which will correspond to a rapid increase in timing residuals. These are usually followed by a fairly exponential recovery towards the pre-glitch period (e.g. Krawczyk et al., 2003). Figure 1.3 shows an idealized glitch and the accompanying recovery period.

The increase in frequency is very fast: for the rise time of the largest Vela glitch, Dodson et al. (2002) obtained an upper limit of 40 sec. Thus the spin-up is typically unresolved and appears as a very sharp change of slope in phase residuals and a positive step in the frequency residuals. For example, the spindown of Vela pulsar over an 11- year period is shown in Figure 1.4. During this interval, 4 glitches can be easily seen, each resulting in a fractional increase in rotation rate of about 2 parts in 10^8 . Although not as widespread as timing noise, glitches have by now been detected in the rotation of more than 165 pulsars.

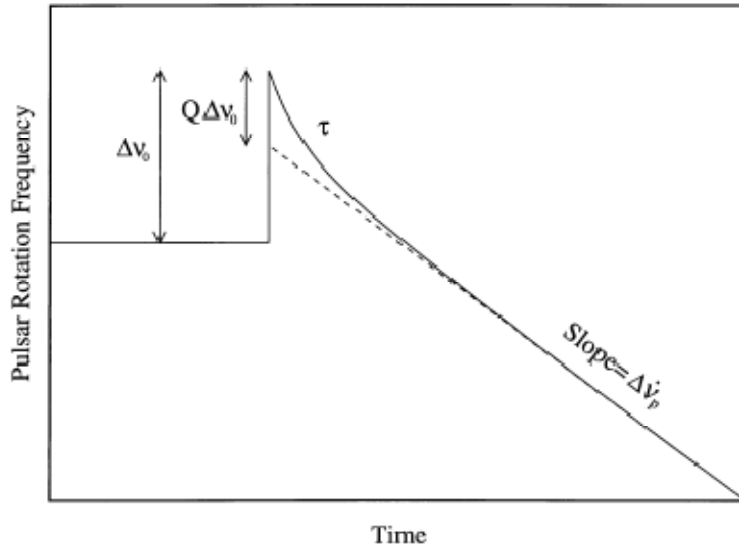


Figure 1.3 An idealized glitch (Lyne et al., 2000). A fraction Q of the initial step Δv_0 in frequency recovers exponentially on a time scale τ . The glitch is often accompanied by a permanent step increase in the slow – down rate – $\Delta \dot{v}_p$

Observed changes in pulsar spin frequency vary over a wide range from $\frac{\Delta v}{v} \sim 10^{-9}$ (D'Alessandro et al., 1993) for small glitches to $\frac{\Delta v}{v} \sim 10^{-6}$ (McCulloch et al., 1990)

for giant glitches. A jump in the spindown rate, usually of relative size $\frac{\Delta \dot{v}}{\dot{v}} \sim 10^{-4} - 10^{-3}$ and a trend for recovery are also characteristics of a glitch. Glitches and post glitch relaxation of $\dot{v}$ have been extensively observed in Vela and Crab pulsars (young pulsars).

A few pulsars are also seen to exhibit Vela like giant glitches but most of them, like the Crab pulsar, present a variety of glitch behavior and broad Δv size distribution (Espinoza et al., 2011). It has also been established that glitch activity is enhanced in younger pulsars with large spindown rates (Alpar & Baykal, 1994; Urama & Okeke, 1999). Glitch activity has been observed to be strongly dependent on pulsar spindown rates in the sense that pulsars with large spindown rates are more prone to glitch activity (Urama & Okeke 1999). Glitch events have been firmly associated with some form of irregular transfer of angular momentum between the

neutron star crust and the more rapidly spinning superfluid neutron interior (Alpar et al., 1993 and references therein).

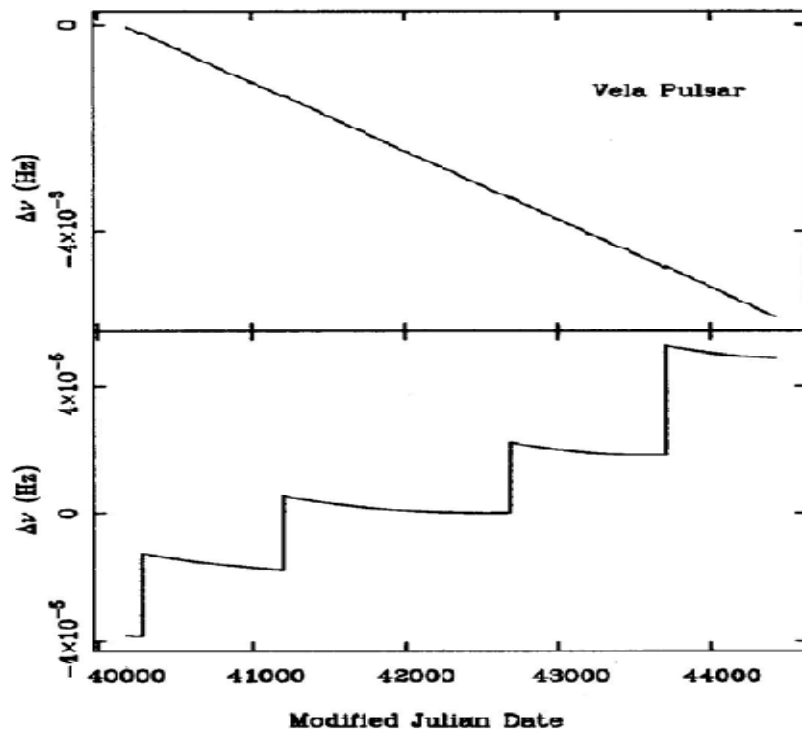


Figure 1.4. *The change in the rotation of the vela pulsar, PSR 0833 – 45, over an 11- year period. In the upper diagram, the steady slow down is interrupted at intervals of a few years by the glitches, seen as sudden small increases in rotation rate. The lower diagram shows the same data after the removal of a constant, arbitrary value of frequency derivative in order to reveal the detail of the glitches and the recovery (Lyne, Pritchards & Shemar, 1995).*

Soon after the first observation of glitches, several mechanisms were put forward to explain their origin. The lack of any radiative changes associated with most radio pulsar glitches provides evidence for an internal, rather than magnetospheric, origin. Furthermore, the very long post-glitch recovery timescales must arise from the relaxation of the slowly responding superfluid that a neutron star is expected to host (Baym et al. 1969). This simple model gives rise to the 'glitch function' which describes the exponential recovery: $\Delta\nu(t) = \Delta\nu_0 \times [1 - \exp(-t/\tau)]$. Here, $\Delta\nu_0$ is the initial rotational frequency increase and τ is the fraction of this which recovers on a

time scale $\gg$ Figure (1.3). The most promising glitch models to date invoke the superfluid to explain both the origin of the observed spin-up and its recovery (Anderson & Itoh, 1975). Advancing our understanding of the glitch phenomenon therefore has a unique potential of constraining the unknown properties of the inaccessible neutron star interior.

1.5.2 Timing Noise

Timing noise is characterized by a continuous, unpredictable, phase wandering of the pulses relative to a simple slow down model (phase jitter); slow variations in the pulsar's period and period derivative, occurring over on a timescale of months to years. It is seen most prominently in the crab and other pulsars with large period derivative (Cordes and Helfand, 1980). Some examples of timing noise in a number of pulsars are shown in the Figure 1.5 where the unpredictability of the period in these pulsars is clear. The older millisecond pulsars show much less timing noise, although it is observed in some sources, albeit with a much smaller amplitude. It nevertheless affects the timing precision of some millisecond pulsars, with the fast rotating pulsar B 1937+21 ($P = 1.56$ ms) as the most prominent example (kaspi et al., 1994).

The amount of timing noise can be quantified by measuring the residuals relative to a simple slow down model as described earlier. Figure 1.6 shows the activity parameters of a logarithmic measure of the timing noise, as a function of the period derivative for a number of pulsars (Cordes and Downs, 1985). The amplitude of this noise correlates fairly well with pulsar age, with older pulsars showing less of an effect (Cordes & Helfand, 1980). There is no widely accepted way to characterize timing noise, mainly due to its complexity and the unknown nature of the underlying processes

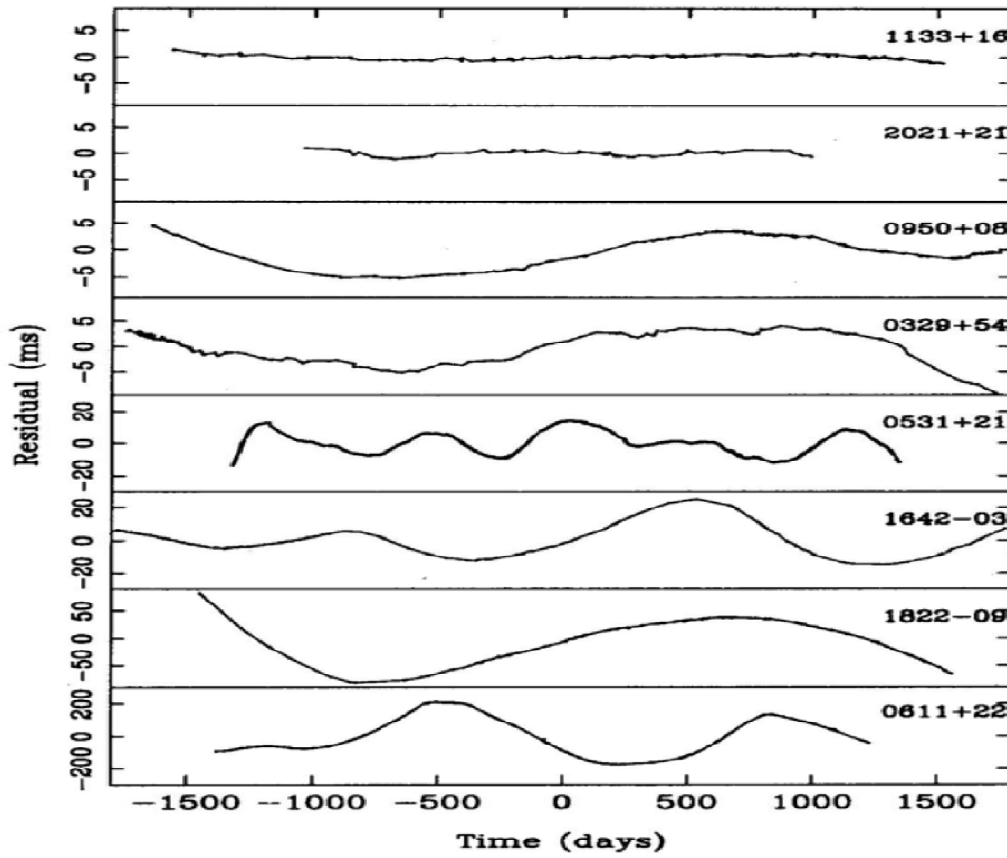


Figure 1.5 Examples of timing noise in 8 pulsars over about a 10 year period, showing increasing amounts of activity from the top to bottom (Lyne et. al., 1995).

In principle, a qualitative assessment of the level of timing noise activity for a given pulsar can be obtained from the (ñexcessò) phase residuals remaining after accounting for its deterministic spin-down (Cordes and Greenstein 1981; Cordes & Downs 1985; Cordes 1993; DôAlessandro et al., 1995). A statistic of importance is the timing noise activity parameter (A) defined, following Cordes & Downs (1985), as

$$A = \log \frac{\sigma_{\text{gross}}^2}{\sigma_{\text{fit}}^2} \quad (1.11)$$

where σ_{fit}^2 is the order of the polynomial fit to the data, T is the time span of the fit in days, σ_{gross}^2 , σ_{fit}^2 is the timing noise contribution to the gross σ_{gross}^2 phase residuals in millisecond (ms),

and σ_{τ}^2 , $\sigma_{\dot{\tau}}^2$ is the timing noise of the Crab pulsar in ms, which scales with τ as $\sigma_{\tau}^2, \sigma_{\dot{\tau}}^2 = 12\tau^2/168\dot{\tau}^2$. The scaling of the Crab pulsar timing noise activity with τ is consistent with frequency noise (Groth, 1975; Cordes, 1980; Cordes & Helfand, 1980; Cordes, 1993). The millisecond pulsars with very small period derivatives are found to be very stable, as indeed might be expected from the extrapolation of the trend in Figure 1.6 to their position (Arzoumanian et al., 1994).

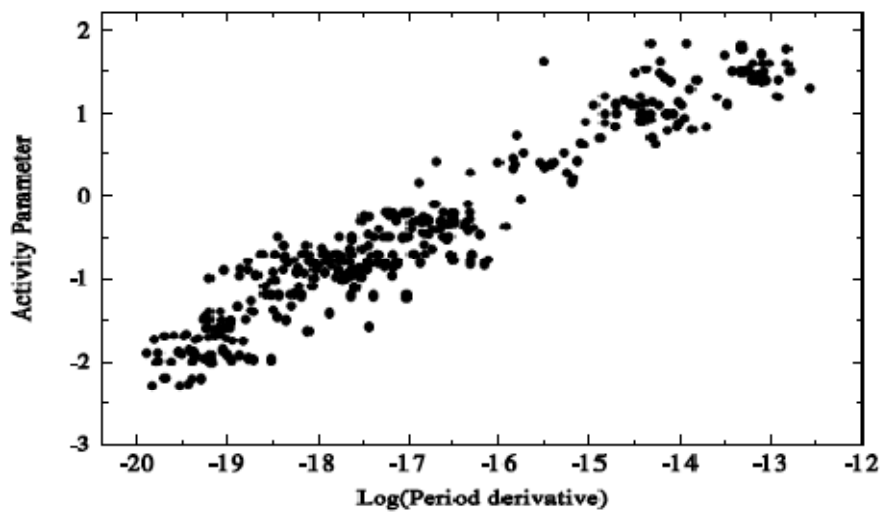


Figure 1.6 The timing activity plotted as a function of period derivative for 366 radio pulsars (Iyida, 2016).

Several ideas for the origin and causes of timing noise have been investigated. The proposed mechanisms include interaction with the interstellar medium (Scherea et al., 1997), accretion (Qiao et al., 2003; Cordes & Shannon, 2008), internal processes due to the superfluid component (Alpar et al., 1986; Jones, 1990; Haskell, 2011) and their combination with magnetospheric instabilities (Cheng, 1987). Despite all these attempts timing noise has not yet been explained successfully and remains unpredictable. The level of timing noise varies greatly among pulsars with the millisecond pulsars at the stable extreme and magnetars showing the highest level of instability (Shannon & Cordes, 2010).

In recent times, considerable attention have shifted to alternative causes of pulsar timing noise (Chukwude, 2002), which are presumably due to some form of systematic variations in pulsar spindown torque. These alternative investigations had been necessitated by the observations of periodicities or, at least quasi-periodicities, in the timing residuals of few pulsars (Lyne et al., 1988, Wolsczjan & Frail, 1992; D'Alessandro & McCulloch, 1997; Stairs, Lyne & Shemar, 2000; Lyne et al., 2000; Stairs et al., 2001; Shabanova et al., 2001). Lyne et al. (1988) observed a quasi-sinusoidal variation, with periodicity of approximately 20 months, in the time residuals of the Crab pulsar. This has been plausibly explained (Jones, 1988) as evidence for small amplitude free precession of the underlying neutron star owing to its structural asymmetry. D'Alessandro & McCulloch (1997) analysed arrival time data on PSR B0959-54 obtained over a period of 7 years, between 1987 and 1999 at Mt pleasant observatory. They found evidence for pulse shape variations which were found to be weakly correlated with variations in the time residuals. These authors interpreted it as possible evidence for free precession of the underlying neutron star. The absence of an apparent sinusoidal feature in the time residuals led D'Alessandro & McCulloch (1997) to argue that free precession model, with precession period much longer than 7 years, was still consistent with the data (Chukwude, 2002). Stairs et al., (2000) discovered the most compelling evidence for free precession of an isolated neutron star Figure 1.7. The authors while investigating the timing noise activity of the pulsar B1828-11, using arrival time data that span nearly 13 years, found three harmonically related periodicities of approximately 1000, 500 and 250 days in the timing residuals. Pulse shape changes which strongly correlated with variations in spindown rate $\dot{P}$ were also observed in the data. This observation has been interpreted in terms of free precession of a solitary neutron star (Jones & Anderson, 2001; Link & Epstein, 2001).

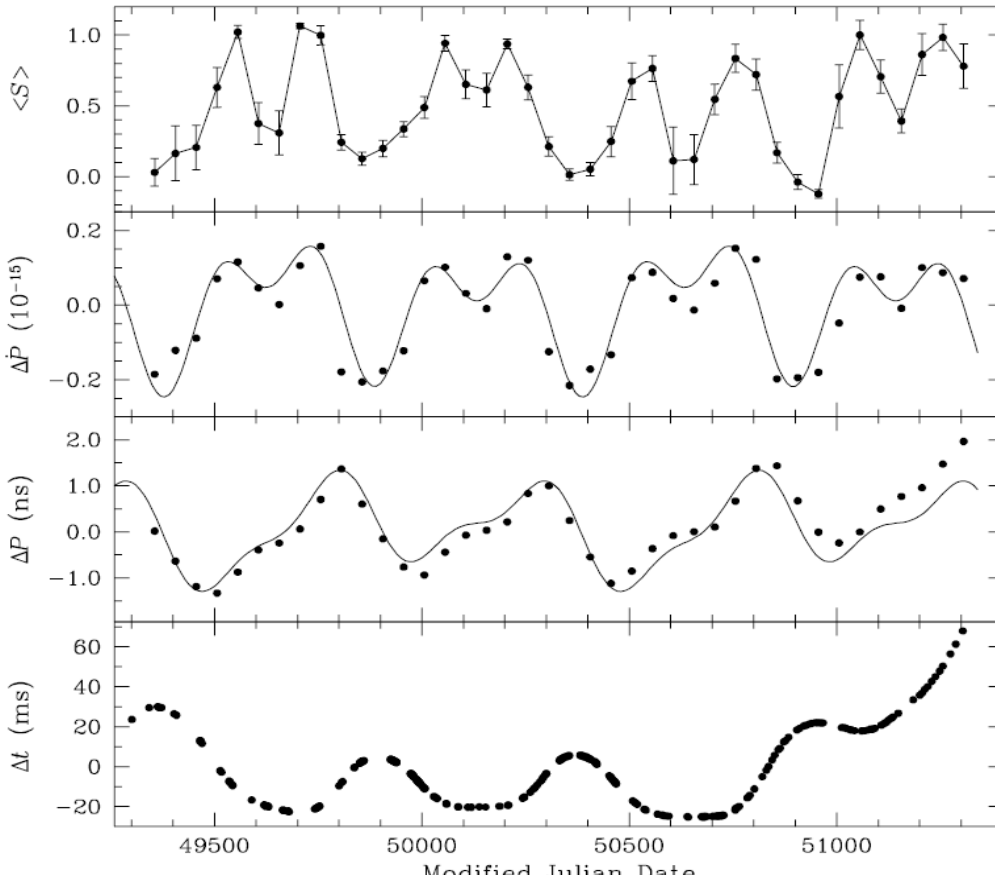


Figure 1.7. The change in arrival time (Δt) change in period (ΔP) and the change in spindownrate ($\Delta \dot{P}$) “shape parameter”, ($\langle S \rangle$), for B1828-11, Showing clear pseudo – sinusoidal variations consistent with a model of precessing pulsars (Stairs et al., 2000).

Similarly further evidences for free precession have been found in few other objects: PSR B1642-03 by shabanova et al. (2001). There has always been a large amount of tentative evidence that appears to point to precession-induced oscillations in the pulse arrival time of several pulsars. The best known is the apparent 35-day quasi-sinusoidal oscillations in the timing residual of Her X-1 (e.g Brecher, 1972; Stouber, 2013). Her X-1 is a binary system and it has been theorized that matter accreted from the companion star has excited precession in the pulsar. It is undetermined whether this is free precession or whether it is geodetic precession i a precession of the rotational axis due to relativistic spin-orbit coupling in a binary system as shown in Figure 1.8.

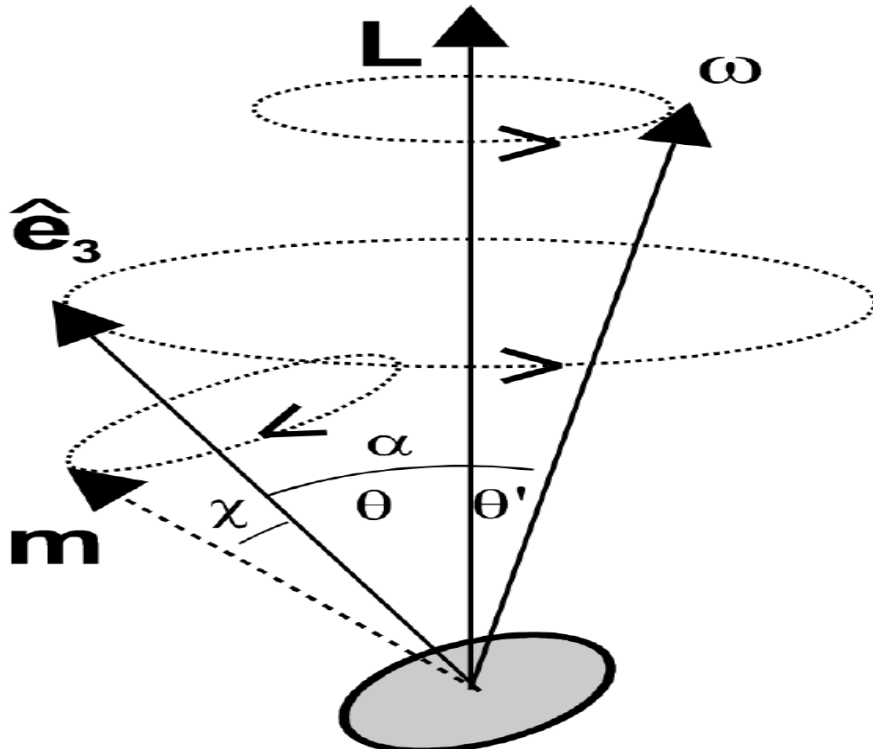


Figure 1.8 *Geometric precession of a biaxial Neutron star in the inertial frame. The body's symmetry axis is denoted by $\hat{e}_3$, the angular momentum by L , and the angular velocity by ω ; the three vectors always span a plane as shown. The angle θ, θ' and α are constant, with $\theta' \approx \varepsilon\theta \ll \theta$ for small oblateness ε . The vectors $\hat{e}_3$ and ω rotate about L and at nearly the spin frequency ω . A dipole moment m fixed in the body, and taking an angle χ with respect to $\hat{e}_3$, rotate in a retrograde sense about $\hat{e}_3$ at frequency $\approx \varepsilon\omega$ (Line & Epstein, 2001),*

Alternatively, periodic or quasi-periodic variations in the timing residuals of few radio pulsars have found explanations in terms of the "Doppler Effect" owing to the gravitationally interacting planets, neutron stars or non-degenerate main sequence stars. Analysis of the quasi-periodic timing residuals of a 6.2 millisecond pulsar B1257+12 (Wolszczan & Frail, 1992) has led to the discovery of the first extrasolar planetary system. The system has been confirmed to consist of three earth-mass planets A, B, and C with orbital periods of $\sim 25, 66$ and 98 days respectively (Wolszczan, 1994). However Wolszczan et al. (2000) have presented a strong argument for a possible fourth planet around the pulsar B125+12. Similar analysis has also revealed the presence of a planetary-mass companion to the pulsar B1620-26 (Thorsett & Chakrabarty,

1999). Timing activity of three pulsars i B1259-63, J0045-7319 and J1740-3052 have been firmly associated with the presence of non-degenerate companions as indicated by the high eccentricity of the binary orbits and the inferred masses of the companions. Johnston et al. (1992) found that the observed timing activity of PSR B1259-63 was consistent with the presence of $\sim 10M_{\odot}$ Be star. Similarly, Kaspi et al. (1994) and Stairs et al. (2001) showed that the observations on the pulsars J0045-7319 and J1740-3052 could be best modeled by hypothetical companions of masses ~ 10 and 11 solar masses, respectively in highly eccentric orbits with objects.

1.6 Pulsars as Astrophysical Tools

Pulsars are very important astronomical objects that have a wide range of both physical and astrophysical applications. According to Lorimer and Kramer (2005), pulsars are in many respects, a physicist's dream come true. Besides testing theories of gravity, one can investigate the gravitational and magnetic field of the galaxy, the interstellar medium, binary systems and their evolution, solid state physics and the interior of neutron stars. The study of the radio emission from pulsars reveals a lot about plasma physics under extreme conditions (Lyne and Smith, 1998). Below, we now discuss the details of each of the applications outlined above.

1.6.1 Pulsars as High – Precision Timing and Time Keeping Devices

Pulsars could be used as high-precision time-measuring instrument. This depends on pulsar timing, which is the measurement of the pulse arrival times of photons emitted by the pulsars. The amount of useful information that could be obtained depends upon the measurement precision of the pulse arrival time, which scales as the pulse width divided by the signal to noise (S/N) ratio and on the rotational stability of the objects. Since bright millisecond pulsars have short periods, hence narrow pulse width and high level of rotational stability, they are mostly used for these high precision measurements (Lyne and Smith, 1998). The current state of the art is the 5.75 ms pulsar J0437-4517, which yields a root mean square residual between measured and model arrival times of about 100 ns over an observing time of 1 year or longer (van Straten et al., 2001). The stability of pulsar depends largely on its rotational kinetic energy and spindown

energy loss rate associated with millisecond pulsar; they are believed to be more stable than normal pulsars (Lorimer and Kramer, 2005). As such, millisecond pulsars give higher timing precision than normal pulsars.

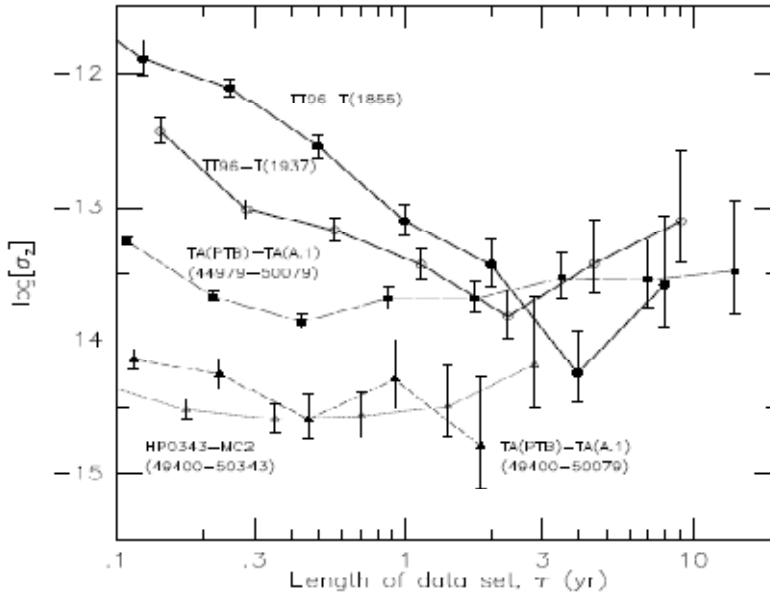


Figure 1.9 comparing the stability of PSRs B1855+09 and B1937+21 with terrestrial atomic clocks (Matsakis et al., 1989).

Figure 1.9 shows $\sigma_z(\tau)$ (the fractional stability) for the two longest observed millisecond pulsar, PSRs B1855+09 and B1931+21 and terrestrial clocks. The performance of different clocks can be compared using their fractional stabilities $\sigma_z(\tau)$. The fractional stability $\sigma_z(\tau)$ is like the Allan variance (Matsakis et al., 1997) and usually decreases over a period of time during which clock behavior is predictable. Although, the stability of millisecond pulsars are less than those of atomic clocks on short time scales, they become similar over time spans of months and years (Matsakis et al. 1997). Ultimately, rotational instabilities intrinsic to most pulsars known as timing noise could become important and limits the stability of the clock. This implies that timing noise limits the timing precision of pulsar clocks. A trend seen among the sample of normal and millisecond pulsars indicates that the timing stability increases with smaller period derivatives and is, hence, greatest for recycled millisecond pulsars (Hobbs et al., 2010).

If recycled millisecond pulsars perform better than terrestrial clocks, it is possible that a time standard could be defined by timing several of most stable millisecond pulsars against each other. The problem is that each pulsar has different spin period and spindown rates that are caused by some processes that are not yet fully understood. Similarly, unlike the current definition of the second that is based on hyperfine transition of Cesium 133, a pulsar time standard would not have a link with any reproducible physical phenomenon in any laboratory. Unless pulsars can be monitored continuously with dedicated telescopes, terrestrial clocks would still be needed to interpolate between the observations and to tie pulsars to some terrestrial endpoint times (Lorimer & Kramer, 2005).

1.6.2 Laboratory for Testing the Predictions of General Relativity

Though, solar system tests provide a number of very stringent tests of general relativity (Will, 2001), none of such tests will ever be able to test the strong $\ddot{}$ gravitational field limit. Solar system tests of the theory of general relativity are made under weak $\ddot{}$ field conditions, illuminated by small orbital velocities and gravitational self energies involved (e.g the self $\ddot{}$ energies for the sun and the Earth, expressed in units of their rest mass energy, are $\varepsilon_{sun} \sim -10^{-6}$ and $\varepsilon_{Earth} \sim -10^{-10}$ whilst for a pulsar and black hole (BH) we find $\varepsilon_{PSR} \sim -0.2$ and $\varepsilon_{BH} \sim -0.5$ (Cordes et al., 2005). Therefore, none of these tests of gravitational theories can be considered to be complete without probing the strong $\ddot{}$ field limit, which is done best and with amazing precision using binary radio pulsars.

1.6.2.1 The Use of Double Neutron Star (DN) Binaries.

Being very compact objects, double neutron star (DNS) binaries are used as perfect point sources for testing theories of gravity in the strong $\ddot{}$ gravitational field limit. For all the known DNS systems, the orbital separation is much larger than the size of the compact companion. An excellent example is the original binary pulsar B1913+16 in which the orbital period is observed to decrease at a rate predicted by general relativity due to gravitational $\ddot{}$ wave damping (Taylor and Weisberg, 1989; Weisberg and Taylor, 2003, 2004). This phenomenal measurement, shown

in fig.1.10 corresponds to an orbital shrinkage of 1 cm day^{-1} and provided the first evidence for the existence of gravitational radiation as predicted by general relativity.

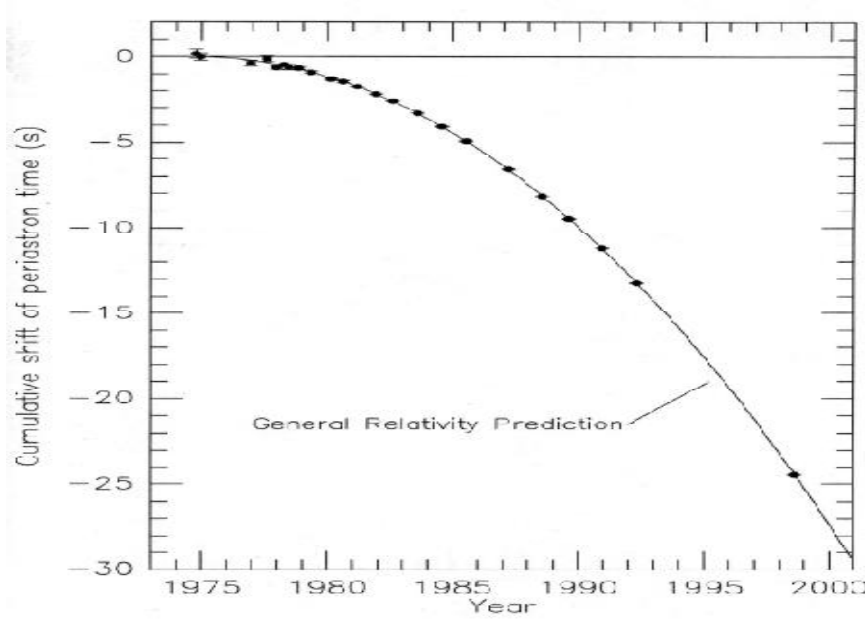


Figure 1.10 The shift in the periastron passage of the binary pulsar B1913+16 plotted as function of time (Taylor and Weisberg, 1989).

Consequently, neither mass transfer nor tidal effects is present and the system then approximates to a pair of point masses that can be used to test the predictions of theories of gravity (Weisberg and Taylor, 2004 and references therein), for instance, the rate of advance of periastron, $a_{\text{GR}}^{\text{[2]}}$ due to the emission of gravitational radiation. Here the crucial factor is the ratio of gravitational potential energy and rest mass energy for pulsar B1913+16, this factor is given by $\frac{GM}{c^2 \tau} \approx 10^{-6}$.

The rate of advance of periastron, $a_{\text{GR}}^{\text{[2]}}$ depends on the total mass of the system. If the respective masses of the pulsar and its companion is m_p and m_c , then the rate of periastron advance is given (e.g. Taylor and Weisberg, 1989) by

$$a_{GR}^{\text{[2]}} = 2.11 \left(\frac{m_p + m_c}{m_{\odot}} \right)^{2/3} \text{ degree yr}^{-1} \quad (1.12)$$

The original binary pulsar B1913+16 has shown a decrease in orbital period which has been measured by (e.g Taylor and Weisberg, 1989) to be

$$\dot{P}_b = - \frac{\dot{v}^2}{v^2} = (-240 \pm 0.09) \times 10^{-12} \quad (1.13)$$

where P_b is the orbital period. This agrees with the predictions of the general relativity due to gravitational- wave damping. This observation provided the first evidence for the existence of gravitational radiation in accord with the prediction of general relativity (Taylor and Weisberg 1989).

1.6.3 The Study of the Galaxy and the Interstellar Medium

The proper motions (the apparent slow movement of a star in a direction that does not change with time) of the pulsars reveal that they have very large space velocities (1000 kms^{-1}) that have carried most of them away from the vicinity of their birth places to the galactic plane (Lyne and Lorimer, 1994). In other words, pulsars should exist in any region of the galaxy. However, the nature of pulsars as galactic objects as well as the interactions between their polarized emission and the magnetized ionized interstellar medium makes it possible for pulsars to be employed in the study of the galaxy and the properties of the interstellar medium (ISM).

The measurement of the delay in arrival times of pulses as they transverse the interstellar medium gives information about the dispersion measure (DM), which is the integrated column density of free electrons along the line of sight of the pulsar. If the distribution of free electrons in the galaxy were known with precision, the measurement of the DM would give the distance to every pulsar (Taylor and Cordes, 1993). Though uncertain, the distribution of free electrons could be estimated through the use of independently calculated pulsar distances. By this means, pulsars are used in determining the galactic distribution of free electrons (Guelin, 1973).

Pulsar signals are highly polarized. Consequently, the magnetized ionized interstellar medium interacts with the linearly polarized signals, thereby rotating the position angle of linear polarization, by an amount that is proportional to the galactic magnetic field component along the line of sight to the pulsar. The effects of the rotation measure (RM) for pulsars over a wide

range of locations in the galaxy can be employed in mapping out large scale structures of the magnetic field (Smith, 1968; Taylor and Cordes, 1993; Wolleben and Reich, 2003). From earlier studies, evidence of the galactic magnetic field shows field line reversals between some nearby spiral arms (Thomson and Nelson, 1980; Lyne and Smith 1989; Rand and Lyne, 1994, Han et al., 2002; Noutsos et al., 2008).

1.6.4 The Study of Super – Dense Matter

The nature of matter inside neutron stars is said to be dense [$\sim (3 - 30) \times 10^{14} \text{ g cm}^{-3}$]. This state of matter is not obtainable in any laboratory on earth. Applications of pulsars as physical tools allow such extremely dense matter to be explored. The study of glitches and post glitch relaxation provides means of probing neutron star materials. This is referred to neutron star seismology (Lorimer and Kramer, 2005). Glitches are believed to occur due to variable coupling between the radio pulsar crust and its superfluid interior. Glitches are, however, rare and have been observed in a small fraction of mostly young pulsars (Lyne et al., 1996; Shemar and Lyne, 1996). Lyne et al., (1996) also discovered that most young pulsars with characteristic age $\tau_c \leq 2 \times 10^3 \text{ yr}$ show no sign of glitch activities. The lack of glitch activities in these young pulsar is attributed to the effects of high internal temperature, which tend to reduce the effect of vortex pinning (Wang et al., 2000)

Glitches are classified into two - macroglitches and microglitches (e.g Cordes et al., 1988). Macroglitches (also known as glitches) are usually characterized by an increase in the magnitude of the spindown rate $\dot{\nu}$ (Lyne et al., 1996; Urama, 2002). Macroglitches are known to originate from some form of dynamical changes within the neutron star which involves a sudden and regular transfer of angular momentum from the more rapidly rotating inner superfluid components to the slowly spinning crust (Anderson and Itoh, 1975; Ruderman, 1976). Some macroglitches have been explained as a consequence of star quakes, where sudden changes in the oblateness of the neutron star crust cause a change in the moment of inertia and, hence, the spin frequency, since angular momentum must be conserved (Baym et al., 1969). Macroglitches have some unique features in that the jumps in the rotation frequency ($\Delta\nu$) and the spindown

rate ($\Delta \nu$) have a definite signature ($\Delta \nu, \dot{\Delta \nu} = (+, -)$) which corresponds to increase in the pulsar's spin rates and magnitude of the spindown rates (Melatos, 2000).

Microglitches on the other hand consist of a class of small amplitude but resolvable jumps in both or either of the pulsar rotation frequency and its first time derivatives. Unlike the macroglitches in which the jumps are associated with definite signatures, the microglitches show all combination of signs and therefore are extremely very difficult to detect and understand in the framework of the available glitch theories (Chukwude, 2002).

1.6.5 The Discovery of Extra – Solar Planets

The technique of pulsar timing is extremely important in the study of pulsars and in the search for extra – solar planets/planetary systems. The existence of planets around a pulsar is ascertained from the times of arrival (TOA) of pulses over a multi-year time span. The pulsar's reflex motion in its orbit about the system's barycentre caused the pulse TOAs to be delayed or advanced relative to what one would predict for an isolated pulsar (Cordes et al., 2005). Thus finding pulsar planetary systems will require long, high-precision timing observations.

The first extrasolar planetary system was found around the Pulsar PSR B125+12 (Wolszczan and Frail, 1992). The system consist of three planets, planet A with approximately a lunar mass, and two – Earth mass planets (planets B and C) with orbital periods of 25, 66, and 98 years respectively. Since then, a planet has also been found around the pulsar PSR B1620 – 26 (Sigurdsson et al., 1997; Reicher et al., 2003), in the globular cluster *M4*.

In contrast to planetary systems around main- sequence stars, pulsar planetary system offer unique insights. Taken together the two pulsar planetary systems indicate that planets can form in a variety of environments. For instance, the planet around PSR B1620-26 challenges conventional notions about the formation of planets (Cordes et al., 2005). It is thought to have been acquired by the pulsar during a dynamical exchange within the globular cluster *M4*. This is a low – metallicity globular cluster, suggesting that planets can form in low – metallicity environments. In contrast, planets orbiting main-sequence stars near the Sun are found almost

exclusively around stars with Solar or super-Solar metallicities (Gonzalez, 1997; Santos et al., 2001), which has led to the belief that only stars with large metal contents, can host planets. Similarly the presence of terrestrial mass planets around PSR B125+12 suggests that terrestrial planets will be widespread, a prediction to be tested by future space missions such as Kepler (Koch et al., 1998) and the Terrestrial planet finder (Beichman, 1998). Shabanova (1995) reported evidence for a planet with at least two earth masses and a semi-major axis of 7.3 AU in orbit of a normal pulsar B0329+54. This is a very slow pulsar, which means a relatively old object (pulsation period of about 0.7 sec).

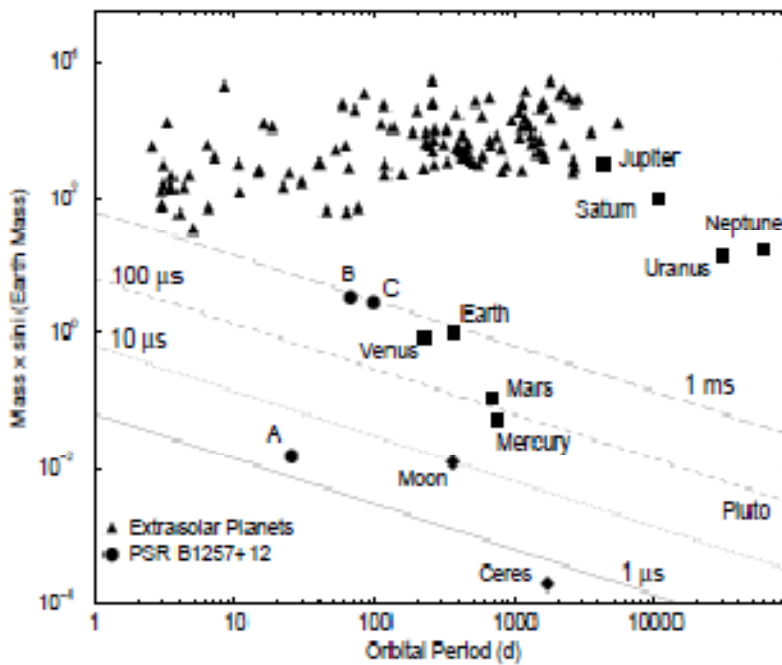


Figure 1.11 Planetary companions that can be detected with pulsar timing observations for different values of timing precision (Cordes et al., 2005).

The unexpected discovery of this extra-solar planetary systems, demonstrates the high sensitivity of pulsar timing in detecting small bodies in orbits around neutron stars. Hence, pulsar timing is now far more sensitive than optical searches for planets around main-sequence stars. Figure 1.11 above shows that Asteroid-sized and even smaller objects can be found with the Square Kilometer Array (SKA) timing (Cordes et al. 2005). With the SKA a routine timing precision of $\sim \leq 1 \mu s$ is anticipated for millisecond pulsars.

1.6.6 Study of Plasma Physics under Extreme Conditions

Plasma physics is the study of charged particles and fluids interacting with self-consistent electric and magnetic fields. These conditions are believed to exist in neutron stars, and hence, they are used as laboratories for the study of such extreme physical conditions. These conditions of very high densities and super-strong magnetic fields occur in a rather complex environment known as the pulsar magnetosphere and are only poorly understood. This situation remains after over 40 years of pulsar research and in spite of the large number of studies and observations devoted to the identification of the relevant physical process (e.g Melrose, 2000). Solving this problem however offers deep insight into the relativistic plasma physics.

The double pulsar binary system consisting of the 22.7 ms pulsar A (Burgay et al., 2003) and the 2.8 sec pulsar B (Lyne et al., 2004) serves as a suitable laboratory for understanding plasma physics. The interesting thing about pulsar A (J0737-3039) is that the mean orbital separation of the two pulsars is only about 3 light seconds (Lorimer and Kramer, 2005). At this distance, the relativistic wind from the radiation beam of A is sufficiently energetic to penetrate into and probe the emission region of B, which is consequently distorted.

The first observation is seen as an occultation of the radiation of A by the magnetosphere of B at conjunction. The size of the region of eclipse can be found from the duration of the eclipse and the relative transverse speeds of the two stars. As they move in their orbits, the line of sight from A passes through and sweeps across the magnetosphere of B, giving the opportunity to probe the physical conditions in its magnetosphere. The determination of changes in the radio transmission properties like the dispersion and rotation measures will then allow the plasma density and magnetic field structure to be probed (Lyne and Smith, 1998).

1.7 Purpose of Study

The purpose of this work is to investigate rotational irregularities in pulsars in order to show that pulsars can be used for high precision measurements.

CHAPTER TWO

LITERATURE REVIEW

D'Alessandro (1997) described the observational aspects of pulsar rotational irregularities, namely, glitches and timing noise. In addition, he also reviewed and assessed the theoretical models that have been proposed to explain the irregularities. D'Alessandro et al. (1997) derived the power spectra of the timing noise observed in 18 southern pulsars based on CLEAN algorithm. Most of the spectra are well described by a single or double- component power-law model. Their results combined with those obtained from the time-domain analysis of the timing activity in these pulsars are used to assess the viability of the various theoretical models of pulsar timing noise. Metasakis et al. (1997) proposed a statistical measure suitable for comparing the rotational stabilities of pulsars with one another and with terrestrial time scales. Applying the new statistical formalism to real pulsar data and terrestrial time scales, they showed that over a 10 years interval, these two kinds of data have comparable stabilities.

Long term timing Observations of radio pulsars have revealed enormous complexities in the true dynamical behavior of most pulsars (Chukwude, 2003). The widely acknowledged rotational irregularities are in the form of glitches and timing noise. While glitches have been observed in just a few radio pulsars (Wang et al., 2000), timing noise is more prevalent among the known pulsar population (Boynton et al., 1972; Cordes & Downs, 1985; Chukwude, 2002). In principle, a qualitative assessment of the level of timing noise activity for a given pulsar can be obtained from the (ñexcessò) phase residuals remaining after accounting for its deterministic spin-down (Cordes & Greenstein, 1981; Cordes & Downs, 1985; Cordes, 1993; D'Alessandro et al., 1995).

Discrete discontinuities in the rotation of pulsars are broadly of two sorts: macroglitches & microglitches. Macroglitches (conventionally known as glitches) are characterized by sudden increase in pulsar rotation frequency, $\dot{\nu}$, usually accompanied by an increase in magnitude of spin-down rate, $\dot{\nu}\dot{\nu}$ (Lyne, 1987; Lyne & Pritchard, 1987; Flanagan, 1990; Lyn et al., 1996; Wang et al., 2001; Urama, 2002). Macroglitches have been extensively studied and are now associated with some unique features. These features are usually observed in the rotation

frequency ($\Delta\nu$) and spin-down rate ($\Delta\dot{\nu}$): ($\Delta\nu, \Delta\dot{\nu}$) = (+, -) and have magnitude, respectively, in the range of $10^{22} - 10^{23}$ and $10^{22} - 10^{23}$ (Janssen & Stappers, 2006; Melatos et al., 2008). Wang et al. (2001) also showed that most glitches have relative amplitude $\frac{\Delta\nu}{\nu}$ of between 10^{-8} and 10^{-6} . Till date about 472 glitches have been detected (Espinoza et al., 2011).

On the other hand, microglitches constitute a class of small amplitude, but resolvable, jumps in both or either of the pulsar rotation frequency and its first time derivatives. Unlike the spectacular glitch events, the study of microglitches have received little attention in the last three decades of pulsar timing observations and very little is known about this class of rotational discontinuities (Cordes et al., 1988; Chukwude, 2002). The amplitudes of the jumps vary over a wide range, but are generally believed to be within $\Delta\nu < 10^{22}$ and $\Delta\dot{\nu} < 10^{22}$. However, unlike macroglitches, where the jumps have definite signature ($\Delta\nu, \Delta\dot{\nu}$) = (+, -), microglitches have all possible combination of signs (Cordes et al., 1988). Cognard and Backer (2004) reported on the observation of a very small glitch observed for the first time in a millisecond pulsar, PSR B1821-24. Mandal et al. (2009) latter showed that the glitch observed in PSR B1821-24 is unusual on two accounts. First, the size of the glitch is, at least, an order of magnitude smaller than the smallest glitch observed to date. Secondly, all the other glitching pulsars have strong magnetic field with $B > 10^{12}$ and are young, whereas PSR B1821-24 is an old recycled pulsar with field strength of 2.25×10^8 .

By selecting a sample of 127 pulsars from the ATNF pulsar Catalogue (Manchester et al., 2005), for which the quoted errors in the second derivative of the spin frequency ($\ddot{\nu}$) are less than ten percent, Urama et al. (2006) found a strong correlation between $\ddot{\nu}$ and $\dot{\nu}$ independent of the sign of $\dot{\nu}$. They suggested that this trend can be accounted for by small stochastic deviations in the spindown torque that is directly proportional (in magnitude) to the spindown torque. Chukwude & Urama (2010) presented an in-depth observation of the phenomenon of microglitches in a sample of 26 radio pulsars. Their results show that within the period of observation (seventeen years) only one pulsar in this sample showed a large jump. Kçdem et al. (2011) found that fractional change in the spin frequency derivative of the anomalous X-ray pulsar 1E2259+586 after its 2002 glitch decreased from -2.2 ± 10^{-2} to $-1.278(3) \times 10^{-3}$, in about 2.5 years. From

the pulse timing analysis, they also discovered two small frequency shifts with fractional changes $\frac{\Delta\nu}{\nu} = 3.08(32) \times 10^{-22}$ and $\frac{\Delta\nu}{\nu} = -1.39(11) \times 10^{-22}$. These changes were interpreted by the authors as positive and negative microglitches.

Lyne et al. (2000) showed quantitatively that glitch activity decreases linearly with decreasing rate of spindown. Their analysis suggests that 1.7 percent of moment of inertia of a typical neutron star is normally contained in pinned superfluid which releases its excess angular momentum at the time of a glitch. They suggested that the low braking index of Vela and Crab pulsars cannot be caused by a decreasing moment of inertia and should be attributed to step increases in the effective magnetic moment of the neutron star at the glitches. Glitches mainly occur in younger pulsars (Lyne et al., 2000) and are usually interpreted as a sudden transfer of angular momentum from a faster rotating component of superfluid to the solid crust of the star (Bayman et al., 1969; Andersson & Itoh, 1975). Andersson et al. (2012) showed that the non-dissipative entrainment coupling between the neutron superfluid and the nuclear lattice leads to a less mobile crust superfluid, effectively reducing the moment of inertia associated with the angular momentum reservoir. Combining the latest observational data for profile glitching pulsars with theoretical results for the crust entrainment, they found that the required superfluid reservoir exceeds that available in the crust. Haskell & Melatos (2015) presented a review of the main glitch models that have been proposed and discussed their understanding in the light of current observations.

Pulsar rotational irregularities (glitches and timing noise) have resulted in discrepancies between model predicted values of braking indices and the measured values. At present, only Eight pulsars have sufficiently steady rotations that stable values of their braking indices are generally accepted (e.g Lyne et al., 2015 and reference therein), among which the most recent case is PSR J1734-3333, which has $n = 0.9 \pm 0.2$ significantly below 3 (Espinoza et al. 2011). Other examples of this category of pulsars are the Crab pulsar with $n = 2.509 \pm 0.001$ (Lyne et al., 1993), PSR B1509-58, $n = 2.837 \pm 0.001$ (Kaspi et al., 1994), PSR B0540-69, $n = 2.04 \pm 0.02$ (Manchester & Peterson, 1989; Nagase et al., 1990; Gouffles et al., 1992), PSR J1119-6127, $n = 2.91 \pm 0.05$ (Calmilo et al., 2000), PSR J1846-0258, $n = 2.65 \pm 0.01$ (Livingstone et al., 2006)

and Vela pulsar, $n = 1.4 \pm 0.2$ (Lyne et al., 1996). It is noteworthy that all these pulsars are relatively young (the oldest being Vela with spindown age $\tau \approx 12$ kyr) with positive braking indices less than 3. Most recently however, Archibald et al. (2016) measured the braking index of PSR J1640-4631 to be $n = 3.15 \pm 0.03$ which is rather high. Using series of simulations, these authors argued that this unusually high braking index is not due to timing noise but is intrinsic to the pulsar's spindown. In the same vein, Chen (2016) interpreted the high braking index and radio quiet nature of this pulsar (PSR J1640-4631) to be as a result of its low-mass and large inclination angle.

Currently, there appears to be a consensus that the observed $\dot{\nu}$ (second frequency derivative) of most pulsars is severely biased by fluctuations of timing noise origin, a situation which precludes significant measurements of $\dot{\nu}$ for most radio pulsars (Baykal et al. 1999; Johnston & Galloway, 1999). For a typical γ -ray pulsar with $\nu = 1$ Hz, $\dot{\nu} = 10^{-30}$ Hzs⁻¹, the expected $\dot{\nu}$ from the spindown law is only $\sim 10^{-30}$ Hzs⁻² which is too small to measure even over hundreds of years of timing. However, this has not been possible due to (a) glitches which happen mostly in young pulsars (Shemar & Lyne, 1996) and (b) timing noise. Glitches lead to discontinuities in both ν and $\dot{\nu}$ making it difficult to phase connect (i.e count the exact number of rotations of the pulsar) over the glitch. Furthermore, the recovery from a glitch can last many hundreds of days and the measured $\dot{\nu}$ could reflect the recovery rather than the intrinsic spin-down. On the other hand, Cordes & Helfand (1980) recognized that the 'timing noise' dominates over the intrinsic $\dot{\nu}$ by a factor of ~ 100 thereby making most of the early published values of braking indices based on $\dot{\nu}$ spurious. More recently, Chukwude (2003) argued that the observed frequency second derivative for the 27 HartRAO pulsars in his data sample was merely manifestations of timing noise activity rather than due to an intrinsic pulsar torque braking process.

Most of the measured braking indices based on frequency second derivative $\dot{\nu}$ has indeed been spurious, ranging from extremely negative small values to moderate positive and negative values and to extremely positive high values. According to chukwude (2003), the inferred braking indices obtained from the observed frequency second derivatives of 27 HartRAO pulsar sample varied over the range $-10^4 < n \leq +10^5$. Braking indices reaching values of $\pm 10^{4 \sim 5}$ were also

reported in Manchester et al. (2005). By analyzing the timing residuals of 366 non-recycled pulsars over the past 36 years, Hobbs et al. (2010) measured their braking indices and showed that they range from -287986 to $+3624$. However, Johnston & Galloway (1999) using a method that excludes frequency second derivatives $\dot{\nu}^2$, computed braking indices for 20 pulsars based on timing solutions available in literature and their results showed that four of these pulsars have large negative braking indices while eight of them have moderate positive braking indices. Alpar and Baykal (1994) suggested that large negative braking indices arise when the glitch occurs before the epoch of the first timing solution. On the other hand, anomalous positive braking indices observed in a few young/middle-aged pulsars have been plausibly explained as characteristics of interglitch recovery in these objects (Alpar, 1998).

There has been several attempts to explain the discrepancy between observed braking indices and the theory predicted value of $n = 3$. Macy (1974) first suggested that the observation of $n \neq 3$ may result from a force-free precession of a neutron star. Deminanski & proszynski (1979) rather attributed it to the existence of a companion star. Peng et al. (1982) suggested that neutrino and photon radiation coming from super fluid neutrons may brake the pulsars. Allen and Horvath (1997) proposed a simple model to account for the difference between the observed braking index and the expected value for a rotating magnetic dipole model, based on a growth of

the torque function $K = -\frac{\Omega^n}{\Omega^n}$, under the constraint that observed braking index is a constant.

Haskell et al. (2006) noted that gravitational wave emission predicts $n = 5$, but it is only efficient during the first minutes or hours of a neutron star life, when rotation is sufficiently fast and the mass quadruple. Magalhaes et al. (2016) proposed a model to explain the observed braking indices $n \neq 3$ by introducing a modification to the canonical dipole model. The modification consists basically of a force component (compensating component) in the energy conservation equation of the system which varies with the first power of the tangential velocity of the pulsar's crust.

Many other authors have proposed various models to explain the observed low value of n . Blandford & Romani (1988) proposed that $n > 3$ is a consequence of multipole field and field evolution. Some authors (e.g Menou et al., 2001; Alpar et al., 2001) proposed that both magnetic

dipole radiation and the propeller torque applied by the debris disk formed after supernova explosion can cause spin-down of pulsars. Recently still on low braking index (Xu & Qiao, 2001; Wu et al., 2003) pointed out that the combination of dipole radiation and unipolar generator may cause $n > 3$. Chen and Li (2006) suggested that the possible reason for the observed low braking indices ($n < 3$) of young pulsars could be due to the increased magnetic field strength of pulsars or braking of fallback disks surrounding pulsars.

On the other hand, the occurrence of very high braking indices of both signs has been considered in the context of internal frictional instabilities occurring between the crust and the super fluid, almost independently of the evolution of the neutron star magnetic field (Shibazaki & Mochizuki 1995). However, this applies only to old neutron stars ($t \geq 2 \times 10^6$ years) and appears as extremely short events oscillating about the canonical value $n = 3$. As noted in Pons et al. (2012), any small relative variation in torque will produce large variation in n for old pulsars. Barsukov & Tsygan (2010) proposed another explanation for the observed distribution with very high positive and negative braking indices (n) by studying the effect of non-dipolar magnetic field components and neutron star precession on magnetospheric electric current losses. They suggested that these large n should be observable over relatively long periods of $10^4 - 10^6$ yrs. Another possibility that can explain the observed variability of braking indices is the time evolution of conductivity in the magnetosphere (Li et al. 2012), which also has implications for the spindown of intermittent pulsars and sub-pulse drift phenomena (Lyne, 2009).

CHAPTER THREE

DATA ANALYSIS AND RESULT

3.1 Sources of Data

The database for the analysis presented in the work consists of the amplitude fluctuations in radio pulsar rotation period and its first time derivative (ΔP and $\Delta \dot{P}$ respectively), the period second derivative ($\ddot{P}$), the pulsar braking indices estimated from different methods, and some key pulsar spindown parameters. Fluctuations in spindown rates of the pulsars were estimated from published measurements of the rotation period (P) and spindown rate ($\dot{P}$) at two different epochs. The period second time derivative of the pulsars were obtained as time rate of change of the pulsar spindown rate ($\frac{\Delta \dot{P}}{\Delta T}$), where T is the epoch of the measurements. The braking indices of objects in our sample were calculated via methods that involved differentiation and integration of the standard vacuum magnetodipolar spindown law (Manchester and Taylor, 1977).

In the preliminary stage of the data analysis, we carefully compiled from published catalogues (Manchester & Taylor, 1981; Taylor, Manchester & Lyne, 1993; Arzoumanian et al., 1994; Wang et al., 2001; Hobbs et al., 2004), a database of all radio pulsars, whose spindown parameters [rotational periods (P) and spindown rates ($\dot{P}$)] have been significantly measured at more than one epoch. The database consists of 315 radio pulsars, out of which 134 have their spindown parameters measured at more than two different epochs.

3.2 Fluctuations in Spindown Parameters of the Pulsar

An objective assessment of radio pulsar rotational stability can be accomplished by comparing measurements of P and $\dot{P}$ obtained at different epochs. The magnitude of fluctuations in the parameter values is a direct measure of the level of instability in rotation history of the object. In current analysis, the fluctuations / change in the spindown parameter of the 315 pulsars in our

sample were estimated as the difference between the measurements obtained at two different epochs (T). For pulsar's spindown rate, which is expected to be a constant for a given pulsar, the calculation of fluctuations (ΔP^2) is straight forward. In this, ΔP^2 was simply calculated as the difference between measurements of P^2 obtained at two widely different epochs as:

$$\Delta P^2 = P^2(T_2) - P^2(T_1) \quad (3.1)$$

where $P^2(T_1)$ and $P^2(T_2)$ are the published measurements of the pulsar spindown rates at earlier and later epochs respectively. For consistency, in current analysis, we assume that $T_2 > T_1$.

In the case of the pulsar rotation period, one has to recognize the fact that pulsars intrinsically spindown, which introduces some epoch-dependent variations in P . This implies that measurements of a pulsar's rotation period at two different epochs will be intrinsically different. Hence such measurements can only be compared after correcting for the spindown. This was practically accomplished by adjusting the period measurements of every pulsar to the same epoch (e.g. Manchester & Taylor, 1977; Kramer & Lorimer, 2005). Subsequently, the fluctuation / change in P was calculated as the difference between the measured and adjusted values of the pulsar rotation period as graphically illustrated in Figure 3.1 below.

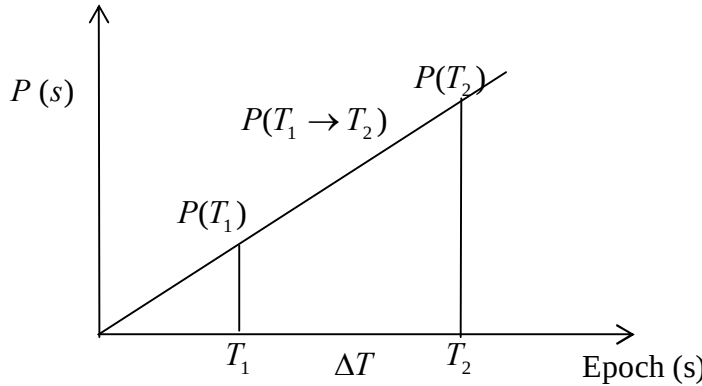


Figure 3.1 A plot of period P against epoch (T)

In current analysis, the amplitude fluctuation in P (ΔP) was calculated as :

$$\Delta P = P(T_2) - P(T_1 \rightarrow T_2), \quad (3.2)$$

where $P(T_2)$ is the measurement of the pulsar rotation period at a later epoch T_2 and $P(T_1 \rightarrow T_2)$ is measurement of P at earlier epoch T_1 after adjusting to the later epoch T_2 . $P(T_1 \rightarrow T_2)$ was

calculated following standard procedure by accounting for the pulsar deterministic spindown(e.g Kramer & Lorimer, 2005) as

$$P(T_1 \rightarrow T_2) = P(T_1) + \dot{P}(T_2 - T_1), \quad (3.3)$$

where $\dot{P}$ is the spindown rate, which is assumed to be constant for a given pulsar, $P(T_1)$ is the measurement of P at the earlier epoch T_1 and T_2 is the later epoch of measurement of P . It is important to note that in current analysis, we have assumed that $\Delta T = T_2 - T_1 > 0$.

For pulsars with more than two epochs of measurements of spindown parameters (P and $\dot{P}$), only the measurements at the first and last epochs were used in computing fluctuations in the parameters. It is also important to note that seven pulsars in our data sample were observed in five different epochs, thirty eight were observed in four epochs, eighty nine were observed in three epochs and the rest one hundred and eighty one pulsars were observed in two epochs.

3.3 Error Estimation

The formula for standard error in sum and differences was used to calculate the error in period and period derivative fluctuations (ΔP and $\Delta \dot{P}$) respectively, as follows: Standard error in the observed fluctuant in period $\Delta P \equiv \epsilon_{\Delta P}$ is given by

$$\epsilon_{\Delta P} = \sqrt{S_{P_1}^2 + S_{P_2}^2}, \quad (3.4)$$

Where S_{P_1} and S_{P_2} are the quoted formal standard errors in the $P(T_1)$ and $P(T_2)$ respectively.

Similarly, the standard error in the observed fluctuation in the pulsar spindown rate ($\Delta \dot{P}$) was estimated as

$$\epsilon_{\Delta \dot{P}} = \sqrt{S_{\dot{P}_1}^2 + S_{\dot{P}_2}^2}, \quad (3.5)$$

where $S_{\dot{P}_1}$ and $S_{\dot{P}_2}$ are, respectively, the quoted formal standard errors in the measured spindown rates at earlier and later epochs. For the current sample of 315 radio pulsars, this criterion resulted in $\Delta \dot{P} \sim 41212800 \pm 809585884.8$ sec.

3.4 Measurement of Braking Indices

The first braking index n_1 was calculated using the equation derived by Johnston and Galloway (1999).

$$n_1 = 1 + \frac{v_1 v_2^2 - v_2 v_1^2}{v_1^2 v_2^2 \Delta T} \quad (3.6)$$

by substituting the period equivalents of frequency and frequency derivative into equation (3.6)

[i.e $v = \frac{1}{P}$; $v^2 = -\frac{\dot{P}}{P^2}$] we obtained :

$$n_1 = 1 + \frac{P_2 \dot{P}_1^2 - P_1 \dot{P}_2^2}{P_1^2 P_2^2 \Delta T}, \quad (3.7)$$

where P_1 and P_2 are the periods at the earlier and later epochs, $\dot{P}_1$ and $\dot{P}_2$ are the spindown rates at the earlier and later epochs respectively, ΔT is the time span between the two epochs. On the other hand n_2 from obtained Hobbs et al. (2004) where it was calculated using equation (1.5). Finally, the third braking index n_3 was obtained by substituting the period equivalents of frequency and frequency derivatives into equation (1.5) to obtain

$$n_3 = 2 - \frac{P \ddot{P}}{\dot{P}^2} \quad (3.8)$$

where $\ddot{P} = \frac{\Delta \dot{P}}{\Delta T} = \frac{\dot{P}_{final} - \dot{P}_{initial}}{T_{final} - T_{initial}}$ is the period second derivative. It is obtained by subtracting the period derivative of the latest epoch from that of the earliest epoch and the resulting change $\Delta \dot{P}$, divided by the epoch deference ΔT .

3.5 Distribution of Observed Parameters

Only the observed fluctuations in period P and period derivative $\dot{P}$ (ΔP and $\Delta \dot{P}$) which exceed the formal standard errors in these parameters ($\sigma_{\Delta P}$ and $\sigma_{\Delta \dot{P}}$) were considered to be significant. Significant changes in period ΔP and period derivatives $\Delta \dot{P}$ were observed in 293 and 178 pulsars, respectively. The fractional changes in period $\frac{\Delta P}{P}$ were calculated using this scale and found to be in the following ranges; 179 pulsars have $\frac{\Delta P}{P}$ between 10^{-10} – 10^{-9} , 104 pulsars have $\frac{\Delta P}{P}$ between 10^{-9} – 10^{-8} , 10 pulsars have $\frac{\Delta P}{P}$ between 10^{-8} – 10^{-7} , 1 pulsar PSR (B1842-04) has $\frac{\Delta P}{P} = 6.6 \times 10^{-7}$. Likewise the absolute values of the fractional change in the spindown rate ($\frac{\Delta \dot{P}}{\dot{P}}$) were also obtained in the following ranges: 138 pulsars between 10^{-10} – 10^{-9} , 41 pulsars $> 10^{-9}$ and one pulsar (B0523+11) has an exceptionally high value of 543. According to the current ATNF glitch catalogue, the largest observed glitch has the magnitude of the fractional change in period derivative as 5.1 and this value was observed in 4U 0142+61 which is an anomalous x-ray pulsar. It is evident that the fractional change in period derivative we calculated for B0523+11 is two orders of magnitude higher than the published value for the largest glitch so far. However, this high value of the fractional change in period derivative may be attributed to the precision of the measurements of the period derivative $\dot{P}$ values (used to calculate this change).

The pulsar B0523+11 was discovered by Manchester et al. (1978) in the survey observations at Molonglo Radio observatory, operated by the University of Sydney. In this survey which was completed in 105 days, the period measurement of this pulsar (B0523+11) was observed to be $P = 0.35447(3)$ sec. A more precise value of the rotation period of the pulsar was obtained by Siegman et al. (1993) using the Molonglo observatory Synthesis Telescope for over 2.4 years from 1986 to 1988. The new parameters were given as $P = 0.354437585224(7)$ and $\dot{P} = 0.0732(6)$. Hobbs et al. (2004) also presented a timing solution for this pulsar with a data-span of about 34 years. The parameters which were given in terms of frequency

($\nu = 2.8213711397405(10)$ and $\dot{\nu} = -0.585907(4)$) are significantly more precise than those in earlier publications. The fractional change in the spindown rate obtained for this pulsar (B0523+11), in current analysis, was calculated using the spindown rates published by Siegman et al. (1993) and Hobbs et al. (2004), respectively.

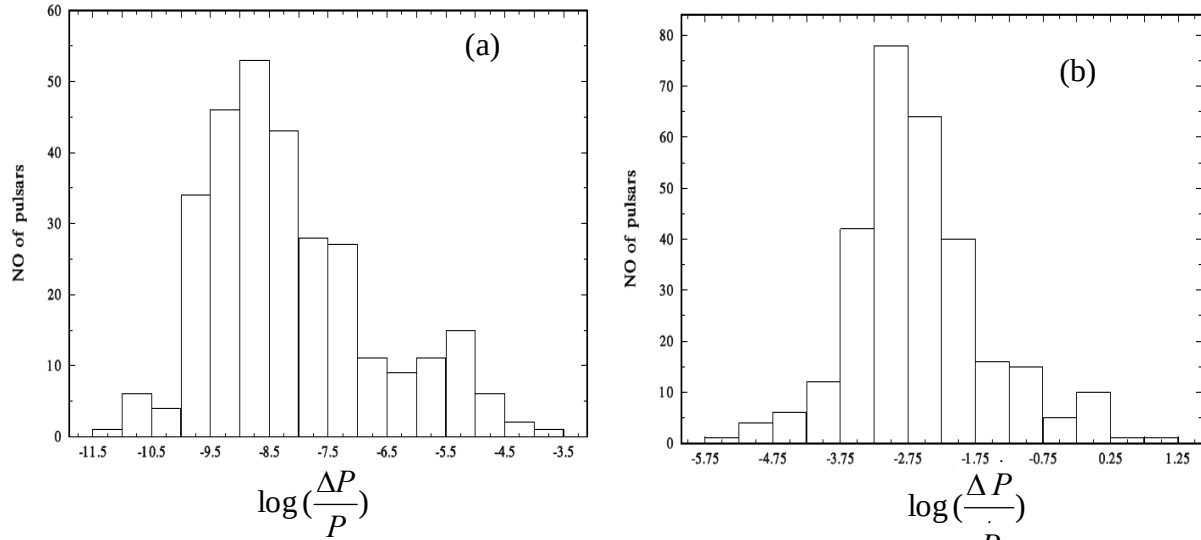


Figure 3.2 the distribution of the logarithm (a) fractional change in period and (b) fractional change in period derivative

Figure 3.2(a) is a histogram showing the distribution of the fractional change in period on a logarithmic scale. From the plot it can be seen that the modal value of the fractional change in the period is 1.5×10^{-8} while the mean and median are 1.15×10^{-8} and 1.46×10^{-8} , respectively. The maximum value and minimum values of the fractional change in period are 1.79×10^{-3} and 1×10^{-11} respectively. The distribution is therefore skewed to the right since the modal value is less than the mean value. Figure 3.2(b) is the distribution of the fractional change in the period derivative. As can be seen from the graph, the mode of the distribution is 1×10^{-3} and the mean and median are 1.58×10^{-2} and 1.70×10^{-2} , respectively. The maximum and minimum values of the fractional change in the period derivative are 0.99 and 1.28×10^{-5} , respectively. The distribution is skewed to the right since the modal value is less than the mean.

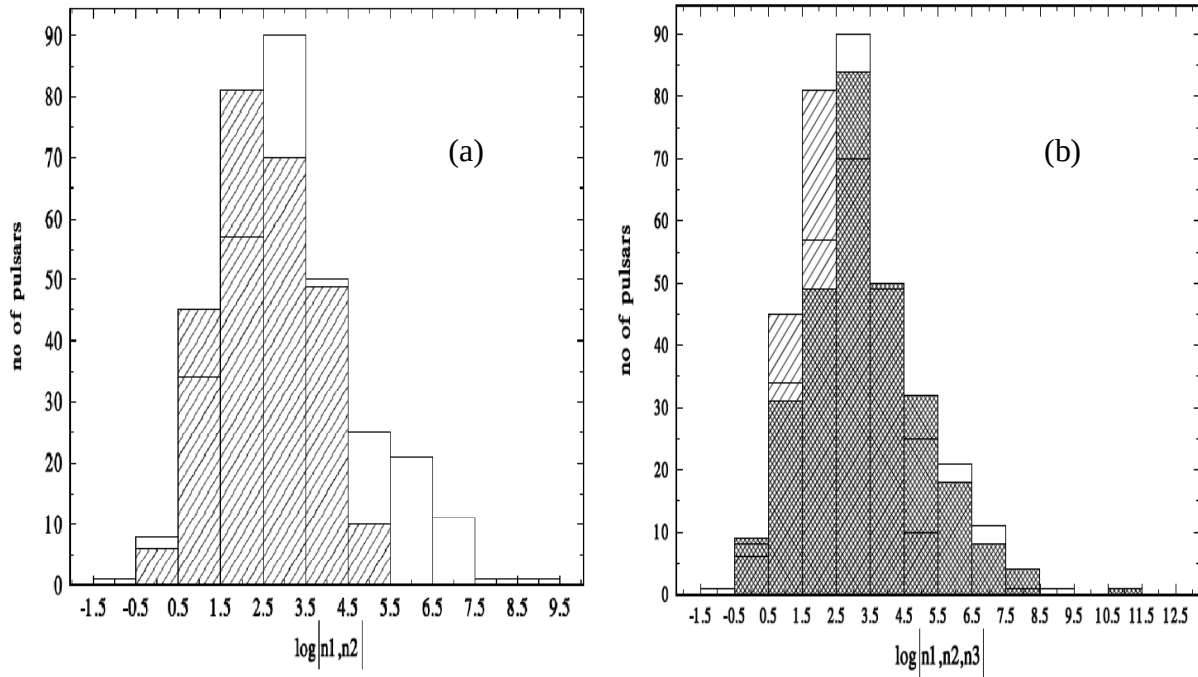


Figure 3.3. Histograms showing the distribution of the logarithm of the absolute values (a) n_1 and n_2 on the same axis with the empty bars representing n_1 while the crossed bars represents n_2 and (b) n_1 , n_2 and n_3 on the same axis with the empty bars representing the distribution of n_1 , crossed bars represents n_2 while the double crossed bars represents n_3 .

Figure 3.3(a) is the distribution of n_1, n_2 on the same axis. It has bimodal values of 1×10^3 and 1×10^2 , respectively and the mean value is found to be 1.22×10^3 . The median, maximum and minimum values of the braking indices are 1.02×10^3 , 1.63×10^8 and 0.95, respectively. Since the mean value is greater than the modes, it is skewed to the left. Figure 3.3(b) is a distribution of n_1, n_2 , and n_3 on the same axis. The mode, mean and median of the distribution are 1.00×10^3 , 1.20×10^3 and 1.08×10^3 , respectively. The maximum and minimum values of the distribution are 1.46×10^{11} and 0.37, respectively. The distribution is skewed to the left, since the mean value is greater than the mode.

3.6 Correlation Studies

Table 3.1; A table of correlation coefficients of some of the parameters used in this study.

parameters	$\langle P \rangle$	$\langle \dot{P} \rangle$	ΔP	$\Delta \dot{P}$	$\langle n_1 \rangle$	$\langle n_2 \rangle$	$\langle n_3 \rangle$
$\langle P \rangle$							
$\langle \dot{P} \rangle$			0.31				
ΔP	-0.06			0.55			
$\Delta \dot{P}$	0.05	0.31					
$\langle n_1 \rangle$	0.28	-0.74				0.70	0.94
$\langle n_2 \rangle$	0.13	-0.73					0.72
$\langle n_3 \rangle$	0.31	-0.79					
$\langle \dot{P} \rangle$			-0.31	-0.27	0.77	0.72	0.82
$\langle \Delta P \rangle$			0.28	0.33	-0.60	-0.63	-0.64

The Figures below (Fig. 3.2 ÷ 3.5) are the regression plots for the 293 pulsars in our data sample whose observed fluctuations in period (ΔP) are deemed significant (i.e exceeds $\epsilon_{\Delta P}$). Also in order to avoid cluster at points close to the origin, the millisecond pulsars (already known to be stable) were extracted from the sample using their surface magnetic field B_{surf} ($10^8 - 10^{10}$ G) as a guide. The total number of pulsars in this class was found to be 27. In order not to mask the observable trend in the plotted parameters, the pulsar (B1842-04) with exceptionally high fluctuation value (0.3245 seconds) was also not included. Finally owing to these reductions, the total number of pulsars that featured in these plots is 265.

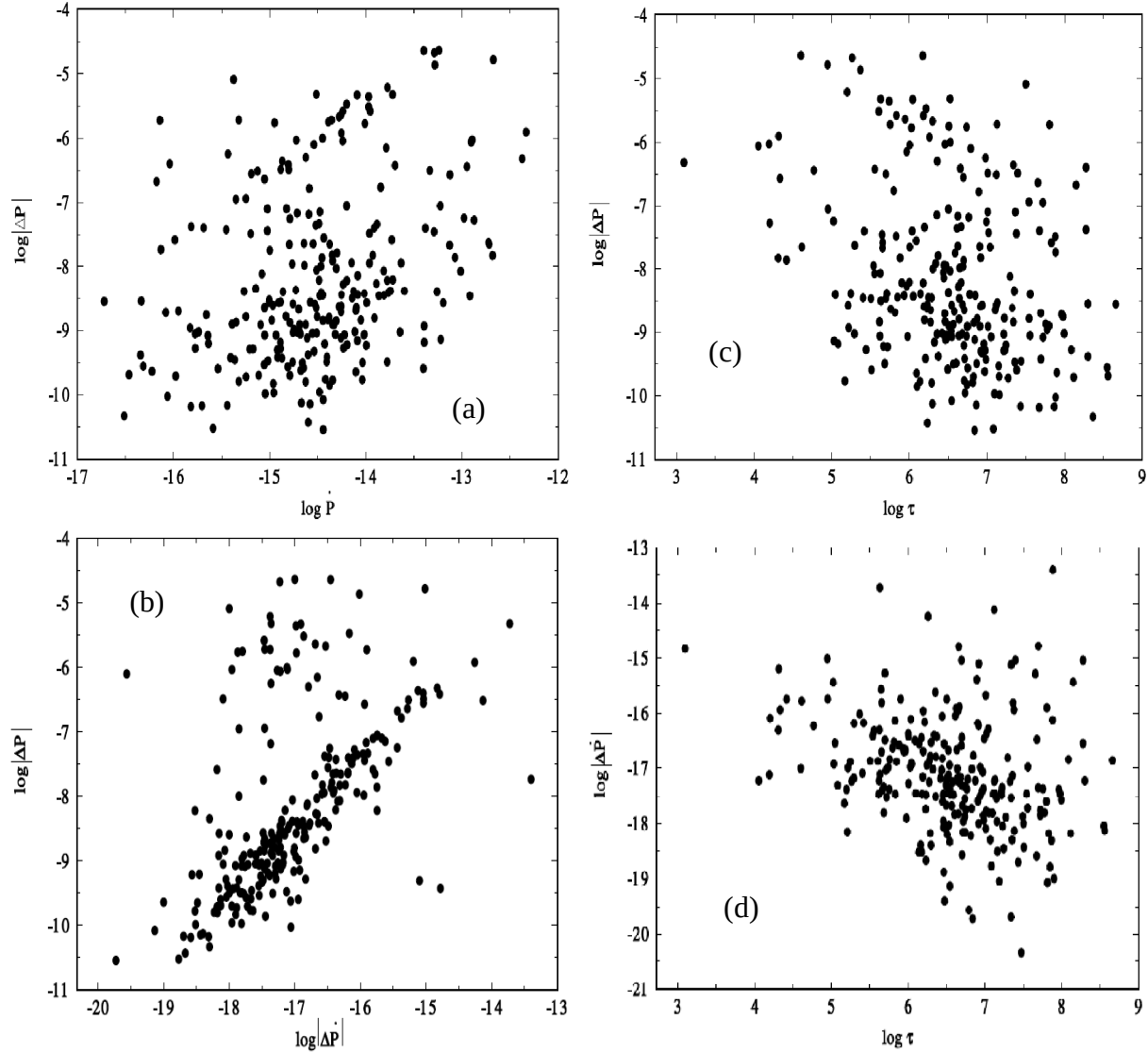


Figure 3.4 : Scatter plots showing the relationships between the observed fluctuations in rotation periods (ΔP) and spindown rate ($\Delta \dot{P}$) and the spindown parameters of the 265 pulsar in our sample on logarithmic scale; (a) change in period (ΔP) against period derivative ($\dot{P}$) (b) change in period (ΔP) against change in period derivative ($\Delta \dot{P}$) (c) change in period (ΔP) against characteristic age (τ) (d) change in period derivative $\Delta \dot{P}$ against characteristic age (τ)

Figure 3.4(a) is a graph of ΔP against $\dot{P}$ on a log-log scale. From the plot it is evident that the change in period does not depend on the period derivative and the correlation coefficient of 0.31 is therefore weak and does not show any trend. Linear regression analysis yield: $\log \Delta P = (0.50 \pm 0.09) \log \dot{P} + (0.71 \pm 1.41)$. The plot of ΔP against $\Delta \dot{P}$ on a log-log scale is shown in Figure 3.4 (b). It is obvious from the plot that ΔP increases with increasing $\Delta \dot{P}$ for the 265

pulsars in the sample. Linear regression analysis yields: $\log \phi \Lambda = (0.69 \pm 0.06) \log \phi \Lambda^{\frac{1}{2}} + (3.69 \pm 1.12)$ with a moderate correlation coefficient of 0.55. Figure 3.4 (c) is a plot of ΔP against τ on a log-log scale. Regression analysis yields: $\log \Delta P = -(0.44 \pm 0.09) \log \tau - (5.22 \pm 0.58)$ with a weak negative correlation coefficient of -0.30. Figure 3.4(d) is a plot of $\Delta \dot{P}$ against τ on a log-log scale. Regression analysis yields: $\log \Delta \dot{P} = -(0.31 \pm 0.07) \log \tau - (15.04 \pm 0.46)$ with a weak negative correlation coefficient of -0.27.

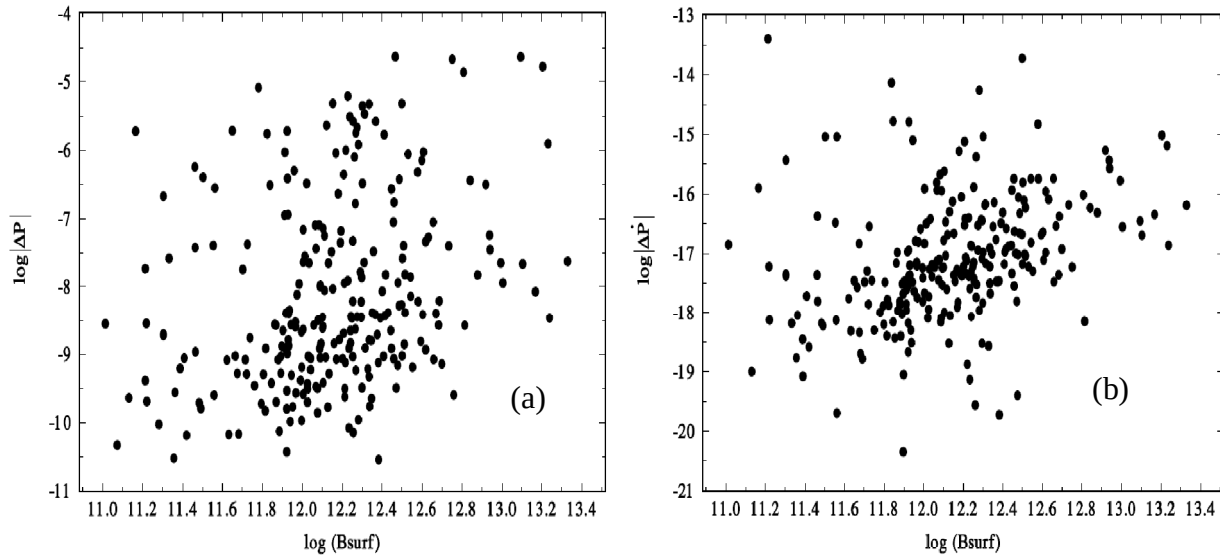


Figure 3.5 : Scatter plots showing the relationships between the observed fluctuations in rotation periods (ΔP) and spindown rate ($\Delta \dot{P}$) and the spindown parameters of the 265 pulsar in our sample on a logarithmic scale; (a) change in period (ΔP) against surface magnetic field and (b) change in period derivative ($\Delta \dot{P}$) against surface magnetic field (B_{surf}).

Figure 3.5 (a) is a plot of ΔP against B_{surf} on a log-log scale. A linear regression analysis yields: $\log \Delta P = (0.88 \pm 0.19) \log B_{surf} - (18.79 \pm 2.32)$ with a weak correlation coefficient of 0.28. Figure 3.5 (b) is a plot of $\Delta \dot{P}$ against B_{surf} on a log-log scale. Linear regression analysis yields: $\log \Delta \dot{P} = (0.84 \pm 0.15) \log B_{surf} - (27 \pm 1.82)$ with a weak correlation coefficient of 0.33.

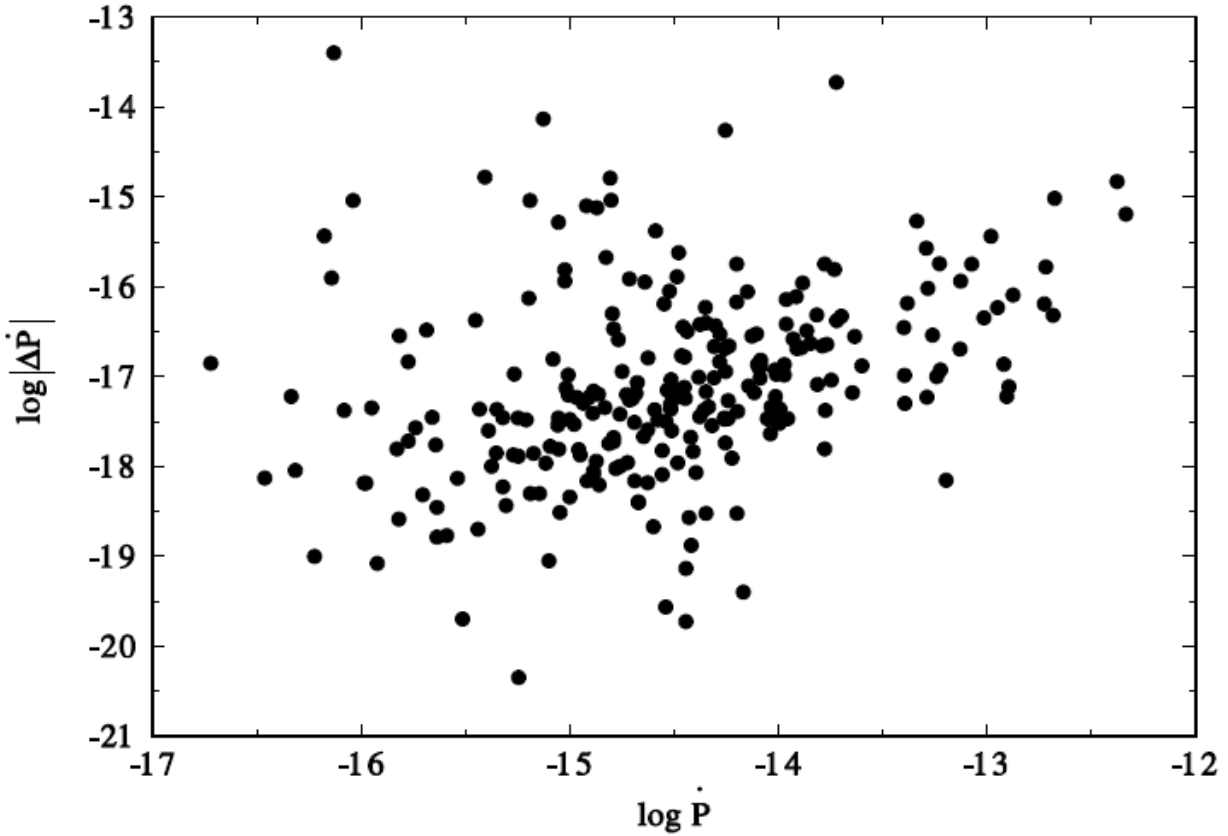


Figure 3.6 : A scatter plot of the change in the spindown rate ($\Delta Ṗ$) against the spindown rate $Ṗ$ for 265 pulsars on a logarithmic scale.

Figure 3.6 is a scatter plot of $\Delta Ṗ$ against $Ṗ$ on a log-log scale. From the graph it is obvious that the change in pulsar spindown rate does not depend on the magnitude of the spindown rate. This is also evident in the weak positive correlation coefficient of 0.31. Linear regression analysis yields: $\log \Delta Ṗ = (0.41 \pm 0.07) \log Ṗ - (11.00 \pm 1.12)$.

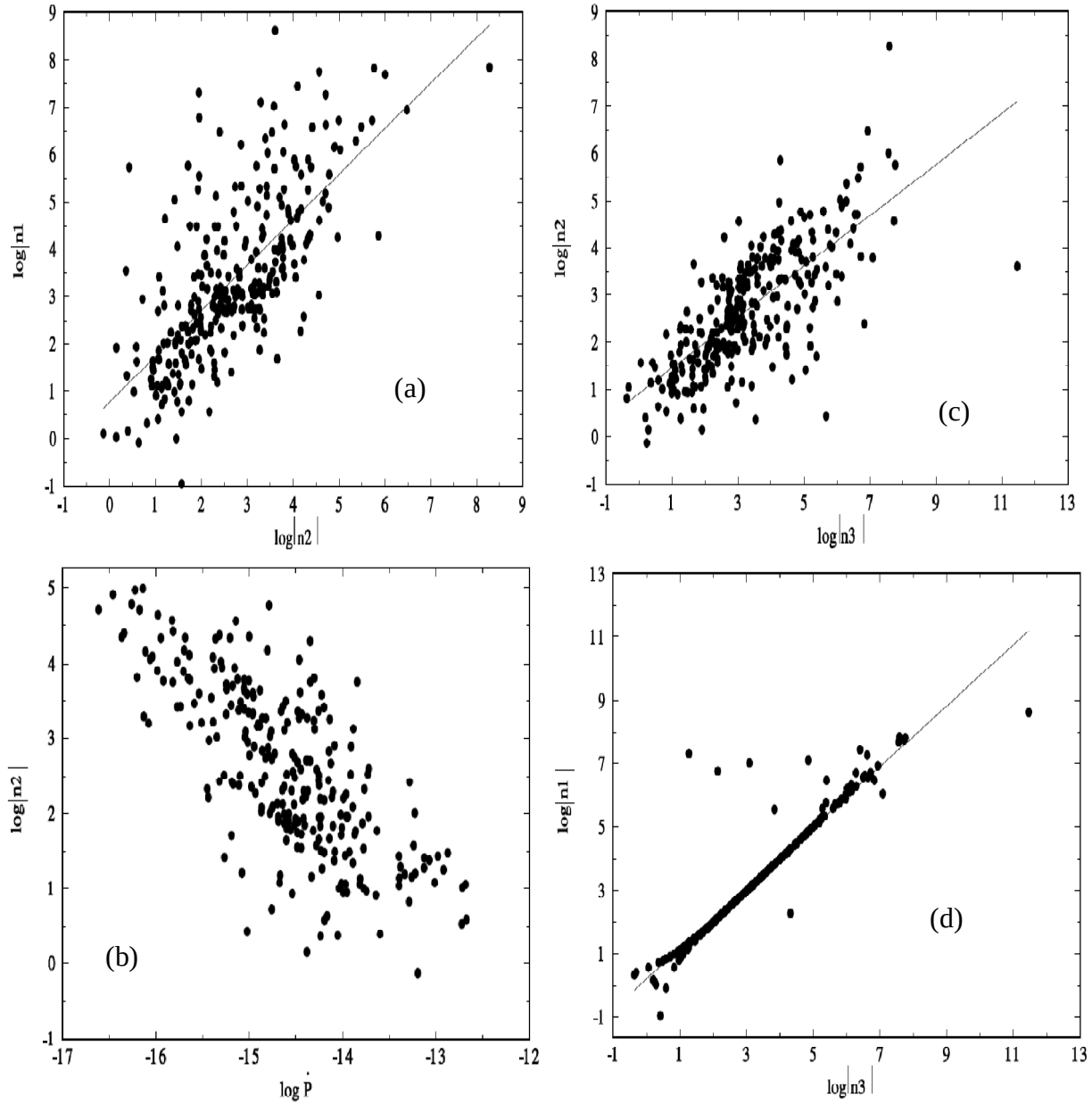


Figure 3.7 : Scatter plots showing the relationship between the braking indices obtained in three different methods and pulsar spindown parameters for the 265 pulsars in our sample; (a) n_2 against n_1 (b) n_2 against period derivative $\dot{P}$ (c) n_2 against n_3 and (d) n_1 against n_3 .

Figure 3.7 (a) is a graph of n_2 against n_1 on a log-log scale. It is obvious from the plot that n_2 increases with increasing n_1 for the 265 pulsars in the sample. Regression analysis yields: $\log n_2 = (0.96 \pm 0.05) \log n_1 + (0.77 \pm 0.17)$ with a strong correlation coefficient of 0.70. Figure 3.7 (b) is a plot of n_2 against $\dot{P}$ on a log-log scale. It is obvious from the graph that n_2 has an

inverse relationship with P . Regression analysis yields: $\log n_2 = -1.04 \pm 0.06 \log P - (12.57 \pm 0.88)$ with a strong correlation coefficient of 0.73. Figure 3.7 (c) is a plot of n_2 against P on a log-log scale. It is obvious from the graph that n_2 increases with increasing P values for the whole pulsars in the sample. Regression analysis yields: $\log n_2 = 0.53 \pm 0.03 \log P + (0.91 \pm 0.11)$ with a strong correlation coefficient of 0.72. Figure 3.7 (d) is a plot of n_1 against n_3 on a log-log scale. It could be seen from the plot that n_1 increases with increasing n_3 values for the 265 pulsars in the sample. A linear regression analysis yields: $\log n_1 = (0.96 \pm 0.02) \log n_3 + (0.20 \pm 0.07)$ with a very strong correlation coefficient of 0.94.

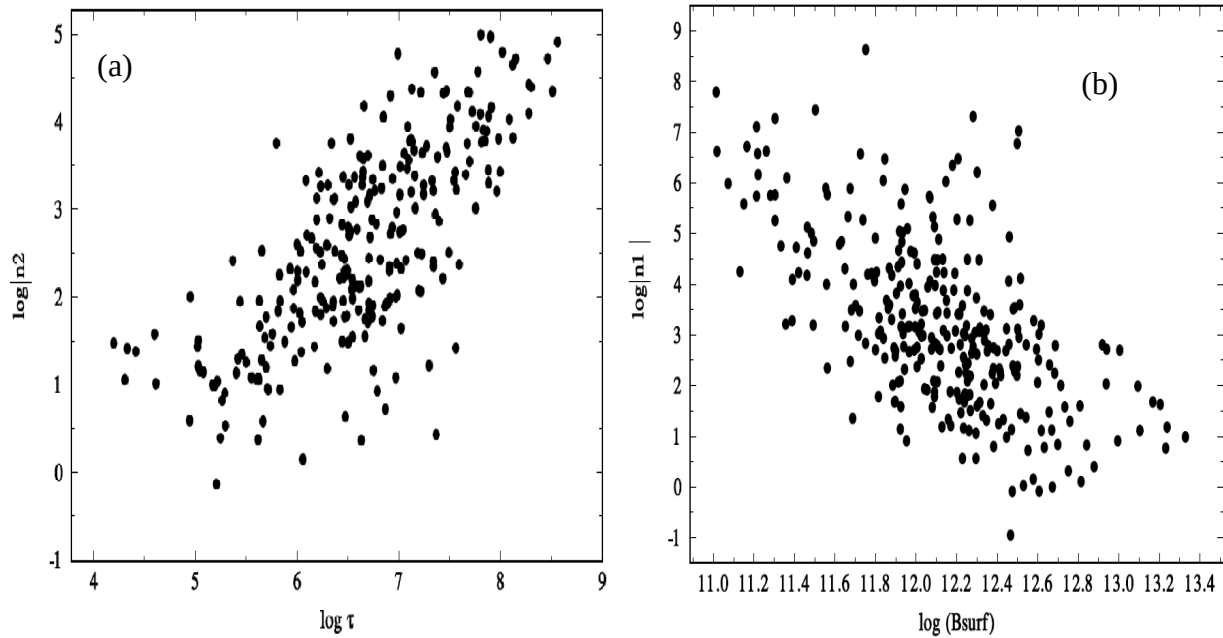


Figure 3.8 : Scatter plots showing the relationship between the braking indices obtained in three different methods and pulsar spindown parameters for the 265 pulsars in our sample; (a) braking index n_2 against pulsar age τ (b) braking index n_1 against surface magnetic field (B_{surf})

Figure 3.8 (a) is a plot of n_2 against τ on a log-log scale. From the plot it is obvious that n_2 increases with increasing τ for the entire pulsars in the sample. Linear regression analysis yields: $\log n_2 = (0.94 \pm 0.05) \log \tau - (3.70 \pm 0.37)$ with a strong correlation coefficient of 0.72. Figure 3.8 (b) is a plot of n_1 against B_{surf} on a log-log scale. It is obvious from the plot that n_1

increases with decreasing $\dot{P}$ for the 265 pulsars in the sample. A linear regression analysis yields: $\log \dot{P} = - (2.36 \pm 0.18) \log \dot{P} + (31.89 \pm 2.20)$ with a moderate - negative correlation coefficient of - 0.60.

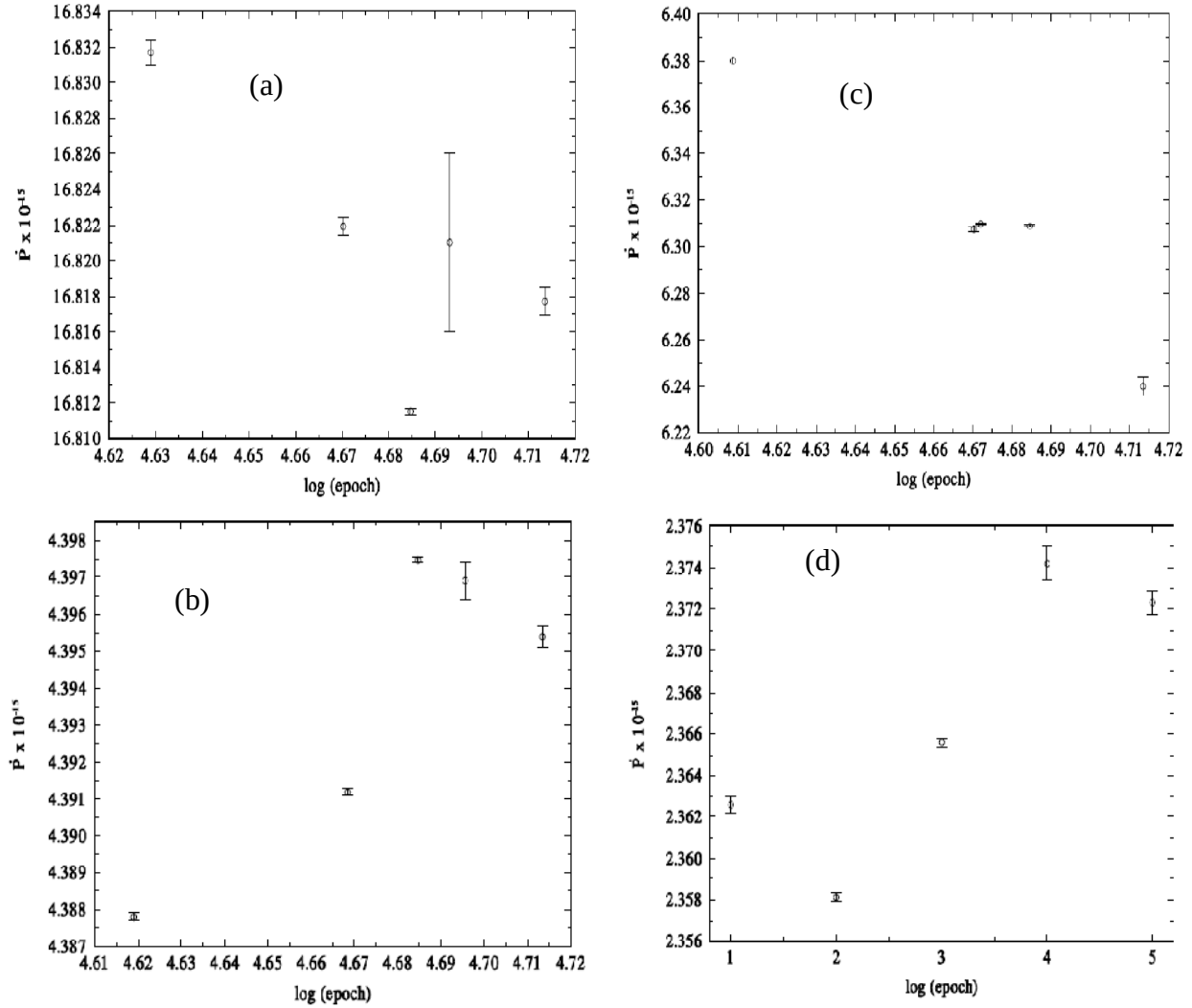


Figure 3.9 plots of the first period derivative ($\dot{P}$) against epoch for four different pulsars PSR (a) B0740 – 28, (b) B0355 + 54, (c) B1706 – 16 and (d) B0455 + 55 respectively.

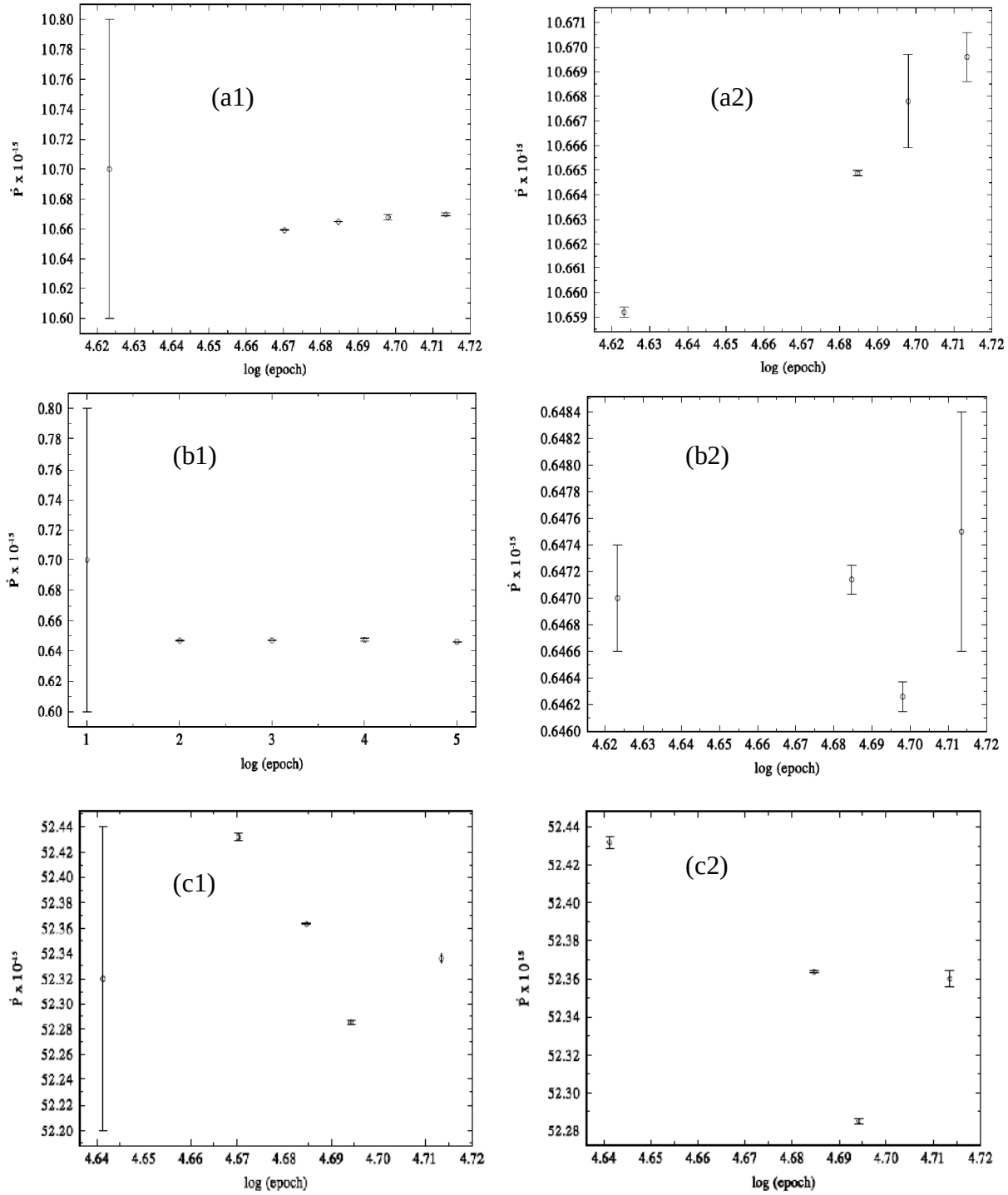


Figure 3.10 plots of the first period derivative ($\dot{P}$) against epoch for three different pulsars PSR (a1 & a2) B1742 – 30, (b1 & b2) B1718 – 32 and (c1 & c2) B1822 – 09 respectively. Each alphabet (e.g a, b or c) refers to one particular pulsar while the numbers 1&2 indicated before and after removal of the high error point with long error bars as indicated in the graphs.

Figure 3.9 and 3.10 shows the graph of the first period derivative, $\dot{P}$, against the epoch of measurement, for the seven pulsars in our data sample observed in five different epochs. Figure 3.9 (a), (b) and (c) shows the relationship between the period derivative, $\dot{P}$, and the epoch of measurement for the first four pulsars namely; PRSs B0740+28, B0355+54, B1706+16 & B0450+55, devoid of abnormal error points in the measured period derivatives for all the epochs. Figure 3.9 (a) shows a weak negative correlation with a correlation coefficient value of $r = -0.32$. Figure 3.9 (b) shows a moderate correlation with a positive correlation coefficient value of $r = 0.58$. Figure 3.9 (c) shows a weak negative correlation with a correlation coefficient value of $r = -0.38$. Figure 3.9 (d) shows a very strong positive correlation with a correlation coefficient value of $r = 0.97$.

On the other hand, Figure 3.10 shows the plots for three of these pulsars namely; PSRs B1742+30, B1718+32 and B1822+09, which have very high error (Uncertainty) value in the period derivative in at least one of the epochs, thereby masking the otherwise observable trend in these graphs. Figure 3.10 ((a1) and (a2)), ((b1) and (b2)) & ((c1) and (c2)) shows the relationship between the period derivative, $\dot{P}$, and the epoch of measurement before and after removal of the abnormally high error points, for PSRs B1742 - 30, B1718 + 32 and B1822 + 09 respectively. The effect of the removal of these abnormal error points could be seen in the values of the correlation coefficients (r) which for figures 3.10 ((a1) and (a2)), ((b1) and (b2)) & ((c1) and (c2)) are found to be (($r_1 = 0.12$) and ($r_2 = 0.98$)), (($r_1 = -0.12$) and ($r_2 = 0.06$)) & (($r_1 = -0.57$) and ($r_2 = -0.69$)), respectively. While Figure 3.9 (a1) showed very weak negative correlation, Figure 3.10 (a2) shows a very strong negative correlation. Despite the change from negative to positive correlation coefficient, Figure 3.10 ((b1) and (b2)) shows a very weak correlation. However Figure 3.10 (c1), moved from moderate to strong (Figure. 3.10 (c2)) negative correlation. The possible cause of this abnormally high error points could be the shortness of the data span in the timing of these pulsars. Therefore enough time should always be allowed for the signal strength to build up to reasonable extent in order to minimize these uncertainties.

CHAPTER FOUR

DISCUSSIONS AND CONCLUSION

4.1 Discussion of Results

We compared period and period derivative measurements of later epochs with the ones observed earlier and obtained changes in period and period derivatives. The change in period has both negative and positive value with about 116 pulsars being negative and the remaining 117 having positive values. The absolute value of change in period $|\Delta P|$ ranges between $10^{-10} < |\Delta P| < 10^{-9}$. However, one of the pulsars PSR B1842-04 has an exceptionally high value of change in period with $|\Delta P| = 3.25 \times 10^{-9}$. The change in period derivative, irrespective of sign is in the range $10^{-22} \leq \Delta \dot{P} \leq 10^{-21}$. We observed different sign combinations in varied number of pulsars for the fractional changes in period and spindown rate $(\frac{\Delta P}{P}, \frac{\Delta \dot{P}}{\dot{P}})$ as follows; 38 pulsars showed $(+, +)$, 32 pulsars showed $(-, -)$, 148 pulsars showed $(+, -)$, and 97 pulsars showed $(-, +)$. Significant changes in period and period derivative were detected in 293 and 178 pulsars, respectively. In our data sample 22 and 137 pulsars have their changes in period and spindown rate below the measurement error and so were considered non-significant. Also within our data sample, 104 pulsars are within the glitch amplitude of $\frac{\Delta P}{P} = 10^{-8} - 10^{-6}$ as proposed by Wang et al. (2001). The majority of the pulsars with no detectable change in period and period derivatives are suspected to be millisecond pulsars because of their low surface magnetic field, relatively small rotational periods and very high spindown rates. Figure 3.4(b) is a scatter plot of change in period against change in period derivative with interesting correlation as can be seen in table 3.1. This is in agreement with Wang et al. (2001), and Zou et al. (2006), who also found a correlation between ΔP and $\Delta \dot{P}$. It is interesting because it shows a strong tendency for ΔP and $\Delta \dot{P}$ to have the same sign and to be correlated in amplitude. For random period noise, it would not produce such a correlated changes in P and $\dot{P}$. The fact that changes in P and $\dot{P}$ are proportional, strongly suggests that long-term systematic changes in pulsar periods and their derivatives are dominated by pulsar glitches (Lyne, 1996; Johnson & Galloway, 1999). Espinoza

et al. (2011) presented a data base containing 315 glitches in 102 pulsars of which 55 of these pulsars are contained in our data sample. Also in the glitch table by Espinoza et al. (2011) and Jodrel Bank catalogue² containing 472 glitches in 165 pulsars, 64 of these pulsars are contained in our data sample.

The absolute change in period $|\Delta P|$ and period derivatives $\dot{P}$ both showed a negative correlation with the characteristic age τ . This is as expected since the older pulsars tend to be more stable than the younger pulsars. On the other hand the absolute change in period $|\Delta P|$ and period derivatives $\dot{P}$ show positive correlation with the surface magnetic field (B_{surf}). This is also an expected result since as the magnetic field goes higher tending to that of magnetars the period of rotation also becomes longer and so the change in period derivatives for magnetars is relatively large. Unlike the absolute change in period $|\Delta P|$ versus period P which is poorly correlated, the absolute change in period derivative $\Delta \dot{P}$ shows a good correlation with the period derivative $\dot{P}$. The absolute change in period derivative $\Delta \dot{P}$ also showed a very weak correlation ($r = 0.05$) with period P .

Assuming minimal or no rotational irregularities, the period derivative of a spinning pulsar is supposed to increase with time (epoch), in accordance with the widely accepted standard model: the vacuum dipole model (e.g Goldreich and Julian, 1969). In this scenario, the observed trends in Figures 3.9 (d) and 3.10 (a2) are in good agreement with expectation (strong positive correlation). However, various forms of irregularities leads to significant deviations from this simple spindown model, and this is most evident in Figures 3.10 (b1) and (b2) and 3.9 (a) and (c) which could be as a result of glitches or timing noise. For instance, PSRs B0355+54, B0740-28 and B1822-09 have been involved in 21, 36 and 21 glitches respectively (Espinoza et al., 2011). Baykal et al. (1999) observed pure random walk (timing noise) in the pulse frequency of PSR B1706-16. Zou et al. 2004 reported an unusual glitch event in PSR B1822-09; characterised by a temporary decrease in the slow down rate. This event resulted in a permanent increase in frequency with fractional size $\frac{\Delta \nu}{\nu} \sim 31.2(2) \times 10^{-9}$ and little effect however still remained in the

² <http://www.jb.man.ac.uk/pulsar/glitches.html>

slow $\dot{\nu}$ down rate. This same pulsar PSR B1822-09 is also well known for its rare properties of interpulse, mode changing, drifting sub-pulse and microstructure in the pulse emission (Fowler, Wright & Morris, 1981; Gil et al., 1994). All these observed irregularities account for the deviant behavior of this pulsars from the theory predicted simple slow down model.

The three methods of measuring braking indices (n_1 , n_2 , and n_3) yielded both negative and positive values, ranging from -7.3×10^8 to $+2.9 \times 10^{11}$. For the measured values of the braking indices (n_1 , n_2 , and n_3), the following sign distribution were observed: 187, 155 and 140 pulsars showed positive value of n_1 , n_2 and n_3 while 128, 133 and 174 pulsars showed negative values of n_1 , n_2 and n_3 , respectively. The braking indices obtained from differentiation (Manchester and Taylor 1977) labeled n_2 plotted against those obtained by integration of the spin-down law (Johnston and Galloway 1999) labeled n_1 showed a strong correlation of 0.7 as visible in the regression plot of Figure 3.7(a). This is in agreement with the observation by Johnston and Galloway (1999) that the new method (integration) conveys no advantage over the previous method (differentiation) for pulsars with regular glitches and/or large timing noise. However the only advantage of n_1 over n_2 is that for pulsars with ages $\sim 10^5$ yrs where both the timing noise and glitch frequency are relatively low, it is not necessary to obtain a phase connected solution across 25 yr or more in order to obtain a braking index. Rather, local fits over 1- 2 yr at large intervals may be sufficient to yield the braking index to an error of ~ 0.1 (Johnston & Galloway, 1999). Also the regression plot of Fig.3.7 (c) and (d) shows that the third braking index n_3 obtained using the period second derivative is not very different from n_2 and n_1 as evident in the strong correlation coefficients of 0.72 and 0.94, respectively.

4.2 Conclusion

Comparison with earlier measurements has shown that long-term period fluctuations are probably dominated by recovery from (mostly unseen) glitches and timing noise. The relationship observed between changes in period & the period derivative (pulsar spin-down rate) is as expected since as the pulsar spin is being braked by any of the spin-down mechanisms, it should equally affect the period of spin. However since this fluctuation/spindown is not detectable in some pulsars or is very small (especially millisecond pulsars), it makes pulsars suitable for high precision measurements over time span of months and years despite timing noise. The spindown of most pulsars is also dominated by a quasi periodic phenomena and this is probably telling us something about the interior of the neutron star.

Despite the fact that the most widely accepted model predicts a braking index of $n = 3$ (i.e a constant value for braking index) it is obvious that most of the observed braking indices deviate appreciably from the expected value of 3, some having low negative values and some having high positive values, pointing to the fact that the existing pulsar spin-down models may have to be revisited. The high correlation between the braking indices and some of the pulsar parameters like age and surface magnetic field as shown in Figures 3.8 (a) and (b) respectively is another example of the discrepancy between model prediction and observation since n is supposed to be constant independent of any variable as predicted by the pure magnetic dipole model.

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