

THE PULSE FREQUENCY NOISE OF MAGNETARS AND PERSISTENT
ACCRETION POWERED PULSARS

A THESIS SUBMITTED TO
THE GRADUATE SCHOOL OF NATURAL AND APPLIED SCIENCES
OF
MIDDLE EAST TECHNICAL UNIVERSITY

BY

DANJELA SERIM

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
PHYSICS

FEBRUARY 2021

ABSTRACT

THE PULSE FREQUENCY NOISE OF MAGNETARS AND PERSISTENT ACCRETION POWERED PULSARS

Serim, Danjela

Ph.D., Department of Physics

Supervisor: Prof. Dr. Altan Baykal

February 2021, 154 pages

In this thesis, the pulse frequency fluctuations of magnetars and six selected persistent accreting powered pulsars (PAPPs) are presented. Using the data from *RXTE*, *XMM-Newton*, *Chandra*, *Swift* and *FERMI* observatories, the timing noise behavior of individual sources on various timescales are examined, depending on the data sampling rate of input frequency measurements. The timing noise amplitudes are analyzed via two separate methods, namely Δ_8 and *r.m.s* methods. The timing noise characteristics of both magnetars and PAPPs are investigated together with a sample of 366 radio pulsars obtained from literature. The relations of timing noise behavior with the physical quantities are examined with an aim of exploring the origin of the noise process in different source samples. The focus of the study is to understand the timing noise behavior of magnetars and accretion powered pulsars. The results show that there is a connection between timing noise behavior of magnetars and radio pulsars, in fact they form a continuum. Furthermore, the timing noise in magnetars do not exhibit footprints of accretion. On the other hand, PAPPs display a rather distinctive timing behavior that is induced by inhomogeneities in the accretion flow. Hence, the results of this study suggests that timing noise of magnetars originate from the

extreme magnetic field strengths and outburst activities.

Keywords: magnetar, timing noise, X-ray timing, accreting pulsars



ÖZ

MAGNETARLARIN VE ISRARLI KÜTLE AKTARIMI YAPAN ATARCARLARIN ATIM FREKANSI GÜRÜLTÜLERİ

Serim, Danjela

Doktora, Fizik Bölümü

Tez Yöneticisi: Prof. Dr. Altan Baykal

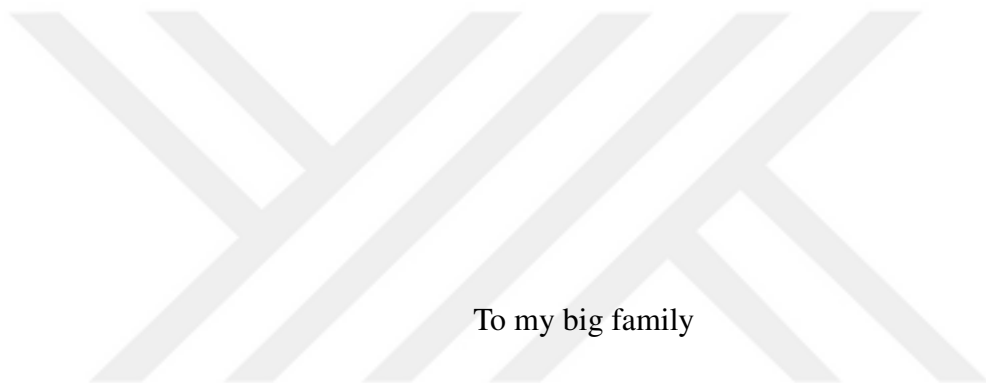
Şubat 2021 , 154 sayfa

Bu tezde, magnetarların ve altı kütle aktarımı yapan atarcanın atım frekanslarındaki dalgalanmalar sunulmuştur. RXTE, XMM-Newton, Chandra, Swift ve Fermi gözlemlerinin verilerinden faydalanılarak, her kaynağın zamanlama gürültüsü davranış, veri yoğunluğuna bağlı olarak, farklı zaman ölçeklerinde incelenmiştir. Zamanlama gürültüsü genlikleri Δ_8 ve *r.m.s* adı verilen iki farklı metot ile analiz edilmiştir. Magnetarlar ve kütle aktarımı yapan atarcaların zamanlama gürültüsü karakteristikleri, literatürde çalışılmış olan 366 radyo atarca ile beraber ele alınmıştır. Zamanlama gürültülerinin oluşum süreçlerinin kökeninin açığa çıkarılabilmesi için, farklı atarca gruplarının zamanlama gürültüsü genliklerinin fiziksel parametreler ile olan ilişkileri araştırılmıştır. Bu araştırmada magnetarların ve kütle aktarımı yapan atarcaların zamanlama gürültüsü davranışlarına odaklanılmıştır. Elde edilen sonuçlar, magnetarların ve radyo atarcalarının gürültü davranışları arasında bir bağıntı olduğunu göstermektedir. Ek olarak, magnetarların zamanlama gürültülerinde kütle aktarım izine rastlanmamıştır. Kütle aktarımı yapan atarcaların, aktarımdaki maddenin inhomojenliğine bağlı olarak daha farklı bir zamanlama gürültüsü davranışı sergilediği gözlemlenmiş-

tir. Bu nedenle, araştırmanın sonuçları magnetarların zamanlama gürültülerinin sıradışı manyetik alan şiddetlerinden ve X-ışını parlaması süreçlerinden kaynaklandığını göstermektedir.

Anahtar Kelimeler: magnetarlar, X-ışını zamanlama, zamanlama gürültüsü, kütle aktarımı yapan atarcılar





To my big family

ACKNOWLEDGMENTS

I own my deepest gratitude to my supervisor Prof. Dr. Altan Baykal for his concern, guidance and encouragement throughout my PhD studies. It was a real honor to have a scientist as exceptional as Prof. Altan as a mentor. He was very patient and extremely understanding with all the obstacles I had, especially with the off-times I needed to take care of my baby. I also would like to thank Prof. Dr. Sıtkı Çağdaş İnam for his guidance, encouragement and his positive attitude during all these years. His discussions and comments on the physical aspects of this study really helped to improve this thesis.

I am especially indebted to my beloved husband and colleague M. Miraç Serim. He has been a solid and invaluable help throughout my PhD studies period and more. It was his patience, guidance and priceless help to all my scientific and emotional problems that made it possible for me to come to the end of this journey. I am so thankful he is part of my life.

Throughout my life, the love and support of my family has been my solid motivation to carry on. I would like to express my deepest thanks to my son, Mikail, for the endless joy he spread around and make me the happiest mother. Every problem would fade away the moment I am around him. I am forever indebted to my family in Albania, they provided unconditional love and support through my whole life. Being away from them is the hardest thing in my life. I also want to express my deepest gratitude to my mother-in-law and father-in-law for being a real family to me and helping me on everything whenever I needed; especially with Mikail.

I acknowledge the scholarships from The Scientific and Technological Research Council of Turkey (TÜBİTAK), through the research projects MFAG 114F345 and MFAG 118F037.

DECLARATION

Hereby, I declare that this thesis describes my own original work, except where explicitly stated. No part of this work has previously been submitted, either in the same or different form, to this or any other University in connection with a higher degree or qualification.

The results of the timing noise analysis of magnetars in this thesis are published in the journal named *Monthly Notices of Royal Astronomical Society* in 2019 under the title **Pulse Frequency Fluctuations of Magnetars** (doi: 10.1093/mnras/sty3213) in collaboration with the authors: Serim, M. M., Sahiner S., Inam S. C. and Baykal A. Whereas the timing noise results of Persistent Accretion Powered Pulsars studied in this work are not yet published in a peer reviewed journal. In these works, I performed timing and noise strength analysis of the examined sources.



TABLE OF CONTENTS

ABSTRACT	v
ÖZ	vii
ACKNOWLEDGMENTS	x
DECLARATION	xi
TABLE OF CONTENTS	xiii
LIST OF TABLES	xvii
LIST OF FIGURES	xviii
LIST OF ABBREVIATIONS	xxi

CHAPTERS

1 INTRODUCTION	1
1.1 PULSARS	2
1.1.1 Mass and Radii of Pulsars	3
1.1.2 Rotation of Pulsars	5
1.1.3 Magnetic Field of Pulsars	5
1.1.4 Magnetic Dipole Braking Model	6
1.1.5 Interior of Pulsars	10
1.1.6 Exterior of Pulsars	11

1.2	PULSARS IN BINARY SYSTEMS	11
1.2.1	LMXBs	12
1.2.2	HMXBs	14
1.2.3	Accretion	16
1.2.3.1	Roche Lobe	16
1.2.3.2	Disk Accretion	18
1.2.3.3	Wind Accretion	19
2	MAGNETARS	21
2.1	A BRIEF HISTORICAL OVERVIEW	21
2.2	GENERAL PROPERTIES OF MAGNETARS	22
2.3	TIMING PROPERTIES	24
2.3.1	Glitches	25
2.4	RADIATIVE BEHAVIORS	27
2.4.1	Giant Flares	27
2.4.2	Outbursts	29
2.4.3	Bursts	30
2.5	X-RAY SPECTRAL PROPERTIES	31
2.6	EMISSION IN OTHER ENERGY BANDS	32
2.7	MAGNETAR MODEL	33
2.7.1	Magnetar Formation	34
2.7.2	Internal Dynamics	35
2.7.3	Crust Instabilities	36
2.7.4	Magnetar Emission	37

2.8	FALLBACK DISK MODEL	39
3	DATA ANALYSIS	43
3.1	DATA REDUCTION	43
3.2	PULSAR TIMING ANALYSIS	46
3.3	NOISE STRENGTH ANALYSIS	49
4	TIMING ANALYSIS RESULTS	55
4.1	MAGNETARS	55
4.1.1	CXOU J010043.1-721134	57
4.1.2	4U 0142+61	58
4.1.3	SGR 0418+5729	59
4.1.4	SGR 0501+4516	61
4.1.5	SGR 0526-66	62
4.1.6	1E 1048.1-5937	63
4.1.7	1E 1547.0-5408	65
4.1.8	PSR J1622-4950	66
4.1.9	SGR 1627-41	67
4.1.10	CXO J164710.2-455216	67
4.1.11	1RXS J170849.0-400910	69
4.1.12	CXOU J171405.7-381031	70
4.1.13	SGR J1745-2900	71
4.1.14	SGR 1806-20	72
4.1.15	XTE J1810-197	74
4.1.16	Swift J1818.0-1607	75

4.1.17	1E 1841-045	76
4.1.18	3XMM J185246.6+003317	77
4.1.19	SGR 1900+14	78
4.1.20	SGR 1935+2154	80
4.1.21	1E 2259+586	81
4.2	ACCRETING PULSARS	83
4.2.1	Vela X-1	84
4.2.2	Cen X-3	85
4.2.3	Her X-1	87
4.2.4	GX 301-2	89
4.2.5	4U 1538-52	91
4.2.6	4U 1626-67	92
5	NOISE CORRELATIONS AND DISCUSSION	95
5.1	MAGNETIC FIELD vs. TIMING NOISE	99
5.2	SPIN DOWN RATE vs. TIMING NOISE	100
5.3	LUMINOSITY vs. TIMING NOISE	102
5.4	CHARACTERISTIC AGE vs. TIMING NOISE	104
6	SUMMARY AND CONCLUSION	107
	REFERENCES	115
	APPENDICES	
	A WEB LINKS FOR PRINTED VERSION	151
	CURRICULUM VITAE	153

LIST OF TABLES

TABLES

Table 4.1	List of magnetars and their properties.	56
Table 4.2	List of persistent X-ray pulsars and their properties.	83
Table 5.1	The Pulse Frequency Noise Measurements of Magnetars	96
Table 5.2	Pulse Frequency Noise Measurements of PAPs	98
Table A.1	List of links for hyper-linked web addresses	151

LIST OF FIGURES

FIGURES

Figure 1.1	A Schematic View of Pulsar's Beamed Emission	2
Figure 1.2	The Mass Distribution of Neutron Stars	4
Figure 1.3	Interior of a NS	10
Figure 1.4	Light Cylinder of a Pulsar	12
Figure 1.5	Schematic of a LMXB system	13
Figure 1.6	Schematic of a HMXB system	14
Figure 1.7	Schematic of a BeXRB system	15
Figure 1.8	3-D Roche Potential Representation	17
Figure 1.9	Transition Region Between Disk and Magnetosphere	18
Figure 1.10	Accretion via Stellar Wind	20
Figure 2.1	Distribution of Magnetars in Milky Way Galaxy	23
Figure 2.2	Glitches of Neutron Stars Population	26
Figure 2.3	The Giant Flare of SGR 1806-20	28
Figure 2.4	Outbursts of Magnetars	29
Figure 2.5	An Example Spectrum of a Magnetar	31
Figure 2.6	The $\alpha\omega$ -effect	35

Figure 2.7	Bursts of Magnetars	38
Figure 4.1	Frequency History of CXOU J010043.1-721134	57
Figure 4.2	Frequency History and PDS of 4U 0142+61	58
Figure 4.3	Frequency History and PDS of SGR 0418+5729	60
Figure 4.4	Frequency History and PDS of SGR 0501+4516	61
Figure 4.5	Frequency History of SGR 0526-66	63
Figure 4.6	PDS of 1E 1048.1-5937	64
Figure 4.7	PDS of 1E 1547.0-5408	66
Figure 4.8	Frequency History and PDS of CXO J164710.2-455216	68
Figure 4.9	Frequency History and PDS of 1RXS J170849.0-400910	69
Figure 4.10	Frequency History of CXOU J171405.7-381031	70
Figure 4.11	Frequency History and PDS of SGR J1745-2900	72
Figure 4.12	Frequency History and PDS of SGR 1806-20	73
Figure 4.13	Frequency History and PDS of XTE J1810-197	75
Figure 4.14	Frequency History and PDS of 1E 1841-045	76
Figure 4.15	Frequency History of 3XMM J185246.6-003317	78
Figure 4.16	Frequency History and PDS of SGR 1900+14	79
Figure 4.17	Frequency History and PDS of SGR 1935+2154	80
Figure 4.18	Frequency History and PDS of 1E 2259+586	82
Figure 4.19	Frequency History and PDS of Vela X-1	84
Figure 4.20	Frequency History and PDS of Cen X-3	86
Figure 4.21	Frequency History and PDS of Her X-1	88

Figure 4.22	Frequency History and PDS of GX 301-2	90
Figure 4.23	Frequency History and PDS of 4U 1538-52	91
Figure 4.24	Frequency History and PDS of 4U 1626-67	93
Figure 5.1	Magnetic Field vs. Timing Noise	99
Figure 5.2	Spin-Down vs. Timing Noise	101
Figure 5.4	Luminosity vs. Timing Noise	103
Figure 5.5	Characteristic Age vs. Timing Noise	105
Figure 6.1	(F_{rmax}) vs. Magnetic Field	109
Figure 6.2	Timing Noise vs. Total Outburst Energy	113

LIST OF ABBREVIATIONS

AGN	Active Galactic Nuclei
PAPPs	Persistent Accretion Powered Pulsars
NS	Neutron Star
EoS	Equation of State
LMXB	Low-Mass X-ray binaries
HMXB	High-Mass X-ray binaries
RLO	Roche Lobe Overflow
SgHMXB	Super-giant High-Mass X-ray binary
BeXRB	Be X-ray Binary
SGR	Soft Gamma-Ray Repeater
AXP	Anomalous X-ray Pulsar
GRB	Gamma Ray Burst
MHD	Magnetohydrodynamic
FBD	Fallback Disk
IR/O	Infrared/Optical
HEASARC	High Energy Astrophysics Science Archive Research Center
NASA	National Aeronautics and Space Administration
RXTE	Rossi X-ray Timing Explorer
PCA	Proportional Counter Array
PCU	Proportional Counter Unit
XMM	X-ray Multi-Mirror
CCD	Charge Coupled Device
HRC	High Resolution Camera
ACIS	Advanced CCD Image Spectrometer

HETGS	High Energy Transmission Grating Spectrometer
LETGS	Low Energy Transmission Grating Spectrometer
BAT	Burst Alert Telescope
XRT	X-ray Telescope
UVOT	Ultraviolet/Optical Telescope
DFT	Discrete Fourier Transform
FFT	Fast Fourier Transform
TOA	Time of Arrival
SMC	Small Magellanic Cloud
HST	Hubble Space Telescope
NSSTC	National Space Science and Technology Center
GBM	Gamma-ray Burst Monitor
BATSE	Burst And Transient Source Experiment
PDS	Power Density Spectrum

CHAPTER 1

INTRODUCTION

X-ray astronomy is the study of the astronomical objects that emit energy in the X-ray part of the electromagnetic spectrum. The energy range that correspond to this part of the spectrum is from ~ 100 eV to ~ 50 keV, and such highly energized photons are created in the presence of extremely high temperatures that can reach hundreds of millions of degrees. This highly heated matter can be formed only in the presence of extreme physical conditions, such as very high magnetic fields, or gravitational fields, or explosive events. The study of the X-ray events is very new compared to other branches of observational astrophysics. The first extraterrestrial X-ray source (apart from the Sun) was detected in 1962 and it was coming from a source called Sco X-1; the brightest X-ray object in the sky. Following that, in 1970, NASA launched the Uhuru satellite which is the first mission dedicated entirely to X-ray events, and it was a huge success. This remarkable mission was followed by many others, and nowadays scientists have a much deeper understanding of the universe and its X-ray nature. As we know it, universe is very vast and numerous different objects reside within it. Many of those object emit (also) in X-ray energy range, such as galaxies, Active Galactic Nuclei (AGN), galaxy clusters, stars, black holes, (super)novas, supernova remnants, compact objects, even some of the planets in our solar system. The content of this dissertation is entirely focused on neutron stars and their properties in the X-ray emission.

The theoretical prediction of neutron stars was made by Baade & Zwicky [1] soon after the discovery of the neutron particle itself in 1932. They proposed that a core-collapse supernova could result in the formation of a star which is composed almost entirely of neutrons, and thus called them neutron stars. Following their work, there

were several other publications which predicted the properties of neutrons stars. However, the observational support for the existence of such compact objects was made possible only when J. Bell detected the first radio pulsations of Crab pulsar in 1967 [2]. This thesis is dedicated to understand the fluctuations in the rotational motion of the pulsating neutron stars (i.e. pulsars), referred to as timing noise. Focusing on the magnetars and Persistent Accretion Powered Pulsars (PAPPs), origin of timing noise in different types of neutron stars is examined. Following sections introduce the particular characteristics of the selected categories of neutron stars.

1.1 PULSARS

After consuming its life in the main sequence, a star enters in an unstable phase where gravity overpasses the pressure of nuclear reactions and, as a result, it collapses. The collapsing of the core releases a huge amount of energy and makes the outer layer of the star explode in a process we call supernova. When a supernova occurs, the outer part of the star is blown off in the interstellar medium, while the inner core becomes either, a neutron star or a black hole, depending on the mass of its progenitor. Even though the limit is uncertain, it is generally accepted that when a star with initial mass of $10\text{-}25M_{\odot}$ explodes in a supernova, its core becomes a neutron star [3].

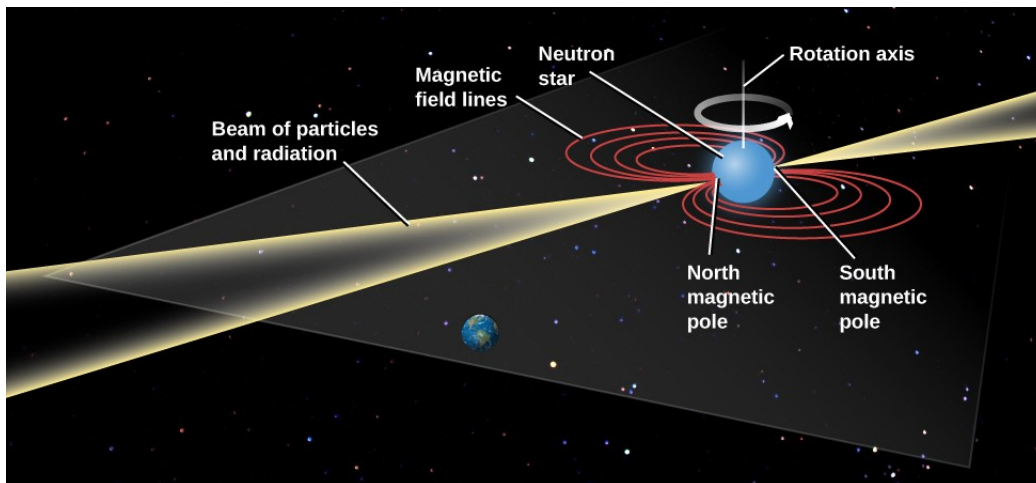


Figure 1.1: A artistic view demonstrating a pulsar's emission beaming towards the Earth, retrieved from Lumen Learning: Astronomy

In neutron stars, the neutron degeneracy pressure become important and balances this gravitational field. In general neutron stars have very high magnetic field strengths (see section 1.1.3) and they emit a radiation beam from their magnetic poles. If the radiation beam passes over the Earth, then detected emission of beams will be in the form of pulsations and that is why those type of neutron stars are called PULSARS.

1.1.1 Mass and Radii of Pulsars

About 90% of the detected pulsars are isolated [4] while the remaining 10% of pulsars are located in binaries. The quasi-precise mass measurements of neutron stars (pulsars) are mostly enabled via the radio observations of the pulsars in binary systems. In order to measure mass and/or radii and to test the equation of state (EoS) models of neutron stars (NSs), one relies entirely on binary systems. The remarkable stable and fast rotation of pulsars permit us to determine the parameters of the binary system very precisely. Neglecting the effects of general relativity, orbital motion of pulsar in a binary system can be specified in terms of the following quantities:

- P : the binary period ,
- i : inclination angle between line of sight and binary plane
- $a_p \sin i$: semi-major axis the projected to the line of sight
- e : the orbital eccentricity,
- ω : the longitude of the periastron
- T_0 : the time of periastron

At this stage, it is useful to introduce the binary function using those parameters [5]:

$$f_p = \left(\frac{2\pi}{P} \right)^2 \frac{(a_p \sin i)^3}{G} = \frac{(M_c \sin i)^3}{M_t^2} \quad (1.1)$$

Here M_c , M_p and $M_t = M_c + M_p$ are the mass of companion, mass of pulsar and the total mass, respectively. If no further information is obtained, this equation cannot provide us with the individual masses of the objects. However, if we can measure the

mass of the companion via timing or spectroscopy (if the star is a white dwarf or a main-sequence star), then making use of the ratio of the masses as:

$$q \equiv \frac{M_p}{M_c} = \frac{x_c}{x_p} \quad (1.2)$$

one can extract the individual mass of the pulsar. However, in order to build a more comprehensive neutron star picture, general relativity effects should also be considered, especially in the double NS and NS-BH binaries. Nevertheless, this study focuses on general statistics of timing noise properties of neutron stars, and hence the aforementioned calculations are beyond the scope of this study.

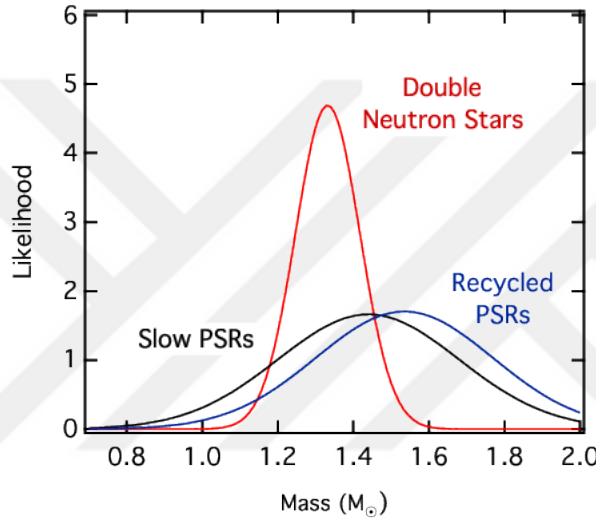


Figure 1.2: A statistical distribution of neutron star masses across different pulsar populations. Picture Credit: [6]

To date, the most massive NS ever detected is the millisecond pulsar J0740+6620 and its mass is estimated to be $2.14^{+0.10}_{-0.09} M_{\odot}$ [7], while the least massive NS ever detected is PSR J0453+1559 and its mass is estimated to be $1.174 \pm 0.002 M_{\odot}$ [8]. In general, the masses of NSs are deduced to be in the range of ~ 1.2 to $\sim 2 M_{\odot}$. The distribution of the NS masses for different types of population ([6]) is demonstrated as an example in Figure 1.2.

Unlike mass measurements, radii measurements of pulsars are not highly-precise. Many of these measurements are extracted from the mass-radius relations by using different techniques according to the properties of the system (see [5] and references

there in). In order to have an accurate radii measurement one must either (i) study a nearby isolated pulsar the distance of which is known precisely, or (ii) study a pulsar in a binary system which resides in a globular cluster the distance of which is also known [5]. The most precise radii measurements are those of an isolated pulsar which resides relatively near and its radii is measured to be 11.9 ± 0.8 km [9].

1.1.2 Rotation of Pulsars

Pulsars are very rapid rotators. The range of their rotational period spans from few milliseconds up to a few thousand seconds. Theoretically, their rapid rotation originate from the angular momentum conservation from the progenitor star. Bowers and Deeming [10] argued that if a star is considered as a spherical object with angular momentum $\vec{L} = \frac{2}{5}MR^2\vec{\omega}$ and that the angular momentum of the star is conserved during its collapse, then the newly born neutron star would have an angular frequency of

$$\vec{\omega}_{\text{NS}} = \vec{\omega} \left(\frac{R}{R_{\text{NS}}} \right)^2 \quad (1.3)$$

where M and R are the mass and radius of progenitor star respectively, and ω_{NS} and R_{NS} are the angular frequency and the radius of the neutron star. Generally, a typical slow rotating main sequence star has an angular velocity of $\sim 10^{-4}$ rad/s and a radius of $\sim 10^{10}$ cm; therefore, during the collapse, a neutron star would have an angular velocity of $\sim 10^4$ rad/s ($R_{\text{NS}} \simeq 10^6$ cm). The rapid rotation of a new-born NS is later on spin-down gradually due to magnetic braking. Moreover, the rotational evolution of such object is not only dependent in the progenitor's parameters, but also in other 'life conditions' they go through. For example, the rapid rotation of millisecond pulsars is a result of the gain of angular momentum by the accretion of matter from their companion.

1.1.3 Magnetic Field of Pulsars

There are several evidences that show that pulsars should have strong magnetic fields. Observationally, the detection of cyclotron emission, polarized light and the absorption feature in the spectra of some sources provide direct evidence of the presence

of B-field in pulsars. The origin of such fields is still an on going area of study. It may be a leftover from the progenitor (assuming that magnetic flux is conserved), or it may be a result of a dynamo process in the first few seconds after explosion, as in the case of magnetars [11].

For the priori case, assuming the B-field is primordial and conserved during the collapse, then from electromagnetic theory [12] the magnetic flux should be proportional to the radius as:

$$\frac{d\Phi}{dt} = \frac{d}{dt} \int_S \vec{B} \cdot \vec{da} = 0 \quad (1.4)$$

$$\int_S \vec{B} \cdot \vec{da} = B \int_S da = B4\pi r^2 \quad (1.5)$$

If the radius of a canonical progenitor is $\sim 10R_{\odot} \sim 10^{11}$ cm and its B-field is ~ 100 Gauss; then after the explosion (taking R_{NS} as 10^6 cm)

$$B_{\text{NS}} = B \left(\frac{R}{R_{\text{NS}}} \right)^2 \sim 10^{12} \text{G} \quad (1.6)$$

This rough calculation shows that neutron stars ought to have magnetic field strengths in the order of 10^{12} Gauss. The latter case is discussed in the Section 2.7 in order to have a more comprehensive picture on magnetars.

1.1.4 Magnetic Dipole Braking Model

After born with high magnetic field strengths, the evolution of the rotational motion of pulsars depend on the circumstantial conditions. If the pulsar is isolated (i.e. not in a binary system or accreting through a fossil disk), then the emission of the pulsar is approximated through the magnetic dipole braking model for an inclined rotator. The magnetic dipole braking model is a model that assumes pulsars are ‘rigid spheres’ that rotates in vacuum, their magnetic field is bipolar and their magnetic moment, $\vec{m}$, makes an angle α with the rotational axis [13]. This model provides a simplistic overview, yet it accounts for many observational characteristics of pulsars. In this

case, the dipole magnetic field can be written as:

$$\vec{B}(\vec{r}) = \frac{3\hat{n}(\vec{m} \cdot \hat{n}) - \vec{m}}{r^3} \quad (1.7)$$

where $r = |\vec{r}|$, $\hat{n} = \vec{r}/r$ and $\vec{m}$ being the magnetic dipole moment. At the magnetic pole $\vec{m} \parallel \hat{n}$, therefore the magnetic field (or magnetic dipole moment) can be approximated as:

$$\vec{B}_{\text{pole}} = \frac{2\vec{m}}{R^3} \quad (1.8)$$

or

$$\vec{m} = \frac{\vec{B}_{\text{pole}} R^3}{2} \quad (1.9)$$

where $r = R$ at the surface.

The power radiated by a time-varying magnetic dipole is ([14], Equation 5.10)

$$\left(\frac{dW}{dt}\right)_{\text{md}} = -\frac{2}{3c^3} |\ddot{\vec{m}}|^2 \quad (1.10)$$

and it is called Larmor's formula. As mentioned above the dipole moment $\vec{m}$ makes an angle α with the rotation axis, and if the coordinate system is oriented in such a way that the rotational axis is in the z -direction, then the magnetic dipole moment $\vec{m}$ can be decomposed as:

$$\vec{m} = m_0 \left(\sin(\alpha) \cos(\omega t) \hat{i} + \sin(\alpha) \sin(\omega t) \hat{j} + \cos(\alpha) \hat{k} \right) \quad (1.11)$$

with $m_0 = B_{\text{pole}} R^3 / 2$. The second time derivative of magnetic dipole moment yields $|\ddot{\vec{m}}|^2 = m_0^2 \omega^4 \sin^2(\alpha)$, therefore the time-varying magnetic dipole radiation power becomes:

$$\left(\frac{dW}{dt}\right)_{\text{md}} = -\frac{B_{\text{pole}} R^6}{6c^3} \omega^4 \sin^2(\alpha). \quad (1.12)$$

On the other hand, since the pulsar is spinning, it posses a kinetic energy of

$$E_{\text{rot}} = \frac{1}{2} I \omega^2 \quad (1.13)$$

with I being the moment of inertia of the NS which is assumed to be in the form of a ‘sphere’. Then the kinetic energy loss over the time (the derivative of equation 1.13) will be:

$$\frac{dE_{\text{rot}}}{dt} = I \omega \dot{\omega} \quad (1.14)$$

Another assumption of magnetic dipole model is that the energy emitted due to time varying magnetic dipole results in rotational energy loss and that is why this model is referred to as ‘magnetic braking’. Therefore, if the time-varying magnetic dipole energy $(dW/dt)_{\text{md}}$ is equated with the time-varying rotational energy $(dE/dt)_{\text{rot}}$ and rearranged for $\dot{\omega}$, then slow down rate of the pulsars rotation can be deduced as:

$$\dot{\omega} = - \frac{B^2 R^6 \omega^3 \sin^2 \alpha}{6c^3 I} \quad (1.15)$$

It can easily be noticed that all the parameters in the equation yield positive values, hence the $(-)$ sign make the equation be always negative. This means that according to this model, isolated pulsars should in principle spin-down, as it is deduced from the observational data. Converting the equation 1.15 into observable quantities P and $\dot{P}$ by using $\omega = 2\pi/P$, then the dipolar magnetic field strength of a pulsar can be approximated as:

$$B_p \sin(\alpha) = \sqrt{\frac{3c^3 I}{2\pi^2 R^6} P \dot{P}} \quad (1.16)$$

Substituting the constants and using the canonical values of the neutron star (i.e. $I \approx 10^{45} \text{ g/cm}^2$, $R \approx 10^6 \text{ cm}$) and taking $\sin(\alpha) \approx 1$, the magnetic field strength can actually be estimated as:

$$B \approx 3.2 \times 10^{19} \text{ G} \sqrt{P \dot{P}} \quad (1.17)$$

This formula is widely used for inferring the magnetic field of pulsars. For instance, the pulsar SGR 0418+5729 has a spin period of ~ 9.078 and a spin derivative of $\sim 4 \times 10^{-15}$ s/s has an inferred magnetic field strength of $\sim 6.1 \times 10^{12}$ G [15].

Astronomical objects with the highest magnetic field known to date are magnetars. Magnetars are basically pulsars with field values that can reach up to $< 10^{16}$ G (See chapter 2). There is a limit, however, when the magnetic energy would be so high it would disrupt the star itself [16]. Following Lai [16] one can equate the magnetic energy of the star with its gravitational binding energy as

$$\frac{4\pi R^3}{3} \left(\frac{B^2}{8\pi} \right) \lesssim \frac{GM^2}{R} \quad (1.18)$$

and rearranging for B:

$$B \lesssim \sqrt{6G} \frac{M}{R^2} \quad (1.19)$$

For a canonical pulsar of mass $\sim 1.4M_\odot$ and a radius of $\sim 10^6$ cm the magnetic field strength values of the order of $B \lesssim 10^{18}$ G would tear the star apart. Besides, above a certain value of magnetic field known as the quantum critical value, the simplistic magnetic dipole braking model approximation turns into a more complicated physical problem (See Chapter 2 for a discussion on magnetars).

Another very important use of the $P - \dot{P}$ identity is the estimate of the inferred characteristic age of a pulsar. Assuming that the pulsar's initial period P_0 was much smaller than the observed period P and that $P - \dot{P}$ identity does not change with time, then:

$$\int_{P_0}^P P dP = \int_0^\tau P \dot{P} dt = P \dot{P} \int_0^\tau dt \quad (1.20)$$

$$\frac{P^2 - P_0^2}{2} = P \dot{P} \tau \Rightarrow \tau \cong \frac{P}{2\dot{P}} \quad (1.21)$$

Even though not exact, the inferred characteristic age formula is widely used to estimate the ages of the isolated pulsars population.

1.1.5 Interior of Pulsars

The composition of matter is usually defined by its equation of state (EoS). EoS is a description of the balance between the density and pressure of a certain mass, material or object. Despite the fact that many studies are conducted regarding EoS of NSs (see e.g. [6]), the exact composition of the neutron star's interior is still very poorly understood. Nevertheless, current models suggest that the interior of such a compact object is composed of three main parts: the atmosphere, the crust, and the core. Atmosphere is a thin layer of $\sim 10^4$ cm and mainly consists of iron nuclei (^{56}Fe) and electrons in degenerate state. Its density is of the orders of 10^6 g/cm³. Just below this outer layer is found an envelope, the purpose of which is the transfer of heat into the star's surface. Beneath the atmosphere lies the crust which is $\sim 10^5$ cm thick and has an elastic solid composed of a Coulomb lattice.

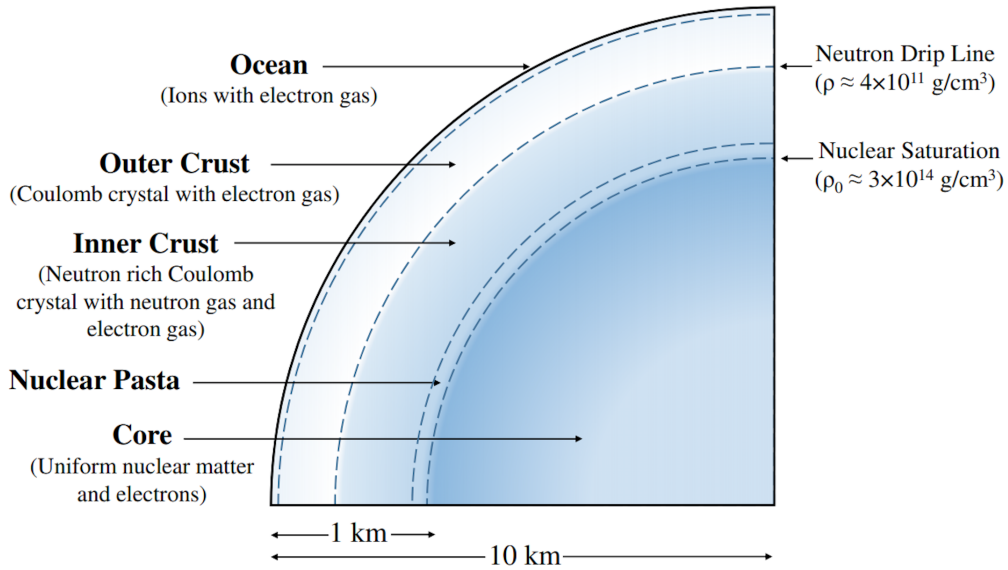


Figure 1.3: Side view of a neutron star's interior. Picture credit: [17].

As the density increases, atomic nuclei are almost uniformly distributed within a background of electrons. In this region, the inverse *beta-decay* ($p + e^- \rightarrow n + \nu_e$) *reactions* convert nuclei into neutron-rich nuclei that can have up to hundreds of nucleons. Neutron star's crust is divided into two: outer and inner crust. The super-high density of the inner crust reaches the limits of co-called *neutron-drip density*, a state

where nuclei particles leak out of its core. Hence, matter in this region consists mostly of super-fluid neutrons and neutron-rich nuclei. The region below the crust there is referred as the core. Its radius is supposed to be $\sim 10^6$ cm and it carries more than 95 % of the stars total mass. Core of neutron stars is also divided into outer and inner core. The density of matter of the outer part can be as high as 6×10^{14} g/cm³. The composition of the inner core region is a mystery, however, it is believed to be composed of quark matter and exotic particle such as hyperons, condensed kaons or/and pions.

1.1.6 Exterior of Pulsars

The magnetosphere of pulsars is filled with plasma [18] which plays a very important role in the observable characteristics of those objects, especially when they exhibit transient events. Even though pulsars have an enormous gravitational field, Shapiro & Teukolsky [20] showed that the electric force of pulsars is $\sim 10^9$ times effective than their gravitational force at the region close to the NS. This remarkable result shows that charged particles are dictated by electromagnetic forces (rather than gravitational field), therefore, they reside in magnetosphere. Being in magnetosphere, charged particles co-rotate with the lines of the magnetic field and hence with the star itself. However, since the velocity of the particles would not exceed that of the speed of light for the outer magnetic field lines, there is a limit of how far they co-rotate [12]

$$r_{lc} = \frac{c}{\Omega} = \frac{cP}{2\pi} \simeq 5 \times 10^8 \left(\frac{P}{1 \text{ s}} \right) \text{ cm} . \quad (1.22)$$

This limit is called the '*Light cylinder*'. Only the magnetic field lines that are within the light cylinder radius will be closed, while those field lines that are beyond this radius are open (see Figure 1.4).

1.2 PULSARS IN BINARY SYSTEMS

A significant portion of neutron stars reside in binary systems. They have a wide range of pulsations starting from milliseconds up to 10^4 s. Accretion is the only sustainable source of energy of such systems by providing external angular momentum

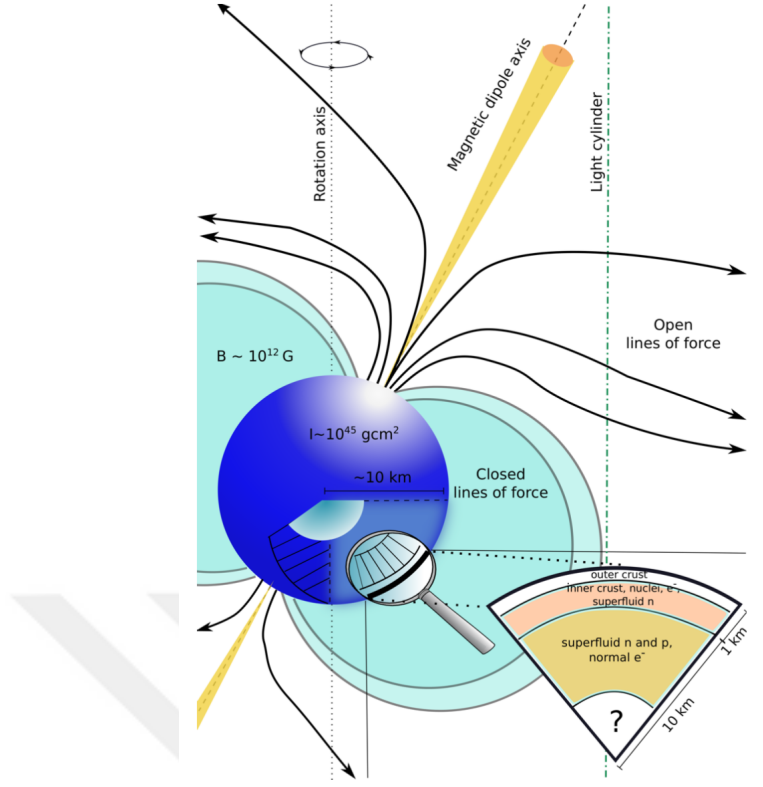


Figure 1.4: A schematic picture of a pulsar's interior and exterior. Light cylinder is the zone where magnetic field lines are closed; beyond it the magnetic field lines are open. Picture credit:[19]

that causes pulsars to spin-up or down. Binary systems hosting a pulsar fall into two main categories: Low-Mass X-ray binaries (LMXBs) and High-Mass X-ray binaries (HMXBs). This division is deduced through the physical characteristics of the binary and they are directly related to the mass of the companion star they co-rotate with.

1.2.1 LMXBs

LMXBs are binary systems composed of a compact object and a donor star of low-mass $M \leq M_{\odot}$. This companion star may be a late type star of the main-sequence, a sub-giant¹ who has field its Roche-lobe and the material exceeding the Roche Lobe is being accreted by the compact object via the so-called Roche Lobe Overflow (RLO)

¹ the companion in the binary system can also be a white dwarf, but such compact systems are beyond the scope of this study

1.2.3.1. The spin period of LMXBs can be as short as few milliseconds and their orbital period ranges from a few minutes to several days.

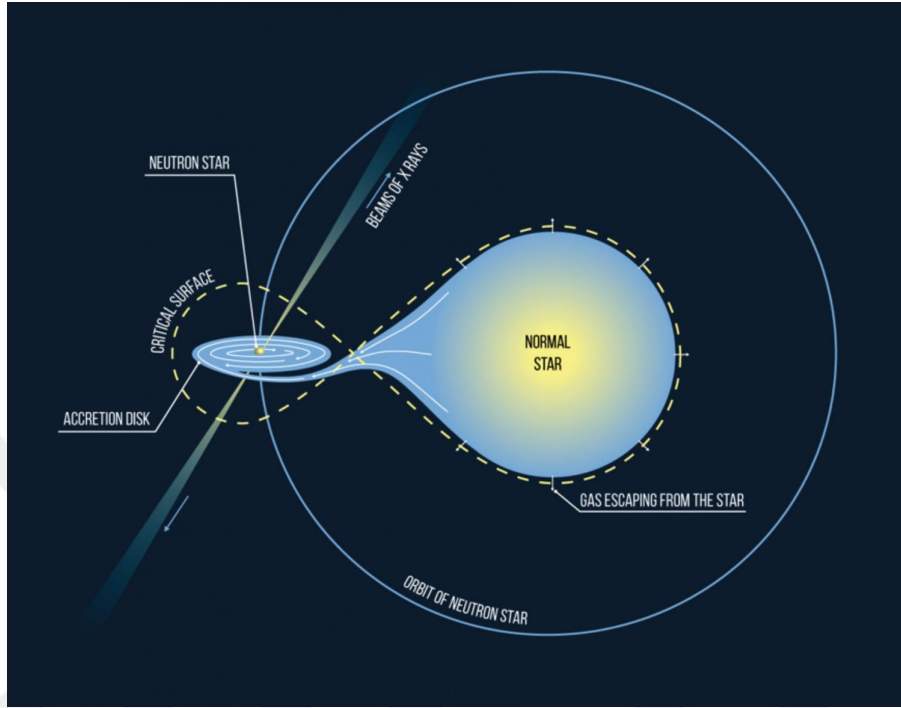


Figure 1.5: An artistic picture of a LMXB system retrieved from The Moscow Institute of Physics and Technology: X-ray pulsars

LMXBs have relatively low magnetic field strengths, generally of the orders of $\sim 10^9$ G [21] and, in general, pulsars of such systems are observed to burst in soft X-ray band, presumably due to the unstable nuclear reactions in the surface of the star while burning the accumulated matter coming from the accretion [22]. This burning heats the surface and generates X-ray radiation we observe here on Earth. X-ray emission also comes from the inner part of the disk due to viscous dissipation, while the outer part of the disk emits in the optical range of the electromagnetic spectrum. The population of LMXBs is generally concentrated in the galactic bulge and in globular clusters, a characteristic distribution regarding their relative old ages ($\sim 10^{10}$ yr) [23].

1.2.2 HMXBs

As indicated by their names, HMXBs consist of an massive star ($\geq 10M_{\odot}$) (generally O or B spectral type,) and a compact object. Containing an early type massive star implies that the system is relatively young ($\sim 10^7$ yr) and they generally reside in the galactic plane (see e.g. [24] for a review of HMXBs). Companion star produces

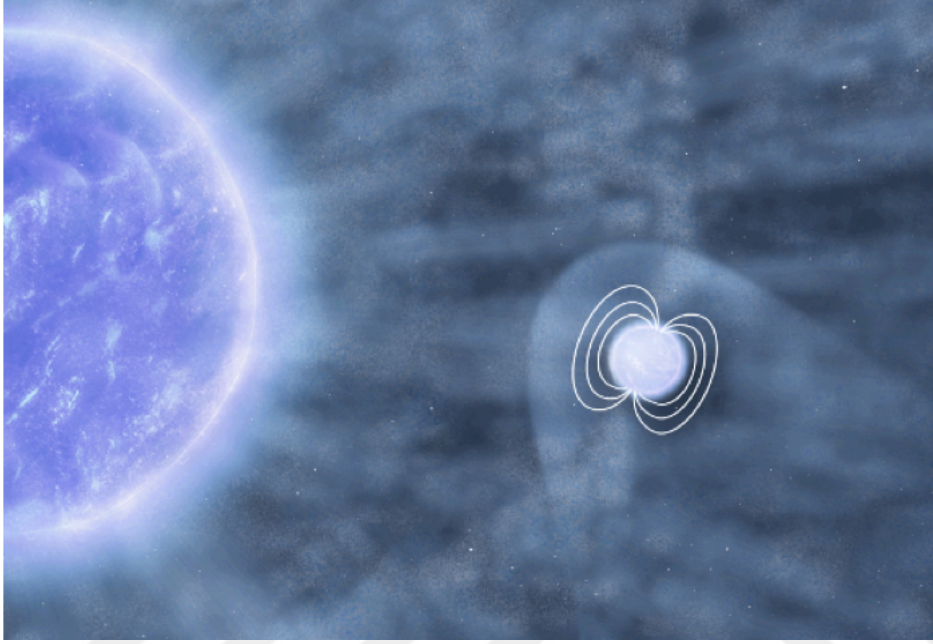


Figure 1.6: An artistic picture of a LMXB system. Picture credit: [25]

strong stellar winds which expels material at a rate of roughly $10^{-6} - 10^{-4} M_{\odot}/\text{yr}$. Some portion of the wind enters the gravitational field of the compact star and then is being accreted by it. Most of the HMXBs are known to accrete matter via the so-called stellar wind accretion process; however, depending of the environment created by the massive star, accretion via RLO is also possible [26]. HMXBs are subdivided into two classes: Super-giant High Mass X-Ray Binaries (SgHMXBs) and Be X-Ray Binaries (BeXRBs).

SgHMBs systems consists of a super-giant companion and a compact star. They can be either disk-fed or wind-fed systems. The disk-fed SgHMBs occurs when the massive star has filled its Roche Lobe and accretes material via L1 point (see e.g. [26]). The accretion of those systems are stable and they have very high accretion luminosities $\sim 10^{38}$ erg/s. Both their spin and orbital periods are short and of the

order of ~ 10 s and $\lesssim 4$, respectively [27].

On the other hand, wind-fed SgHMBs are composed of an OB type of companion star and feed the compact object via wind accretion. In those systems the accretion is not very stable because the wind is not uniformly distributed but it rather comes in forms of clumps. Wind accretion luminosity rates are of the order of $L_x \approx 10^{35} - 10^{36}$ erg/s and they are observed to have significant fluctuation in these luminosity rates because of the clumpy nature of the accreted plasma. The spin and orbital periods of wind-fed SgHMXBs are of the orders of $\sim 10^3$ s and $\lesssim 15$ d, respectively [24].

BeXRBs are another type of HMXBs which includes a non-supergiant companion star with a spectral type of Be or Oe, and a compact object. They are the most common type of HMXBs constituting 60% of their population (see [27] and references there in for a review). The companion star is very massive ($M \sim 10 - 20 M_\odot$) and

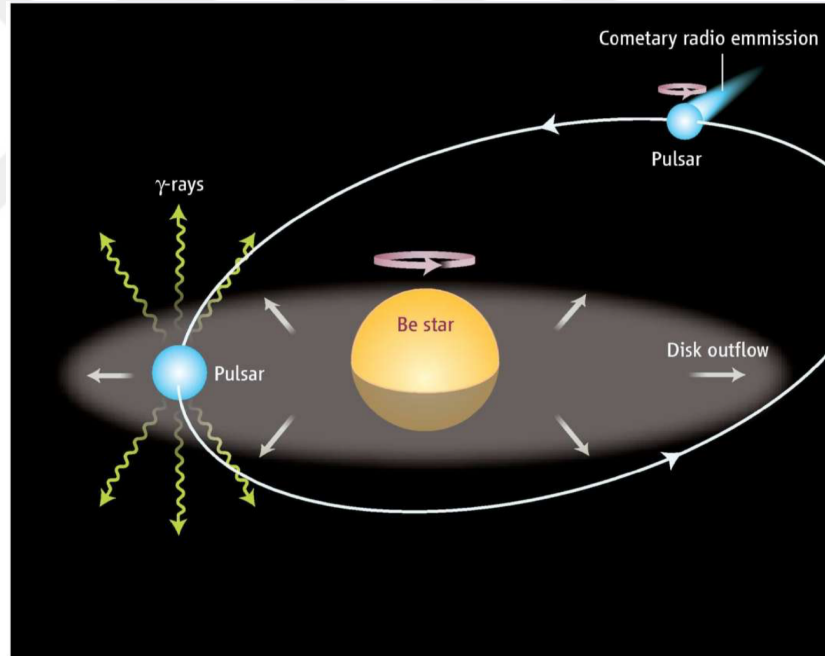


Figure 1.7: An artistic picture of a BeXRB system. Picture credit: [28]

they have a disk around them which expands as much as $\sim 20R_c$ where R_c being the radius of companion. Hence, in general BeXRB systems are transient with luminosities of $L_X = 10^{36} - 10^{37}$ erg/s. However, when the compact star has a relatively slow rotational period they tend to pulsate even when in quiescence phase [29].

1.2.3 Accretion

As mentioned above, the fundamental process which powers an X-ray binary is thought to be the accretion. Because, for reasonable mass accretion rates, the accretion onto a pulsar can lead to X-ray emission easily. For instance, for a pulsar of mass M and radius R the infalling matter of mass m carries a gravitational potential energy E_{acc} of

$$E_{\text{acc}} = \frac{GMm}{R} \quad (1.23)$$

where G stands for gravitational constant. This gravitational energy release will generate a luminosity of [30]

$$L_{\text{acc}} = \frac{GM\dot{m}}{R} \quad (1.24)$$

where $\dot{m}$ is the mass accretion rate. Pulsars usually are observed to have luminosities of $\sim 10^{37}$ erg/s, hence their accretion rate ought to be of the orders of $\sim 10^{17}$ g/s or, converted into solar mass, $\sim 10^{-9}M_{\odot} \text{ yr}^{-1}$ [31]. As indicated by the equation 1.24, luminosity is proportional to $\dot{m}$, i.e. the higher the mass accretion rate, the higher the luminosity.

1.2.3.1 Roche Lobe

Roche lobe refers to the ‘lobe’ region around a star in a binary system where the material is gravitationally bounded to it. Outside this boundary the material is no longer attached to its own star but rather it overflows to the compact object (because it has entered to the Roche lobe of it and now gravitational bound to the other) via the so-called Lagrangian (L1) point. This process is called *accretion via Roche Lobe Overflow*, and the fundamentals of it lay in the principles of equi-potential surfaces.

Describing the geometry of a lobe in a binary system is quite complicated because the shape of it resembles to a ‘tear-drop’ rather than being circular, as it would have been the case for isolated stars. To find when the mass starts to flow from one star to another one must examine the effective potential of the system and locate its Lagrangian points. Lagrangian points are called the equilibrium points in a many-body system (i.e. the points where any particle will remain at rest under the influence of gravita-

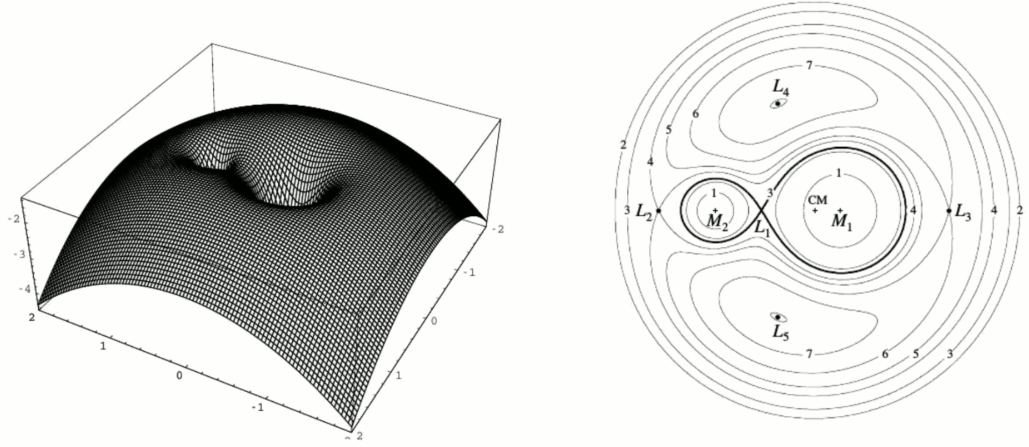


Figure 1.8: A 3-D representation of Roche Potential in a binary system and the corresponding Lagrangian Points. Picture credit: [31]

tional fields of large bodies). The equation of effective potential of a binary system includes the gravitational potential of the first and second body and its centrifugal potential.

Therefore, if the mass and the radius of the donor star is denoted as $M_1, \vec{r}_1$, the mass and the radius of the compact star as $M_2, \vec{r}_2$ and the angular velocity of the synchronized rotation as $\vec{\omega}$; then the effective potential is :

$$\Phi_{eff} = -\frac{GM_1}{|\vec{r} - \vec{r}_1|} - \frac{GM_2}{|\vec{r} - \vec{r}_2|} - \frac{|\vec{\omega} \times \vec{r}|^2}{2} \quad (1.25)$$

where $\vec{r}$ is the position of a particle moving in this system.

When the gradient of the effective potential is equated to zero (i.e. $\vec{\nabla}\Phi = 0$) the calculations gives five extrema points known as Lagrangian points, as shown in Figure 1.8.

Either due to orbital shrinkage of the system or expansion of the companion, the matter can exceed the inner Lagrangian point L1 and, eventually, the neutron star will accrete it.

1.2.3.2 Disk Accretion

The disk accretion scenario in this section is built upon the model suggested by [32] [33]. Indeed, over the decades, many other disk models are also formulated in the literature (e.g. [34], [35], [36], [37]). Nevertheless, this section draws a rough scheme and describes the fundamentals of the disk accretion scenario.

During the accretion, the magnetic field and the accreting matter will interact at a region that is called transition region (See Figure 1.9). This region referred to the zone between the unperturbed disk material and the inner edge of the disk that penetrates through the magnetosphere of the pulsar [32]. The moving plasma of the disk around the magnetic field lines of the pulsar creates currents. Those currents, in return, confine the magnetic field inside a so-called screening radius r_s and this radius can expand as much as (10 - 100) co-rotation radius, r_{co} (i.e. the radius where the disk material co-rotates with the star). Despite being screened, there are three main physical processes responsible for the magnetic field to penetrate the disk; namely, Kelvin-Helmholtz instability, turbulent diffusion and re-connection [33].

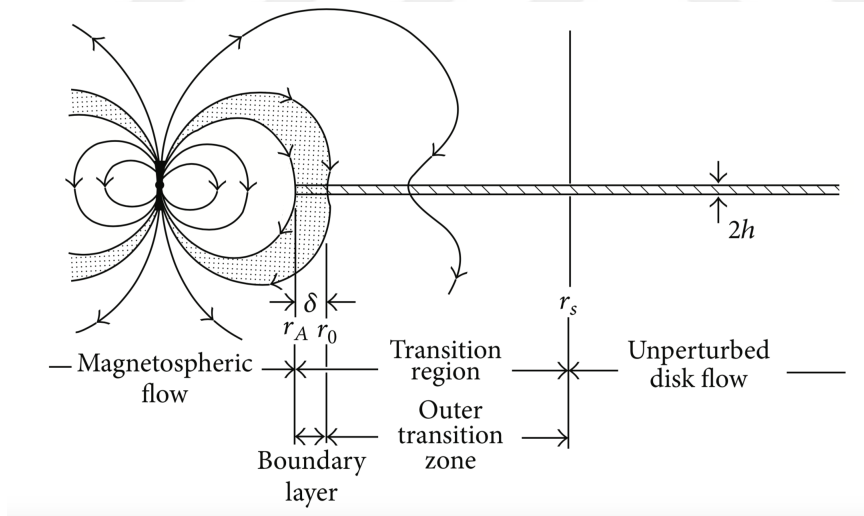


Figure 1.9: Transition region between disk and magnetosphere during accretion. Picture credit: [32]

In principle, all those three processes cause the infiltration of magnetic field into the plasma of accretion disk in a much shorter time-scales then radial-drift time T_d (see [33] for a detail description of these interactions). As a result, the magnetic field of

the source threads the disk in a considerable portion of its inner edge.

As the matter approaches the star, the angular momentum transportation within the transition zone differs depending on whether viscous stress dominated or magnetic field stress dominated. Thus, transition zone is further divided into outer and inner zones, depending on the stress dominated processes. In the outer transition zone, the angular velocity is Keplerian, while in the inner zone, or so-called boundary layer, the angular velocity is sub-Keplerian as it is reduced from magnetic field stresses up to the point where the plasma starts to co-rotate with compact star (see Figure 1.9) [33]. Basically, the boundary layer is the region where the disk material is disrupted by the B-field stress and the mass starts to flow alongside the magnetic field lines. Within the boundary layer there is formed a thread of magnetic field lines, called accretion bundle, which accretes the matter into the poles of the star.

1.2.3.3 Wind Accretion

Stellar wind accretion occurs when the companion of a binary system is a massive star with an OB spectral type which, at some stage of its life, ejects a considerable portion of its mass via stellar wind [38]. The mass loss rates of such stars are calculated to be of the order of $\dot{M} \sim 10^{-6} - 10^{-5} M_{\odot}/\text{yr}$ and their wind velocities are highly supersonic ($v_w \sim 10^8 \text{ cm/s}$) [39]. Ejected mass of companion in those so-called wind-fed systems is uniformly distributed, hence some of the material is captured by the compact star [40]. In that case, the compact star will accrete only if its gravitational potential energy is greater than the kinetic energy of the wind plasma:

$$\frac{GMm}{r} \geq \frac{1}{2}m(v_w^2 + v_{\text{orb}}^2) \quad (1.26)$$

where M is the mass of the NS and m is the mass of the material to be accreted, (v_{orb}) is the pulsar's orbital velocity and (v_w) the wind velocity. Even if the capturing material from a stellar wind seems to be an inefficient process, accreting only a small portion of it still can result in high luminosities. Since the condition described in the equation 1.26 sets a boundary for commencement of accretion, the balance condition should lead to a "bow shock" at a certain radius, known as Bondi radius [42]). This

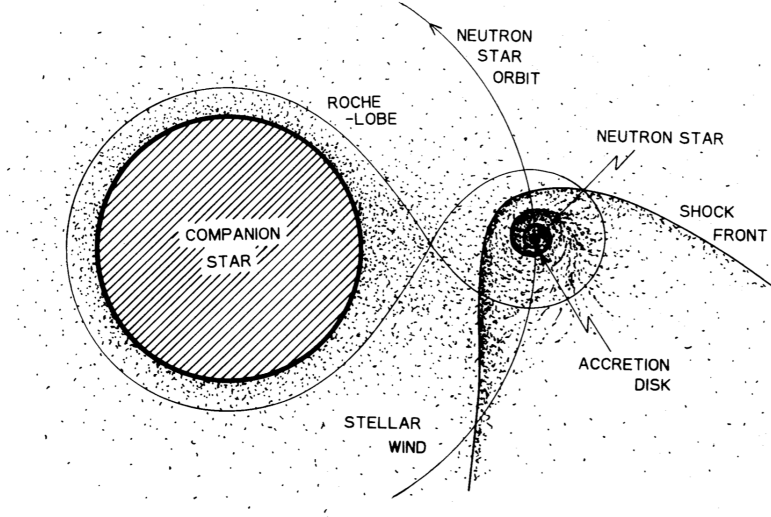


Figure 1.10: An artistic image showing the accretion process during stellar wind accretion. Picture credit [41]

shock radius r_{sh} , can be expressed as:

$$r_{sh} = \frac{2GM}{v_w^2 + v_{orb}^2} \quad (1.27)$$

The plasma that enters inside this radius will be effectively steered and undergo free-fall motion towards the NS until it experiences the dominance of the magnetic field at the proximity of NS ([42], or see [43] for review). In terms of typical known parameters ($M \approx 1.4 M_{\odot}$, v_w^2 in the order of 10^3 km/s), the shock radius will be in the order of $\sim 10^7$ km.

CHAPTER 2

MAGNETARS

2.1 A BRIEF HISTORICAL OVERVIEW

Until recent years magnetars were subdivided into two groups, namely Soft Gamma-Ray Repeaters (SGRs) and Anomalous X-Ray Pulsars (AXPs). Their names have historical backgrounds related to their behavior while being discovered. The first ever emission of a SGR (coming from SGR 1806-20) was a 0.1 seconds of γ -ray burst detected on January 7, 1979 onboard Venera 11 [44]. Back then it was categorized as a Gamma Ray Burst (GRB)¹ despite the fact that there were some characteristic differences of this burst compared to canonical GRBs (e.g. its spectra was softer). The next SGR burst (i.e. the first giant flare) was detected almost two months later, it was coming from the source SGR 0526-66 and its enormous intensity was beyond the capacity of the detectors at that time [45]. The same source bursted repeatedly on the following month and this evidence excluded the possibility of the burst coming from a GRB. Moreover, the discovery of the source SGR 1900+14 [46] exhibiting similar repetitive soft γ -ray bursts further supported the idea that a new class of galactic sources was being discovered.

In 1981, Fahlman et al. [47] detected the first pulsations from the source 1E 2259+586 residing in CTB 109 supernova remnant. Its pulse period was reported to be ~ 8 s and it had an unusual soft X-ray spectra. The discovery of two more sources with similar characteristics, namely 1E 1048.1-5937 [48] and 4U 0142+61 [49], made astrophysicists think they had discovered a new class of accretion-powered low-mass X-ray binaries. Since they were anomalous compared to ‘normal’ pulsars, van Paradijs et

¹ GRBs are an one time event originating from the explosion of a super massive star in a hyper-nova.

al. [23] named this type of stars as Anomalous X-Ray Pulsars. In 1992, Duncan & Thompson [11] articulated a theory in attempt to explain the high activity of bursts and flares of SGRs calling it the *Magnetar model*. In brief, they suggested that the magnetic field of such sources is higher than other types of pulsars and this high magnetic field is effectively responsible for the burst and flare activities. When [50] measured the spin-down rate of the SGR 1806-20, they calculated the inferred magnetic field to be $\sim 8 \times 10^{14}$ G which was above the quantum critical limit² as suggested by the magnetar model. Furthermore, Thompson & Duncan [51] also predicted that AXPs may be magnetars as well, and this prediction was confirmed when a SGR-like burst was detected from the AXP 1E 1048.1-5937 [52]. Since then, many SGR characteristics are observed in AXPs and vice-versa which has led to merge these classes into one with the label ‘magnetars’.

2.2 GENERAL PROPERTIES OF MAGNETARS

The main energy release of magnetars is detected in the X-ray range. All of the confirmed magnetars emit in the soft X-ray band (< 10 keV) and most of them also emit in the high X-ray energy band (see e.g. [53]). The pulsations of magnetars are narrowly clumped in the range of 1 to 12 s meanwhile their spin-down rates are rather diverged ($10^{-15} - 10^{-11}$ s/s). Under the assumption of magnetic braking (see equation 1.17), the dipole magnetic field strengths of 22 out of 24 magnetars are estimated to be above 5×10^{13} G (See table 4.1) which is regarded as crucial for empowering the magnetar emission according to [11]. The remaining two sources, namely SGR 0418+5729 [15] and Swift J1822.3–1606 [54], have inferred B-fields below the quantum critical limit, however, they show the similar observational behaviors with other magnetars. In fact, there are also two rotation-powered pulsars, namely PSR J1846-0258 and PSR J1119-6127, which have unusual high B-field values and have exhibited magnetar-like bursting behaviors ([55], [56], [57],[58]). The discovery of low B-field magnetars and relatively high B-field rotational powered pulsars may indicate that there is not a clear-cut between these two classes of pulsars.

Some of the magnetars exhibit persistent emission, while there are also sources with

² The quantum critical limit for the magnetic field is $B_{QC} = 4.4 \times 10^{13}$ G

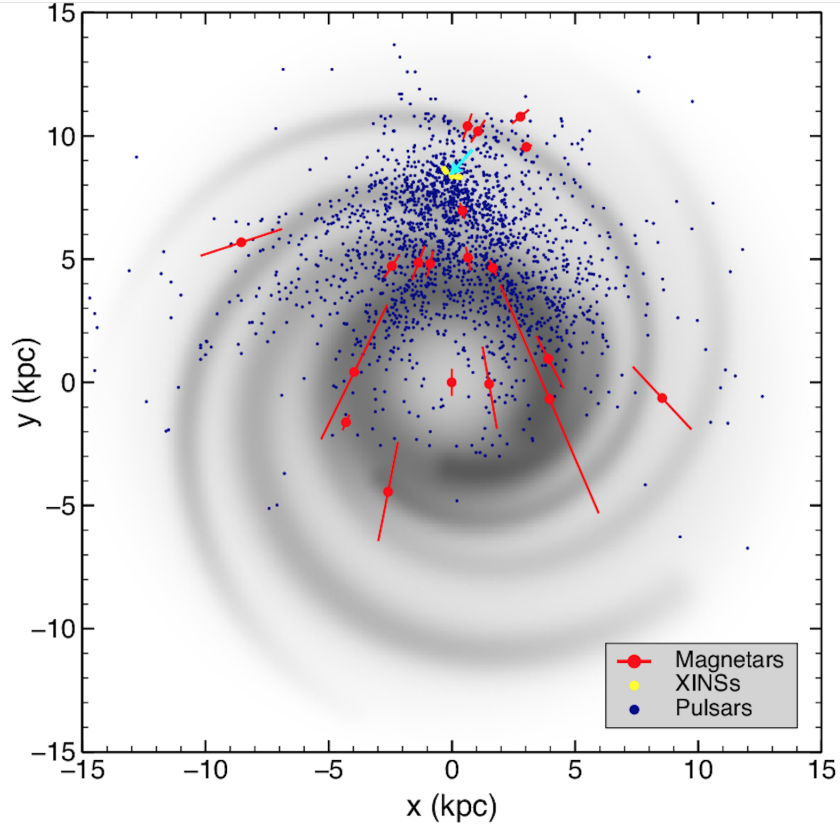


Figure 2.1: Magnetar's distribution in the Milky Way Galaxy. Red, blue and yellow dots stands for magnetars, pulsars and XINSSs, respectively. Picture credit: [59]

transient emission behavior. The term transient or persistent is based on the quiescent luminosities and luminosity increase factors during the outbursts [60]. For transient sources, the quiescent luminosity level is below $\sim 10^{33}$ erg/s and their luminosity level during outburst episodes is higher than two orders of magnitude. On the other hand, the persistent sources exhibit smaller luminosity increase during the outburst (less than two orders of magnitudes) with quiescent luminosity levels higher than $\sim 10^{33}$ erg/s.

The confirmed magnetars are mostly distributed in the galactic plane (Figure 2.1, taken from [59]). Eight of the magnetars are associated with supernova remnants (SNRs) and two more sources are proposed to reside in SNRs but their association have not been confirmed yet (see [59] and references there in). Being associated with SNRs implies that the sources are still young as consistent with the young age estimation obtained via characteristic age approximation.

2.3 TIMING PROPERTIES

The timing behavior of magnetars has been continuously studied since their discovery. Since timing analysis requires long exposures, before the launch of RXTE the spin-down rates of the sources were in general measured by using the pulse periods at different epochs, usually separated by several weeks to several months (e.g. [61]; [62]). However, thanks to the sensitivity of RXTE observatory, ‘Phase Coherent Timing Method’ become widely applicable. The following X-ray missions such as XMM-Newton, Chandra and SWIFT further enable to perform phase coherent timing studies of pulsars. For example, five persistent magnetars, namely 4U 0142+61, 1E 2259+586, 1E 1048.1-5937, 1E 1841–045 and 1RXS J170849.0-400910 have been monitored on a regular basis with RXTE, until the decommissioning of the satellite in 2012 (see [63] and references therein), and now they are been monitored with Swift satellite (see e.g. [64]). On the other hand, transient magnetars are very difficult to phase-connect (sometimes impossible) given their low quiescent luminosities and bursting activities, even though they are being continuously studied (see [60]).

The pulse profile of magnetars are multi-shaped and variable. Their variability is energy dependent, (i.e. the higher the energy, the more complex the shape), as well as time dependent. Although in most magnetars the pulse profile changes are correlated with the outburst events and timing irregularities, there exists at least one exceptional example, the magnetar 4U 0142+61, in which the pulse profile has slightly evolved during its long-term quiescent phase [65].

Even though it is noticed earlier (e.g. [66], [67], [68], [69], [70]), with the success of phase coherent timing method to describe pulsars’s spin down trends, it has become clear that the pulse frequencies significantly wander off or fluctuate over a general spin-down trend and those fluctuations are independent of the measuremental or instrumental uncertainties. And over the years, the timing studies have shown that magnetars show more variability compared with other isolated pulsar classes. Actually, there is an exact consensus on what part of the rotational evolution should be considered as the timing noise: in some cases the rotational motion of pulsars is modeled by a second order spin-down trend, but in some cases they are modeled by high order (up to 10th order) derivatives. Nevertheless, even modeling the high order polynomials is

not able to erase the strains of timing noise. And in general, the residuals after fitting with second order polynomial (i.e. spin-down trend) is considered to be the timing noise since the physical picture of a pulsar is described as an magnetically-braking oblique rotator (see Section 1.1.4) in which the physical quantities are derived from P and $\dot{P}$. For example, Arzoumanian et al. [71] argued that $\ddot{\nu}$ term can be used as a rough metric for the timing noise. In this thesis, the residuals after spin-down trends are utilized for timing noise amplitude measurements (see Section 3.3 for details). Over the decades, it has been observed that the residuals of timing solution of pulsars not only fluctuate randomly but also exhibit clear sudden frequency jumps that are recovered gradually. This sudden change in the rotational motion of pulsars is referred to as glitches.

2.3.1 Glitches

As mentioned in the previous section, the pulsars are rapid and stable rotators apart from the low-level pulse frequency fluctuations (when compared with overall rotational evolution). However, in the long time scales the rotational stability is occasionally interrupted by a sudden jump in spin frequency, i.e. a glitch. In such events, spin frequencies are fractionally altered (with $\Delta\Omega/\Omega \sim 10^{-11} - 10^{-5}$) and the frequency derivatives changes by the fractional amount of $(\Delta\dot{\Omega}/\dot{\Omega}) \sim 10^{-4} - 10^{-1}$ ([72],[73], [63]). Glitches are very common characteristics of pulsars and they are observed in $\sim 10\%$ of the known pulsar population [74]. The distribution of glitch activities of pulsar population across the $P - \dot{P}$ diagram is illustrated in Figure 2.2. Although pulsars of all ages are observed to glitch, the younger sources have a tendency to exhibit glitches more often. Glitches can either be a step up in frequency that does not recover, or they can decay with a trend that can be exponential or power law function and recover partially or fully. The type and relaxation time can change from pulsar to pulsar or even from glitch to glitch of the same pulsar ([72], [73]). Recovery fraction $Q \equiv \Delta\nu_d = (\Delta\nu_d + \Delta\nu)$ is a parameter that is a measure of the recovery of the glitches and, in general, older pulsars have smaller recovery fractions than younger ones (see e.g. [74]).

Magnetars experience glitching episodes as well, however, there are some differences

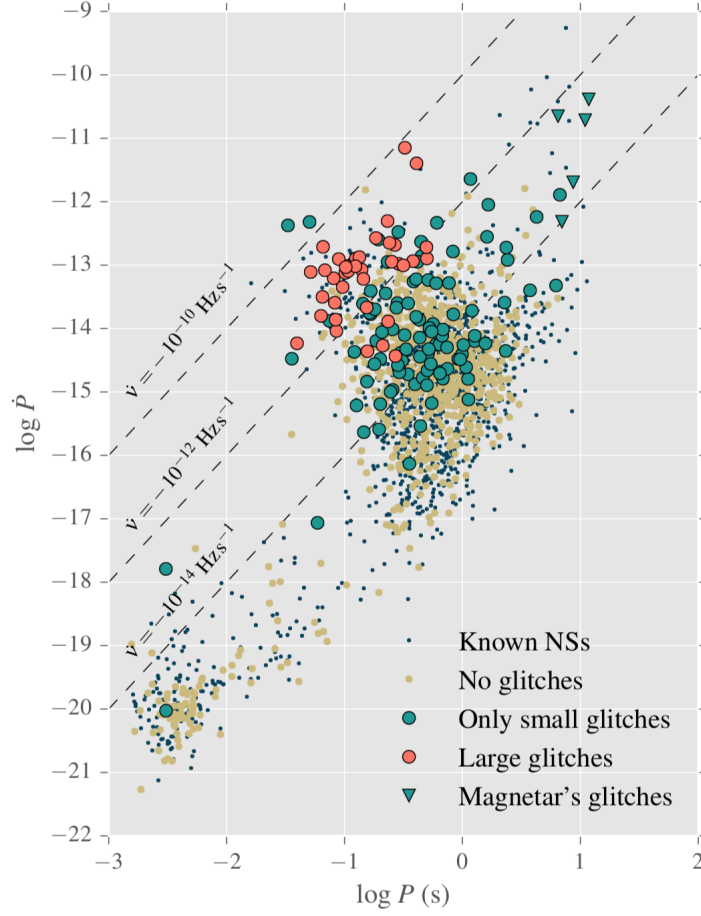


Figure 2.2: Observed glitches in neutron star population. Picture credit: [74]

compared with the glitches of standard pulsars. While the glitches of pulsars are radiatively quiet (i.e. not accompanied by significant radiative changes such as bursts, outburst, pulse profile changes etc), those of magnetars can be both radiatively-quiet or radiatively-loud ([72], [73],[54], [63]). In addition, glitches of magnetars have strong recoveries compared with the glitches of pulsars and sometimes the magnetar glitches can even ‘over-recover’ of the spin-down rate (e.g. [75], [63]). Magnetars also seem to exhibit anti-glitches which is not detected in any radio pulsar yet (see e.g. [76] [77]).

The physics of glitch events are believed to be tied to the interior dynamics of NSs. The most accepted scenario suggests that sudden shift in crust’s rotation is created when there is an abrupt angular momentum transfer from the core to the crust of the object [78]. The nuclei of the neutron star is widely believed to be composed

of superfluid matter (see Section 1.1.5). Since the superfluid has zero viscosity, it is irrotatable. However, the crust's rotation enforces the superfluid to mimic the rotation by creating quantized vortices. Even though the superfluid is not 'rotating', the rotation is only allowed inside the vortices and these vortices are locked or 'pinned' to the crustal lattice of ions. However, as the crust slow-down (as it is observationally seen in all isolated pulsars) due to magnetic braking, it builds a lag between crust's rotation and mimicked superfluid rotation. The lag becomes unsustainable when it reaches to a critical value. Then outer vortices suddenly are unpinned from the crust and the inner vortices move quickly outward in an avalanche which transfers angular momentum to the crust. Thus, the crust gains a sudden angular momentum and its rotation is suddenly spun-up, leading to the observed glitches (see, e.g. [79]).

On the other hand, the mechanism of anti-glitches is theoretically more obscure. An anti-glitch may occur when the superfluid's mimicked rotation is slower than the crustal rotation because anti-glitches require sudden angular momentum loss in the crust (i.e sudden spin-down). In the accreting pulsars (see [80] and [81]), the crust gains angular velocity from the accretion, which implies that the crust can rotate faster than superfluid component, hence making anti-glitch scenario possible. While in isolated pulsars, there is no clear spin-up episodes. For magnetar anti-glitch events, [51] suggests that the decay of the magnetic field lines create an internal free energy which is responsible for the differential rotation between the superfluid and the crust of the magnetar. Further investigation is needed to better understand the nature of glitches and their driving mechanism.

2.4 RADIATIVE BEHAVIORS

2.4.1 Giant Flares

Giant flares are one of the most prominent characteristics of magnetars. Historically, they are important because it was the famous March 5th, 1979 event, (i.e. the first detected flare [45]) which led to the discovery of magnetars. Physically, they are also important because the giant flares are the rarest and the most energetic events coming from compact objects. To date, only three giant flares have been observed: one from

SGR 0526-66 on march 5th 1979 [45] , one from SGR 1900+14 on August 27th 1998 [46] and one from SGR 1806-20 on December 27th 2004 [82]. All three flares started with instant flashes (roughly 0.1 – 0.2 s) in the hard X-ray, followed by their peak luminosities and then softened and eventually faded within a few minutes. Their peak luminosity varies between $10^{44} - 10^{47}$ ergs/s [60]. The energy release of the giant flare of SGR 1806-20 was almost 100 times larger than that of the first two sources and it is recorded as the most energetic event coming from any transient object in our Galaxy [60]. Interestingly, several scientist argue that giant flares are counterparts of soft-GRBs, and as much as 40 % of soft-GRBs observed with BATSE may have been giant flares coming from magnetars residing in other galaxies (see e.g. [60] and references within).

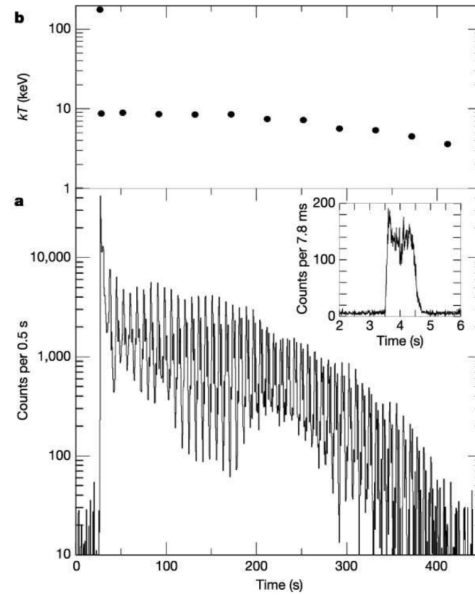


Figure 2.3: The lightcurve and effective temperature evolution of SGR 1806-20 the 2004 giant flare from SGR 1806-20 [82]

The spectral characteristics of all three flares were similar to each other: they had a very hard initial spike with a peak in the soft γ -ray band and then the emission is rapidly softened in several minutes at most. The peak luminosity spectra of SGR 0526-66 and SGR 0526-66 can be modeled by a thermal (i.e. black body) component with kT value of ~ 30 keV and ~ 175 keV, respectively. The decay phase requires and addition of a non-thermal component (e.g. blackbody plus power-law) ([46], [82];

[83]). As an example of a giant flare event, the lightcurve and effective temperature evolution of SGR 1806-20 on December 27th 2004 is demonstrated in Figure 2.3 (for details see [82]). In principle, spectral evolution of giant flares resembles that of magnetar outbursts but much more energetic.

2.4.2 Outbursts

During the outbursts, X-ray luminosities of magnetars can be enhanced by $\sim 1 - 3$ orders of magnitude and it can reach up to $\sim 10^{36}$ erg/s (see e.g. [53] and references there in). Most of the magnetars have displayed at least one outburst in their monitoring life [84]. These outbursts are in general accompanied by a variety of other radiative events such as short X-ray bursts, spectral hardening and pulse morphology changes. Short bursts may be observed before and after the outbursts. Actually it is not clear whether an outburst is triggered by a burst or not because most of those events are not being monitored prior to the explosion; however, in few fortunate cases when the source was being monitored before the start of the event, there were observed rapid flux changes within 1 – 2 day before the outburst activity (see e.g.

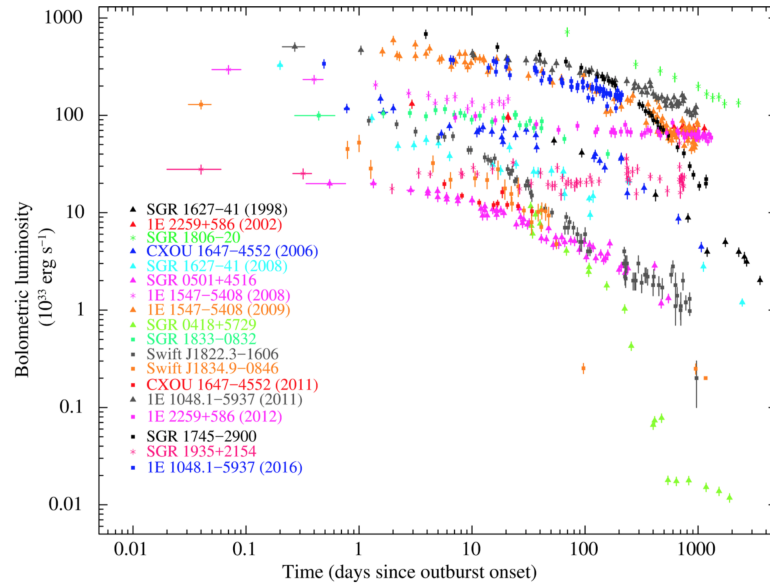


Figure 2.4: The light curves of all monitored outbursts of magnetars until 2017. Picture credit: [53]

[85]). Magnetar outbursts often leaves strains on the timing properties as well, such as glitches (or anti-glitches) and increase of timing noise level (e.g. [86]).

The decay phases of the outbursts vary from source to source (or sometimes in the different outbursts of the same source) and can last few several hours or month to years [87] [53]. This phase is rather complicated, but in brief the outburst is followed by a rapid decay and an afterglow that evolves quasi-exponentially which is sometimes accompanied by short bursts. Figure 2.4 shows the light-curves of all the monitored outbursts of magnetars until 2017 [53]. Despite the anomalies, there are some correlations in the characteristics of outbursts. For example, the total energy release of on outburst is directly proportional to the peak luminosity and the relaxation time-span: i.e. the higher the peak luminosity, the more energy released in total, and the longer it takes for the source's characteristics to go to the pre-outburst behavior [88].

2.4.3 Bursts

Short bursts are another feature characterizing magnetars, in fact they are the most common. Some magnetars have had thousands of them, even in a relatively short time, while some other have emitted only a dozen despite being monitored regularly. Usually the bursts are observed near outburst episodes, nevertheless, this is not always the case; occasionally burst are also observed when a source is in quiescence phase (e.g. [52]). Detailed statistical studies of such phenomena (e.g. [89], [90]) have shown that the peak luminosities of the magnetar's short burst range from 10^{36} up to 10^{43} erg/s and their duration varies from several milliseconds to a few seconds.

The profiles of bursts are quite variable with no clear pattern to model the morphology of such phenomena. Short bursts are usually single-peaked and their rise is faster than their decay; nevertheless, multiple-peaked bursts are also observed occasionally. In general, the brightest bursts (i.e. intermediate flares) have been followed by tails that have lasted several minutes up to several hours (see e.g. [91], [92]). In this regard, those bursts are like miniature giant flares, except that the energy release of the tail can sometimes exceed the energy release of the spike itself [60]. Burst to tail energy ratio can differ by one order of magnitude from source to source, or even from burst to burst of the same source (see e.g. [93]). The spectrum of short bursts of magnetars

can usually be fitted by a single or a double-blackbody model with typical kT values of $\sim 2 - 12$ keV, however, numerous other models have also been used to model them.

2.5 X-RAY SPECTRAL PROPERTIES

In the quiescent phase, magnetar spectrum can be generally modeled with a thermal and a non-thermal component in the form of a blackbody plus a power-law component, with the temperatures around $kT \sim 0.3 - 0.5$ keV and photon-index values around $\Gamma \sim 2 - 4$, respectively [59]. Theoretically, origin of the thermal component is attributed to emission from the surface of the star, while the non-thermal component is thought to be arising from the atmospheric and magnetospheric interactions [94]. Enormous inferred B-field strengths is thought to play a very crucial role in the spectra of magnetars. Non-thermal emission usually dominates above ~ 3 keV and its energy is in general twice as much as the energy of the blackbody. It should be noted that most of the known magnetars reside in the galactic plane (with N_H values of $\sim 10^{22} - 10^{23} \text{ cm}^{-2}$) and absorption parameter is degenerate with the photon-index parameter that describes the non-thermal continuum. Thus, interpreting the spectra

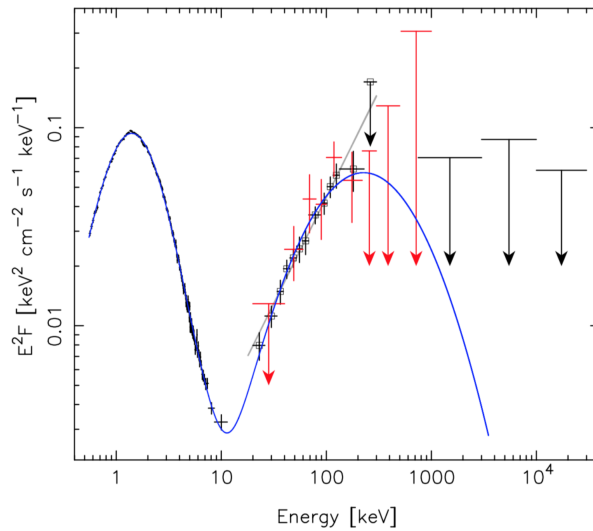


Figure 2.5: The unabsorbed soft-to-hard-X ray spectral energy distribution of magnetar 4U 0142+61. Picture credit: [95]

physically need a lot of prudence given the uncertainties and many complications. Fortunately, one of the magnetars, CXOU J010043.1-721134, resides in the SMC (with N_H values of $\sim 6 \times 10^{20} \text{ cm}^{-2}$) thus it enables to measure its spectral components with very low absorption. It is argued that the spectrum of this source is best described by a double-blackbody model [96].

Apart from soft X-rays, magnetars are observed to emit in the hard X-ray band as well. The studies of magnetars above 10 keV was carried out using the data of RXTE, INTEGRAL and Suzaku. Such studies showed that the hard X-ray emission covers a considerable portion of energy release in magnetars (see [88] and references there in). To date, there are six known magnetars which emit in hard X-ray band. Their spectra can be fitted by a flatter (when compared with emission in soft X-rays) power-law component with photon index range between $\Gamma \sim 0.5 - 2$. Figure 2.5 demonstrates an example spectrum of a magnetar (4U 0142+61) covering both soft and hard X-ray band [95]. The origin of hard X-ray emission on magnetars is still blurry; however, similar to the origin of non-thermal component in the soft X-ray spectra, the mechanism behind is thought to be the interaction of the highly magnetized atmosphere with ultra relativistic charged particles [94], [97].

2.6 EMISSION IN OTHER ENERGY BANDS

Detecting a magnetar in optical and/or infrared energy band is rather challenging regarding their intrinsic faintness in those energy bands and the galactic absorption. Despite the difficulties, there are six magnetars whose emissions in infrared/optical (IR/O) energy bands are uncovered [98], [99], [100]. In overall, the pulsations in IR/O band are variable and their pulse profiles are similar to their X-ray counterparts (but broader) and most importantly, the pulsed fraction of IR/O emission is 20-50% broader than that of X-ray emission [100]. The relation between X-ray emission and IR/O emission is unclear because in some cases IR/O flux enhancements are correlative to X-ray flux increase during an outburst phase (e.g. [101], [102]), while in some other cases IR/O flux enhancements have no correlation with X-ray flux (e.g. [103], [104], [105], [102]). The origin of infrared and/or optical emission may be a possible fossil disk surrounding a magnetar (see Section 2.8) or it may have

magnetospheric origin (see e.g. [106], [97]).

Five magnetars are also found to emit energy in the radio band ([107], [108]; [109]; [110]; [111] [112]). Interestingly, all of these radio emissions are detected during an outburst phase of transient magnetars. The properties of radio emission of magnetars are quite different compared with those of rotation-powered pulsars. For instance, radio emission of magnetars has a very flat spectrum, it is very bright and shows large variabilities in pulse morphology [108], [113].

The radio emission from transient magnetar SGR 1729-45 is particularly interesting because it resides in the vicinity of the galactic center, with a distance of only ~ 0.1 pc away from the super massive black hole Srg A* [114]. Detection of radio emission from a magnetar around the galactic center region implies that more radio pulsars in that region can also be discovered. Discovery of such pulsars around the the super massive black hole Srg A* is crucial for parameterizing its accretion disk [111], [115], [116].

2.7 MAGNETAR MODEL

Given their extreme flaring activities, the magnetars need a particular attention when interpreted physically. Several models try to explain magnetar's characteristics, however, the most widely excepted one is the 'Magnetar Model'. This model was firstly formulated by Duncan and Thompson [11] in attempt to explain the giant flare of March 5th, 1979 (see Section 2.4.1) and to show that SGRs should posses immense B-fields that is enhanced by dynamo action. Almost four years later they proposed that the same mechanism is valid for AXPs as well [51]. In order to understand the effects of extremely high B-fields, it is crucial to introduce the concept of so called *quantum critical magnetic field*. The quantum critical magnetic field is reached when the Larmor radius (i.e. the radius of spiraling motion) of an electron $r_L = vm_e c / eB$ is comparable with the reduced de Broglie wavelength $\lambda_{dB} = \hbar / m_e \nu$ where m_e is the mass of electron and ν is the velocity perpendicular to the magnetic field. Equating and rearranging these two equations one obtains a magnetic field of the values

$$B_{QC} = \frac{m_e^2 c^3}{\hbar e} \approx 4.4 \times 10^{13} \text{ G} \quad (2.1)$$

Physical phenomena act differently when B-fields reach above B_{QC} [117]. For instance, when the B-field strength exceeds the B_{QC} value the photons can split and re-merge very rapidly, the vacuum can get unstable or birefringent, the shapes of atoms and molecules can be deformed from ‘spherical’ to long cylindrical, the electron-photon scattering can be strongly suppressed [117].

2.7.1 Magnetar Formation

The question of how magnetars were born with such high magnetic field strengths is still very poorly understood. A possible mechanism, which can generate and maintain extreme B-field strengths, is the $\alpha\omega$ – *dynamo* scenario proposed by Duncan and Thompson [11]; [118] [51]. Following the calculations of Thompson & Duncan [122], the combination of Ampere’s Law, Faraday’s Law and Ohm’s Law generate a dynamo equation of the form:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left((\vec{\omega} \times \vec{r}) \times \vec{B} - \frac{c^2}{4\pi\sigma} \vec{\nabla} \times \vec{B} \right) \quad (2.2)$$

Assuming that the star is rotating differentially, a poloidal field will wrap and stretch the star as shown in the Figure 2.6 (left panel), and such a phenomenon is called ω -effect. This process can not represent the magnetic field of magnetars alone because i) unstable magnetic fields can not survive for a longtime [119] and ii) the effective magnetic field configuration of neutron stars is ‘supposed’ to be bipolar not poloidal [120]. Nevertheless, addition of an another parameter ($\alpha\vec{B}$) to the above equation (see equation 2.3) leads to a an effect (known as the α -effect)[121]. Thompson & Duncan [122] argued that combining α -effect and ω -effect together may result in the expected configuration of the B-field:

$$\frac{\partial \vec{B}}{\partial t} = \vec{\nabla} \times \left((\vec{\omega} \times \vec{r}) \times \vec{B} - \frac{c^2}{4\pi\sigma} \vec{\nabla} \times \vec{B} + \alpha \vec{B} \right) \quad (2.3)$$

Tajima and Shibata [120] suggested that if the convective elements inside a star have velocities which are not aligned to a specific axis, then it is possible for a stable bipolar magnetic field configuration to be generated. Videlicet, the moving convective elements inside the source will grow bigger due to the pressure of the interior, and as a response, the Coriolis force will enforce them to twist. Since the newborn twist

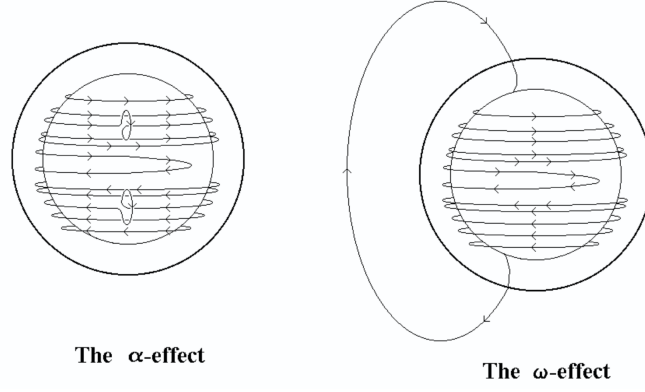


Figure 2.6: An illustration of α -effect (right) and ω -effect (left). Picture retrieved from NASA:Solar Dynamo

moves along with the star, the entire field will be twisted and small-scale loops of magnetic field will be generated. In the end, small-scale fields will reconnect and a large scale magnetic field configuration will be formed. This vigorous action is called $\alpha\omega$ -dynamo. Duncan and Thompson [11] proposed that if the spin velocity of a proto-NS is 3 ms or less, then the convective mixing would be enough for a magnetar to be born.

2.7.2 Internal Dynamics

A newly born magnetar should have an ultra-strong toroidal magnetic field inside its perfect conducting interior [123]. Therefore, the magnetic field inside the conductor is almost frozen and it evolves very slowly through two main mechanisms called ambipolar diffusion and Hall effect.

Ambipolar diffusion in magnetars is defined as the diffusion of charged particles (i.e. electrons and protons) from the core to the crust in the presence of ultra-high magnetic fields [124], [51]. While moving out, the electrons collide with protons within the star and create various reactions, most common of which are beta and inverse-beta decay (also known as the URCA and inverse-URCA reactions) [51]; [125].

$$n + n \rightarrow n + p + e^- + \bar{\nu}_e \quad (2.4)$$

$$n + p + e^- \rightarrow n + n + \nu_e \quad (2.5)$$

At the very first stages of stars life, the proton-neutron collision rate is so high that the plasma inside the super-heavy liquid core remains motionless. However, as the magnetar ages, the collision rate drops [126] and developing ambipolar drift (which aims to relax the magnetic stress within the star) will cause the magnetic energy to be dissipated via p-n friction. In normal conditions the superfluid core is capable of suppressing these reactions and terminating the ambipolar diffusion [127]; however, given a moderate temperature value of the core, the ambipolar diffusion may still be the main mechanism of magnetars activity [128].

Hall effect: When a current (J) flows in the vicinity of B-field, it will lead to creation of an electric field (E), known as the Hall effect. In magnetars, Hall effect can be described as [51]:

$$\vec{E} = \frac{\vec{J} \times \vec{B}}{n_e e c} \quad (2.6)$$

where n_e is the electron density. Even though the magnetic energy is conserved during the drift process, it plays a very important role because it displaces the magnetic field lines toward crust where they are then converted into heat via ohmic dissipation [124].

With the Hall effect, electrons can be drifted at a velocity (v_H)[129]:

$$\vec{v}_H = -\frac{c}{4\pi n_e e} \vec{\nabla} \times \vec{B} = -\frac{\vec{j}}{n_e e} \quad (2.7)$$

where $\vec{\nabla} \times \vec{B} = 4\pi \vec{j} / c$. Since the density of the electrons is very high in the core and decreases toward the crust, the v_H is relatively slow in the core but it is notable in the crust. Both ambipolar effect and Hall drift, can accumulate huge amount of energy in the crust, thus deforming it. The deformation of the crust can lead to the ‘star-quakes’ which release energy into the magnetosphere and initiate the observable bursts [118].

2.7.3 Crust Instabilities

Neutron stars are extremely dense. Event though the Hall drift and ambipolar diffusion accumulate huge amount of energy toward the surface, the enormous amount of

hydrostatic pressure [130] and the magnetic pressure [131] do not allow the surface to compress or crack. Nevertheless, the Coulomb lattice composition of the crust is suitable for the accumulation of shear stresses which can lead to the plastic failures of it, provided the shear strain reaches to a critical value [132]. When the plastic failures occur, the magnetic field in the surface will rearrange, hence magnetic energy will be released into magnetosphere. In return, the plasma in the surface will dissipate the released magnetic energy into heat and reduce the stress. This process is called thermoplastic instability [133]. The propagate of a front originating from the plastic failures in the crust is called an thermoplastic wave and it has a speed of

$$v \sim \left(\frac{\chi B^2}{4\pi\eta} \right)^{1/2} \quad (2.8)$$

where χ is the diffusion coefficient of the heat ($\sim 10 \text{ cm}^2/\text{s}$), η is the viscosity of the plastic flow.

2.7.4 Magnetar Emission

As argued in the Section 2.7.2, magnetars ought to have a highly twisted magnetosphere in order to account for the observed characteristics they display. A twisted magnetic field, $\vec{\nabla} \times \vec{B} \neq 0$, implies a nonzero current ($\vec{j} = (c/4\pi)\vec{\nabla} \times \vec{B}$) and this current is partially dissipated via ohmic dissipation process. This dissipation enforces the magnetosphere to gradually untwist and the energy released from the untwisting process powers the persistent emission observed in magnetars [134]. Since the magnetic energy is very huge, it dominates the plasma energy and, as a result, the charged particles can only move along B-field lines. (see e.g. [135]; [60] for a detailed description of magnetospheric dynamics of magnetars).

Regarding ‘Transient Events’ Thompson & Duncan [118] [51] proposed that the bursting events of magnetars are a result of the ejection of huge amount of energy from the interior of the star to the magnetosphere. Due to their enormous magnetic fields (which theoretically are even greater in the interior of the star than their estimated dipole values), a gigantic amount of magnetic stress is accumulated into the interior of the star; and a triggering mechanism such as MHD instability or a failure of the crust in the core-crust region would result in immense amount of magnetic

energy ejection from the interior to the exterior in the form of Alfvén waves. If the displacement in the core is χ then the released energy would be $\sim E_B(\chi/R)^2$, where E_B is the magnetic energy ($\sim 10^{48}$ erg) in the core and R is the radius of the source. Another alternative scenario suggests that the continuous deformation of the magnetosphere (from twisting) accumulates magnetic energy and this energy would eventually be released into a powerful event called giant flare [136]. Both, theoretical calculations [137] and numerical simulations [138] have illustrated that the twist of the magnetosphere beyond a critical value would result in global instabilities of the magnetar.

On the other hand, less energetic events (i.e. outbursts) are also thought to be a product of magnetic stresses in the crust, which eventually result in local energy release (i.e. starquakes) [51]. With this approach, [139] provided a robust model for numerically estimating how often outbursts take place and how much energy can be released during such an event. Figure 2.7 is an artistic impression of the bursting events of SGR 0418+5729 depicted by ESA/ATG medialab.

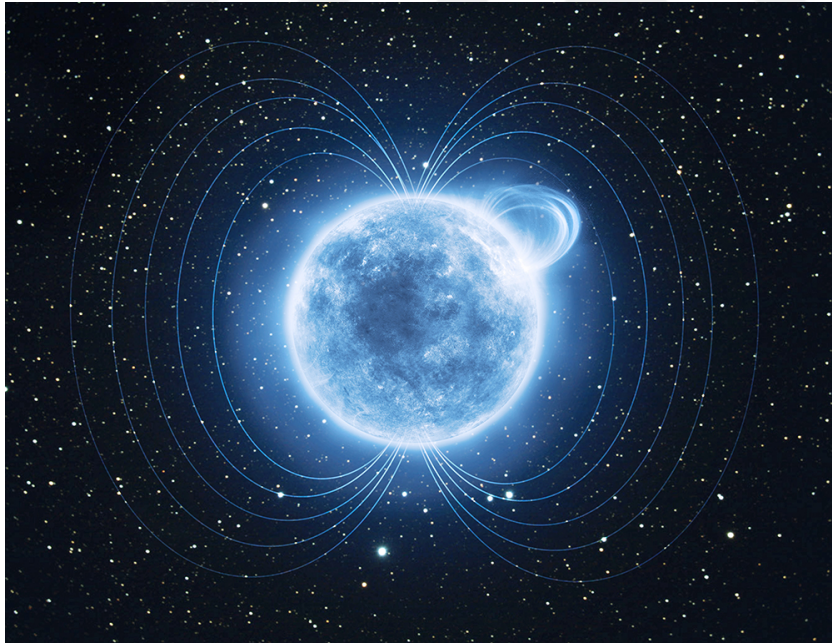


Figure 2.7: An artistic impression of the bursting events of SGR 0418+5729. Picture credit: ESA/ATG medialab

2.8 FALLBACK DISK MODEL

As described in Section 1.1.4, the magnetic dipole braking model explains many observational characteristics of pulsar population; yet, it is unable to account for the different classes of pulsars in the $P - \dot{P}$ diagram and the calculated braking indices which differ very much from $n = 3$ (see [140]). If the evolution of pulsars is governed by the dipole model solely, then there are two initial conditions (i.e. initial spin-period P_0 and magnetic field strength) which decides the fate of a newborn star.

An alternative model which attempts to explain the properties of magnetars is called ‘Fallback Disk Model’ (FBD Model). This model was formulated by [141] and [142] and, in principle, it is based on an idea that magnetars are surrounded by a left over disk (as a remnant from the supernova explosion). In this model, existence of a debris disk constitutes a third initial condition for the fate of a NS. According to FBD scenario, it is argued that the mass ejection may not be entirely efficient during core collapse event and a small ratio of the un-ejected mass ($< 0.1M_{\odot}$; [143], [144]) eventually settles to form an accretion disk around the NS ([141]. The expected lifetime of such debris disk is in the order of few kyrs [145], [146]. It should be noted that a pulsar can still be spun-down by an external torque even if the disk plasma is not accreted due to pulsar’s centrifugal barrier [147]. It is suggested that such conditions for spin-down in propeller-phase and accretor-phase can also be valid for magnetars [141], [142] .

The existence of inflowing plasma naturally leads to both spin-up and spin-down torques, and long-term rotational evolution of a pulsar is regulated by the balance between them [33]. The propeller stage ceases when a certain critical limit of spin period (P_{acc}) is attained which can be approximated and upper-bounded using the equilibrium period P_{eq} . In general, when a pulsar is a slow rotator (in a sense that $P_{spin} > P_{eq}$), the accretion can be initiated which would lead to spin-up. On the other hand, for rather fast rotating pulsars (in a sense that $P_{spin} < P_{acc}$), the propeller regime should be active and slow-down the pulsar’s rotation. In fact, rotational evolution towards the equilibrium period (P_{eq}) is rather asymptotic. Following the work of

Alpar [142], the propeller torque (τ_{prop}) can be approximated as:

$$\tau_{\text{prop}} = \frac{I}{2\pi} |\dot{\nu}| = \frac{\mu^2}{r_A^3} \quad (2.9)$$

where I is the moment of inertia, μ is the magnetic moment and r_A is the Alfvén radius. At the propeller spin-down stage (i.e. when there is no accretion), energy dissipation inside the pulsar leads to a luminosity of [142]:

$$\dot{E}_{\text{diss}} = \frac{I_p}{2\pi} \Delta\nu |\dot{\nu}| \quad (2.10)$$

where $\dot{E}_{\text{diss}}$ energy dissipation rate, $\Delta\nu$ is the rotational rate difference between the crust and a component (with moment of inertia I_p) which rotates faster than the crust.

The period clustering (i.e. the narrow range of observed periods) of magnetars (also of dim isolated NSs) indicates that the asymptotic spin-down regime involves both the propeller and the accretion stages [142]. Hence, the accretion can commence on a spin period slightly lesser than equilibrium but it should still be above the critical period for propeller regime (i.e. if $P_{\text{acc}} < P_{\text{spin}} < P_{\text{eq}}$). The equilibrium value for the pulsar's spin period is [142]:

$$P_{\text{eq}} = 16.8 \left(\frac{\mu}{10^{30} \text{ G cm}^3} \right)^{6/7} \left(\frac{\dot{m}}{10^{15} \text{ g s}^{-1}} \right)^{-3/7} \left(\frac{M}{M_{\odot}} \right)^{-5/7} \text{ s} \quad (2.11)$$

where $\dot{m}_{\text{eq}}$ is mass accretion rate and M is the mass of NS. At the limit $P_{\text{spin}} = P_{\text{eq}}$, the mass accretion rate is delimited by [142]:

$$\left(\frac{\dot{m}_{\text{eq}}}{10^{15} \text{ g s}^{-1}} \right) = \left(\frac{16.8 \text{ s}}{P_{\text{eq}}} \right)^{7/3} \left(\frac{\mu}{10^{30} \text{ G cm}^3} \right)^2 \left(\frac{M}{M_{\odot}} \right)^{-5/3} \quad (2.12)$$

Since the debris disk will be consumed gradually, mass accretion rate will not be constant and should decay over time [142], [148]. Indeed, such a condition is a necessity for explaining perpetual spin-down behavior of magnetars. Otherwise, P_{spin} eventually oscillates around P_{eq} and it would lead both spin-down and spin-up episodes. For example, if the mass accretion rate is assumed to be decaying in the form of a power

law (i.e. $\dot{m}_{\text{eq}} \propto t^{-\Gamma}$), then the equilibrium period P_{eq} grows with $3\Gamma/7$ (see equation 2.11) which implies that P_{eq} is pushed further and P_{spin} cannot reach to P_{eq} during the lifetime of the debris disc.

The equation 2.12 can be re-arranged to estimate the magnetic moment as:

$$\left(\frac{\mu}{10^{30} \text{ G cm}^3}\right) = \left(\frac{P_{\text{eq}}}{16.8 \text{ s}}\right)^{7/6} \left(\frac{\dot{m}_{\text{eq}}}{10^{15} \text{ g s}^{-1}}\right)^{1/2} \left(\frac{M}{M_{\odot}}\right)^{5/6} \quad (2.13)$$

If the magnetars are assumed to be accreting, then the typical X-ray luminosities of magnetars imply $\dot{m}_{\text{eq}} \sim 10^{15} - 10^{17} \text{ g s}^{-1}$. Since the observed spin period of magnetars are clustered in the range of 1-12 s ([59]), the magnetars should possess ordinary dipolar magnetic field strengths (in the order of 10^{12} G) when magnetars are considered as accretors asymptotically close to rotational equilibrium.

During the spin-down episode, the torque can be written as $I\dot{\nu}_{\text{spin}} = \dot{m}r_A^2\nu_{\text{spin}}$ where $\nu_{\text{spin}} = 1/P_{\text{spin}}$ is the spin frequency, $\dot{\nu}_{\text{spin}}$ is its derivative, respectively [141]. Then using the relation between mass accretion rate and luminosity as $L = GM\dot{m}/4R$, the torque relation can be re-arranged as [149]:

$$I\dot{\nu}_{\text{spin}} = \frac{4LR}{GM}r_A^2\nu_{\text{spin}}. \quad (2.14)$$

Furthermore, inserting the Alfvén radius into the equation 2.14 reveals torque-luminosity dependence in the case of accretion from a debris disc as [149]:

$$I\dot{\nu}_{\text{spin}} = L^{3/7} \left(\frac{16B^8 R^{27} \nu_{\text{spin}}^7}{G^5 M^5} \right)^{1/7}. \quad (2.15)$$

This equation shows that there exists a correlation between the spin-down torque and the luminosity of the sources with a FBD which is even greater than the correlation of spin-up vs. luminosity of canonical binary systems [150].

Fallback disk model is an eloquent model and explains many observational characteristics of magnetars that are unresolved via magnetar model 2.7. To begin with, this naturally accounts for the period clustering of this sources as they are regarded as accretors asymptotically close to period equilibrium. In addition, this model can

account for the optical/IR emission detected in six magnetars so far (i.e. 4U 0142+61, SGR 0501+4516, 1E 1048.1-5937, SGR 1806-20, XTE J1810-197 and 1E 2259+586) (see McGill Online Magnetar Catalog and references there in). Furthermore, 4U 0412+61 is observed to exhibit optical pulsations [98] and there is a compelling evidence for a dusty debris disk surrounding 4U 0412+61, deduced from the Spitzer Space Telescope observations (even though the source is not empowered by accretion from this debris disk) [151].

SGR bursts constitute a prominent characteristic for magnetars. In such burst events, enormous energy release occurs, typically in the range of $\sim 10^{40} - 10^{44}$ ergs in very short timescales ($\sim 10 - 10000$ ms). These strong bursts cannot be explained by the small accretion rates from debris disc [152]. It should be noted that a similar burst activity has never been observed in a binary system. Over the years, there has been postulates for a hybrid model combining magnetar model and fallback disk model (e.g. [153]), though a conclusive model is not yet been achieved.

CHAPTER 3

DATA ANALYSIS

3.1 DATA REDUCTION

Before conducting data analysis, one must prepare the data very carefully in order to have accurate results. In this work, timing analysis of 18 magnetars and 6 accreting pulsars is performed using the observations of RXTE, CHANDRA, XMM-Newton, SWIFT and FERMI satellites. The data are taken from the High Energy Astrophysics Science Archive Research Center (HEASARC) archive of the National Aeronautics and Space Administration (NASA). As this thesis work is concentrated on the timing noise properties of pulsars, all the data are selected from glitch-free intervals with an aim of preventing their contributions to the timing noise amplitude. Below is a very brief description of each satellite and its data reduction process used prior to the timing analysis of this thesis.

Rossi X-ray Timing Explorer (RXTE)- Most of the data utilised in this dissertation are generated through the Proportional Counter Array (PCA) onboard RXTE. Named after Bruno Benedetto Rossi, who was a pioneer in X-ray astronomy and instrumentation, RXTE initiated its operations in December 1995 and lasted until January 2012. The main goal of the observatory was to enlighten and level up our understanding of timing properties of X-ray sources. PCA, which utilized five Proportional Counter Units (PCU) into one array, was the primary instrument detecting the incident photons in 2-60 keV energy range inside a 1 degree FoV with microsecond accuracy.

In this work, RXTE data reduction process is conducted using HEASOFT v.6.19 software. The PCA data are filtered via following criteria: electron contamination is constrained to be at most 0.1, the Earth elevation angle is selected to be greater

than 10° and the pointing offset angle of the observations are chosen with an upper limit of 0.02° . Once the event files are cleaned with criteria defined above, the time series are binned with 0.05 s resolution to generate the light curve. As the number of operating PCUs varies within different observations, the photon counts of the created light curve is normalized using CORRECTLC command of the FTOOLS software as if all PCUs are operational in all observations. Then, the reference of time of arrivals of the photons in lightcurve are transformed through Barycenter of the Solar System with an aim of eliminating Doppler delays due to motion of the satellite observatory and hence, the photon arrival times can be assumed to be recorded in a rather inertial frame.

X-ray Multi-Mirror Newton Mission is a space observatory named after Sir Isaac Newton on-board of which there are three X-ray telescopes and one Optical monitor. The primary goals of XMM-Newton are to investigate X-ray sources by performing narrow- and broad-range spectroscopy and by making simultaneous imaging of a source in both X-ray and optical energy bands. It was launched in December 1999 by European Space Agency (ESA) and still operates to date, despite the fact that its mission duration was planned for ten years only.

Data gathered via XMM-Newton observations are handled with the data reduction software SAS v.15.0.0. The events are cleaned for image shade patterns 0-4 with FLAG=0 option to include only good events. The data is further filtered for high-energy background events, i.e. the time intervals, for which background level exceeds 5% source count rate, are removed. In order to obtain source count rates, the events within 20-arcsecond radius from source location are selected. Away from the source location, another 40-arcsec circular area on the same CCD is utilized for acquiring background events.

Chandra X-ray Observatory, similar to XMM-Newton, is also a space observatory designed to detect X-ray emissions and its most prominent feature is the high angular resolution of its mirrors. Named after the Indian astrophysicist Subrahmanyan Chandrasekhar, Chandra is part of NASA's 'Great Observatories' which was launched in July 1999 and still operates to date. On-board this observatory there reside four science instruments namely, High Resolution Camera (HRC) and Advanced CCD Im-

age Spectrometer (ACIS) -which record information about the incoming X-rays; and High Energy Transmission Grating Spectrometer (HETGS) and Low Energy Transmission Grating Spectrometer (LETGS) -which are complementary instruments with the aim to provide detailed information about the incoming X-ray. Due to its sensitivity, Chandra observatory is able to detect much fainter X-ray sources than any X-ray observatory operating in the past.

In this work, Chandra archival data are analyzed using the CIAO V.4.9 software. Firstly, level 2 event files are produced by proceeding the data through the REPRO tool of CALDB v.4.7.6. Afterwards the sources counts are gathered by centering it in a 5-arcsec circle and the background counts are gathered by choosing a source-free 10-arcsec circle on the same CCD.

Swift X-ray Telescope (XRT) is another NASA observatory (in partnership with UK and Italy) with a primary aim to detect and investigate the GRBs. It was launched in November 2004 and still operates to date. On-board the spacecraft there are three instruments, namely Burst Alert Telescope (BAT), X-ray Telescope (XRT) and Ultraviolet/Optical Telescope (UVOT), the combined data of which studies an event in different wavelength simultaneously. The most prominent feature of Swift is its ability to rapidly coordinate itself toward a bursting events, thus its name is after the nimble bird with the same name (Swift bird).

In this thesis, the data from Swift/XRT instrument are cleaned by using the standard pipeline script XRTPIPELINE v.0.13.2 and the default screening criteria. Then, the event files are barycentered by using an up-to-date clockfile and the coordinates of the source. Afterwards, the extraction of lightcurves is conducted using the XSELECT v.2.4D command. For windowed timing mode observations, no region selection is applied during light-curve extraction. For photon counting mode observations, a 20-pixel circular source region and a 60-pixel circular background region are used.

3.2 PULSAR TIMING ANALYSIS

When the data reduction process is accomplished, the resulting lightcurves are held subject to timing analysis. Initially, a search for periodicity (i.e. a pulse signal) in the data is commenced by switching from time domain to frequency domain which can be achieved by making use of the so called discrete Fourier Transform (DFT) as:

$$F_k = \frac{1}{N} \sum_{n=0}^{N-1} C_n e^{-i2k\pi\nu nT/N} \quad (3.1)$$

where C_n is the count in the bin n , T is the total time span and N is the number of all bins. In computational aspects, DFTs are handled through fast Fourier transform (FFT) which is actually a computationally effective way of calculating Fourier transforms of discrete data sets¹. After converting the data, the power (P_k) of the signal can be found as:

$$P_k = F_k(\nu) F_k^*(\nu) = |F_k|^2 \quad (3.2)$$

where $F_k^*(\nu)$ and $|F_k|$ are the conjugate and the magnitude of $F_k(\nu)$, respectively. Distributing the power (P_k) calculated for different frequency ranges with a step of $\Delta\nu$ (which is limited as N/T with number of data points N and observation time span T), will yield the power spectrum. This transformation enables us to identify a clear signal in the power spectra (i.e. power vs. frequency plot) of a specific source since the frequency corresponding to the coherent signal will result in the highest power.

Once the signal frequency is roughly determined from the power spectra, the initial guess period can be used for further refinement of the accuracy with more improved techniques such as *Epoch Folding Technique*. In this technique, the time series of an observation are folded over the initial signal frequency guess. Folding over a period yields a histogram, referred to as *pulse profile*. Each observation has its own pulse profile constructed by aforementioned method. Assuming that the frequency at which the time series are folded is correct, then the pulse profile will be unique and belong to the target source. And such profiles (assuming that it has enough flux to

¹ As the efficiency of an FFT algorithm approaches to unity, the term FFT and Discrete Fourier Transform (DFT) can be used interchangeably.

be determined and detector yields high signal-to noise ratio) will oscillate around a ‘mean value’. Therefore, if we calculate χ^2 value of the pulse profile based on the mean value, those χ^2 values foretell the strength or significance of the pulse profile; the higher χ^2 value is, the more significant the pulse profile will be. To test the period guess, one uses the χ^2 - test:

$$\chi_d^2 = \frac{1}{d} \sum_{i=0}^{N-1} \left(\frac{c_i - \langle c \rangle}{\sigma_{c_i}} \right)^2 \quad (3.3)$$

Where d is the degree of freedom, $N = d + 1$ is the number of phase bins, c_i is the number of counts in phase bin i and σ_{c_i} is the uncertainty in c_i .

If the pulse frequency is incorrect, the counts (c_i) will not be added into ‘correct’ phase bins during folding process, eventually wiping out the pulse profile. Hence, the phase bins will not produce a ‘pulse profile’ shape and will be close to and randomly fluctuate around the mean value; therefore, resulting in a χ^2 value much close to 1. Sometimes the folding frequency may be close to, but not exactly the same with the correct signal frequency and, if this is the case, the pulse profile will be altered from the original shape due to similar reasons. On the other hand, the observed signal frequency will maximize the χ^2 value for that observation.

Assuming that the folding pulse frequency is correct, a similar procedure can also be deployed for all of the observations to reveal which observation has the most statistically significant pulse profile, and that profile will constitute the template or master profile for timing analysis. As it is the most significant profile, the pulse profile which has the highest χ^2 value is generally chosen as the *master pulse* which will be utilized as the reference pulse profile, and used to determine the phase shift of other pulse profiles². The determination of the phase shift is generally carried out using cross correlation technique which requires a harmonic representation of the pulse profiles. Following the study of [154], generic harmonic representation for the master profile

² Actually, the highest χ^2 approximation for choosing the master pulse is not always valid. Increasing χ^2 implies that the pulsed fraction of the given profile is increasing. However, the shapes and stability of pulse profiles should also be taken into account since the reference pulse will be cross-correlated with the rest of them eventually.

can be defined as:

$$g(\phi) = G_0 + \sum_{k=1}^N G_k \cos k(\phi - \phi_k) \quad (3.4)$$

Assuming that the shape of the pulse profile is stable, then individual pulse profiles generated from other observations can be associated with master profile as its adjusted forms (i.e. scaled and/or shifted). Hence, they can be mathematically interpreted as;

$$f(\phi) = F_0 + \sum_{k=1}^N F_k \cos k(\phi - \phi_k + \Delta\phi_k) \quad (3.5)$$

where $\Delta\phi_k$ is the phase shift and F_k/G_k is the scaling factor of the individual pulse from the master pulse. Then, utilizing their harmonic representations, the master pulse and the individual pulses are cross-correlated via

$$C(\Delta\phi) = \int_0^{2\pi} f(\phi)g(\phi + \Delta\phi)d\phi \quad (3.6)$$

Similar to the techniques in other disciplines, cross-correlating different functions enables one to determine how strongly they are correlated. In the case of pulse profiles, the crosscorrelation is repeated by shifting the individual pulse profile with an amount of $\Delta\phi$. Therefore, calculated cross-correlation values $C(\Delta\phi)$ are dependent on $\Delta\phi$ and the maximum value will be reached when two cross-correlated pulses are aligned. Hence, from here one can find the phase-shift of the individual pulses as [154]:

$$\Delta\phi = \frac{\sum_{k=1}^N k F_k G_k \sin k \Delta\phi_k}{\sum_{k=1}^N k^2 F_k G_k \cos k \Delta\phi_k} \quad (3.7)$$

The phase-shifts are also referred to as pulse time of arrivals (TOAs) of each observation since they are indicating the delay time of pulse arrivals in phase domain. It should be noted that evaluations in the phase domain suppress the information on the exact amount of rotation cycles between TOAs. Time evolution of the TOAs reflects the time-dependent rotational motion of the pulsar if the phase connection is

established (i.e. correctly counting the rotation cycles between TOAs). The rotational phase of the pulsar is then represented in terms of *timing parameters*: pulsation frequency and its higher derivatives for a given epoch. In order to determine the timing parameters of a specific source, the TOAs are modeled through Taylor series as;

$$\phi(t) = \phi_0 + \nu(t - t_0) + \frac{1}{2}\dot{\nu}(t - t_0)^2 + \dots \quad (3.8)$$

where ϕ_0 is the epoch folding, ν is the frequency, $\dot{\nu}$ the frequency derivative etc. Utilizing this polynomial expansion, the regular rotational motion of a pulsar can be revealed.

The TOA measurements can be converted to the frequency measurements by exploiting the fact that frequency evolution is actually the time derivative of the rotational phase evolution (see equation 3.8). For a discrete data set (e.g. TOA measurements), the derivative can also be approximated by fitting a linear model for consecutive data points. Hence slope of the linear fit for consecutive TOAs ($\delta\nu = \frac{\delta\Phi}{(t-t_0)}$) can be used to estimate the pulse frequency corresponding to the mid-times of these intervals. Uncertainty range of these frequency measurements can be approximated through the error range of the slope of the linear model fit within the corresponding time interval.

3.3 NOISE STRENGTH ANALYSIS

Pulsar are the most precise ‘clocks’ in a sense that some of them completes its one-cycle rotation within the orders of milliseconds, and current measurement techniques for unveiling a pulsars rotational motion enable to us to reckon the pulsars rotation period within nanosecond accuracy. Such precise measurements help to deduct time dependent evolution of pulsar’s rotation from which physics that governs this evolution is being theorized and developed. The rotational motion of pulsars and associated timing parameters are derived and modeled via pulsar timing techniques described above. However, as it is shown through various studies in the literature (see e.g. [155] and references there in), the pulsar rotation is not that simple and it carries stains of timing irregularities. Timing residuals are referred to the remains of TOAs after they are fitted with a suitable model. For an isolated pulsar, it is the polynomial model de-

scribed in Equation 3.8. But for the pulsars in binary systems, a model accounting for the orbital Doppler delays of TOAs should also be added. If every parameter is taken into account and the TOAs are modeled with the best fit than the residuals would be zero. Unfortunately, fitting with absolute zero residuals is never the case.

Over decades, many scientist have put their efforts in modeling and understanding the origin of pulsar timing noise (see e.g. [155], [140], [156], [157], [71], [158]; however, the exact mechanism behind this phenomena is far from completely understood. The origin of timing residuals can be either instrumental (i.e. originating from measurement accuracy of the detectors) or intrinsic to the source. The residuals which have an intrinsic origin are mapped into two groups: glitches and timing noise. Glitches are defined as a sudden jump in the frequency of a source (see Section 2.3.1 for a detailed description) while timing noise is defined as stochastic wandering of TOAs observed even after modeling (those TOAs) with high-order polynomials.

In the literature, many studies have been conducted as an attempt to reveal the origin and characteristics of timing noise and extend those studies to as many pulsars as possible to understand the noise processes via statistical correlations and source specific features (see e.g. [159], [155] and references therein), and it has been concluded that timing noise analysis is much more complicated than just a random walk process in a specific timing parameter. For example, Cordes et al. [158] showed that noise activity could originate from small, discrete jumps (i.e. micro-glitches) in one of the three timing parameters. Alpar et al. [160] examined the results of timing noise published in the literature and they concluded that large glitches had no observable impact in timing noise. For the pulsars in binary systems, Baykal & Ögelman [69] showed that the timing noise amplitudes of these systems are in correlation with their X-ray luminosity, indicating that the timing noise in binary systems is linked with their mass accretion rate.

The calculation of the strength of timing noise is conducted and interpreted in different ways. For example, Arzoumanian et al. [71] formulated the so called ‘ Δ_8 -parameter’. This approach calculates the noise strength using the ν and $\ddot{\nu}$ values of a

pulsar for a fixed time interval:

$$\Delta_8 = \log\left(\frac{|\dot{\nu}|}{6\nu} T_8^3\right) \quad (3.9)$$

Note that the time-span of $T_8 = 10^8$ s has no specific purpose but rather is the average time interval of the observations of the sources calculated by [71]. This method is very model-dependent (e.g. order of the polynomial model to describe TOAs), nevertheless, [71] used this method to show that timing noise strength of pulsars is correlated with their spin-down rate. This correlation was further confirmed using other timing noise strength estimation methods, for example, by [140] when they estimated the timing noise of 366 pulsars and by [159] when they represented the timing noise properties of magnetars.

Another method used to estimate the timing noise of pulsars is by using the Bayesian technique (see e.g. [155] and references in for a detailed description). This technique is the newest approach in estimating the timing noise, and in principle it makes use of a timing solution estimated before in order to construct posterior probability distributions and obtain the most accurate timing solution for any specified source. Hence, if there exists a prior timing model $\mathcal{M}$ and its residuals $\mathcal{R}$, then the posterior distributions sampling of parameters θ is estimated by using the Bayes' theorem:

$$Pr(\theta|\mathcal{R}, \mathcal{M}) = \frac{Pr(\mathcal{R}|\theta, \mathcal{M})Pr(\theta, \mathcal{M})}{Pr(\mathcal{R}, \mathcal{M})} \quad (3.10)$$

where $Pr(\theta|\mathcal{R}, \mathcal{M})$ is the posterior probability distribution of the parameters, $Pr(\mathcal{R}|\theta, \mathcal{M})$ is the likelihood function for the residuals given a timing model and model parameters, $Pr(\theta, \mathcal{M})$ is the prior probability distribution, and $Pr(\mathcal{R}, \mathcal{M})$ is the Bayesian evidence.

Lower et al. [155] developed and used this technique to examine the timing noise of approximately 300 Southern Sky pulsars, and they reported that red noise in those pulsars is proportional to $\nu^q |\dot{\nu}|^p$ with $q = -0.84_{-0.49}^{+0.47}$ and $p = 0.97_{-0.19}^{+0.16}$.

The most widely known methodology for measuring the timing noise strength of pulsars, which is also the one used in the calculations of this work, is the one put forward

by Boynton et al. [66] and later enhanced by Deeter et al. [68]. Fundamentally, this method uses the root-mean-squares (rms) of the timing residuals (TOA or frequency strain after modeling the regular spin behavior of the pulsar with polynomials) for interpreting the timing noise strength level. In this method (similar to the other timing noise strength estimation techniques), the rotational motion of the pulsar is split into two parts:

$$\Phi(t) = \Phi_s + \Phi_r \quad (3.11)$$

where Φ_s is the regular rotational evolution indicated by equation 3.8, and Φ_r corresponds to *random fluctuations*. Evidently, Φ_r is hinged on at least two arguments: *i*) the preceding model that describes Φ_s and hence the order of the polynomial m ; *ii*) the time span T over which preceding model is fitted. As the gauging of timing noise strength is implemented by evaluating the mean-squared value σ_R^2 of residuals Φ_r , indeed same parameter space that affects Φ_r also penetrates to evaluated rms value σ , and hence σ will be dependent on m and T as $\sigma_R^2(m, T)$.

The fundamentals on the stochastic wandering of TOAs have been settled by [66] when they proposed that observed fluctuations in the residuals could be interpreted as ‘random walks’ in either phase (PN), frequency (FN) or spin-down rate (SN) of the source. These residuals are called ‘white noise’ when the distribution of the power of fluctuations is analysis-frequency-independent, and ‘red noise’ when the power of fluctuations is analysis-frequency-dependent. Utilizing this information, the timing noise strength S_r (where subscript r denotes the order of red noise) can be deduced from;

$$\langle \sigma_R^2(m, T) \rangle = S_r T^{2r-1} \langle \sigma_R^2(m, 1) \rangle_u \quad (3.12)$$

where $\langle \sigma_R^2(m, 1) \rangle_u$ is the normalization factor for a unit timescale. The normalization factor can be obtained either through numerical simulation [161] or mathematical evaluation [68] by determining the expected mean square residual for unit-strength red noise ($S_r = 1$) over a unit time interval ($T = 1$). S_r derived from this equation gives an order of magnitude estimate for the timing noise strength. It should be noted

that, inverse of the timescale T is referred to as analysis-frequency ($f = 1/T$) with the purpose of evading a confusion with the rotational frequency of the pulsar. For instance, if the distribution of the power of fluctuations (or S_r values) is analysis-frequency-independent, the obtained power density spectrum yields a zero slope (i.e. white noise structure). It should be further understood that the parameter space describing the rotational motion of the pulsar are time integrated of one another. For example, $\phi(t) = \int \nu dt = \int \dot{\nu} d^2t$ where $\phi(t)$ is given in the Equation 3.8. Therefore, a white noise obtained for some parameter space may indicate a red noise for the other since their rms values are further connected through the integral of the Equation 3.12.

For magnetars, a precursory investigation of the residuals of pulse frequencies indicate that they can be characterized by first-order red noise. As the red noise order of timing noise is linked with the timing parameter for which the rms calculation is performed (see Section 3.3 for details), a first order red noise ($r = 1$) for spin frequency residuals and a second order red noise ($r = 2$) for TOA residuals are used. In this analysis, the simple spin-down trend; quadratic model ($m = 2$) for pulse TOAs or linear model ($m = 1$) for pulse frequency histories for all magnetars. For PAPs, the residuals after quadratic trend in pulse frequency histories ($m = 2$) are used for noise strength analysis. Associated normalization factors for noise strengths of unit timescales are retrieved from Deeter [68](see Tables 1 and 2). Afterwards, the timing noise amplitude calculations are performed for the maximum time-scale (T) of the available data. Depending upon to sampling rate of the data, calculations are re-iterated for smaller time-scales ($T/2, T/4, T/8, \dots$) till the smallest time scale for polynomial fitting or measuremental noise level is reached. For each time-scale, the timing noise amplitude estimations are logarithmically re-binned and accumulated into a single power estimate. The power density spectra are then constructed by mapping each power estimate to the corresponding analysis-frequency.



CHAPTER 4

TIMING ANALYSIS RESULTS

4.1 MAGNETARS

In this section, the calculations and results of timing noise of selected magnetars and accretion powered pulsars are presented. Initially, the calculations and results of each source, together with a compact description of the sources general characteristics, are reported. Afterwards, the analysis on the timing noise of the sample sources are demonstrated. In Table 4.1, the list of confirmed magnetars and their properties are illustrated. The pulse frequency measurements of the listed sources are conducted in literature by using different techniques; pulse timing, epoch folding or spline fitting.

This thesis utilizes the most recent data of the magnetars listed in Table 4.1. Pulse frequency evolution history for each source is constructed making use of both the pulse frequency measurements and the phase connected timing solutions reported in literature (see the following sections on the analysis and results for each source). The time intervals in which a glitch event is observed are omitted for the timing noise analysis since they will contribute as misleading excess noise. Timing noise measurements of 3 of the 24 confirmed magnetars listed in Table 4.1 are already conducted by [162]. Furthermore, 3 of them (PSR J1622-4950, SGR 1627-41 and Swift J1818.0-1607) do not have enough number of observations to carry out timing noise analysis for power density spectra of pulse frequency fluctuations. Depending on the sampling rate of observations, either noise strength upper limit or power density spectra of the pulse frequency derivative fluctuations is established for the remaining 18 magnetars on the list.

Table 4.1: List of magnetars and their properties.

Source name	P (s)	$\dot{P}$ (10^{-11} s/s)	B_{surf} (10^{14} G)	L_x (10^{33} erg/s)
CXOU J010043.1–...	8.020392(9)	1.88(8)	3.9	65
4U 0142+61	8.68869249(5)	0.2022(4)	1.3	105
SGR 0418+5729	9.07838822(5)	0.0004(1)	0.061	0.00096
SGR 0501+4516	5.7620695(1)	0.594(2)	1.9	0.81
SGR 0526–66	8.0544(2)	3.8(1)	5.6	189
1E 1048.1–5937	6.457875(3)	2.25	3.9	49
1E 1547.0–5408	2.0721255(1)	4.77	3.2	1.3
PSR J1622–4950	4.3261(1)	1.7(1)	2.7	0.44
SGR 1627–41	2.594578(6)	1.9(4)	2.2	3.6
CXOU J164710.2–...	10.610644(17)	<0.04	<0.66	0.45
1RXS J170849.0–...	11.00502461(17)	1.9455(13)	4.7	42
CXOU J171405.7–...	3.825352(4)	6.40(5)	5	56
SGR J1745–2900	3.76363824(13)	1.385(15)	2.3	<0.11
SGR 1806–20	7.54773(2)	49.5	20	163
XTE J1810–197	5.5403537(2)	0.777(3)	2.1	0.043
Swift J1818.0–1607	1.363490(3)	9(1)	3.5	–
Swift J1822.3–1606	8.43772106(6)	0.0021(2)	0.14	<0.00040
SGR 1833–0832	7.5654084(4)	0.35(3)	1.6	–
Swift J1834.9–0846	2.4823018(1)	0.796(12)	1.4	<0.0084
1E 1841–045	11.788978(1)	4.092(15)	7	184
3XMM J185246.6+...	11.55871346(6)	<0.014	<0.41	<0.0060
SGR 1900+14	5.19987(7)	9.2(4)	7	90
SGR 1935+2154	3.2450650(1)	1.43(1)	2.2	–
1E 2259+586	6.9790427250(15)	0.0483695(63)	0.59	17

Notes. The content of this table is directly taken from McGill Online Magnetar Catalog

4.1.1 CXOU J010043.1-721134

CXOU J010043.1-721134 is an AXP discovered by utilizing the observations of the Einstein satellite in 1979. However, ~ 8 s pulsations of the neutron star were not detected until 2002 [163]. This source resides in the Small Magellanic Cloud (SMC) and has a luminosity of the order of $\sim 10^{34}$ erg/s [164]. Using the Chandra archive data taken between 2001-2004, McGarry et al. [165] reported its period derivative to be $\sim 1.88 \times 10^{-11}$ s/s. CXOU J010043.1-721134 is also observed to emit in optical waveband which is detected through Hubble Space Telescope (HST) observations [166]. Existing observations of CXOU J010043.1-721134 are separated by large

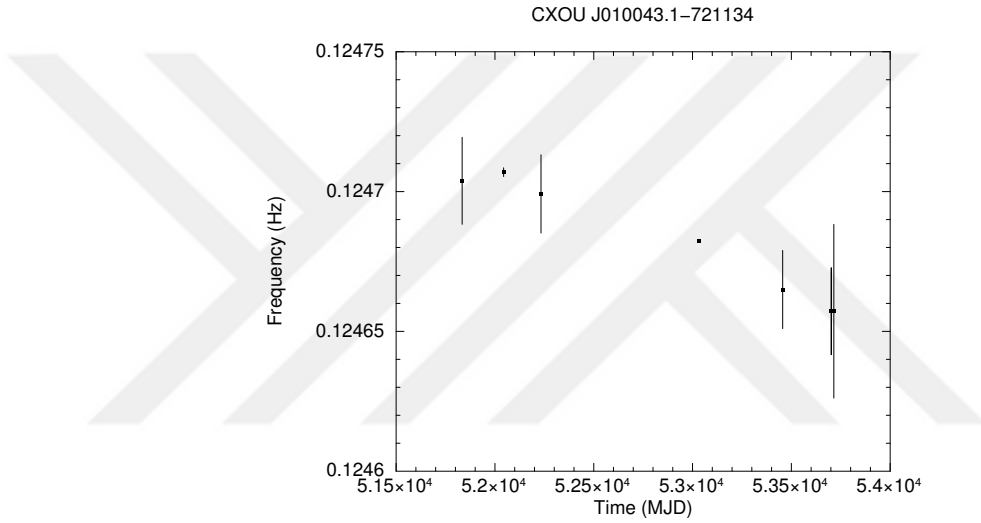


Figure 4.1: Frequency history of CXOU J010043.1-721134. See Table 5.1 for references.

time gaps, preventing a phase coherent timing solution to be established. In the literature, there are very few pulse frequency measurements for CXOU J010043.1-721134 due to its transient nature. In this work, the existing pulse frequency measurements ([165] and [96]) are collected to compose the time dependent frequency evolution of the source (Figure 4.1). Despite the large time gaps, the frequency evolution extends to a time span of 1881 days.

For CXOU J010043.1-721134, the sampling rate of pulse frequency measurements do not allow to construct a power density spectrum of pulse frequency fluctuations. Nevertheless, it allows to calculate a timing noise amplitude corresponding the max-

imum timescale of frequency measurements ($T = 1881$) days. For the maximum time scale, the timing noise amplitude is estimated to be $\sim 3.39 \times 10^{-21} \text{ s}^{-3}$. As the sampling rate is not appropriate for generating power density spectrum, the analysis-frequency dependent timing noise structure (e.g. red or white noise components) of CXOU J010043.1-721134 can not be resolved.

4.1.2 4U 0142+61

4U 0142+61 is an Anomalous X-ray Pulsar (i.e. magnetar) discovered in 1978 with Uhuru observations [167]. Located at a distance of $\sim 3.6 \text{ kpc}$, it resides in the Cassiopeia constellation [168]. This AXP has a spin period of $\sim 8.7 \text{ s}$ which slows-down gradually at a rate of $\sim 0.2 \times 10^{11} \text{ s/s}$ [84]. Using the $P - \dot{P}$ relation (Equation 1.17), the magnetic field strength value is estimated to be $1.3 \times 10^{14} \text{ G}$. The persistent X-ray luminosity of 4U 0142+61 is $\sim 10^{35} \text{ erg/s}$, making it the brightest magnetar in $2 - 10 \text{ keV}$ energy band [95]. 4U 0142+61 has been part of RXTE-Swift monitoring campaign, thus it has been monitored regularly since 1996. Over the years the source has experienced four active phases, first episode in 2006-2007 (see [84] and references there in), second episode in 2011-2012 [169], third episode in 2015 [170] and last episode in 2017 [64]. During those episodes, 4U 0142+61 has exhibited many bursting events and several timing irregularities.

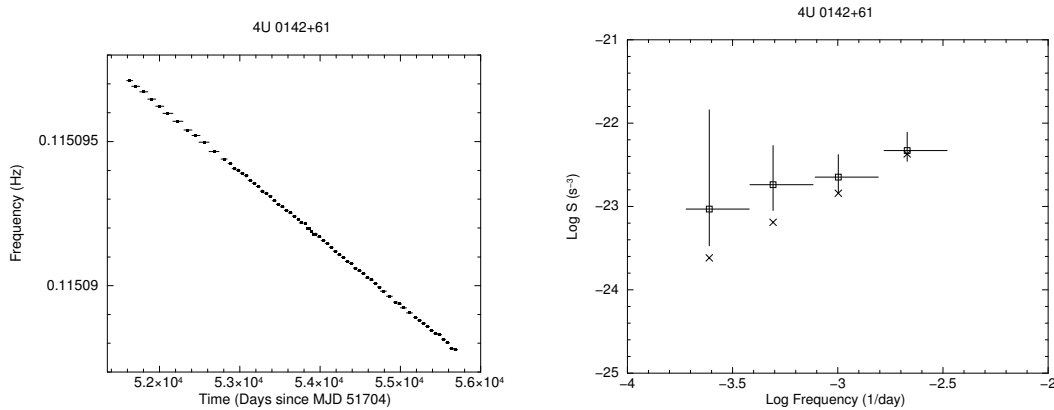


Figure 4.2: Frequency history and power density spectrum of 4U 0142+61. See Table 5.1 for references.)

In this work, 4U 0142+61 is studied using the raw data gathered from ~ 16 years RXTE monitoring campaign. Following the data reduction procedure described in Section 3.2, the data is filtered and the time series are converted to the barycenter. The lightcurve generated for a time interval between MJD 51610-55720 is held subject to pulse timing analysis (excluding glitch episodes) by using the timing solution of [84]. As a result of pulse timing analysis, pulse TOAs are re-generated for 4U 0142+61. Afterwards, by evaluating the slope between sequential pulse TOAs, the TOA measurements are converted to the pulse frequency measurements. The resulting pulse frequency history of 4U 0142+61 is demonstrated in Figure 4.2 left panel.

The pulse frequency history of 4U 0142+61 (Figure 4.2 left panel) covers almost ~ 4000 days and has sufficient data sampling rate for investigating noise strength variations on different timescales. Using the noise strength evaluation procedure described in Section 3.3, firstly the timing noise strength is calculated for the maximum available time span of ~ 4000 days. Then the calculations are repeated for smaller time segments down to ~ 468 days on which the noise strength amplitude coincides with instrumental noise level. In the -3.61 to -2.67 logarithmic analysis frequency range, the noise strength values reside in bracket $9.31 \times 10^{-24} \text{ s}^{-3}$ to $4.69 \times 10^{-23} \text{ s}^{-3}$. The power density spectrum of the pulse frequency fluctuations is obtained by distributing the calculated noise strength values to their corresponding analysis-frequencies. The constructed power density spectrum of this magnetar is shown in Figure 4.2 (right panel). The noise structure of the source is consistent with a white noise component and the level of timing noise is unusually low. Interestingly, 4U 0142+61 exhibits quiet timing behaviour between glitch events, compared with other magnetars, and its spin evolution is represented by low-order polynomials [84] despite the fact that it has had four active phases (to date) and it possesses a high magnetic field value $B \simeq 10^{14} \text{ G}$.

4.1.3 SGR 0418+5729

SGR 0418+5729 was discovered in June 2009 while exhibiting SGR-like bursts [171]. Its X-ray luminosity has reached approximately $\sim 10^{34} \text{ erg/s}$ during its outbursts in 2009 and resides at a distance of $\sim 2 \text{ kpc}$ [172], [171]. SGR 0418+5729 has a pulse

period of ~ 9.1 s and a pulse derivative of $\sim 4 \times 10^{-15}$ s/s [15]. Using the $P - \dot{P}$ relation 1.17, the inferred dipole magnetic field is estimated to be $\sim 6 \times 10^{12}$ G; far lower than the quantum critical level (i.e. $B_{\text{qed}} \sim 4.4 \times 10^{13}$ G) and it is the lowest value among magnetars. Even though many different models have been proposed to explain its behavior (e.g. [173], [174], [175], [176]), it is still blurry how SGR 0418+5729 exhibits SGR-bursts.

In this thesis, the archival RXTE, SWIFT, CHANDRA and XMM-Newton observations (between MJD 54993-56858) are used for extracting lightcurves. For each observatory, associated data reduction procedures are performed for data screening (see Section 3.1 for details). The barycentric lightcurve generated through this process is examined with pulse timing analysis. The pulse TOAs are re-generated by utilizing the timing solution presented by [15].

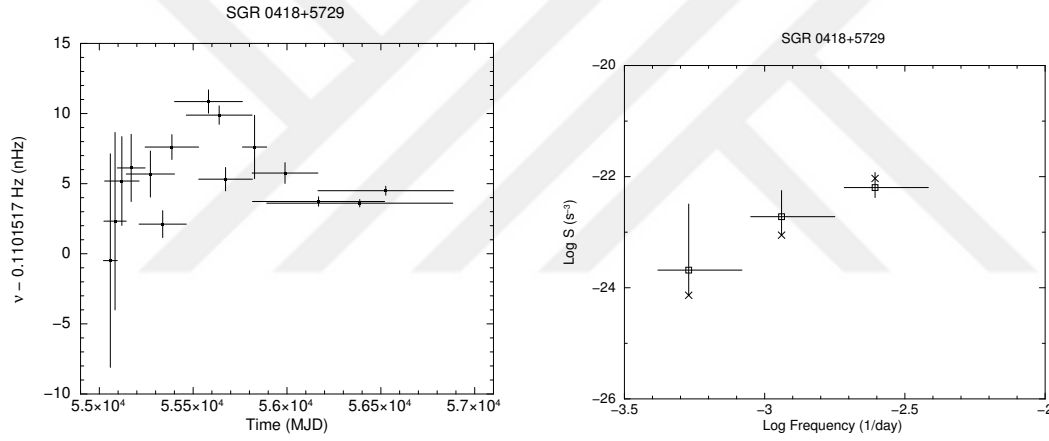


Figure 4.3: Frequency history and power density spectrum of SGR 0418+5729. See Table 5.1 for references.)

The slow slow-down rate of this magnetar makes it possible to achieve long-term phase-coherent timing solution. Identical to the procedure applied for other magnetars, pulse TOA measurements are transformed to pulse frequency measurements by fitting a linear model to the successive pulse TOAs. The pulse frequency history obtained for SGR 0418+5729 comprise 1865-days long interval (Figure 4.3 left panel).

The pulse frequency history SGR 0418+5729 is then used to calculate the timing noise strength for three time intervals, $T_1 = 1865$ days, $T_2 = 870$ days and $T_3 = 404$

days, respectively. The limited sampling rate of pulse frequency measurements do not allow to estimate noise strength at lower timescales. The power density spectrum of SGR 0418+5729 generated from those noise strength measurements is demonstrated in Figure 4.3 (right panel). The level of timing noise of SGR 0418+5729 is very low; altering from $\sim 6.37 \times 10^{-23} \text{ s}^{-3}$ to $\sim 2.08 \times 10^{-24} \text{ s}^{-3}$ and approximately scaling up with instrumental noise level. Such a low-level noise behavior for SGR 0418+5729 is indeed expected since the source has a very low spin-down rate [15]. On the other hand, the power-density spectrum lacks the red noise contribution that shall arise from SGR-like bursts.

4.1.4 SGR 0501+4516

SGR 0501+4516 is a transient magnetar discovered on August 22, 2008 during when it exhibited a number of bursts and flares which triggered BAT onboard SWIFT observatory [177]. It pulsates every $\sim 5.7 \text{ s}$ which gradually spin-down at the rate of $\sim 5.9 \times 10^{-12} \text{ s/s}$, leading to dipolar magnetic strength estimate of $\sim 2 \times 10^{14} \text{ G}$ [178], [179]. In addition to its pulsations in X-rays, SGR 0501+4516 is also been detected to pulsate in the optical band [100]. Timing properties of this SGR have been examined thoroughly by [180] using the observational data of various satellites.

In this work, the light curve of SGR 0501+4516 is created using archival data of

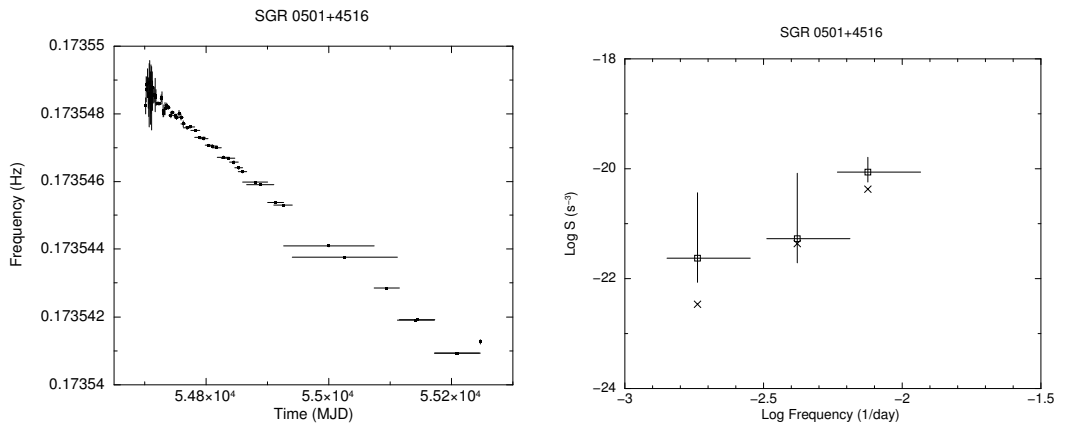


Figure 4.4: Frequency history and power density spectrum of SGR 0501+4516. See Table 5.1 for references.)

RXTE, SWIFT and XMM-Newton observatories. The photon arrival times were bary-centered and then subjected to pulse timing analysis using the timing parameters introduced in [180]. After the re-generation of pulse TOAs, the slope of each successive pulse TOA measurement was utilized to assemble the pulse frequency history (see Figure 4.4 left panel).

The obtained pulse frequency history of SGR 0501+4516 covers 547 days between MJD 54701 - 55248 and contains enough number of measurements to conduct noise analysis for smaller timescales. Hence the noise strength analysis of SGR 0501+4516 is carried out in a time-range of 547 to 130 days after which the instrumental noise becomes more dominant. In this range, measured noise strength values alters in between $\sim 2.36 \times 10^{-22} \text{ s}^{-3}$ and $\sim 8.68 \times 10^{-21} \text{ s}^{-3}$. The power density spectrum produced from those noise strength measurement is shown in Figure 4.4 (right-panel). SGR 0501+4516 exhibits rather low timing noise level and the power density spectrum of SGR 0501+4516 track the noise levels of measurements, except for only one significant power estimates at the low analysis frequency. Therefore, further observations are required to resolve actual noise behavior of SGR 0501+4516.

4.1.5 SGR 0526-66

In March 5th, 1979, astronomers witnessed a giant flare event which led to the discovery of a new type of stars (that constitutes the focus of this thesis study) called Soft Gamma-Ray Repeaters (SGR) (i.e. magnetars). The source that exhibited this famous event is now known as SGR 0526-66. In the tail of the giant flare there were recorded pulsations of $\sim 8.1 \text{ s}$ [45]. After this event, SGR 0526-66 went into a quiescence phase to re-activate again in 1994, when it was re-detected with ROSAT satellite [181]. The period derivative and its dipole magnetic field strengths are estimated to be $\sim 3.8 \times 10^{-11} \text{ s/s}$ and $\sim 5.6 \times 10^{14} \text{ G}$, respectively [182].

There are very few observations of this magnetar and the pulse frequency measurements of this observations are reported in the literature [45], [181], [183],[182], [184]. In this work, the pulse frequency history of SGR 0526-66 is constructed using the existing measurements (see Figure 4.5). The pulse frequency history of the source has a very low sampling rate and covers a time span of 3500 days.

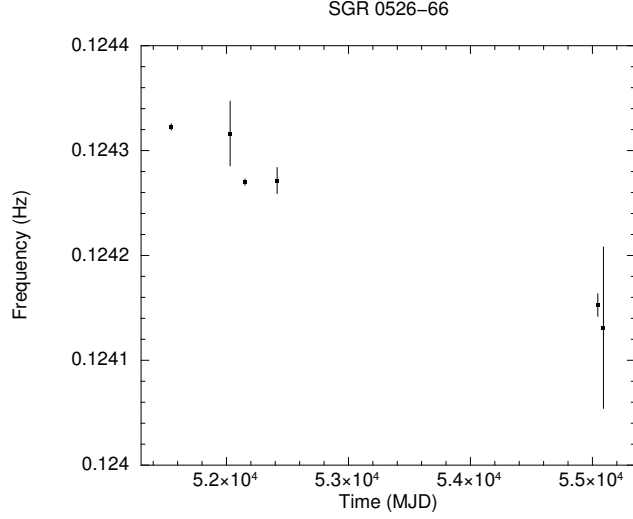


Figure 4.5: Frequency history of SGR 0526-66. See Table 5.1 for references.)

Since the pulse frequency history of SGR 0526-66 is composed of only six pulse frequency measurements over a very long time span (i.e. ~ 3500 days), the sampling rate of measurements is inadequate for constructing a power-density spectrum. Therefore, the timing noise strength is calculated for only the maximum time span of the available data and the result yields a noise strength value of $1.23 \times 10^{-17} \text{ s}^{-3}$. Regarding its timing noise behavior on different time scales, more observations are required to unveil its red or white noise components.

4.1.6 1E 1048.1-5937

1E 1048.1-5937 is an AXP that resides in Carina Nebula, pulsates every ~ 6.5 s and is located ~ 9 kpc away from Earth [48], [168]. Its behavior is very anomalous even among magnetars. Being part of the RXTE-SWIFT monitoring campaign, 1E 1048-5937 has been monitored frequently and regularly since late 1996 until 2018. Early timing analyses showed that the source exhibits very noisy pulse TOAs, hence phase-coherent timing could not be maintained for intervals of more than a few weeks [150]. During the monitoring campaign, 1E 1048.1-5937 has shown to be the most active magnetar with its four flux-flares (relatively long-term) and several bursting events accompanied by pulse profile changes. The most prominent feature of this magnetar is the drastic changes of the spin-down rate immediately after the outburst episodes

[185], [84], [186], [187]. In addition, the extreme variations of torque in very short timescales after every detected flux flare ([186]) still remains as an unexplained characteristic of 1E 1048-5937. This magnetar has experienced three main active phases in 2001-2004, 2007 and 2016-2017. However, its quiescence phase is also more ‘active’ compared to other magnetars. During the 2007 active phase, 1E 1048-5937 exhibited the biggest glitch event known among magnetars [102], [188].

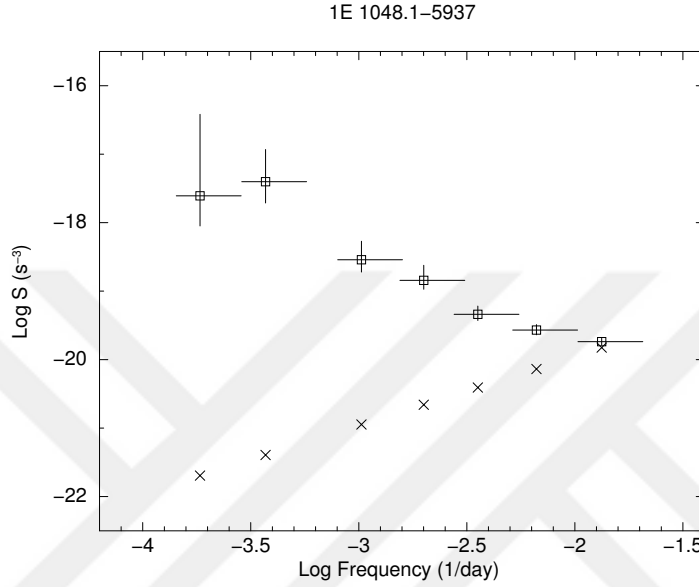


Figure 4.6: Power density spectrum of 1E 1048.1-5937. See Table 5.1 for references.)

As mentioned above, the coherent timing solutions of this source cannot be established for long time periods [150], [84]. Therefore, the timing analysis of 1E 1048.1-5937 is usually carried out using a different technique: by using the short-time spline-fittings to the pulse TOAs (the same technique is also applied for magnetar 1E 1547.0-5408). Dib & Kaspi [84] used 16 years of data gathered during RXTE monitoring campaign and reported the pulse frequency measurements for 1E 1048.1-5937 obtained with the spline-fitting technique. In this work, the frequency evolution presented by [84] are directly used (see Figure 5a of [84]).

Excluding the reported glitch intervals [102], [188], the pulse frequency history is investigated in terms of timing noise strain as outlined in Section 3.3. The sampling rate of measurements during its ~ 5400 days-long monitoring campaign is adequate for noise analysis at lower timescales. Hence, the timing noise analysis is resumed down to the time scale of ~ 150 days. In the range of 5400 to 150 days, noise strength

values alter between $\sim 2.46 \times 10^{-18} \text{ s}^{-3}$ to $2.70 \times 10^{-20} \text{ s}^{-3}$. The shape of the power density spectrum (Figure 4.6) is in agreement with flicker type red noise structure of power index -1.00 ± 0.22 . The red noise component of 1E 1048.1-5937 is possibly a result of the rather more ‘active’ quiescence episodes [84]. The footprints of red noise structure persist for time scale of ~ 2000 days. Beyond this time scale, the shape of the power density spectrum flattens and the timing noise becomes whiter.

4.1.7 1E 1547.0-5408

1E 1547.0-5408 is a transient magnetar discovered in 1980 [189]. With a spin-period $\sim 2.069 \text{ s}$, it is the second fastest rotating magnetar known to date and it is also the first magnetar whose period was detected in radio energy band [190]. The pulse signals in X-rays were not detected until 2007, when Halpern et al. [191] reported that the source was in a recovering phase, probably from an X-ray outburst activity. 1E 1547.0-5408 is possibly the most active transient magnetar in its class, exhibiting many radiative events such as outburst and SGR-like bursts (see e.g. [192], [193], [194], [195]). The timing behavior of 1E 1547.0-5408 is studied in detail by [196] for an interval of ~ 500 days including the outburst events. They reported that a phase-coherent solution could be obtained for only two short intervals of less than one month period. They also resolved the spin-down rate of the source to be $\sim 4.77 \times 10^{-11} \text{ s/s}$, inferring a magnetic field strength of $\sim 3.2 \times 10^{14} \text{ G}$ (see Section 1.17).

Similar to 1E 1048.1-3947, the timing properties of magnetar 1E 1547.0-5408 do not allow a long term phase coherent timing solution [196], [197]. Therefore, the pulse frequency measurements of 1E 1547-5408 are conducted through various techniques that include Z_1^2 tests, incoherent timing model and short-term phase coherent ephemerides [197].

In this thesis study, the existing pulse frequency history of 1E 1547-5408 presented by [197], which extends to ~ 810 days, is directly used for noise strength analysis. Fortunately, the data sampling rate of 1E 1547-5408 is very high, therefore, the timing noise strength calculations are re-iterated for timescales down to ~ 24 days on which the instrumental noise levels starts to dominate the actual noise strength estimates. Within this time interval, the noise strength values of 1E 1547.0-5408 reside

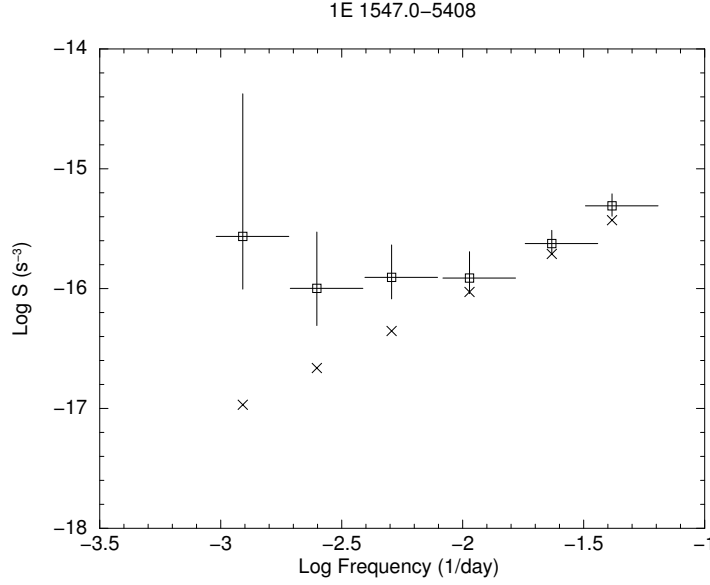


Figure 4.7: Power density spectrum of 1E 1547.0-5408. See Table 5.1 for references.)

in $\sim 4.90 \times 10^{-16} \text{ s}^{-3}$ and $\sim 1.00 \times 10^{-16} \text{ s}^{-3}$ range. The power density spectrum, generated via the distribution of noise strength estimates as function of analysis frequencies, is presented in Figure 4.7. In general the timing noise floor of this magnetar is rather high (of the orders of 10^{-16} s^{-3}) probably due to its ‘active’ nature and high spin down rate. The shape of the power density spectrum is rather flat and consistent with white noise model except when exhibits a marginal excess noise at the lowest analysis frequency. After its outburst in 2009, the spin-down rate of 1E 1547.0–5408 approximately receded back to its value at 2007 [196], hence, excess noise appeared only on the lowest frequency. For shorter time-scales, $\dot{\nu}$ fluctuations yield a white noise component. Considering that the timing properties of 1E 1547.0-5408 significantly resembles to 1E 1048.1-3947, the 1E 1547.0-5408 is also expected to possess a red noise structure; however, it should possibly arise at longer timescales than the time-coverage of the pulse frequency history used in this work.

4.1.8 PSR J1622-4950

PSR J1622-4950 is discovered by [109] using Parkes radio telescope observations. Regular pulsations of PSR J1622-4950 has a periodicity of $\sim 4.3 \text{ s}$. Being a transient source, it faded away and become undetectable from 2014 to 2017. After 2017, it re-

detected again by exhibiting a burst [198]. Similar to other magnetars which emit in radio-band, PSR J1622-4950 also is characterized by a flat spectrum, unsteady pulse profile and density flux [199]. Owing to its nature, PSR J1622-4950 has scarcely been observed. Thus, the pulse period of PSR J1622-4950 has not been tracked continuously enough for a timing noise analysis.

4.1.9 SGR 1627-41

SGR 1627-41 is a magnetar discovered in 1998 when it underwent a bursting phase, which lasted less than two months [200]. Following this bursting activity, the flux of the source decreased continuously until it reached the lowest luminosity ever seen in a SGR [201]. In 2008, SGR 1627-41 entered another bursting phase during which it exhibited several short bursts, characteristics of which were comparable with the ones detected a decade earlier [201]. The spin period and spin-down rate of this magnetar are ~ 2.59 s and $\sim 1.9 \times 10^{-11}$ s/s, respectively [202]. The magnetic field of SGR 1627-41 is estimated to be $\sim 2.2 \times 10^{14}$ G. Unfortunately, SGR 1627-41 is scarcely observed and there are not enough pulse frequency measurements to conduct a reliable noise strength measurement.

4.1.10 CXO J164710.2-455216

CXO J164710.2-455216 is a transient magnetar discovered in 2006 during an outburst episode with BAT onboard SWIFT [203]. It resides in Westerlund 1 stellar population at a distance of $2.5 - 5$ kpc and pulsates at rate of 10.6 s [204]. The period derivative of CXO J164710.2-455216 is not known precisely, however reported upper limit is $\sim 4 \times 10^{-13}$ s/s, implying a dipole magnetic field upper limit value of 10^{13} G [205]. The X-ray luminosity of the source is in the order of $\sim 3 \times 10^{33}$ erg/s [204], [206]. Using the data of Very Large Telescope, Testa et al. [207] has reported a possible infrared emission which is yet to be confirmed.

In this work, the CXO J164710.2-455216 is studied using the raw data gathered by SWIFT, Chandra and XMM-Newton. For all the observations, the data are screened via the data reduction procedure delineated in Section 3.1. The lightcurve generated

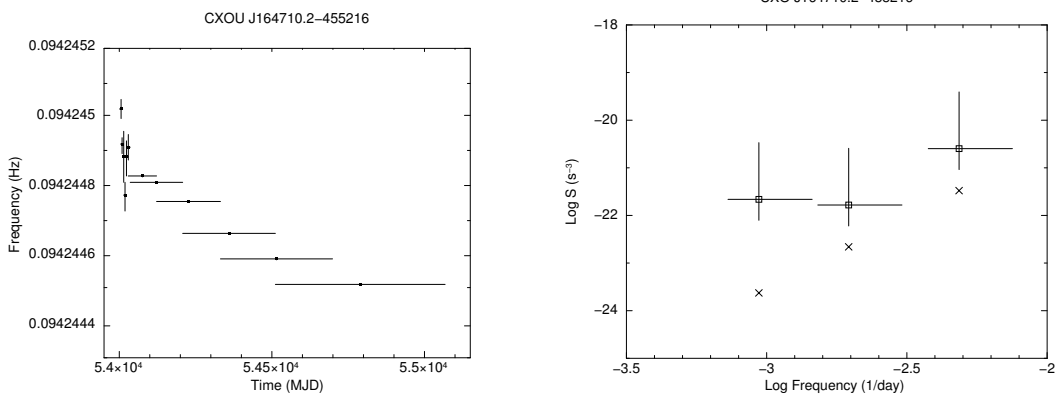


Figure 4.8: Frequency history and power density spectrum of CXO J164710.2-455216. See Table 5.1 for references.)

by this process is held subject to pulse timing analysis by taking advantage of the timing solution presented by [206]. The obtained pulse TOAs cover a time interval of 1066 days between MJD 53994 and 56060. Then, pulse TOA measurements are converted into pulse frequency measurement by utilizing the recurrent linear model fitting technique described in Section 3.2. The pulse frequency history, generated from the slope of pulse TOAs, are illustrated in Figure 4.8 (left panel).

Even though the pulse frequency history of CXO J164710.2-455216 has a fair time coverage, the sampling rate of measurements is limited. Following the procedure described in Section 3.3, the timing noise strength of CXO J164710.2-455216 is only calculated for time spans $T_1 = 1066$ days, $T_2 = 510$ days and $T_3 = 206$ days because density of measurements for a lower timescale is not suitable for polynomial fitting. The distribution of calculated noise strength versus analysis-frequencies is represented in Figure 4.8(right panel). In the power density of pulse frequency fluctuations, the noise strength varies in between $\sim 1.66 \times 10^{-22} \text{ s}^{-3}$ to $\sim 2.53 \times 10^{-21} \text{ s}^{-3}$. CXO J164710.2-455216 has a flat power density spectrum with ~ 0 power law index, thus the pulse frequency derivative fluctuations of this magnetar are in accord with white noise within the given analysis frequency range.

4.1.11 1RXS J170849.0-400910

AXP 1RXS J170849.0-400910 is a ROSAT discovered source in 1996 [208]. It pulses every ~ 11 s and has an period derivative of $\sim 2 \times 10^{-11}$ s/s which implies a B-field of $\sim 4.7 \times 10^{14}$ G [168]. This magnetar is observed 525 times with RXTE satellite in a time period of 14 years. Analyzing those observations, it is seen that 1RXS J170849.0-400910 is a frequent glitching source [209], [210], [211], [212], [213].

In this thesis study, a glitch free interval of ~ 2000 days is selected for timing studies of AXP 1RXS J170849.0-400910. All the RXTE observations during this interval (MJD 52400-54400) is held subject to the data reduction process specified in Section 3.2. The phase coherent timing technique is applied for the lightcurve in the selected interval by using the timing solution presented by [63] (see Ephemeris C and F of [63]). The TOAs re-generated by this process are converted to the pulse frequency measurements by fitting a linear models to each 3 subsequent TOAs. The pulse frequency evolution of AXP 1RXS J170849.0-400910, which is composed through recurrent TOA fitting procedure, is illustrated in Figure 4.9 (left panel).

For AXP 1RXS J170849.0-400910, the timing noise amplitude at various timescales are estimated by following the analysis procedure defined in Section 3.3 and 4.1. The time scales of noise calculations ranges from ~ 2000 days to ~ 260 days during

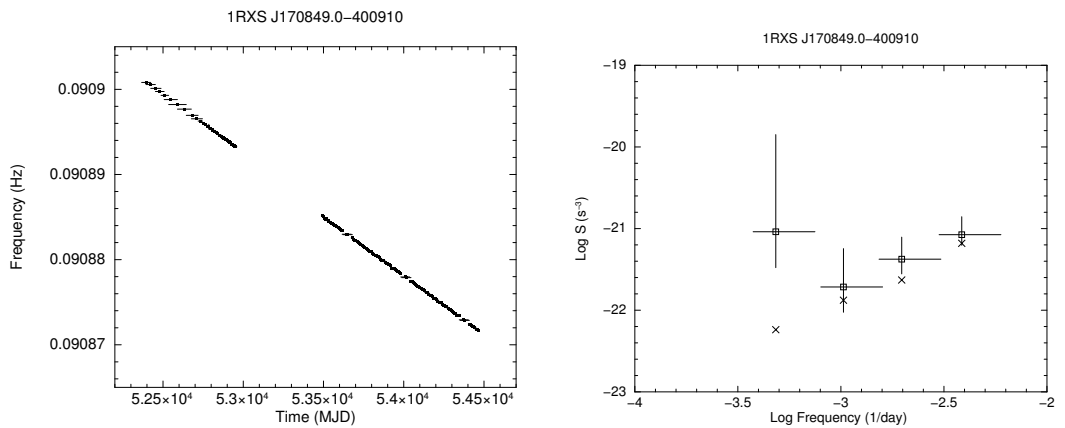


Figure 4.9: Frequency history and power density spectrum of 1RXS J170849.0-400910. See Table 5.1 for references.)

which the noise level varies in between $1.93 \times 10^{-22} \text{ s}^{-3}$ and $9.14 \times 10^{-22} \text{ s}^{-3}$ as shown in Figure 4.9(right panel). Similar to the noise structure of 1E 2259+586, AXP 1RXS J170849.0-400910 only exhibits a significant noise level on the highest time scale and the rest of the noise amplitude measurements almost matches with instrumental noise level. Due to lack of observations to cover much longer time scales, the red noise component at low analysis-frequencies can not be determined, yet.

4.1.12 CXOU J171405.7-381031

CXOU J171405.7-381031 was discovered to be residing in the supernova remnant CTB 37B during a galaxy survey in 2006 [214]. This source had not been categorized until 2009 when [215], using Chandra observations, detected its $\sim 3.8 \text{ s}$ pulsations and classified it to be an Anomalous X-ray Pulsar. Later in 2010, the spin-down rate of this source was measured to be $\sim 6.4 \times 10^{-11} \text{ s/s}$ using the XMM-Newton observations which re-ensured the magnetar nature of CXOU J171405.7-381031 ([216]). Using the rotating dipole radiation approximation (equation 1.17), estimated magnetic field strength is $\sim 5 \times 10^{14} \text{ G}$ ([216]).

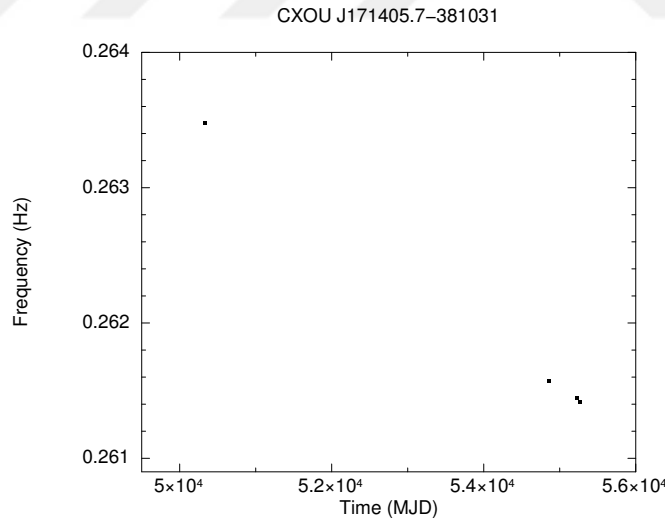


Figure 4.10: Frequency history of CXOU J171405.7-381031. See Table 5.1 for references.)

Unfortunately, CXOU J171405.7-381031 has been infrequently observed over the years. In literature, there are only four reported pulse frequency measurements ([216];

[215]). The pulse frequency history of CXOU J171405.7-381031 is compiled via those existing measurements. The total time coverage of the pulse frequency measurements is 370 days (Figure 4.10).

Similar to the case of SGR 0526-66, pulse frequency measurements of CXOU J171405.7-381031 do not have enough sampling rate to carry out timing noise analysis on different time-scales. Hence, the timing noise amplitude can only be estimated for the maximum available time-span (~ 370 days) which results in a noise strength value of $2.34 \times 10^{-17} \text{ s}^{-3}$. For CXOU J171405.7-381031, further pulse frequency measurements are needed to build a more comprehensive picture on analysis-frequency dependency of its noise structure.

4.1.13 SGR J1745-2900

SGR J1745-2900 was discovered while displaying SGR-like burst of few milliseconds [217]. It is located in the constellation Sagittarius A*, only four angular second away from central supermassive blackhole of our Milky Way Galaxy. It is thought to be 8.3 kpc away from Earth and it has an X-ray luminosity of $\sim 5 \times 10^{35} \text{ erg/s}$ [218]. The regular $\sim 3.76 \text{ s}$ pulsations of magnetar SGR J1745-2900 were detected in both X-ray and Radio wavelengths [219], [114], [220]. The spin-down rate of SGR J1745-2900 is determined to be $1.385 \times 10^{-11} \text{ s/s}$, implying a dipolar magnetic field strength of $2.3 \times 10^{14} \text{ G}$ [220].

Using the archival observations of Chandra, XMM-Newton and SWIFT observatories, a barycentered lightcurve for SGR J1745-2900 is extracted for a time interval between MJD 56416 - 56929. Then the pulse TOAs for SGR J1745-2900 are recreated by making use of the timing solution presented by [220], [221]. The slope between each successive pulse TOAs are evaluated with an aim of converting TOAs in the pulse frequency measurements. The pulse frequency history obtained from this procedure is illustrated in Figure 4.11(left panel).

The created frequency history of SGR J1745-2900 has a time span of ~ 500 days and has a rich sampling rate. Following the noise analysis routine depicted in Section 3.3, initially the timing noise strength for maximum time span is measured. Then, by

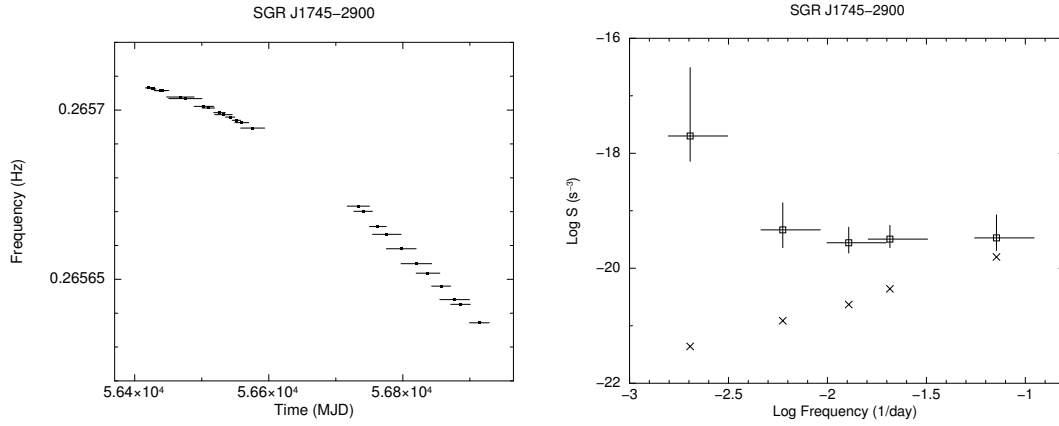


Figure 4.11: Frequency history and power density spectrum of SGR J1745-2900. See Table 5.1 for references.)

halving the time segments, the noise calculations are repeated until it matches the instrumental noise level (at ~ 14 days). For each analysis frequency, the noise strength measurements were logarithmically re-binned into one single power estimate. The power estimations are situated in between $\sim 2.00 \times 10^{-18} \text{ s}^{-3}$ and $\sim 2.78 \times 10^{-20} \text{ s}^{-3}$. The power density spectrum of SGR J1745-2900 is in the form of a white noise except from one high-noise strength measurement at the lowest analysis frequency (see Figure 4.11 right panel). The white noise floor is rather high: staying constant around $\sim 3 \times 10^{-20} \text{ s}^{-3}$. This may imply a red noise formation at longer timescales when considered together with the excess power density estimate at the longest time scale.

4.1.14 SGR 1806-20

Soft Gamma-Ray Repeater 1806-20 was discovered in 1979 [222] and, using the RXTE data, it was found to pulsate every ~ 7.55 seconds [223]. It has a period derivative of $\sim 4.9 \times 10^{-10} \text{ s/s}$ and its estimated dipole magnetic field strength is of the orders of $\sim 10^{15} \text{ G}$ [224]. This SGR is the most active among other sources of the same category and has continuously exhibited radiative behavior since its discovery. The most active phase of SGR 1806-20 was in between 2003-2004 when it exhibited many burst and the most energetic Giant Flare know to date [225], [226], [224].

SGR 1806-20 has been observed with many X-Ray observatories over the years

and its pulse frequency evolution is tracked through those observations [227], [228], [229], [225], [226], [224], [230] [231], [232]. In this work, the pulse frequency history of SGR 1806-20 is created using all the available frequency measurements found in the literature. The pulse frequency history of the source (illustrated in Figure 4.12 left panel) extends to a time interval of 4500 days.

Woods et al. [228] constructed a phase coherent timing solution and a power density spectra of SGR 1806-20 for a time period of ~ 150 days. In their work, it is reported that the timing noise behavior of the source is characterized by a steep red noise structure. In this dissertation, the pulse frequency measurements are extended for a time interval of ~ 4500 days using the measurements reported in literature. Even though SGR 1806-20 is observed frequently over the years, the time gap between observations does not allow the construction of a coherent phase timing for the whole time span of available frequency measurements. Implementing the same procedure for the noise analysis, the timing noise strength is firstly calculated for the maximum time interval (i.e. $T \simeq 4500$ days) and then repeated for smaller time scales ($T/2, T/4, T/8$ and $T/16$) until when timing noise strength becomes comparable with measuremental noise level at $T \simeq 197$ days. By mapping the calculated noise strength values with their corresponding analysis-frequencies, the power density spectra of SGR 1806-20 is obtained as presented in Figure 4.12 (right panel). Within the referred analysis-frequency range, the timing noise strength values of this

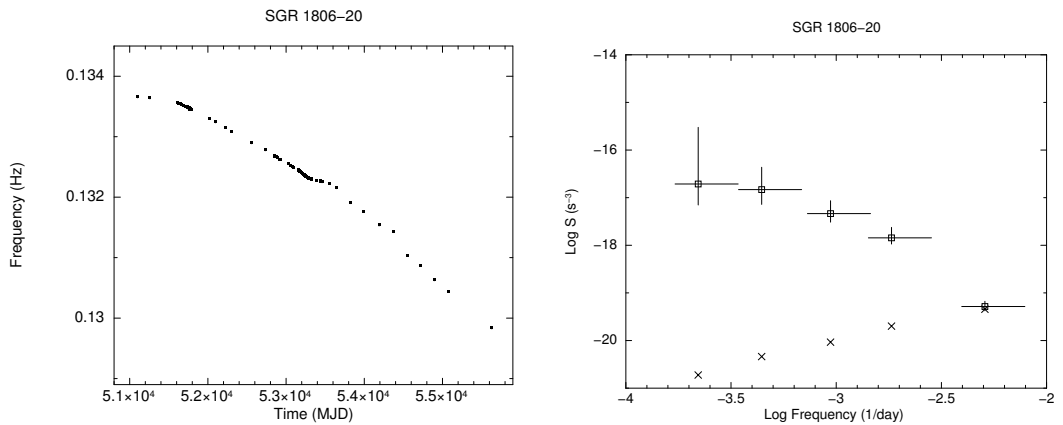


Figure 4.12: Frequency history and power density spectrum of SGR 1806-20. See Table 5.1 for references.)

magnetar alter from $\sim 1.30 \times 10^{-18} \text{ s}^{-3}$ to $\sim 1.94 \times 10^{-17} \text{ s}^{-3}$. As can be inferred from Figure 4.12, SGR 1806-20 has a red noise structure in shorter time scales which tends to be whiter in longer time scales. In the previous power density estimates, [228] reported that the red noise structure is extremely steep and have power law index of -3.6 ± 0.7 for a time scale up to ~ 150 days. The power density spectrum generated in this work is fully consistent with the spectrum reported by [228] for short time scales. As this work extends the noise measurements up to timescales of ~ 4500 days, the timing noise structure is comprehensively revised. It is seen that the effect of red noise is significantly reduced on long time scales and the overall power law index diminishes to -2.58 ± 0.46 . This result implies that contribution of SGR 1806-20 outbursts are substantially influential on short-timescale noise structure.

4.1.15 XTE J1810-197

XTE J1810-197 is the first magnetar discovered to have a transient nature and it was detected during an outburst it exhibited in 2003 [233]. Initial observations reveal that XTE J1810-197 rotates at a period of $\sim 5.5 \text{ s}$ [233] and later observations indicate that the source's period is slowing down at a rate of $\sim 0.77 \times 10^{-11} \text{ s/s}$ [234]. XTE J1810-197 is also the first magnetar to be observed to emit in the radio energy band [235], [107].

Over the years, XTE J1810-197 has also been observed with various satellites such as Chandra and XMM-Newton and the pulse frequency measurements corresponding to this distinct observations were reported by different authors [236], [235], [237], [238]. In this study, a pulse frequency history of this magnetar covering approximately 4200 days is compiled by gathering the measurements reported in the literature (see Figure 4.13 left panel).

The pulse frequency history of XTE J1810-197 is extensive enough to estimate its timing noise strength for a relatively long time interval of $T = 4200 \text{ d}$ and fortunately, the data sampling rate is adequate for noise estimations at shorter time scales (i.e. $T/2$, $T/4$ and $T/8$) as described in Section 3.2. At $T = 525 \text{ d}$ the timing noise value becomes comparable with that of the instrumental noise, therefore the minimum time scale for noise strength calculations is ceased at that value. The power density spec-

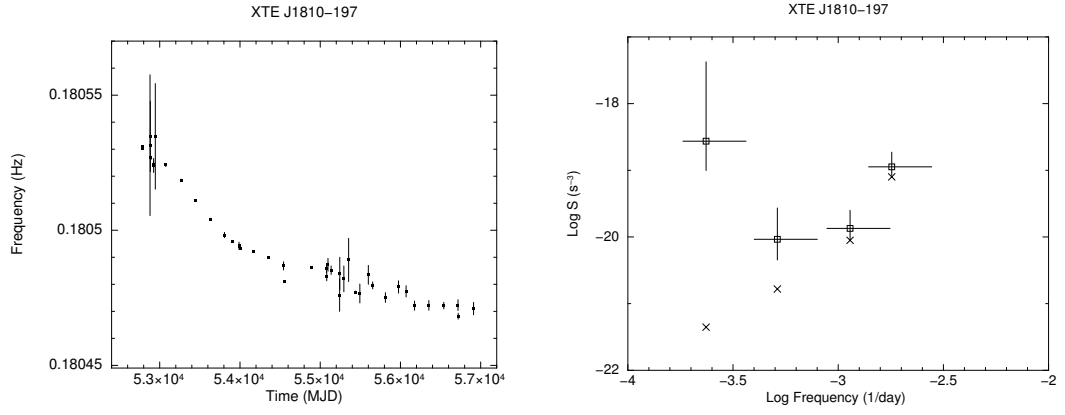


Figure 4.13: Frequency history and power density spectrum of XTE J1810-197. See Table 5.1 for references.)

trum of XTE J1810-197 is created by mapping the estimated noise strength values in accordance with their analysis-frequencies. Resulting power density spectrum of the pulse frequency fluctuations of XTE J1810-197 is presented in 4.13 (right panel). The maximum and minimum noise strength values estimated (in range of 525 to 4200 days) are $\sim 2.73 \times 10^{-19} \text{ s}^{-3}$ and $\sim 9.22 \times 10^{-21} \text{ s}^{-3}$, respectively. As can be seen from the figure 4.13, XTE J1810-197 is characterized by a steep red noise component in its longest time-scale, and a flattened structure of white noise in shorter time-scales. Nevertheless, further data and analysis are required in order to define the noise structure of this source more precisely.

4.1.16 Swift J1818.0-1607

Swift J1818.0-1607 is the newest confirmed member of magnetar class. It was discovered on March 12, 2020 with SWIFT observatory [239]. Using SWIFT and NICER observations, [240] discovered the pulse period of the source be 1.36 s, making it the shortest pulse period among magnetars. Its spin-down period is estimated to be $8.2 \times 10^{-11} \text{ s/s}$ implying a B-field strength and characteristic age of $B \sim 6.8 \times 10^{14} \text{ G}$ and $\sim 300 \text{ yr}$, respectively [241]. Swift J1818.0-1607 has also been detected in radio energy band, making it the fifth source among magnetars [112]. Unfortunately, there is no frequency history data of Swift J1818.0-1607 to perform timing analysis and extract power density spectrum, yet.

4.1.17 1E 1841-045

1E 1841-045 is an AXP discovered in 1985 [242]. It pulsates every ~ 11.8 s, has a period derivative of $\sim 4.1 \times 10^{-11}$ s/s and resides in the supernova remnant Kes 73 at a distance ~ 8.5 kpc [84], [243]. Using the equation 1.17, the estimated dipole magnetic field strength of 1E 1841-045 is $\sim 7.1 \times 10^{14}$ G. The very first timing behavior of this AXP was studied by [244] using BeppoSAX, Ginga, ROSAT, ASCA and RXTE archival data from 1993-1999. They showed that this source had a constant spin-down rate, an unvarying pulse profile and a persistent flux. Later studies also have shown similar characteristics of this magnetar's activity, except several radiatively quiet timing events (i.e. four glitches, one anti-glitch and two X-ray burst activities) [84], [245], [246].

1E 1841-045 has been observed 227 times with RXTE satellite over the time-period of MJD 51224-55587. During this period, three distinct radiatively quiet episodes are selected for analysis and the lightcurves corresponding to each episode is extracted using the data reduction routine described in Section 3.2. Those light curves are subjected to timing analysis using the timing parameters reported in literature [84]. Then, using the slopes of the linear models fitted to the successive TOAs (see Section 3.3 for details), time dependent pulse frequency evolution of the source is produced as seen in Figure 4.14 (left panel).

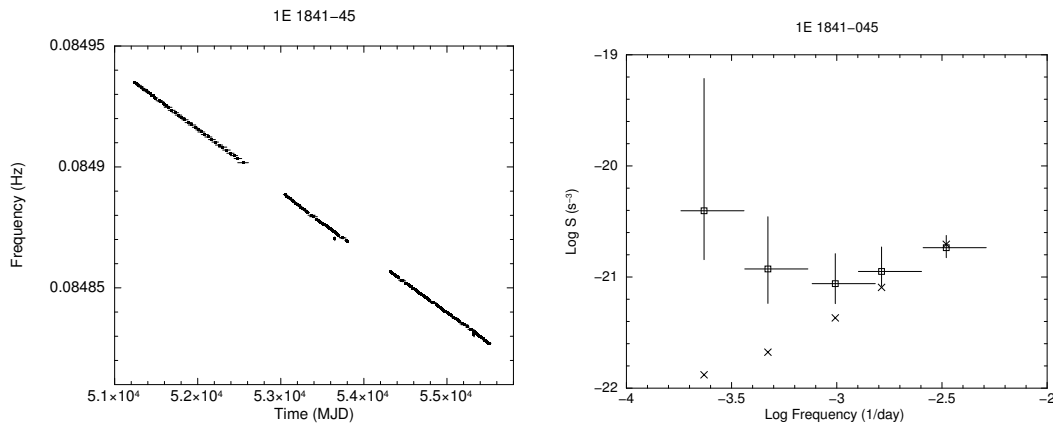


Figure 4.14: Frequency history and power density spectrum of 1E 1841-045. See Table 5.1 for references.)

The timing noise analysis of 1E 1841-045 is carried out using the pulse frequency history illustrated in Figure 4.14 (right panel) which covers ~ 4350 days of almost continuous measurements. The power density spectrum of pulse frequency fluctuations of 1E 1841-045 is generated by mapping the timing noise amplitude estimations at different timescales. The smallest timescale of the timing noise amplitude measurement is ~ 300 days (logarithmic analysis-frequency $f_a \sim -2.48$) where the timing noise level and instrumental noise level becomes comparable. Within the given time span, the timing noise amplitude ranges from $8.72 \times 10^{-22} \text{ s}^{-3}$ to $3.95 \times 10^{-21} \text{ s}^{-3}$. The shape of the power density spectrum suggests a red noise component for low analysis frequencies ($f_a < -3$). At rather high analysis frequencies ($f_a > -3$), the power density spectrum is flattened, resembling to a white noise structure, eventually matching with the instrumental noise level.

4.1.18 3XMM J185246.6+003317

3XMM J185246.6+003317 is an X-ray emitting source in the supernova remnant Kes 79 which was discovered using the XMM-Newton data [247]. Using initial observations of it, 3XMM J185246.6+003317 is shown to be rotating at a period of ~ 11.5 s and the spin-down rate of the source is reported to be lower than $< 1.4 \times 10^{-14}$ s/s [248]. Hence, using rotating dipole approximation, only an upper limit for the magnetic field strength can be interpolated as 4.1×10^{13} G [248]. Although, the aforementioned magnetic field is lower than the quantum critical level (i.e. $B_{QC} \sim 4.4 \times 10^{13}$ G), 3XMM J185246.6+003317 exhibits magnetar like behavior, such as burst, and therefore it is categorized as magnetar [248]. Interestingly, its X-ray luminosity in the quiescence phase is lower than that of other sources of the same class [248].

In this work, the pulse frequency history of 3XMM J185246.6-003317 is compiled through the existing measurements reported by [248] and [247]. Unfortunately, the pulse frequency measurements in the literature suffers both sampling rate and high measuremental uncertainties. The total time coverage of pulse frequency history is only 215 days (Figure 4.15). Therefore, the timing noise strength value is estimated only for the maximum time coverage (i.e. $T = 215$ d). The timing noise strength

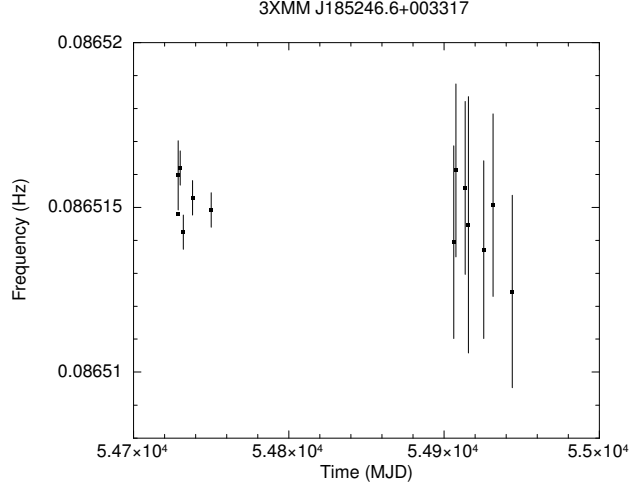


Figure 4.15: Frequency history of 3XMM J185246.6-003317. See Table 5.1 for references.)

of 3XMM J185246.6-003317 for this time scale is calculated to be $2.4 \times 10^{-24} \text{ s}^{-3}$. As mentioned above, the sampling rate of measurements is not suitable for creating a power density spectrum of pulse frequency fluctuations. Future observations of 3XMM J185246.6-003317 should be carried out more frequently to draw a better conclusion on the timing noise behavior of the source.

4.1.19 SGR 1900+14

Soft Gamma Repeater SGR 1900+14 was discovered in 1979 by Mazets et al. [249], making it one of the earliest discovered magnetars. This source is best known for the giant flares it exhibited in 1998 [46]. SGR 1900+14 was shown to pulse at a spin period of $\sim 5.2 \text{ s}$ [46] and slows down at a rate of $\sim 9.2 \times 10^{-11} \text{ s/s}$, leading to dipolar magnetic field estimate of $\sim 2 - 8 \times 10^{14} \text{ G}$ [250].

The phase coherent timing solution of the initial observations of RXTE satellite was constructed by Woods et al. [228]. They also examined the power density spectra of frequency fluctuations (for a time span of ~ 200 days) and reported that the noise spectrum is characterized by strong red noise strain. SGR 1900+14 is also observed by other X-ray observatories, for which the pulse frequency measurements are achieved through various techniques [228], [251], [252]; however, time gap between

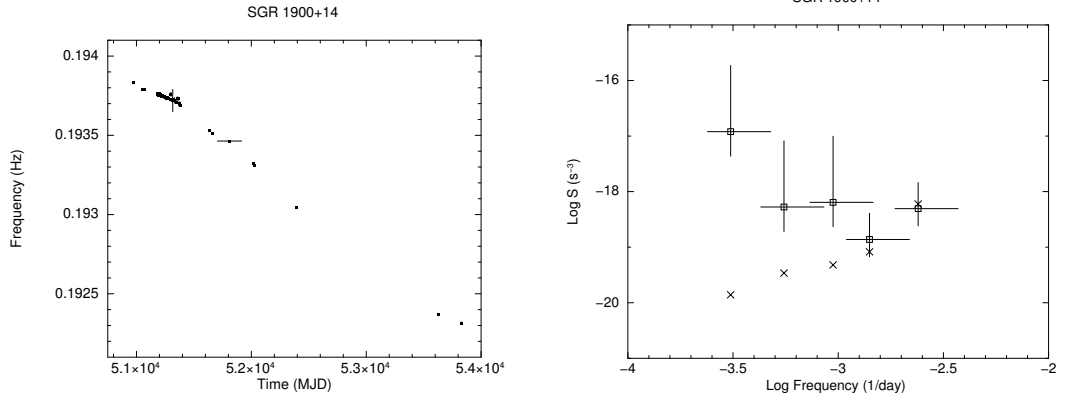


Figure 4.16: Frequency history and power density spectrum of SGR 1900+14. See Table 5.1 for references.)

those observations, in general, is very wide and the phase coherent timing is impossible (except for the initial observation sequence analyzed by [228]). In this study, existing pulse frequency measurements in the literature are combined into a total frequency evolution history (e.g. [228], [251]). The established pulse frequency history covers ~ 3245 days which is demonstrated in Figure 4.16 (left panel).

Similar to the other magnetars, the timing noise strength calculations of SGR 1900+14 starts from the maximum time scale of the constructed pulse frequency history. Since the data sampling rate of 3245 days of pulse frequency history is sufficient to calculate the noise amplitudes at lower timescales, the calculations are re-iterated till it coincides with the instrumental noise level at timescale of ~ 417 days. Distributing the noise strength amplitudes to their corresponding analysis-frequencies, the power density spectrum of the pulse fluctuations is created and shown at Figure 4.16 (right panel). Within this analysis-frequency range, noise strength level alters between $6.42 \times 10^{-19} s^{-3}$ and $1.20 \times 10^{-17} s^{-3}$. As it is stated above that the power density spectra was created by [228] with comparatively lower time coverage to this work and they reported that this magnetar had a red noise spectrum. In this work, power density spectra is extended for a longer time period and it is shown that SGR 1900+14 is still characterized by a red noise component in the longer timescales as well. In addition, the slope of the power density spectra of this pulsar is observed to be rather complicated because the power law index changes rapidly for the noise strength measurements for different time intervals and deviates from a well defined

structure. Nevertheless, the overall continuum of the power density spectrum carries a very steep red noise footprints with power law index of 2.61 ± 1.49 .

4.1.20 SGR 1935+2154

Magnetar SGR 1935+2154 was discovered during SWIFT detection of a short episode of soft gamma-ray burst in July 4, 2014 [253]. Posterior observations have shown that it has a period of $P = 3.25729$ s [254] and a spin-down period of 1.43×10^{-11} s/s [255]. Given the equations 1.17 and 1.21, the magnetic field and characteristic age can be inferred as $\sim 7 \times 10^{14}$ G and 3.6 kyr, respectively. SGR 1935+2154 underwent to an active phase in 2015 [255] and to another one very recently in 2020 [256].

In this work, SGR 1935+2154 is studied via archival observations taken by XMM-Newton and Chandra observatories. Adhere to the data reduction routine described in Section 3.1, a light curve between MJD 56853-57137 is created. In this work, the timing parameters published by [254] are used to re-construct the pulse TOAs. Afterwards, the slope of each successive pulse TOAs was calculated with an aim of generating the pulse frequency history of the source. The time span of the frequency measurements covers a time interval of 284 days (Figure 4.17 (right panel)).

The aforementioned generated pulse frequency history is then used to construct the power density spectrum of SGR 1935+2154 by implementing the procedure described

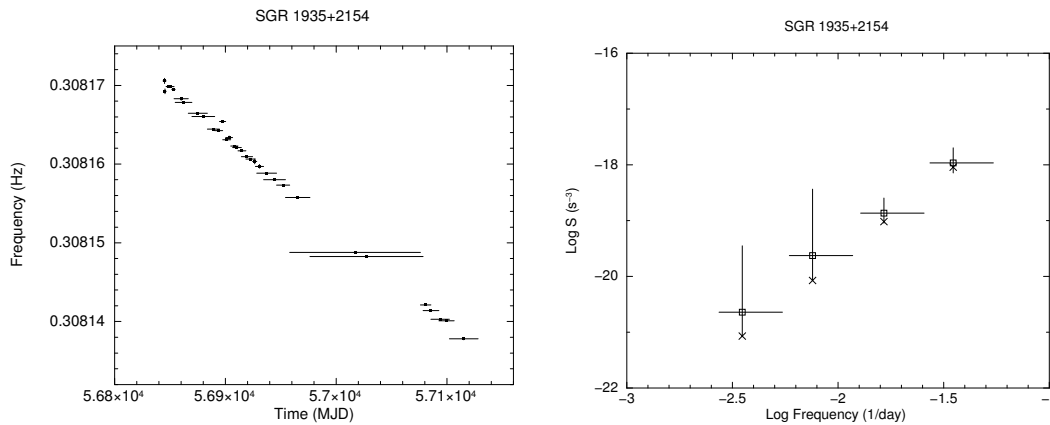


Figure 4.17: Frequency history and power density spectrum of SGR 1935+2154. See Table 5.1 for references.)

in Section 3.3. Videlicet, the timing noise strength value is initially estimated for the maximum time scale ($T = 284$ days), and then the calculations are re-iterated for halving segments ($T/2$, $T/4$ and $T/8$) until the noise strength value is matched with instrumental noise level at 28 days. The power density spectrum of pulse frequency fluctuations for SGR 1935+2154 is illustrated in Figure 4.17 (left panel). And for the given input time range, noise strength values of the source vary from $2.28 \times 10^{-21} \text{ s}^{-3}$ to $1.10 \times 10^{-18} \text{ s}^{-3}$. Even though, SGR 1935+2154 exhibited many bursts during its active phase in 2015 [255], the timing noise structure of SGR 1935+2154 follows the trend of instrumental noise levels.

4.1.21 1E 2259+586

1E 2259+586 is the first discovered AXP and among one of the most studied magnetars [47]. It resides in the SNR G109.1-01.0, has a spin period of ~ 7 s and slows down at a rate of $\sim 5 \times 10^{-13} \text{ s/s}$ [84]. The magnetic field strength of 1E 2259+586 is estimated through dipolar approximation expressed in equation 1.17 which yields $\sim 6 \times 10^{13} \text{ G}$ and it has an X-ray luminosity of $\sim 1.8 \times 10^{34} \text{ erg/s}$ ([257]. 1E 2259+586 has been monitored regularly for 16 years with RXTE with an average of one observation per 10 days. Within this long monitoring campaign, the source has been reported to exhibit glitching (anti-glitching) events several times [210], [258], [212], [259]. In fact, 1E 2259+586 is the first magnetar to show an anti-glitch episode [76].

In this work, 1E 2259+586 is studied using the raw data gather through RXTE observations which spans approximately 16 years. Using the data reduction procedure described in Section 3.1, the barycentric corrected lightcurve is generated from all observations. Then, utilizing the timing solutions presented by [84], the phase connected TOA series are re-generated (see Ephemeris A, B2, D of [84]). Afterwards, the time dependent frequency evolution of 1E 2259+586 is constructed by employing recurrent linear TOA fitting technique described in Section 3.2. This technique allows to estimate the pulse frequency at the mid-time of the TOA fitting range. Resulting pulse frequency history of 1E 2259+586 is illustrated in Figure 4.18 (right panel).

Omitting the reported glitch event contributions, the pulse frequency history of 1E

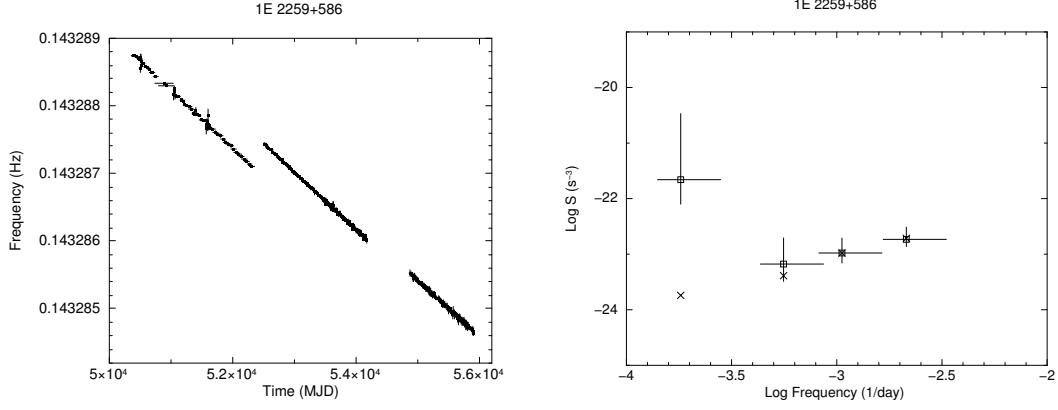


Figure 4.18: Frequency history and power density spectrum of 1E 2259+586. See Table 5.1 for references.)

2259+586 is held subject to the timing noise analysis described in Section 3.3 and 4.1. Starting from the maximum time coverage of the frequency measurements ($T \sim 5520$ days), the timing noise calculations are iterated for $T/2$ time intervals (i.e. $T, T/2, T/4, T/8$). The smallest timescale of timing noise amplitude that can be achieved for this data set is 446 days due to the dominance of instrumental noise at lower timescales. The constructed power density of the pulse frequency fluctuations are illustrated in Figure 4.18 (left panel). The timing noise amplitudes varies in the range of $6.64 \times 10^{-24} \text{ s}^{-3}$ to $2.2 \times 10^{-22} \text{ s}^{-3}$. The power density spectra of 1E 2259+586 shows that the source has a small timing noise level in the short intervals where it matches almost the instrumental noise level, however, in the longest time interval, the timing noise level increases considerably. Thus, it implies formation of possible red noise component at longer timescales which indeed requires further observations to be ascertained. It should be noted that even though the noise calculations are conducted for glitch free intervals, the pulse frequency history of the source has a spin frequency jump around $\sim \text{MJD } 52300$ (see Figure 4.18 (right panel) which is not recovered later on. Hence, the high level of timing noise in the longest timescale can also be an artifact of the not-recovered frequency jump.

4.2 ACCRETING PULSARS

The persistent accretion powered pulsars (PAPPs) are very well known sources because they have been observed on regular bases since their first discoveries in the early 70s. Currently, Fermi Gamma-ray Burst Monitor (GBM) performs follow-up observations of eight PAPPs, namely Her X-1, Vela X-1, GX 301-2, Cen X-3, 4U 1538-53, GX 1+4, OAO 1657-415 and 4U 1626-67. Based on FERMI-GBM data, pulse frequency and X-ray flux measurements of the aforementioned PAPPs are conducted by the National Space Science and Technology Center (NSSTC) in USA in association with Fermi GBM Pulsar Project.

Table 4.2: List of persistent X-ray pulsars and their properties.

Source Name	Class	$P_{orb}^{(a)}$ (days)	$P_{spin}^{(a)}$ (s)	$B/(1+z)^{(b)}$ (10^{12} G)	$L_X^{(c)}$ (10^{36} erg/s)
Vela X-1	sgHMXB-wind	8.964427(12)	283	2.1	1.3
Cen X-3	sgHMXB-RLO+wind	2.08704106(3)	4.8	2.6	4
Her X-1	LMXB-RLO	1.700167590(2)	1.237	3.5	20
GX 301-2	sgHMXB-wind	41.506(3)	684.1618	3	2.8
4U 1538-52	sgHMXB-wind	3.7284140(76)	526.8	2	0.92
4U 1626-67	LMXB-RLO	0.02917(3)	7.66	3.2	10

Notes:

(a) P_{orb} and P_{spin} values are taken from [260] (also see references therein)

(b) Magnetic field values are taken from [261] (also see references therein)

(c) L_X values of Vela X-1, GX 301-2, 4U 1538-52 and Cen X-3 are compiled from from [262] and L_X values of 4U 1626-67 and Her X-1 are taken from [69]

In this dissertation, the timing noise strength analysis is carried for six of PAPPs tracked by Fermi GBM using the pulse frequency histories generated by NSSTC team, since two of them have updated studies about their pulse frequency fluctuations (GX 1+4: [263] and OAO 1657-415: [264]). In this Section, analysis frequency dependent behavior of the timing noise of those PAPPs are investigated. The regular rotational evolution of PAPPs are represented in terms of second degree polynomials (i.e. up to $\ddot{\nu}$) and remaining pulse frequency residuals are examined for pulse

frequency fluctuations. The results are then compared with the timing noise measurements and their correlation of magnetars in order to investigate the noise behavior for different types of stars in the next Chapter.

4.2.1 Vela X-1

Vela X-1 is a persistent accreting pulsar and one of the best known sources of X-ray astronomy. It was discovered in 1975 by [265] and, using the data of SAS-3 satellite, they detected a spin period of ~ 283 s. It resides in a HMXB system orbited by a super-giant companion HD 77581 every ~ 9 days [266]. The ‘random walks’ of the spin frequency in the long time-span indicates that the neutron star is a wind-fed source [267], however, many studies over the years (see e.g. [260] and references there in) suggest that the orbital configuration of this binary system is indeed much more complex than just a wind-fed structure. During the years, Vela X-1 has shown various spin up/down episodes with $\dot{\nu} \sim 1 \times 10^{-13} / -2 \times 10^{-14}$ Hz/s, respectively. The Gaia estimated distance of this pulsar is $2.42^{+0.19}_{-0.17}$ kpc [268].

Being part of FERMI/GBM Project, Vela X-1 has been monitored continuously and its pulse frequency measurements are conducted on almost regular basis. In this dissertation, the pulse frequency history of this pulsar between MJD 54691-58507 is used and presented in Figure 4.19 (right panel). The sampling rate of pulse fre-

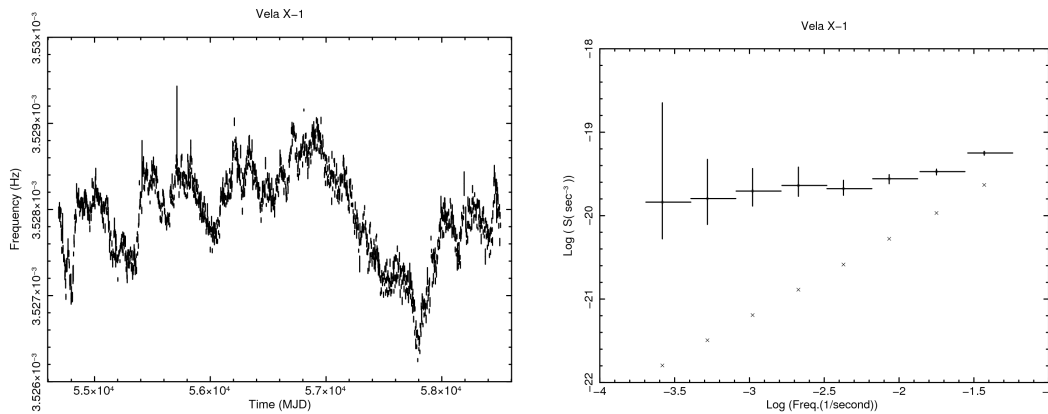


Figure 4.19: Frequency history and power density spectrum of Vela X-1. See Table 5.2 for references.

quency measurements provide an adequate input for noise strength analysis on various timescales. Thus, following the *r.m.s* method described in Section 3.3, noise strength amplitude of Vela X-1 is initially calculated for the longest time span of the data, which is $T \sim 3816$ days. Then, noise strength calculations are repeated for smaller timescales ($T/2$, $T/4$, ...) until it is dominated by the measuremental noise level at $T \sim 27$ days. The noise strength estimations in each timescale are logarithmically re-binned to obtain one single power density estimate in given timescale. Each power density estimate is then re-distributed to corresponding analysis frequencies to generate the power density spectrum of the pulse frequency fluctuations of Vela X-1 (Fig 4.19 (right panel)). For the timescales between 3816 to 27 days, the power density estimates vary from $\sim 5.63 \times 10^{-20} \text{ s}^{-3}$ to $\sim 1.45 \times 10^{-20} \text{ s}^{-3}$.

Using the data of BATSE detector onboard Compton-GRO, Bildsten et al. [70] studied the timing behavior of Vela X-1. In their work, the power density spectrum covers up to ~ 1200 days. In this study, the noise strength analysis is extended up to $T \sim 3816$ days in light of new pulse frequency measurements conducted via FERMI observations. The power density spectrum of the pulse frequency fluctuations of Vela X-1 is totally consistent with a white noise shape throughout all timescales available in this study and in agreement with [70]. The white noise structure, that arise from uncorrelated events, indicates that the source is accreting material from the wind of the companion as it is independently reported by various authors considering different properties of the binary system (e.g. [70]; [268]).

4.2.2 Cen X-3

Cen X-3 was discovered in 1971 with Uhuru observations and it is the first pulsar detected in X-rays [269], [270]. The companion of the pulsar in the binary system Cen X-3 is a supergiant star named V779 Cen [271]. The pulsar in the Cen X-3 system spins at a period of ~ 4.8 s, revolves in the orbit around the common center of mass of the system in each ~ 2.1 days [272], [266] and it resides at a distance of $\sim 6.4_{-1.1}^{+1.4}$ kpc way from Earth [260]. Although it has exhibited several spin-down episodes [41], the overall trend of rotation of the neutron star is in spin-up state with an frequency derivative of roughly $\sim 3 \times 10^{-12} \text{ Hz/s}$ ([260]. The thorough studies of

Cen X-3 over the years shows that the most probable accretion scenario of this neutron star is RLO via a ‘wind-captured’ disk [24] and references therein). While examining the energy spectrum of Cen X-3, Suchy et al. [273] reported an cyclotron resonance scattering feature at ~ 30 keV implying a magnetic field strength $\sim 3.4 \times 10^{12}$ G.

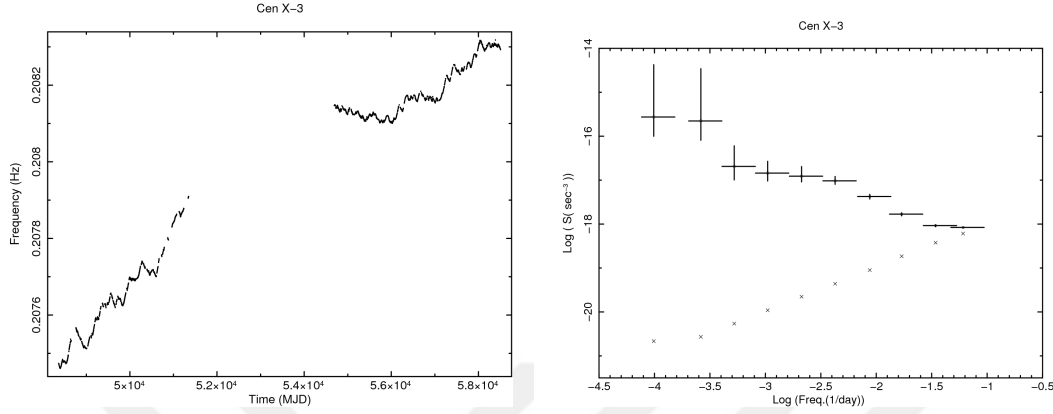


Figure 4.20: Frequency history and power density spectrum of Cen X-3. See Table 5.2 for references.

Currently, Cen X-3 is a part of monitored sources of Fermi/GBM pulsar project through which the pulse frequency and flux measurements are provided on regular basis. In addition, similar to the Fermi/GBM monitoring campaign, GRO-BATSE team also provides pulse frequency measurements of Cen X-3 for the observations that held almost a decade earlier. The existing measurements of both FERMI/GBM and GRO/BATSE is compiled to produce the pulse frequency history of the source. The total frequency history of Cen X-3 used in this work consists of very dense set of measurements that spans approximately ~ 10000 days, with a ~ 3000 days gap between FERMI and GRO observations (Figure 4.20 right panel).

The approximately ~ 30 years-long pulse frequency history of Cen X-3 is investigated in terms of time-dependent noise strength variations. Videlicet, the timing noise amplitude over the regular rotational motion of the pulsar is calculated at diverse timescales. The time-scale lower limit of power density estimations is ~ 16 days since the instrumental noise level rules out the amplitude of the pulse frequency fluctuations. For the timescales between 16 to 10000 days, the power density estimations drift from $\sim 2.74 \times 10^{-16} \text{ s}^{-3}$ to $\sim 8.41 \times 10^{-19} \text{ s}^{-3}$.

Using the BATSE data, Bildsten et al. [70] examined the timing noise behavior of Cen X-3 on timescales up to ~ 1500 days. They reported a red noise in the continuum of the power density spectrum which is attributed to the disk accretion. In their power density spectrum of Cen X-3, it can also be seen that the effect of red noise is reduced at long timescales. In the power density spectrum generated in this study (and presented in Figure 4.20 left panel), Cen X-3 has a flicker noise of f^{-1} type (i.e. red noise) for timescales longer than 50 days. Finger et al. [274] have suggested that the systematic spin-up/spin-down trends of this pulsar may have a long term impact in its timing parameters. When torque vs. spin-up relations, predicted by accretion disk models, are considered, the disk accretion is supposed to produce a red noise spectra. In the short timescales (< 50 days), the slope of the power density spectrum reduces and turns to a white noise shape. Cen X-3 shows significant changes in the X-ray flux in short times scales of days to weeks [70]. Therefore, the white noise spectra in lower time-intervals (< 50 days) should be associated with the changes in its X-ray flux.

4.2.3 Her X-1

Her X-1 was discovered in 1971 when its ~ 1.2 s periodic pulsations were detected using the data of Uhuru satellite [275]. Her X-1 is a LMXB in which there exist a $\sim 2M_{\odot}$ optical counterpart known as HZ Hercules [276]. The orbital period of the pulsar in the system is 1.72 days [277]. Utilizing Gaia data, the estimated distance of this LMXB is $5^{+0.8}_{-0.4}$ kpc [260]. Based on its cyclotron scattering feature, magnetic field strength of Her X-1 is estimated to be in the order of 10^{12} Gauss [278]. In addition, systematic changes in the X-ray flux level show that the source has a 35-day super-orbital cycle [275]. Her X-1 has a secular spin-up trend of $\dot{\nu} \sim 5 \times 10^{-13}$ Hz/s (see e.g. [279], however, it also exhibits spin-down intervals with $\dot{\nu} \sim -7 \times 10^{-12}$ Hz/s (e.g. [70]).

Due to its persistent emission and the interesting characteristics it possesses, Her X-1 is being observed continuously since its discovery with many different observatories. For instance, the frequency evolution of Her X-1 has always been intriguing due to its 35-day super-orbital cycles, and thus the spin frequencies have been monitored

with various observatories such as EXOSAT, Astron, Kvant, Ginga and BATSE (e.g. [41], [280], [281], [282], [70]. Furthermore, Her X-1 also takes part in list of regularly monitored sources with Fermi /GBM. In the scope of this dissertation, the spin frequency history of Her X-1 is complied through the measurements reported in the literature.

The pulse frequency fluctuation of Her X-1 is examined through the noise strength estimation method described in Section 3.3. As the data sampling rate is excessive, the noise calculations are re-iterated for smaller timescales and the noise strength amplitudes in each timescale is logarithmically rebinned for power estimates. Then, the power density spectrum of pulse frequency fluctuations is generated by distributing power estimates to its corresponding analysis-frequencies. The minimal timescale of the power estimate is approximately ~ 11 days, after which the instrumental noise level dominates. The timing noise level of Her X-1 is gauged in between $\sim 1.87 \times 10^{-19} \text{ s}^{-3}$ and $\sim 5.09 \times 10^{-20} \text{ s}^{-3}$.

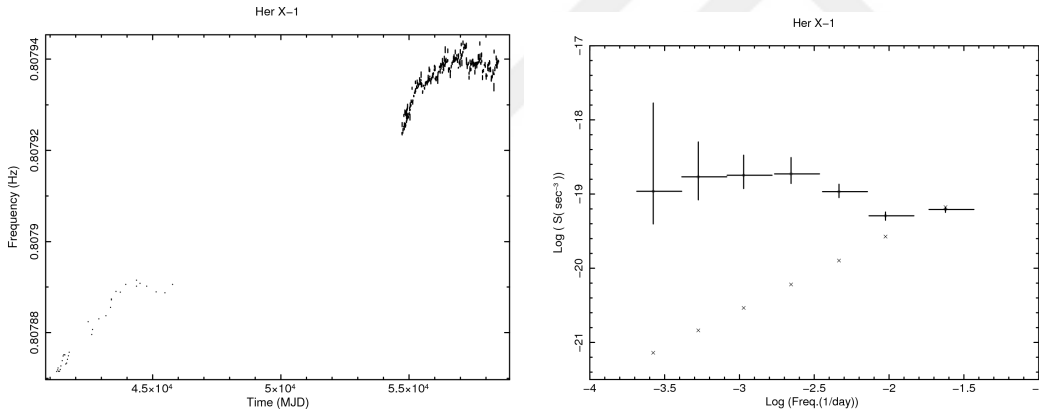


Figure 4.21: Frequency history and power density spectrum of Her X-1. See Table 5.2 for references.

The timing noise strength analysis for the several persistent accreting pulsars, including Her X-1, was carried out by [70]. In their study, they examined the timing noise behavior of Her X-1 using almost ~ 2000 days-long BATSE observations. In the work of [70], the shape the power density spectrum of the source was not resolved due to the limited amount of data. The timing noise strength estimations of this work covers a much longer period of time (~ 17250 days) since the input data

set is enriched with FERMI/GBM measurements. The power density spectrum of Her X-1 shows that the source has a flicker noise (i.e. f^{-1} type red noise) in the analysis-frequency range of -2.7 to -2. For lower analysis frequencies ($f < -2.7$ or $T > 500$ days), the power density spectrum bears the stamp of a clear white noise trend. The structure of the power density spectrum is governed by Flicker type red noise behavior that arises from a transient disk formation on timescales lower than 500 days. On the other hand, the long term torque fluctuations are dominated by the inhomogeneities of the material captured from the wind.

4.2.4 GX 301-2

GX 301-2 was firstly discovered through X-ray balloon experiments [283], and later observations reveal ~ 11.6 minutes periodic modulations in the X-ray lightcurve [284]. GX 301-2 consists of a pulsar in an eccentric orbit ($e \sim 0.46$; [285]) and a hyper-giant companion [286], namely Wray 77, around which pulsar revolves every 41.5 days ([287] and references there in). The Gaia estimated distance of this HMXB system is $3.1^{+0.6}_{-0.5}$ kpc ([260] and references therein). Due to the super gigantic nature of the companion star, the pulsar is ‘fed’ via wind accretion, and this accretion is responsible for the observed high X-ray luminosity values (approximately $\sim 1.5 \times 10^{37}$ ergs/s [288]). The general evolution of the spin-period of this pulsar is rather stable and it resembles to a random-walks in spin frequency [289]. Nevertheless, GX 301-2 exhibited rapid, and relatively long (~ 30 -40 days) spin-up events with $\dot{\nu} \sim 5 \times 10^{-12}$ Hz/s [285], [288]. The most probable explanation of such events is that the source is accreting from a transient disk.

Enlisted in FERMI/GBM tracked pulsars, GX 301-2 is continuously monitored and associated pulse frequency and X-flux measurements are provided through NSSTC. Similarly, the source was also a regular monitoring target of GRO-BATSE. In this thesis work, the pulse frequency measurements from both BATSE and FERMI are combined to obtain a long term pulse frequency history for GX 301-2. Thanks to the continuous observations provided by both facilities, the compiled pulse frequency history has an ample sampling rate over a time span of ~ 10000 days with exception of the ~ 4000 days gap between BATSE and FERMI observations (Figure 4.22).

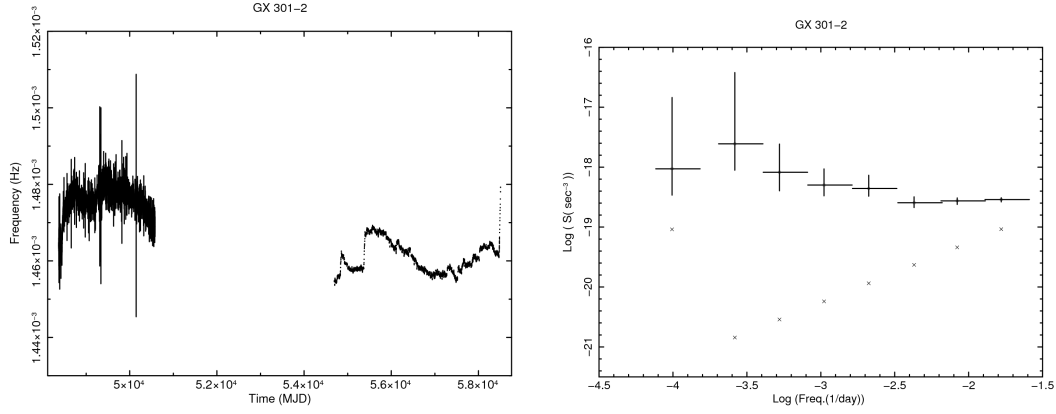


Figure 4.22: Frequency history and power density spectrum of GX 301-2. See Table 5.2 for references.

Collective pulse frequency measurements of GX 301-2 is used as input for noise strength analysis. High sampling rate of the measurements allow to estimate timing noise strengths down to ~ 30 days timescales. In each timescale, noise strength estimations are grouped into single power density estimations. For timescales lower than 30 days, the power density estimates and instrumental noise level begin to converge. Hence, the noise analysis for GX 301-2 is employed in a range of 10000 to 30 days. Within this range, power density estimates varies between $\sim 2.54 \times 10^{-19} \text{ s}^{-3}$ and $\sim 2.45 \times 10^{-18} \text{ s}^{-3}$. The resulting power density spectrum indicates that the source has a white noise structure in the short time-scales. Considering the fact that the companion is a gigantic B-type star which constantly emits an intense star wind and the uncorrelated mass transfer is indeed expected to generate a white noise structure in the power density spectra; therefore, the indicated results of GX 301-2 are in accordance with the expectations.

On the other hand, in the long time-scales the shape of the power density spectrum of GX 301-2 has a tendency to evolve into a red noise structure. As described above, GX 301-2 is thought to have a transient accretion disk which is responsible for the prolonged and rapid spin-ups since the wind accretion mechanism is insufficient to explain such behaviors (see e.g. [285]). Nabizadeh et al. [288]. further suggested that there is a transient disk formation on high spin-up rate episodes and a continuous accretion from the dense wind material of the supermassive star. Therefore, it is concluded that the tendency toward red noise structure observed in this power density

spectra is as a result of the transient disk formed around the pulsar. And the white noise structure should be originating from short-term fluctuations due to inhomogeneities in the incoming stellar wind.

4.2.5 4U 1538-52

4U 1538-52 is a HMXB system composed of a pulsar with the supergiant optical companion named QV Nor [290]. It was discovered with Uhuru satellite [291] and its pulsations of ~ 8.8 minutes were firstly reported by [292] using the data from Ariel 5 mission. The orbital period of the system is suggested to be ~ 3.7 days, whereas its distance (measured with GAIA) is estimated as $6.6^{+2.2}_{-1.5}$ kpc [260]. The orbit of pulsar in the system is observed to decay at a rate of $\dot{P}_{\text{orb}}/P_{\text{orb}} = (0.4 \pm 1.8) \times 10^{-6} \text{ yr}^{-1}$ [293]. Former observations of 4U 1538-52 show a general spin-up trend, interfered by random variations in short-timescales [294], [41]. This trend was reversed in late 80s and, since then, the source has a general spin-down trend with a value of $\dot{\nu} \sim -1.8 \times 10^{-14} \text{ Hz/s}$ [295].

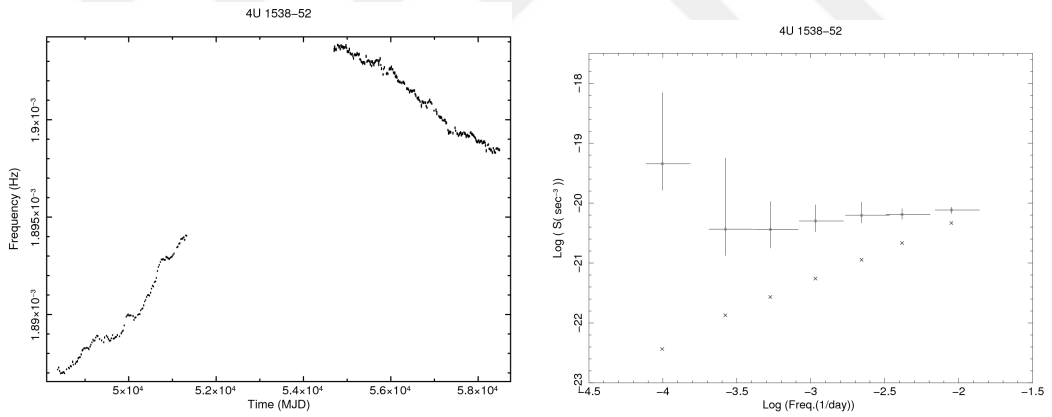


Figure 4.23: Frequency history and power density spectrum of 4U 1538-52 . See Table 5.2 for references.

4U 1538-52 also takes part in both FERMI-GBM and GRO-BATSE continuous monitoring campaign. Ever since, both facilities kept track of pulse frequency and flux measurements of 4U 1538-52, which are updated and shared regularly by NSSTC. The pulse frequency history used in this work is compiled through those measure-

ments. Similar to the other accreting pulsars examined in this thesis, the total pulse frequency history of 4U 1538-52 covers ~ 10000 days of high sampling rate measurements. The measurements halt for 3000 days, starting from the end of GRO mission to the beginning of FERMI observations.

The entire set of pulse frequency history of 4U 1538-52 is analyzed for pulse frequency fluctuations. For the analysis, the noise strength measurements is initially conducted for the longest time span (~ 10000 days). Owing to the high sampling rate of input data, the timing noise calculations are repeated for smaller timescales until the instrumental noise becomes dominant (around ~ 112 days). In each timescale, noise strength measurements are combined into one single power estimate and distributed to corresponding analysis frequencies to obtain power density spectrum. The power density estimations are rather stable, residing in between $\sim 4.51 \times 10^{-20} \text{ s}^{-3}$ and $\sim 3.61 \times 10^{-21} \text{ s}^{-3}$. The shape of the power density spectrum is rather flat and consistent with white noise structure for analysis-frequencies higher than -3.7 days^{-1} . It is previously known that 4U 1538-52 accretes material via wind accretion from a supergiant, type B0 companion [292]. The white noise shape of the spectrum most likely stems from the uncorrelated events (random angular momentum additions) generated from torque variations associated with stellar wind of the B0 type companion. It should be also noted that there is an excess power density estimate at the lowest analysis-frequency (or the highest timescale) which implies formation of a long term red noise structure possibly owing to the torque reversal around $\sim \text{MJD } 54000$.

4.2.6 4U 1626-67

4U 1626-67 is a LMXB system that contains a pulsar and a low mass optical counterpart named KZ TeA [296], [297]. It was discovered in 1972 using the UHURU satellite data [291], has a spin period of 7.66s and a orbital period of 42 minutes [298], [299]. The system resides $3.5^{+2.3}_{-0.3} \text{ kpc}$ away from the solar system [300]. The most prominent characteristic of 4U 1626-67 is the two long term torque reversals in its spin frequency that the source experienced since its discovery. Initially, the source was found to be spinning-up at a rate of $\dot{\nu} = 8.5 \times 10^{-13} \text{ Hz/s}$ until 1990, then it switched to spin-down with a similar rate, $\dot{\nu} = -3.5 \times 10^{-13} \text{ Hz/s}$ [301], [302]. The

spin-down episode lasted for almost 7 years, until when Swift/BAT and Fermi/GBM observed another torque reversal episode in 2008 [303]. To date, 4U 1626-67 is still spinning up with an average rate of 4×10^{-13} Hz/s.

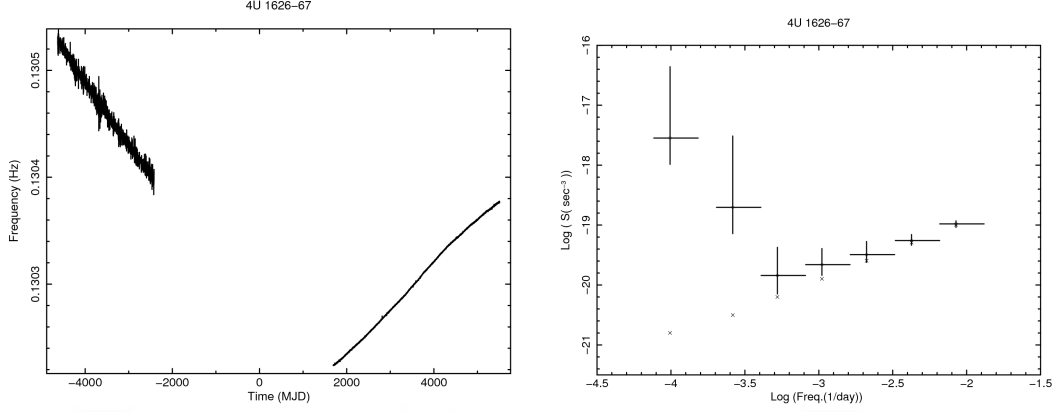


Figure 4.24: Frequency history and power density spectrum of 4U 1626-67 . See Table 5.2 for references.

4U 1626-67 is the last persistent accreting pulsar studied in this thesis. Similar to the other sources, 4U 1626-67 was also a target of both FERMI and GRO observations. Starting from early observations of both observatories, the pulse frequency and pulsed X-ray flux measurements of 4U 1626-67 is conducted for ~ 30 years almost in a regular fashion, apart from the gap of ~ 10 years in between launch of FERMI satellite and end of GRO mission. In this study, the FERMI and GRO pulse frequency measurements are collected with an aim of building the pulse frequency history of 4U 1626-67 (Figure 4.24 left panel). The spin evolution of 4U 1626-67 is rather stable except from the torque reversal event experienced in 2008 [303].

The pulse frequency history is later then investigated in terms of pulse frequency fluctuations. The frequency history of 4U 1626-67 covers ~ 10000 days with high sampling rate that allows to perform noise strength measurements at various timescales. Thus, a power density estimate at each timescale is established by calculating and re-binning the noise strength measurements of the corresponding timescale. Each power density estimate is then mapped to their analysis-frequencies to build the power density spectrum for 4U 1626-67 (Figure 4.24 right panel). Minimal timescale for power density estimation is reached at ~ 118 days, after which instrumental noise level over-

shadow pulse frequency fluctuations. Within the given timescales, the noise strength of 4U 1626-67 drifts from $\sim 2.84 \times 10^{-18} \text{ s}^{-3}$ to $\sim 1.44 \times 10^{-20} \text{ s}^{-3}$.

The noise behavior of 4U 1626-67 was previously studied by Bildsten et al. [70] using BATSE data and they could not resolve the shape of the power spectrum. In this study, it is found that the shape of the power density spectrum of 4U 1626-67 is moderately different from the other selected accreting sources in this thesis. In general, the rest of the accreting pulsars studied in this thesis exhibits white and/or red noise structure, even if the timescales varies from source to source. For timescales lower than ~ 2000 days, the power density spectrum of 4U 1626-67 tracks the level of instrumental noise levels. Considering that 4U 1626-67 is an ultra-compact binary with an very low mass ($0.03\text{--}0.09 M_{\odot}$) companion [296] and its stable spin evolution, the pulsar is not "fed" through a stellar wind. Absence of the stellar wind in the system leads to lack of white noise component in the power density spectrum. At very long timescales (> 2000 days), 4U 1626-67 exhibits a red noise behavior, perhaps arising from the accretion via material disk formed during the evolution of the binary.

CHAPTER 5

NOISE CORRELATIONS AND DISCUSSION

This chapter is based on building a framework for understanding the connection between the timing noise strains and the physical characteristics of pulsars. With this purpose, initially each magnetar or accreting pulsar is individually investigated in terms of timing noise strength variabilities on different timescales, results of which were illustrated in previous chapter. Here, a systematic cross-examination is performed to reveal possible correlations of the timing noise strength with the physical parameters such as $\dot{P}$, $\dot{\nu}$, B , L_X and τ_c , to understand the physical mechanisms that produces the fluctuations observed in spin frequency evolution of pulsars.

As demonstrated in Chapter 4 and also in previous studies in literature (e.g. [70], [228], [159]), both magnetars and accreting pulsars exhibit red noise behavior, which indicates that the timing noise amplitude changes on different timescales and that should be taken into account. Therefore, in order to make a meaningful or a robust comparison for timing noise strength amplitudes of different sources, they should be examined in similar timescales. For each pulsar/magnetar, the power density estimation on a timescale of approximately 1000 days is selected for comparison. The timescale preference is favored by also taking into account that further elaborations can be made on both *r.m.s*- and Δ_8 -value methods for examining the noise strength amplitudes. For determination of Δ_8 parameter, random intervals (10^8 seconds) in the pulse frequency are selected.

Table 5.1: The Pulse Frequency Noise Measurements of Magnetars.

Source Name	Log(S) log (s ⁻³)	Time Span ^(a) days	Noise Type	Δ_8	Timing Parm. References
CXOU J010043.1—...	-20.47 ^{+1.19} _{-0.44}	1881	—	3.51	[165],[96] ^(b)
4U 0142+61	-22.65 ^{+1.19} _{-0.44} **	993	White	0.30	[84] ^(c) (Eph B,C,D)
SGR 0418+5729	-23.68 ^{+1.19} _{-0.44}	1865	IN	—	[15] ^(c)
SGR 0501+4516	-21.63 ^{+1.19} _{-0.44}	547	IN	—	[180] ^(c)
SGR 0526-66	-16.91 ^{+1.19} _{-0.44}	3543	—	3.11	[183], [184] ^(b)
1E 1048.1-5937	-18.54 ^{+0.27} _{-0.18}	972	Red	4.12	[84] ^(d)
1E 1547.0-5408	-15.56 ^{+1.19} _{-0.44}	810	White	4.75	[197] ^(e)
PSR J1622-4950	—	—	—	—	— ^(f)
SGR 1627-41	—	—	—	—	— ^(f)
CXOU J164710.2—...	-21.66 ^{+1.19} _{-0.44}	1066	White	—	[206] ^(c)
1RXS J170849.0—...	-21.71 ^{+1.19} _{-0.44} **	972	RIN	0.93	[84] ^(c) (Eph C,F)
CXOU J171405.7—...	-16.63 ^{+1.19} _{-0.44}	370	—	—	[216], [215] ^(b)
SGR J1745-2900	-17.70 ^{+1.19} _{-0.44}	494	White/Red	4.46	[220], [221] ^(c)
SGR 1806-20	-17.33 ^{+0.27} _{-0.18}	1063	Red	3.97	^(g) ^(b)
XTE J1810-197	-19.87 ^{+0.27} _{-0.18}	878	RIN	3.35	^(h) ^(b)
Swift J1818.0-1607	—	—	—	—	— ^(f)
Swift J1822.3-1606	-22.60 ^{+1.19} _{-0.44} *	842	—	—	[54] ^(c)
SGR 1833-0832	-20.52 ^{+1.19} _{-0.44} *	275	—	—	[304] ^(c)
Swift J1834.9-0846	-19.60 ^{+1.19} _{-0.44} *	100	—	—	[87] ^(c)
1E 1841-045	-21.06 ^{+0.27} _{-0.18} **	1016	Red	—	[84] ^(c) (Eph A,C,E)
3XMM J185246.6+...	-23.62 ^{+1.19} _{-0.44}	215	—	—	[248], [247] ^(b)
SGR 1900+14	-18.19 ^{+1.19} _{-0.44}	1058	Red	4.48	[229], [232] ^(b)
SGR 1935+2154	-20.64 ^{+1.19} _{-0.44}	284	IN	—	[254] ^(c)
1E 2259+586	-22.98 ^{+0.47} _{-0.31} **	944	RIN	0.35	[84] ^(c) (Eph A,B2,D)

* and ** Noise measurements are previously presented by [162] and [305], respectively.

^(a) Noise levels are measured in this work. Time span column gives the length of time for the noise measurement.

^(b) Timing references are for frequency measurements taken from literature.

^(c) Timing references are for timing solutions used in phase coherent timing analysis.

^(d) Frequencies of 1E 1048.1-5937 are digitally obtained from Fig. 5(a) of the given reference.

^(e) Frequencies of 1E 1547.0-5408 are digitally obtained from Fig. 1(b) of the given reference.

^(f) The sampling rate of observations are not sufficient to measure the noise strength of these sources.

^(g) The frequency history of SGR 1806-20 is compiled from following references [227], [228], [229], [225], [226], [224], [230], [231], [306], [232]

^(h) The frequency history of XTE J1810-197 is compiled from following references [236], [307], [233], [235], [308], [234], [309], [237], [238]

However, it should be noted that some magnetars do not have enough pulse frequency measurement sequence to perform noise analysis on ~ 1000 days timescale. In this case, the noise strength corresponding to the maximum time-span of the data set is used for comparison. The resulting pulse frequency noise of magnetars, the method of generating pulse frequency histories and associated references are listed in Table 5.1. On the other hand, PAPP sample is examined only via *r.m.s*-value method because preliminary analysis showed that their $\ddot{\nu}$ values do not constitute a reliable metric for timing noise analysis due to their drastic variability over relatively short timescales.

For magnetars, the known physical parameters ($\dot{P}$, B , L_X and τ_c) listed in Table 4.1 are compiled through literature (see McGill Online Magnetar Catalog and references therein). In magnetars, most of the quantities are actually inferred via P_{spin} and $\dot{P}$ measurements. For example, the dipolar field strength is found from Equation 1.17 as an isolated pulsar considered to be an inclined dipolar radiator. Similarly, age of a magnetar is also approximated through P_{spin} - $\dot{P}$ measurements. For accreting pulsars, the determination of the physical parameters of the systems methodologically differs from magnetars. The magnetic field of accreting pulsars are determined either through torque models (i.e. accretion-dependent $\dot{P}$ behavior) or the cyclotron resonance features observed in energy spectra. In the latter case, the magnetic field strength can be approximated as $B = 3.8 \times 10^{12}(1 + z)E_{\text{cyc}}$ where z is redshift and E_{cyc} is the energy of the cyclotron feature in keV. Due to the nature of accretion, the X-ray luminosity of accreting pulsars are significantly variable. Hence, it is difficult to decide on a quiescent level of X-ray luminosity in accreting pulsars and, therefore, the upper and lower limits of reported luminosity values are compiled in order to allow L_X vary in that range for comparison. The parameters used for accreting pulsars are listed in Table 4.2 (see also references noted in the Table). The identified pulse frequency noise properties of PAPPs and the references for frequency measurements are described in Table 5.2.

Table 5.2: The Pulse Frequency Noise Measurements of PAPs

Source Name	Log(S) $\log(s^{-3})$	Time Span ^(a) days	Noise Type	Freq. Hist. References
Vela X-1	$-19.71^{+0.27}_{-0.18}$	956	White	(1)
Cen X-3	$-16.84^{+0.27}_{-0.18}$	952	White/Red	(1), (2)
Her X-1	$-18.75^{+0.27}_{-0.18}$	937	White/Red	(1), (2)
GX 301-2	$-18.30^{+0.27}_{-0.18}$	951	Red/White	(1), (2)
4U 1538-52	$-20.30^{+0.27}_{-0.18}$	930	Red/White	(1), (2)
4U 1626-67	$-19.66^{+0.27}_{-0.18}$	952	IN/Red	(1), (2)

^(a) Noise levels are measured in this work. Time span column gives the length of time for the noise measurement.

(1) The frequency measurements are retrieved from the regular monitoring program of Fermi/GBM Pulsars Project by the National Space, Science, and Technology Center (NSSTC), Gamma-Ray Astrophysics Team.

(2) The frequency measurements are retrieved from the regular monitoring program of BATSE: Pulsars Project by the National Space, Science, and Technology Center (NSSTC), Gamma-Ray Astrophysics Team.

To build a more comprehensive picture on noise behavior of a broader range of pulsars, a sample of radio pulsars are also added to the correlation studies. To enable such a comparison between the timing noise behavior of our target sources with radio pulsars, we converted the reported rms values of 366 radio pulsars [140] to the noise strength values S_r , using the corresponding normalization factor from Table 1 of [68]. Similarly, the physical quantities of the sample set of radio pulsars are directly used from [140] Table 1.

5.1 MAGNETIC FIELD vs. TIMING NOISE

Initially, the connection between the magnetic field and noise strength of the pulsars are examined via both $r.m.s$ - and Δ_8 - value method and the results are illustrated in Figure 5.1. In the B vs. S_r diagram, magnetars are located in the upper-right region with their immense magnetic fields and high level of timing noise. The pulsars are correlatively distributed in the bottom, owing to their moderate magnetic field strengths and rather low timing noise levels. On the other hand, accreting pulsar sample is located in the upper-mid region of the diagram with their high level of timing noise originating from accretion torques.

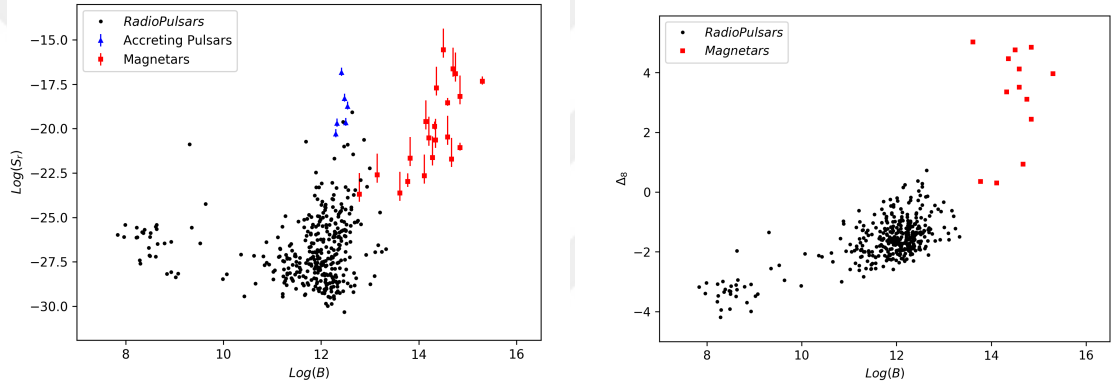


Figure 5.1: Correlation of Magnetic Field vs. Timing Noise using the $r.m.s$ -value method (left), and Δ_8 -method (right). The timing noise strength values of radio pulsars are converted from r.m.s values reported by [140].

Previously, the timing noise behavior for a subset of magnetars (1E 1841-045, RXS J170849.0-400910, 1E 2259.1+586 and 4U 0142+61) along with a large set of pulsars were examined by [310]. Similar to the correlation observed in Figure 5.1, they also reported a correlation between timing noise and magnetic field strength. They suggested that the variations in the magnetospheric moment of inertia of isolated pulsars/magnetars can be responsible for this behavior. In this study, an almost identical but a more comprehensive correlation is revealed among magnetars (with a Pearson correlation coefficient $p = 0.71$). Furthermore, investigation of the timing noise with Δ_8 method yields a similar correlation. When the magnetar model is concerned, the

physical mechanism that can affect the level of timing noise in magnetars (e.g. decay rate and structural changes of the magnetic field, crust cracking, internal stresses, outbursts, etc.) are indeed connected with magnetic field strength [134], [311], [135]. Hence, such a correlation between magnetic field strength and the noise strength of magnetars are expected in magnetar model.

On the other hand, accreting pulsars are located in a narrow band in B vs. S_r diagram. The narrow clump of the PAPPs can be associated with the B-field measurement technique that is used in accreting pulsars. The magnetic field strength determined through cyclotron resonance feature is also limited by the spectral range of instruments and only a small set of accreting pulsars that have B-field measurements is used in this thesis. Nevertheless, they seem to have a higher level of timing noise compared to radio pulsars. Obviously, inhomogeneities in accretion flow increases the fluctuations in torque exerted to the pulsar and the measured timing noise strengths scales up accordingly.

5.2 SPIN DOWN RATE vs. TIMING NOISE

To investigate the noise behavior of different classes of pulsars, the question whether the timing noise strength is connected to the spin-down rate is addressed. Indeed, torque fluctuations of any origin (whether accretion or magnetic braking etc.) are observationally linked and measured through the variations in the spin evolution of pulsars. Hence, a diagram for each possible combination of $\dot{P}$, $\dot{\nu}$, S_r and Δ_8 is built to understand how the noise behavior of pulsars is connected with their spin-down rate (see Figure 5.2). In this particular section, only three PAPP sources (which have a long term spin-down episode in their pulse frequency history, namely GX 1+4, 4U 1538-53 and 4U 1626-67) are included in the correlation figures of spin-down rate vs. S_r . The noise strength estimates on ~ 1000 days scale of each of this three accreting sources are derived only from their spin-down episodes and values of $\dot{\nu}$ & $\dot{P}$ are determined for those episodes with a quadratic fit to pulse frequency histories in that interval.

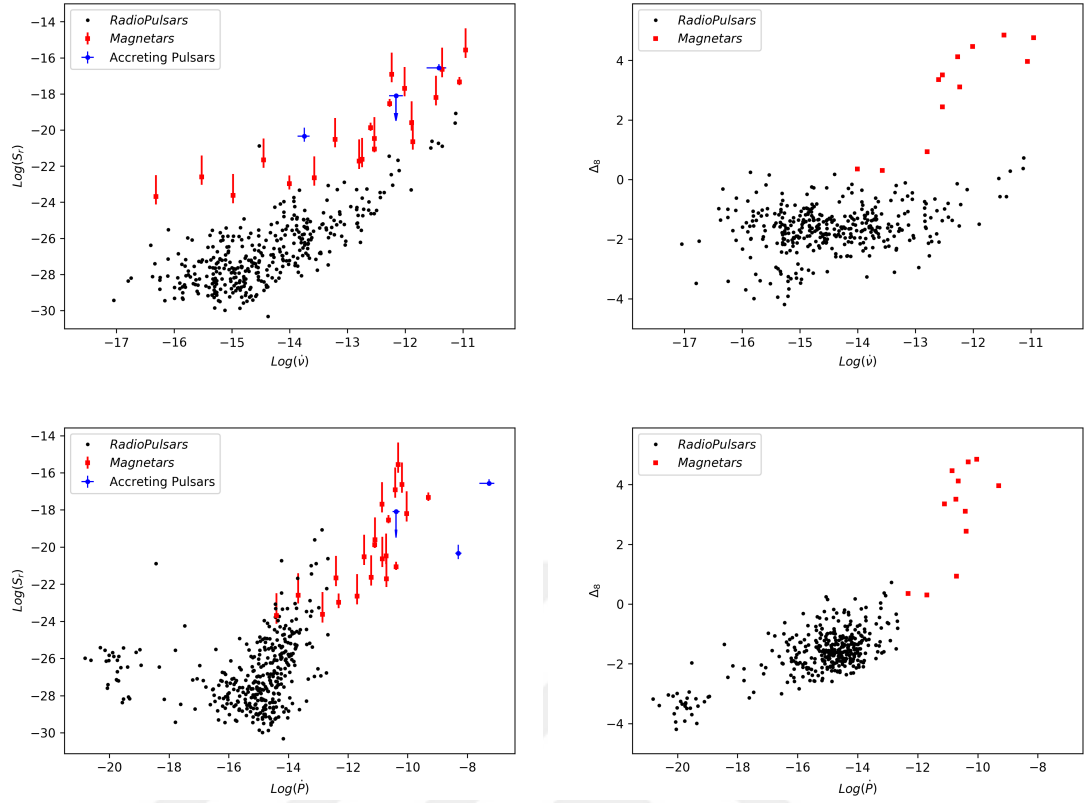


Figure 5.2: Correlation of frequency derivative vs. $r.m.s$ (upper-left), frequency derivative vs. Δ_8 (upper-right), period derivative vs. $r.m.s$ -value (lower-left) and period derivative vs. Δ_8 (lower-right) of magnetars, and radio pulsars. Radio pulsar values are converted from $r.m.s$ values reported by [140].

In the case of $\dot{\nu}$ vs. timing noise (for both $r.m.s$ - and Δ_8 -value methods), the level of timing noise of magnetars is relatively higher than that of pulsars. Magnetars seem to exhibit a correlation that resembles to radio pulsars. The Pearson correlation coefficient between S_r and $\dot{\nu}$ is found to be $p = 0.85$ in this case. However, the level of timing noise of magnetars is significantly higher from the pulsars within similar $\dot{\nu}$ range. When $\dot{P}$ vs S_r (and Δ_8) diagram is inspected closely, all the sources seem to exhibit a correlative behavior and form an overall continuum. For magnetars, the Pearson correlation coefficient is calculated to be $p = 0.78$. This behavior can be associated with increased timing activities during magnetar outbursts [84], and/or noise dominated $\dot{\nu}$ parameters observed in some cases (see [312]). On the other hand, the timing noise values of PAPPs resemble those of magnetars and they also seem to

have a correlative behavior in a similar fashion, however, more sources with similar characteristics should be added in order to have a more comprehensive understanding of the behavior of timing noise vs. spin down rate of accreting pulsars.

In the first argument, the neutron stars that possess higher initial magnetic field strengths ($B > 10^{14}$ G) demonstrate tendency for more frequent bursting behaviors [311], [139]. Burst events may leave a timing noise strain on pulse frequency evolution, even if the glitch events are excluded. Therefore, it can be suggested that the noise strain after outburst events can explain the high level of timing noise observed in magnetars. On the other hand, the noise dominated $\ddot{\nu}$ [312] may also account for this behavior because it is known that the observed values of $\ddot{\nu}$ do not solely arise from pure dipole braking, rather they are dominated by timing noise [312], [313], [140]). When a pulsar slows down due to magnetic braking, $\ddot{\nu}$ can be calculated as $(n\dot{\nu}^2)/\nu$ where n is braking index. The braking index of pure dipole radiator should be $n = 3$; nevertheless, observed values of braking indices vastly differs from the expected value of 3 (e.g. between $-287\,986$ and $+36\,246$ [140]). Hence, measured $\ddot{\nu}$ values should also encapsulate the timing noise. In the case of magnetars, the timing noise may also originate from a mechanism that combines both of the pictures described above. For example, the noise strain that arise from bursting sequence may affect $\ddot{\nu}$ parameter, which in return can explain both the high level of timing noise and the variety of braking indices observed in magnetars.

5.3 LUMINOSITY vs. TIMING NOISE

In order to differentiate the origin of timing noise processes in different classes, the connection of timing noise amplitude to the X-ray luminosity is also investigated. For magnetars, the X-ray luminosities are compiled from the literature (see McGill Magnetar catalog and references therein) which represents their luminosity in the quiescent level. For PAPPs, the X-ray luminosities reported in literature [262] is gathered and the range from minimum to maximum level of X-ray luminosities are included for comparison. For magnetars, the luminosities are not defined as a range, since their quiescent luminosity level is rather stable and unfortunately, outbursts change their luminosity for several orders in magnitude.

Similar to the previous sections, two diagrams for S_r and Δ_8 vs. X-ray luminosity is constructed (see Figure 5.4). In both cases, magnetars are distributed randomly over the diagrams, indicating that there is no connection between timing noise level and X-ray luminosity for magnetars (Pearson correlation coefficient $p = 0.41$). On the other hand, PAPPs exhibit a correlative behavior in S_r vs. L_X diagram.

For accreting pulsars, the mass accretion leads to an increase in both external torque applied to the pulsar and X-ray luminosity. In 1993, Baykal & Ogelman [69] suggested that the X-ray luminosity and the timing noise strength of accreting pulsars are correlative. The results of this thesis also demonstrate an identical correlation. This correlation implies that the noise strength of accreting pulsars grows with the mass accretion rate. Indeed, higher mass accretion rates signify larger inhomogenties in the accreted material which will induce higher timing noise floor. It should also be

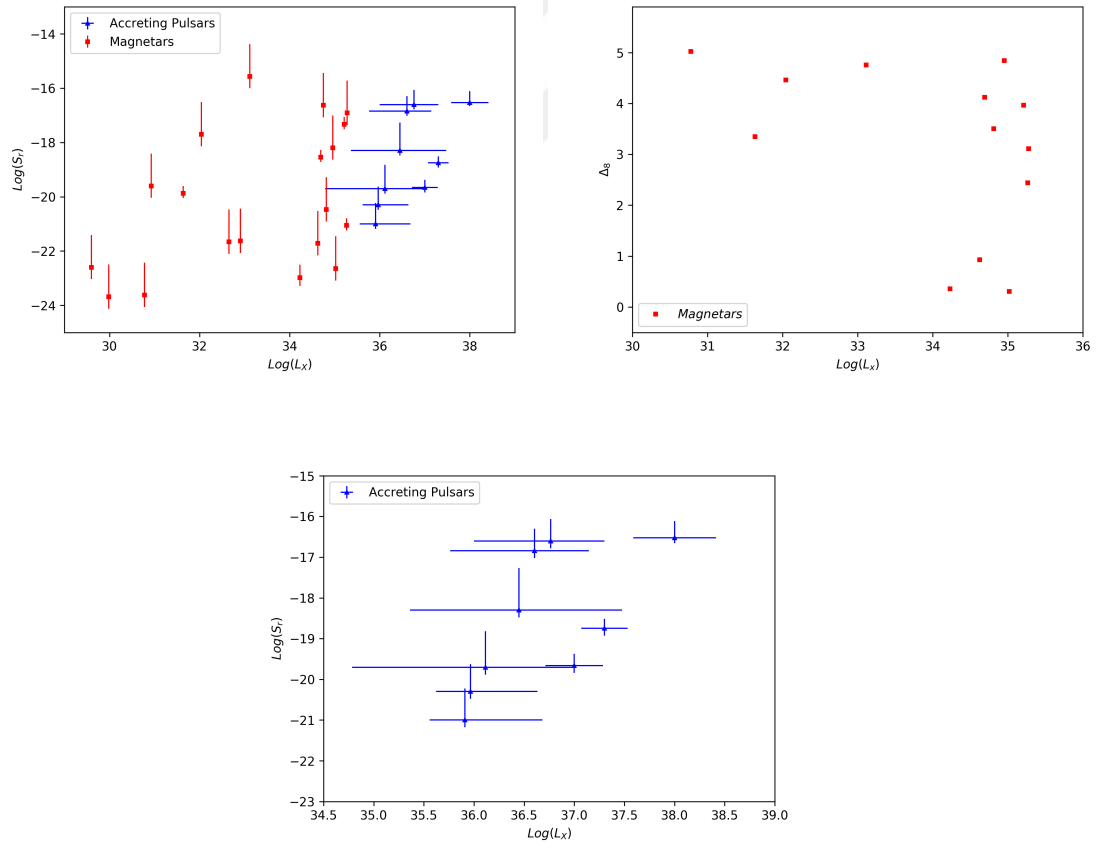


Figure 5.4: Correlation of Luminosity vs. Timing Noise using the $r.m.s$ -value method (left), and Δ_8 -value method (right) and S_r vs L_x for PAPPs is zoomed at bottom panel

noted that such a correlation is not valid for radio pulsars [67].

Cordes & Helfand [67] studied the timing behaviour of 50 pulsars and found that the timing noise of these objects is uncorrelated with their radio luminosity, similar to the uncorrelative behavior of magnetars found in this study. This implies that the fallback disc model [142], which suggests that the observed X-ray emission and spin-down behavior of magnetars are sustained by accretion from a debris disc after the supernova explosion, is a less likely explanation for the timing noise of these sources. Therefore, the timing noise of magnetars possibly arises from fluctuations of high dipolar fields and outburst activities, rather than fluctuations of external torque exerted by a debris disc.

5.4 CHARACTERISTIC AGE vs. TIMING NOISE

In order to understand how the timing noise floor changes on very large time scales, we further examined the relation between characteristic age τ_c and the timing noise amplitude of the sample pulsars and magnetars. The PAPP sample in this study is excluded from this diagram owing to the fact that their age cannot be estimated with reasonable uncertainties for comparison. For the pulsar and magnetar sample, the crude estimation of the age is obtained via characteristic age definition $\tau_c = P/2\dot{P}$ using the period and spin-down rate values reported in McGill Online Magnetar Catalog and [140]. The constructed diagram for τ_c vs. S_r and Δ_8 is illustrated in Figure 5.5.

In this diagram, it can clearly be seen that the timing noise level of magnetars exhibit an *anti*-correlation with respect to the characteristic age ($p = -0.82$). Similar *anti*-correlation also exist in the case of pulsars, which was already reported by [140]. It should be noted that the *anti*-correlation exist for both methods (S_r and Δ_8). Furthermore, magnetars and pulsars form a continuum on the diagram. The magnetar sample is distributed over the upper left part of the diagram since they are rather young objects which possess high timing noise floors. The *anti*-correlation between the age and timing noise indicates that the younger sources demonstrate more noisy timing behaviors and older sources have lower timing noise levels. Thus, it can be inferred

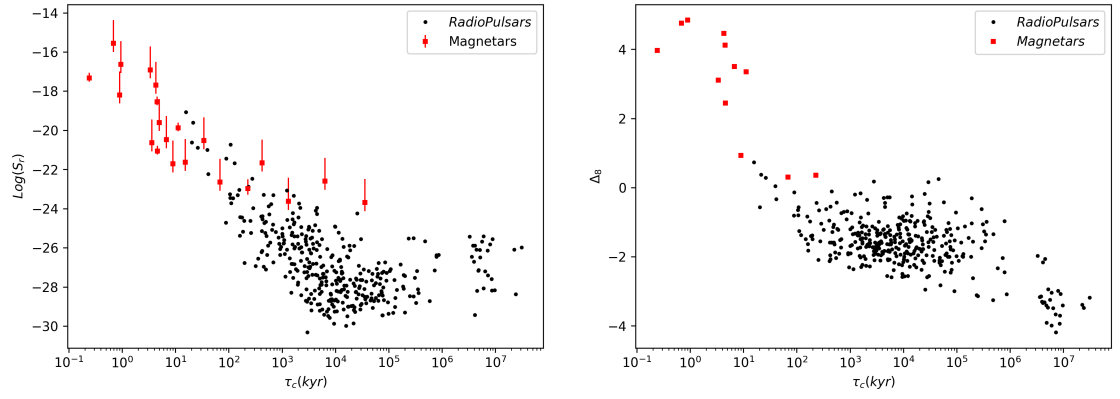


Figure 5.5: Correlation of Characteristic Age vs. Timing Noise using the *r.m.s*-value method (left), and Δ_8 -value method (right). Timing noise strength of radio pulsars are converted from r.m.s values reported by [140].

that these sources have high level of timing noise when they are born and rotational motion of the sources are gradually stabilized as they get older. And it further supports the idea that the timing noise level is linked with the magnetic field strength [310]) and it is decreasing as the magnetic field of the source decays over the time.



CHAPTER 6

SUMMARY AND CONCLUSION

In this thesis, a comprehensive analysis of timing noise properties of all magnetars and six persistent accreting pulsars is conducted. For each source a frequency history is generated either from the spin frequency measurements reported in literature or pulse timing of the data gathered through the public observations of *RXTE*, *Swift*, *XMM-Newton*, and *Chandra* observatories. The timing noise analyses are performed via two different techniques, namely *r.m.s*- and Δ_8 -value methods.

In the case of *r.m.s*-value method, of all 24 confirmed magnetars, three sources (i.e. PSR J1622-4950, SGR1627-41 and Swift J1818.0-1607) have not enough frequency measurements to accomplish a reliable noise strength calculation. Furthermore, three other magnetars (i.e. Swift J1822.3-1606, SGR 1833-0832 and Swift J1834.9-0846) were already studied in literature in terms of pulse frequency fluctuations [162]. For the remaining 18 sources, the noise strength measurements are performed for all of them for the maximum available input data set. Depending on the data sampling rate, noise strength measurements are delineated into various timescales for individual sources. Relying on the sampling rate of pulse frequencies, the power density spectra of the pulse frequency fluctuations of 15 magnetars are constructed. In addition to magnetars, the noise strength analyses of the six PAPPs are also carried out using the pulse frequency measurements obtained via *BATSE* and *FERMI* observatories. For each source in the PAPP sample, the power density spectra of the pulse frequency fluctuations are also generated. In the case of Δ_8 -value method, the noise strength amplitude is calculated for only 12 out of 18 magnetars because the sampling rate and error range of the historical spin frequency measurements of the remaining 6 magnetars do not allow to resolve significant $\ddot{\nu}$ parameter that is required for Δ_8

calculation. The PAPP sample is excluded from Δ_8 analysis due to their rapid $\ddot{\nu}$ variations in very small timescales that are not noise dominated but rather induced by accretion flow.

After performing noise calculation for each source with both methods, each source is investigated individually by utilizing their power density spectrum. Afterwards, the whole different sub-class of sources are examined together with an aim of distinguishing the underlying physics via their noise behaviors. Hence, for understanding how it comports with other physical parameters, the correlation of timing noise with $B, \dot{\nu}, \dot{P}, L_X$ and τ_c of all magnetars and six persistent accreting pulsars is established. Regarding the fact that timing noise measurements may change on different timescales, the timing noise level corresponding to the similar timescales are used for comparison. The selected timescale is determined to be ~ 1000 days by considering the fact that a further comparison between Δ_8 and *r.m.s*-value method can be elaborated. It should be noted that when a time span of measurements do not extend to 1000 days (or 10^8 s in the case of Δ_8), the timing noise level corresponding to maximum timescale used for comparison (see Table 5.1). In order to have a more complete understanding of timing noise behavior across different populations, a sample of 366 radio pulsars studied by Hobbs et al. [140] are also included in correlation studies.

Power Density Spectra

The structure of the power density spectra can be divided into three groups, i.e. *red*, *white* and *instrumental* noise (IN) power density spectrum. The *IN* shape in our study actually refers to a power noise spectrum that it scaling up with instrumental noise level and it is further sub-categorized as RIN for the sources that has an excess power density estimate at the lowest analysis-frequencies. The shape of the power density spectrum of pulse frequency fluctuations of each individual magnetar is represented and discussed in Chapter 4. The results of this study show that the magnetars rather exhibit complex noise structures on different timescales, making it hard to achieve direct conclusions for individual sources. Nevertheless, they seem to have tendency towards red noise for lower analysis-frequencies. When compared

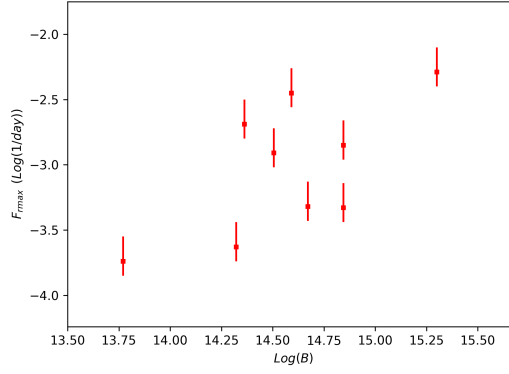


Figure 6.1: The highest analysis-frequency of red noise component (F_{rmax}) as a function of dipolar magnetic field strengths of magnetars.

to the isolated pulsars [312], the magnetars exhibit steeper red noise component that arise at smaller timescales. To examine this behavior, we further investigated the connection between the smallest timescale of red noise components and the dipolar magnetic field strengths¹ (Fig. 6.1). The smallest timescale of red noise structure is in *anti*-correlation with the magnetic field (i.e. in positive correlation with the analysis-frequency) which indicated that the sources with higher magnetic fields have a tendency to start the red noise processes at smaller timescales. Thus, the red noise processes in magnetars should be associated with the magnetospheric fluctuations and/or the outbursts that is originating from high magnetic field stresses.

Timing Noise Correlations

The *Magnetic Field vs. Timing Noise Strength* diagrams, using both *r.m.s*- and Δ_8 -value methods, shows that there is a correlation between these two parameters. However, the timing noise strength values of magnetars are higher than those of radio pulsars and they form a continuum. Using those information, it can be deduced that the higher S_r values of magnetars are associated to their enormous magnetic field

¹ The determination of the highest frequency of the red noise component is rather subjective and model dependent. Here, the first excess noise over a white noise or IN continuum of the power density spectrum is chosen as F_{rmax} . Even though the results are not exact, it will give rough idea about the relation between the B-field and smallest timescale of red noise process

strengths. According to Magnetar model [11], [118], [51] the higher the magnetic field of the source is, the more ‘active’ it is regarding the timing and radiative behaviors (see e.g. [60] and references there in). Thus, higher magnetic field strengths will result in generation of higher timing noise levels as expected. It is also important to note that when each magnetar is investigated individually for analysis-frequency dependent timing noise behavior, it can be observed that the more ‘active’ sources generally exhibit red noise behavior starting from smaller timescales when compared with more ‘quiet’ sources. Hence, it is possible that the timing noise level of magnetars are further connected to the bursting sequences and burst energies.

On the other hand, PAPPs form a discrete group by residing in the upper-middle part of the B vs. noise amplitude diagrams without a clear significance of a correlation. Thus, it can be inferred that the noise observed in the PAPPs frequency fluctuations is associated with the inhomogeneities of the accreted matter, not with the magnetic field values they possess, as expected. Unfortunately, the conclusion on PAPPs remain vague due to limited number of sources included in this sample.

In the *Spin-down Rate vs. Timing Noise Strength Correlations*, the relation between $\dot{\nu}$ and S_r reveals correlation among all included magnetars and radio pulsars. Since magnetars have higher timing noise levels compared with radio pulsars, they reside above radio pulsar subset as shown in Figure 5.2. In the case of S_r , each sample (pulsars or magnetars) exhibit a correlation within their sample. On the other hand, the relation between $\dot{P}$ vs. S_r (and Δ_8) also reveals a correlation for all examined sources/samples and they form an overall continuum (Figure 5.2).

For magnetars and pulsars, the magnetospheric fluctuations are thought to be responsible for observed timing noise levels [310]. As a result of magnetic braking assumption, there is a direct connection between $\dot{\nu}$ with magnetic field strength for isolated sources. This is actually reflected in the Noise vs. $\dot{\nu}$, $\dot{P}$, τ_c diagrams as well, since all of them are connected to each other in a similar fashion (as a product of P and $\dot{P}$). For magnetars, these correlative behaviors can also be attributed to their frequent transient bursting behaviors which affects the $\dot{\nu}$ values, and in return these values account for the high timing noise levels. In this diagram, the noise strength amplitudes of three accreting pulsars with long-term spin-down episodes are also included for

comparison. Their noise levels and spin-down rates are seen to be in alignment with magnetars; however, it is not possible to draw a conclusion on S_r vs. $\dot{\nu}$ behavior of PAPPs as their sample is very limited.

In this study, *Luminosity vs. Timing Noise Strength* diagram is constructed for further investigation of the origin of noise processes in magnetars and PAPPs. The aim is to distinguish the dominant process for timing noise generation in magnetars since it is argued that the magnetars can also accrete from a fall back disk [141], [142]. If that is the case, the timing noise behavior of magnetars should resemble to the behavior of accreting pulsars. According to theoretical models for accretion, the pulse frequency evolution of an accreting pulsar is connected to the observed bolometric X-ray luminosity (e.g. [33], [35], [34]) since higher mass accretion rates should yield higher luminosities. In that case, mass accretion rate will also determine the torque exerted to the pulsar. In return, inhomogenities in the accretion flow will create fluctuations in the pulse frequency evolution. Therefore, the timing noise level of accreting pulsars should be in correlation with their luminosity level, which observationally is demonstrated by [69]. The constructed diagram for L_x and S_r (and Δ_8) do not show any correlation for magnetars, instead they are rather distributed randomly over the diagram.

Despite the low number in the PAPP sample, they exhibit a correlative behavior as demonstrated by [69]. Hence, the results imply that dominant mechanism in timing noise floor of magnetars cannot be accretion from a fall back disk. Considering the fact that a correlation between X-luminosity vs timing noise strength is also absent in radio pulsars [67], the timing noise behavior of magnetars resemble more to the radio pulsars. Main difference between timing noise level of magnetars and pulsars possibly originate from immense magnetic field strengths and/or outburst activities of magnetars.

The last studied diagram in this thesis is *Characteristic Age vs. Timing Noise Strength*. The aim was to investigate how the timing noise behavior changes on very large timescales. Since the τ_c is unknown for PAPPs, the investigation includes only magnetars and radio pulsars. As it can be clearly seen from the Figure 5.5, magnetars (same as radio pulsars) form an *anti*-correlation with τ_c with a Pearson Correlation

Coefficient of $p = -0.82$. This *anti*-correlative behavior is observed in both *r.m.s.*- and Δ_8 - measurement methods. In addition, magnetars form a continuum with radio pulsars. The overall continuum of this *anti*-correlative behavior suggest that the younger the pulsar is, the higher its timing noise level, and vice-versa. Therefore, it can be inferred that pulsars exhibit a more noisy behavior in the first stages of their life and their rotational behavior stabilizes as they get older. Furthermore, this process should also be related with the decay of the magnetic field: as the pulsars gets older, the magnetic field decays and the processes that creates timing noise also diminishes.

The Overall View

The examination of the results of this dissertation in a broader range shows that magnetar's timing noise strength behavior resembles that of radio pulsars, indeed they form a continuum with them, as suggested by [314] and [310]. However, magnetars have higher timing noise levels and their red-noise component rises at shorter-timescales compared with radio pulsars. This phenomenon is anticipated as an outcome of Magnetar model [11], [118], [51] which predicts that an ultra-strong initial magnetic field leads to bigger internal stresses, and these stresses account for the observed frequent bursting behavior and timing irregularities of magnetars. Since both the investigation of the power density spectra and correlation diagrams hints for a connection between outburst activities and the timing noise strain, we further examined the relation between total outburst energy and timing noise level of magnetars. The resulting diagrams for E_{outburst} vs for both S_r and Δ_8 are illustrated in Figure 6.2 (E_{outburst} values are compiled from [53]). The calculation of burst energetics (i.e. $E_{\text{outburst}} = \int_0^{t_q} L_{\text{bol}}(t)dt$ [53], where t_q is the time elapsed to reach quiescent state after the outburst event) are independent from P and $\dot{P}$ measurements.

Both diagrams show a clear correlation between total outburst energies and the noise strength values of magnetars who have had outbursting episodes. This clear correlation indicates that timing noise strength floor of magnetars are strongly tied to the total energy released during outbursts. Considering the fact that the perturbation of the crust via outburst events should diminish in dynamical timescales (i.e. within sev-

eral rotational periods), outbursts are not expected to leave timing noise strain that spreads out to 1000 days timescale as used in this study. Therefore, this correlation is possibly a reflection and further support of the correlation between timing noise and the inferred magnetic field strengths, since E_{outburst} and B -fields are shown to be correlative already [53].

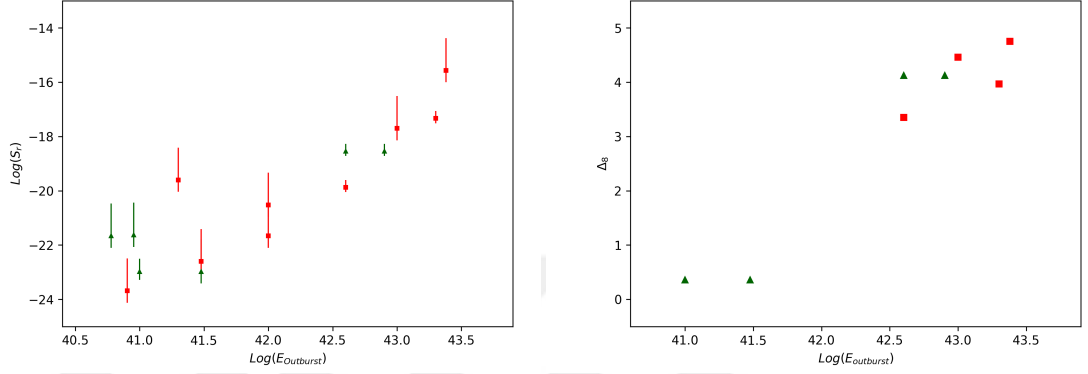


Figure 6.2: Timing Noise Strength vs. Total Outburst Energy of Magnetars using the *rms*-value method (left), and Δ_8 method (right). Green color stands for the sources with two outburst episodes. Total outburst energies are taken from [53]

When all the correlations are comprehensively considered, the timing noise strengths of magnetars and pulsars are seen to be linked and they possess similar noise floor that is possibly associated with their magnetic fields as suggested by [310]. A link between these two neutron star populations was also suggested considering their surface temperatures, quiescent X-ray luminosities, magnetic fields [314], [315] and magnetar-like bursts observed from the high B-field pulsars PSR J1119-6127 [316], [317], [318] and PSR J1846-0258 [55]. Magnetars induce higher timing noise levels due to the timing noise strains that originate from their strong outbursts. It should be noted that there has been substantial efforts in revealing debris discs around magnetars, which is observationally supported through optical and infrared emission detected in several magnetars, [319], [320], [151], [321]). Nevertheless, existence of such fossil disks will not certainly affirm that the observed X-ray emission is empowered by accretion via the fossil disk. In fact, when the Fourier power spectra of various kind of X-ray sources are compared, the magnetars do not show any evidence

of a strong red-noise type aperiodic variability [322] which exist in all the accreting sources [323] [324], [325], [326]. Thus, the results of this study also lacks the evidence for accretion footprints on the timing noise, making fallback disk model not a possible option for describing pulse frequency fluctuations of magnetars. Moreover, the timing noise behavior of magnetars in this study is principally consistent with the behavior of radio pulsar sample. Magnetars do have a higher timing noise level compared to the radio pulsars, owing the fluctuations in the magnetosphere and strains of timing noise related to the outburst activities. Thus, Magnetar model presents a more coherent and viable picture for describing the timing noise of magnetars. Even when the outbursts are ‘quiet’ and leave not trace on the pulse morphology, the impact of the outburst events leads to fluctuations of the rotational motion of the crust and inner superfluid responds the events by unpinning limited number of vortices, just like ‘micro-glitches’. The trace of such inner response of the neutron stars would also be visible in the power density spectrum of the noise fluctuations for very small ($<$ few days) timescales. Unfortunately, the sampling rate of the input frequency measurements do not allow to resolve the timing noise behavior on very short timescales. Thus, very-dense-sampled long observations with new X-ray observatories are required to understand the inner response of the neutron stars in terms of timing noise.

As a final remark regarding the S_r and Δ_8 measurement methods, it is important to note that the Δ_8 -value method gives a reasonable estimate when considering the timing noise of isolated sources, however, it does not function properly for PAPPs. Such a result is expected since, by definition, Δ_8 is proportional to $\ddot{\nu}$ which assumes that the $\ddot{\nu}$ values are dominated by timing noise. For PAPPs, $\ddot{\nu}$ values are not noise dominated, they are rather linked to accretion flow hence Δ_8 parameter do not deliver a sufficient metric for representing noise amplitudes. Furthermore, the Δ_8 values of some magnetars can not properly be determined due to the unstable $\ddot{\nu}$ values they possess. On the other hand, $r.m.s$ -value method measures the amplitude of pulse frequency fluctuations using their average variability, thus it provides a more reliable measurement metric; consequently, $r.m.s$ -value method work for both isolated and accreting pulsars. In addition, this method also enable to resolve timing noise strength values for different timescales, unlike Δ_8 method which, by definition, is estimated for $\sim 10^8$ s only.

REFERENCES

- [1] W. Baade and F. Zwicky, “Cosmic Rays from Super-novae,” *Proceedings of the National Academy of Science*, vol. 20, pp. 259–263, May 1934.
- [2] A. Hewish, S. J. Bell, J. D. H. Pilkington, P. F. Scott, and R. A. Collins, “Observation of a Rapidly Pulsating Radio Source,” *Nature*, vol. 217, pp. 709–713, Feb. 1968.
- [3] A. Heger, C. L. Fryer, S. E. Woosley, N. Langer, and D. H. Hartmann, “How Massive Single Stars End Their Life,” *ApJ*, vol. 591, pp. 288–300, July 2003.
- [4] R. N. Manchester, G. B. Hobbs, A. Teoh, and M. Hobbs, “The Australia Telescope National Facility Pulsar Catalogue,” *AJ*, vol. 129, pp. 1993–2006, Apr. 2005.
- [5] J. M. Lattimer, “The Nuclear Equation of State and Neutron Star Masses,” *Annual Review of Nuclear and Particle Science*, vol. 62, pp. 485–515, Nov. 2012.
- [6] F. Özel and P. Freire, “Masses, Radii, and the Equation of State of Neutron Stars,” *ARAA*, vol. 54, pp. 401–440, Sept. 2016.
- [7] H. T. Cromartie, E. Fonseca, S. Ransom, P. Demorest, and NANOGrav Team, “A larger-than-2-solar-mass pulsar in NANOGrav: leveraging Shapiro delay to constrain the neutron star equation of state,” in *APS April Meeting Abstracts*, vol. 2019 of *APS Meeting Abstracts*, p. T09.002, Jan. 2019.
- [8] J. G. Martinez, K. Stovall, P. C. C. Freire, J. S. Deneva, F. A. Jenet, M. A. McLaughlin, M. Bagchi, S. D. Bates, and A. Ridolfi, “Pulsar J0453+1559: A Double Neutron Star System with a Large Mass Asymmetry,” *ApJ*, vol. 812, p. 143, Oct. 2015.
- [9] W. C. G. Ho, D. L. Kaplan, P. Chang, M. Van Adelsberg, and A. Y. Potekhin, “Magnetic hydrogen atmosphere models and the neutron star RX

- J1856.5–3754,” *Monthly Notices of the Royal Astronomical Society*, vol. 375, pp. 821–830, 01 2007.
- [10] R. L. Bowers and T. Deeming, *Astrophysics. Volume 1 - Stars*. 1984.
- [11] R. C. Duncan and C. Thompson, “Formation of Very Strongly Magnetized Neutron Stars: Implications for Gamma-Ray Bursts,” *ApJL*, vol. 392, p. L9, June 1992.
- [12] P. Meszaros, *High-energy radiation from magnetized neutron stars*. University of Chicago Press, 1992.
- [13] R. N. Manchester and J. H. Taylor, *Pulsars*. 1977.
- [14] S. Rosswog and M. Brüggen, *Introduction to High-Energy Astrophysics*. 2007.
- [15] N. Rea, G. L. Israel, J. A. Pons, R. Turolla, D. Viganò, S. Zane, P. Esposito, R. Perna, A. Papitto, G. Terreran, A. Tiengo, D. Salvetti, J. M. Girart, A. Palau, A. Possenti, M. Burgay, E. Göğüş, G. A. Caliendo, C. Kouveliotou, D. Götz, R. P. Mignani, E. Ratti, and L. Stella, “The Outburst Decay of the Low Magnetic Field Magnetar SGR 0418+5729,” *ApJ*, vol. 770, p. 65, June 2013.
- [16] D. Lai, “Matter in strong magnetic fields,” *Reviews of Modern Physics*, vol. 73, p. 629, July 2001.
- [17] M. E. Caplan and C. J. Horowitz, “Colloquium: Astromaterial science and nuclear pasta,” *Reviews of Modern Physics*, vol. 89, p. 041002, Oct. 2017.
- [18] P. Goldreich and W. H. Julian, “Pulsar Electrodynamics,” *ApJ*, vol. 157, p. 869, Aug. 1969.
- [19] M. Zajack, V. Karas, and D. Kunneriath, “Galactic center minispiral: Interaction modes of neutron stars,” *Acta Polytechnica*, vol. 55, p. 203–214, Jun 2015.
- [20] S. L. Shapiro and S. A. Teukolsky, *Black Holes, White Dwarfs and Neutron Stars: The Physics of Compact Objects*. Wiley, 1986.
- [21] D. Psaltis and F. K. Lamb, “Magnetic fields of neutron stars in low mass X-ray binaries,” *Astronomical and Astrophysical Transactions*, vol. 18, pp. 447–454, Jan. 1999.

- [22] T. Strohmayer and L. Bildsten, *New views of thermonuclear bursts*, vol. 39, pp. 113–156. 2006.
- [23] J. van Paradijs and N. White, “The Galactic Distribution of Low-Mass X-Ray Binaries,” *ApJL*, vol. 447, p. L33, July 1995.
- [24] R. Walter, A. A. Lutovinov, E. Bozzo, and S. S. Tsygankov, “High-mass X-ray binaries in the Milky Way. A closer look with INTEGRAL,” *AAPR*, vol. 23, p. 2, Aug. 2015.
- [25] M. Orlandini, V. Doroshenko, L. Zampieri, E. Bozzo, A. Baykal, P. Blay, M. Chernyakova, R. Corbet, A. D’Aì, T. Enoto, C. Ferrigno, M. Finger, D. Klochkov, I. Kreykenbohm, S. C. Inam, P. Jenke, J. C. Leyder, N. Masetti, A. Manousakis, T. Mihara, B. Paul, K. Postnov, P. Reig, P. Romano, A. Santangelo, N. Shakura, R. Staubert, J. M. Torrejón, R. Walter, J. Wilms, and C. Wilson-Hodge, “Probing stellar winds and accretion physics in high-mass X-ray binaries and ultra-luminous X-ray sources with LOFT,” *arXiv e-prints*, p. arXiv:1501.02777, Jan. 2015.
- [26] M. Bachetti, F. A. Harrison, D. J. Walton, B. W. Grefenstette, D. Chakrabarty, F. Fürst, D. Barret, A. Beloborodov, S. E. Boggs, F. E. Christensen, W. W. Craig, A. C. Fabian, C. J. Hailey, A. Hornschemeier, V. Kaspi, S. R. Kulkarni, T. Maccarone, J. M. Miller, V. Rana, D. Stern, S. P. Tendulkar, J. Tomsick, N. A. Webb, and W. W. Zhang, “An ultraluminous X-ray source powered by an accreting neutron star,” *Nature*, vol. 514, pp. 202–204, Oct. 2014.
- [27] P. Reig, “Be/X-ray binaries,” *APSS*, vol. 332, pp. 1–29, Mar. 2011.
- [28] I. F. Mirabel, “Very energetic gamma-rays from microquasars and binary pulsars,” *Science*, vol. 312, p. 1759, June 2006.
- [29] A. T. Okazaki and I. Negueruela, “A natural explanation for periodic X-ray outbursts in Be/X-ray binaries,” *AAP*, vol. 377, pp. 161–174, Oct. 2001.
- [30] J. E. Pringle and M. J. Rees, “Accretion Disc Models for Compact X-Ray Sources,” *AAP*, vol. 21, p. 1, Oct. 1972.
- [31] J. Frank, A. King, and D. J. Raine, *Accretion Power in Astrophysics: Third Edition*. 2002.

- [32] P. Ghosh and F. K. Lamb, “Disk accretion by magnetic neutron stars.,” *ApJL*, vol. 223, pp. L83–L87, July 1978.
- [33] P. Ghosh and F. K. Lamb, “Accretion by rotating magnetic neutron stars. III. Accretion torques and period changes in pulsating X-ray sources.,” *ApJ*, vol. 234, pp. 296–316, Nov. 1979.
- [34] R. V. E. Lovelace, M. M. Romanova, and G. S. Bisnovatyi-Kogan, “Spin-up/spin-down of magnetized stars with accretion discs and outflows,” *MNRAS*, vol. 275, pp. 244–254, July 1995.
- [35] W. Kluźniak and S. Rappaport, “Magnetically Torqued Thin Accretion Disks,” *ApJ*, vol. 671, pp. 1990–2005, Dec. 2007.
- [36] N. I. Shakura and R. A. Sunyaev, “A theory of the instability of disk accretion on to black holes and the variability of binary X-ray sources, galactic nuclei and quasars.,” *MNRAS*, vol. 175, pp. 613–632, June 1976.
- [37] F. H. Shu, H. Shang, M. Gounelle, A. E. Glassgold, and T. Lee, “The Origin of Chondrules and Refractory Inclusions in Chondritic Meteorites,” *ApJ*, vol. 548, pp. 1029–1050, Feb. 2001.
- [38] R.-P. Kudritzki and J. Puls, “Winds from Hot Stars,” *ARAA*, vol. 38, pp. 613–666, Jan. 2000.
- [39] J. Wang, “Physical Environment of Accreting Neutron Stars,” *Advances in Astronomy*, vol. 2016, p. 3434565, Jan. 2016.
- [40] K. Davidson and J. P. Ostriker, “Neutron-Star Accretion in a Stellar Wind: Model for a Pulsed X-Ray Source,” *ApJ*, vol. 179, pp. 585–598, Jan. 1973.
- [41] F. Nagase, “Accretion-powered X-ray pulsars.,” *PASJ*, vol. 41, p. 1, Jan. 1989.
- [42] H. Bondi and F. Hoyle, “On the mechanism of accretion by stars,” *MNRAS*, vol. 104, p. 273, Jan. 1944.
- [43] R. Edgar, “A review of Bondi-Hoyle-Lyttleton accretion,” *NAR*, vol. 48, pp. 843–859, Sept. 2004.

- [44] T. L. Cline, U. D. Desai, G. Pizzichini, B. J. Teegarden, W. D. Evans, R. W. Klebesadel, J. G. Laros, K. Hurley, M. Niel, and G. Vedrenne, “Detection of a fast, intense and unusual gamma-ray transient,” *ApJL*, vol. 237, pp. L1–L5, Apr. 1980.
- [45] E. P. Mazets, S. V. Golentskii, V. N. Ilinskii, R. L. Aptekar, and I. A. Guryan, “Observations of a flaring X-ray pulsar in Dorado,” *Nature*, vol. 282, pp. 587–589, Dec. 1979.
- [46] K. Hurley, T. Cline, E. Mazets, S. Barthelmy, P. Butterworth, F. Marshall, D. Palmer, R. Aptekar, S. Golenetskii, V. Il’Inskii, D. Frederiks, J. McTiernan, R. Gold, and J. Trombka, “A giant periodic flare from the soft γ -ray repeater SGR1900+14,” *Nature*, vol. 397, pp. 41–43, Jan. 1999.
- [47] G. G. Fahlman and P. C. Gregory, “An X-ray pulsar in SNR G109.1-1.0,” *Nature*, vol. 293, pp. 202–204, Sept. 1981.
- [48] F. D. Seward, P. A. Charles, and A. P. Smale, “A 6 Second Periodic X-Ray Source in Carina,” *ApJ*, vol. 305, p. 814, June 1986.
- [49] G. L. Israel, S. Mereghetti, and L. Stella, “The Discovery of 8.7 Second Pulsations from the Ultrasoft X-Ray Source 4U 0142+61,” *ApJL*, vol. 433, p. L25, Sept. 1994.
- [50] C. Kouveliotou, S. Dieters, T. Strohmayer, J. van Paradijs, G. J. Fishman, C. A. Meegan, K. Hurley, J. Kommers, I. Smith, D. Frail, and T. Murakami, “An X-ray pulsar with a superstrong magnetic field in the soft γ -ray repeater SGR1806 - 20,” *Nature*, vol. 393, pp. 235–237, May 1998.
- [51] C. Thompson and R. C. Duncan, “The Soft Gamma Repeaters as Very Strongly Magnetized Neutron Stars. II. Quiescent Neutrino, X-Ray, and Alfven Wave Emission,” *ApJ*, vol. 473, p. 322, Dec. 1996.
- [52] F. P. Gavriil, V. M. Kaspi, and P. M. Woods, “Magnetar-like X-ray bursts from an anomalous X-ray pulsar,” *Nature*, vol. 419, pp. 142–144, Sept. 2002.
- [53] F. Coti Zelati, N. Rea, J. A. Pons, S. Campana, and P. Esposito, “Systematic study of magnetar outbursts,” *MNRAS*, vol. 474, pp. 961–1017, Feb. 2018.

- [54] P. Scholz, V. M. Kaspi, and A. Cumming, “The Long-term Post-outburst Spin Down and Flux Relaxation of Magnetar Swift J1822.3-1606,” *ApJ*, vol. 786, p. 62, May 2014.
- [55] F. P. Gavriil, M. E. Gonzalez, E. V. Gotthelf, V. M. Kaspi, M. A. Livingstone, and P. M. Woods, “Magnetar-Like Emission from the Young Pulsar in Kes 75,” *Science*, vol. 319, p. 1802, Mar. 2008.
- [56] H. S. Kumar and S. Safi-Harb, “Variability of the High Magnetic Field X-Ray Pulsar PSR J1846-0258 Associated with the Supernova Remnant Kes 75 as Revealed by the Chandra X-Ray Observatory,” *ApJL*, vol. 678, pp. L43–L46, May 2008.
- [57] L. Kuiper and W. Hermsen, “High-energy characteristics of the schizophrenic pulsar PSR J1846-0258 in Kes 75. Multi-year RXTE and INTEGRAL observations crossing the magnetar-like outburst,” *AAP*, vol. 501, pp. 1031–1046, July 2009.
- [58] R. F. Archibald, V. M. Kaspi, S. P. Tendulkar, and P. Scholz, “A Magnetar-like Outburst from a High-B Radio Pulsar,” *ApJL*, vol. 829, p. L21, Sept. 2016.
- [59] S. A. Olausen and V. M. Kaspi, “The McGill Magnetar Catalog,” *ApJS*, vol. 212, p. 6, May 2014.
- [60] V. M. Kaspi and A. M. Beloborodov, “Magnetars,” *ARAA*, vol. 55, pp. 261–301, Aug. 2017.
- [61] A. Baykal and J. Swank, “Pulse Frequency Changes of 1E 2259+586 and the Binary Interpretation,” *ApJ*, vol. 460, p. 470, Mar. 1996.
- [62] A. Baykal, T. Strohmayer, J. Swank, M. Ali Alpar, and M. J. Stark, “Differences between the two anomalous X-ray pulsars: variations in the spin-down rate of 1E 1048.1-5937 and an extended interval of quiet spin-down in 1E 2259+586,” *MNRAS*, vol. 319, pp. 205–208, Nov. 2000.
- [63] R. Dib and V. M. Kaspi, “16 yr of RXTE Monitoring of Five Anomalous X-Ray Pulsars,” *ApJ*, vol. 784, p. 37, Mar. 2014.

- [64] R. F. Archibald, V. M. Kaspi, P. Scholz, A. P. Beardmore, N. Gehrels, and J. A. Kennea, “SWIFT Observations of Two Outbursts from the Magnetar 4U0142+61,” *ApJ*, vol. 834, p. 163, Jan. 2017.
- [65] M. E. Gonzalez, R. Dib, V. M. Kaspi, P. M. Woods, C. R. Tam, and F. P. Gavriil, “Long-term X-ray Changes in the Emission from the Anomalous X-ray Pulsar 4U 0142+61,” *ApJ*, vol. 716, pp. 1345–1355, June 2010.
- [66] P. E. Boynton, E. J. Groth, D. P. Hutchinson, J. Nanos, G. P., R. B. Partridge, and D. T. Wilkinson, “Optical Timing of the Crab Pulsar, NP 0532,” *ApJ*, vol. 175, p. 217, July 1972.
- [67] J. M. Cordes and D. J. Helfand, “Pulsar timing .III. Timing noise of 50 pulsars.,” *ApJ*, vol. 239, pp. 640–650, July 1980.
- [68] J. E. Deeter, “Techniques for the estimation of red power spectra. II Evaluation of alternative methods,” *ApJ*, vol. 281, pp. 482–491, June 1984.
- [69] A. Baykal and H. Oegelman, “An empirical torque noise and spin-up model for accretion-powered X-ray pulsars.,” *AAP*, vol. 267, pp. 119–125, Jan. 1993.
- [70] L. Bildsten, D. Chakrabarty, J. Chiu, M. H. Finger, D. T. Koh, R. W. Nelson, T. A. Prince, B. C. Rubin, D. M. Scott, M. Stollberg, B. A. Vaughan, C. A. Wilson, and R. B. Wilson, “Observations of Accreting Pulsars,” *ApJS*, vol. 113, pp. 367–408, Dec. 1997.
- [71] Z. Arzoumanian, D. J. Nice, J. H. Taylor, and S. E. Thorsett, “Timing Behavior of 96 Radio Pulsars,” *ApJ*, vol. 422, p. 671, Feb. 1994.
- [72] C. M. Espinoza, A. G. Lyne, B. W. Stappers, and M. Kramer, “A study of 315 glitches in the rotation of 102 pulsars,” *MNRAS*, vol. 414, pp. 1679–1704, June 2011.
- [73] M. Yu, R. N. Manchester, G. Hobbs, S. Johnston, V. M. Kaspi, M. Keith, A. G. Lyne, G. J. Qiao, V. Ravi, J. M. Sarkissian, R. Shannon, and R. X. Xu, “Detection of 107 glitches in 36 southern pulsars,” *Monthly Notices of the Royal Astronomical Society*, vol. 429, pp. 688–724, 12 2012.

- [74] J. R. Fuentes, C. M. Espinoza, A. Reisenegger, B. Shaw, B. W. Stappers, and A. G. Lyne, “The glitch activity of neutron stars,” *AAP*, vol. 608, p. A131, Dec. 2017.
- [75] F. P. Gavril, R. Dib, and V. M. Kaspi, “The 2006-2007 Active Phase of Anomalous X-ray Pulsar 4U 0142+61: Radiative and Timing Changes, Bursts, and Burst Spectral Features,” *ApJ*, vol. 736, p. 138, Aug. 2011.
- [76] R. F. Archibald, V. M. Kaspi, C. Y. Ng, K. N. Gourgouliatos, D. Tsang, P. Scholz, A. P. Beardmore, N. Gehrels, and J. A. Kennea, “An anti-glitch in a magnetar,” *Nature*, vol. 497, pp. 591–593, May 2013.
- [77] S. Şaşmaz Muş, B. Aydın, and E. Göğüş, “A glitch and an anti-glitch in the anomalous X-ray pulsar 1E 1841-045,” *MNRAS*, vol. 440, pp. 2916–2921, June 2014.
- [78] P. W. Anderson and N. Itoh, “Pulsar glitches and restlessness as a hard superfluidity phenomenon,” *Nature*, vol. 256, pp. 25–27, July 1975.
- [79] B. Haskell and A. Melatos, “Models of pulsar glitches,” *International Journal of Modern Physics D*, vol. 24, p. 1530008, Jan. 2015.
- [80] M. M. Serim, Ş. Şahiner, D. Cerri-Serim, S. İ. Inam, and A. Baykal, “Discovery of a glitch in the accretion-powered pulsar SXP 1062,” *MNRAS*, vol. 471, pp. 4982–4989, Nov. 2017.
- [81] P. S. Ray, S. Guillot, W. C. G. Ho, M. Kerr, T. Enoto, K. C. Gendreau, Z. Arzoumanian, D. Altamirano, S. Bogdanov, R. Campion, D. Chakrabarty, J. S. Deneva, G. K. Jaisawal, R. Kozon, C. Malacaria, T. E. Strohmayer, and M. T. Wolff, “Anti-glitches in the Ultraluminous Accreting Pulsar NGC 300 ULX-1 Observed with NICER,” *ApJ*, vol. 879, p. 130, July 2019.
- [82] K. Hurley, S. E. Boggs, D. M. Smith, R. C. Duncan, R. Lin, A. Zoglauer, S. Krucker, G. Hurford, H. Hudson, C. Wigger, W. Hajdas, C. Thompson, I. Mitrofanov, A. Sanin, W. Boynton, C. Fellows, A. von Kienlin, G. Lichti, A. Rau, and T. Cline, “An exceptionally bright flare from SGR 1806-20 and the origins of short-duration γ -ray bursts,” *Nature*, vol. 434, pp. 1098–1103, Apr. 2005.

- [83] S. E. Boggs, A. Zoglauer, E. Bellm, K. Hurley, R. P. Lin, D. M. Smith, C. Wigger, and W. Hajdas, “The Giant Flare of 2004 December 27 from SGR 1806-20,” *ApJ*, vol. 661, pp. 458–467, May 2007.
- [84] R. Dib and V. M. Kaspi, “16 yr of RXTE Monitoring of Five Anomalous X-Ray Pulsars,” *ApJ*, vol. 784, p. 37, Mar. 2014.
- [85] G. Younes, M. G. Baring, C. Kouveliotou, A. Harding, S. Donovan, E. Göğüş, V. Kaspi, and J. Granot, “The Sleeping Monster: NuSTAR Observations of SGR 1806-20, 11 Years After the Giant Flare,” *ApJ*, vol. 851, p. 17, Dec. 2017.
- [86] M. A. Livingstone, P. Scholz, V. M. Kaspi, C.-Y. Ng, and F. P. Gavriil, “The spin-down of swift j1822.3–1606: A new galactic magnetar,” *The Astrophysical Journal Letters*, vol. 743, no. 2, p. l38, 2011.
- [87] P. Esposito, A. Tiengo, N. Rea, R. Turolla, A. Fenzi, A. Giuliani, G. L. Israel, S. Zane, S. Mereghetti, A. Possenti, M. Burgay, L. Stella, D. Götz, R. Perna, R. P. Mignani, and P. Romano, “X-ray and radio observations of the magnetar Swift J1834.9-0846 and its dust-scattering halo,” *MNRAS*, vol. 429, pp. 3123–3132, Mar. 2013.
- [88] P. Esposito, N. Rea, D. Lazzati, M. Matsuura, R. Perna, and J. A. Pons, “Can a Bright and Energetic X-Ray Pulsar Be Hiding Amid the Debris of SN 1987A?,” *ApJ*, vol. 857, p. 58, Apr. 2018.
- [89] E. Göğüş , P. M. Woods, C. Kouveliotou, J. van Paradijs, M. S. Briggs, R. C. Duncan, and C. Thompson, “Statistical Properties of SGR 1900+14 Bursts,” *ApJL*, vol. 526, pp. L93–L96, Dec. 1999.
- [90] E. Göğüş, P. M. Woods, C. Kouveliotou, J. van Paradijs, M. S. Briggs, R. C. Duncan, and C. Thompson, “Statistical Properties of SGR 1806-20 Bursts,” *ApJL*, vol. 532, pp. L121–L124, Apr. 2000.
- [91] S. Ş. Muş, S. , E. Göğüş, Y. Kaneko, M. Chakraborty, and B. Aydın, “Burst Tails from SGR J1550-5418 Observed with the Rossi X-Ray Timing Explorer,” *ApJ*, vol. 807, p. 42, July 2015.

- [92] F. Pintore, S. Mereghetti, A. Tiengo, G. Vianello, E. Costantini, and P. Esposito, “The effect of X-ray dust scattering on a bright burst from the magnetar 1E 1547.0-5408,” *MNRAS*, vol. 467, pp. 3467–3474, May 2017.
- [93] E. Göğüş, T. Güver, F. Özel, D. Eichler, and C. Kouveliotou, “Long-term Radiative Behavior Of SGR 1900+14,” *ApJ*, vol. 728, p. 160, Feb. 2011.
- [94] A. M. Beloborodov, “Electron-Positron Flows around Magnetars,” *ApJ*, vol. 777, p. 114, Nov. 2013.
- [95] P. R. den Hartog, L. Kuiper, W. Hermsen, V. M. Kaspi, R. Dib, J. Knödlseider, and F. P. Gavriil, “Detailed high-energy characteristics of AXP 4U 0142+61. Multi-year observations with INTEGRAL, RXTE, XMM-Newton, and ASCA,” *AAP*, vol. 489, pp. 245–261, Oct. 2008.
- [96] A. Tiengo, P. Esposito, and S. Mereghetti, “XMM-Newton Observations of CXOU J010043.1-721134: The First Deep Look at the Soft X-Ray Emission of a Magnetar,” *ApJL*, vol. 680, p. L133, June 2008.
- [97] A. M. Beloborodov, “On the Mechanism of Hard X-Ray Emission from Magnetars,” *ApJ*, vol. 762, p. 13, Jan. 2013.
- [98] B. Kern and C. Martin, “Optical pulsations from the anomalous X-ray pulsar 4U0142+61,” *Nature*, vol. 417, pp. 527–529, May 2002.
- [99] V. S. Dhillon, T. R. Marsh, S. P. Littlefair, C. M. Copperwheat, P. Kerry, R. Dib, M. Durant, V. M. Kaspi, R. P. Mignani, and A. Shearer, “Optical pulsations from the anomalous X-ray pulsar 1E1048.1-5937,” *MNRAS*, vol. 394, pp. L112–L116, Mar. 2009.
- [100] V. S. Dhillon, T. R. Marsh, S. P. Littlefair, C. M. Copperwheat, R. D. G. Hickman, P. Kerry, A. J. Levan, N. Rea, C. D. J. Savoury, N. R. Tanvir, R. Turolla, and K. Wiersema, “The first observation of optical pulsations from a soft gamma repeater: SGR 0501+4516,” *MNRAS*, vol. 416, pp. L16–L20, Sept. 2011.
- [101] C. R. Tam, V. M. Kaspi, M. H. van Kerkwijk, and M. Durant, “Correlated Infrared and X-Ray Flux Changes Following the 2002 June Outburst of the

- Anomalous X-Ray Pulsar 1E 2259+586,” *ApJL*, vol. 617, pp. L53–L56, Dec. 2004.
- [102] C. R. Tam, F. P. Gavriil, R. Dib, V. M. Kaspi, P. M. Woods, and C. Bassa, “X-Ray and Near-IR Variability of the Anomalous X-Ray Pulsar 1E 1048.1-5937: From Quiescence Back to Activity,” *ApJ*, vol. 677, pp. 503–514, Apr. 2008.
- [103] M. Durant and M. H. van Kerkwijk, “Multiwavelength Variability of the Magnetar 4U 0142+61,” *ApJ*, vol. 652, pp. 576–583, Nov. 2006.
- [104] V. Testa, N. Rea, R. P. Mignani, G. L. Israel, R. Perna, S. Chaty, L. Stella, S. Covino, R. Turolla, S. Zane, G. Lo Curto, S. Campana, G. Marconi, and S. Mereghetti, “Adaptive optics, near-infrared observations of magnetars,” *AAP*, vol. 482, pp. 607–615, May 2008.
- [105] Z. Wang, C. Bassa, V. M. Kaspi, J. J. Bryant, and N. Morrell, “Optical/Infrared Observations of the Anomalous X-Ray Pulsar 1E 1048.1-5937 during Its 2007 X-Ray Flare,” *ApJ*, vol. 679, pp. 1443–1446, June 2008.
- [106] S. Zane, L. Nobili, and R. Turolla, “The magnetar emission in the IR band: the role of magnetospheric currents,” *Astrophysics and Space Science Proceedings*, vol. 21, p. 329, Jan. 2011.
- [107] F. Camilo, S. M. Ransom, J. P. Halpern, J. Reynolds, D. J. Helfand, N. Zimmermann, and J. Sarkissian, “Transient pulsed radio emission from a magnetar,” *Nature*, vol. 442, pp. 892–895, Aug. 2006.
- [108] F. Camilo, S. M. Ransom, J. P. Halpern, and J. Reynolds, “1E 1547.0-5408: A Radio-emitting Magnetar with a Rotation Period of 2 Seconds,” *ApJL*, vol. 666, pp. L93–L96, Sept. 2007.
- [109] L. Levin, M. Bailes, S. Bates, N. D. R. Bhat, M. Burgay, S. Burke-Spolaor, N. D’Amico, S. Johnston, M. Keith, M. Kramer, S. Milia, A. Possenti, N. Rea, B. Stappers, and W. van Straten, “A Radio-loud Magnetar in X-ray Quiescence,” *ApJL*, vol. 721, pp. L33–L37, Sept. 2010.
- [110] R. M. Shannon and S. Johnston, “Radio properties of the magnetar near Sagittarius a* from observations with the australia telescope compact array,” *MNRAS*, vol. 435, pp. L29–L32, Aug. 2013.

- [111] R. P. Eatough, H. Falcke, R. Karuppusamy, K. J. Lee, D. J. Champion, E. F. Keane, G. Desvignes, D. H. F. M. Schnitzeler, L. G. Spitler, M. Kramer, B. Klein, C. Bassa, G. C. Bower, A. Brunthaler, I. Cognard, A. T. Deller, P. B. Demorest, P. C. C. Freire, A. Kraus, A. G. Lyne, A. Noutsos, B. Stappers, and N. Wex, “A strong magnetic field around the supermassive black hole at the centre of the Galaxy,” *Nature*, vol. 501, pp. 391–394, Sept. 2013.
- [112] R. Karuppusamy, G. Desvignes, M. Kramer, N. Porayko, D. Champion, P. Torne, B. Stappers, A. van der Horst, C. Kouveliotou, and B. O’Connor, “Detection of pulsed radio emission from new magnetar Swift J1818.0-1607,” *The Astronomer’s Telegram*, vol. 13553, p. 1, Mar. 2020.
- [113] F. Camilo, J. Reynolds, S. Johnston, J. P. Halpern, and S. M. Ransom, “The Magnetar 1E 1547.0-5408: Radio Spectrum, Polarimetry, and Timing,” *ApJ*, vol. 679, pp. 681–686, May 2008.
- [114] N. Rea, P. Esposito, J. A. Pons, R. Turolla, D. F. Torres, G. L. Israel, A. Possenti, M. Burgay, D. Viganò, A. Papitto, R. Perna, L. Stella, G. Ponti, F. K. Baganoff, D. Haggard, A. Camero-Arranz, S. Zane, A. Minter, S. Mereghetti, A. Tiengo, R. Schödel, M. Feroci, R. Mignani, and D. Götz, “A Strongly Magnetized Pulsar within the Grasp of the Milky Way’s Supermassive Black Hole,” *ApJL*, vol. 775, p. L34, Oct. 2013.
- [115] L. G. Spitler, K. J. Lee, R. P. Eatough, M. Kramer, R. Karuppusamy, C. G. Bassa, I. Cognard, G. Desvignes, A. G. Lyne, B. W. Stappers, G. C. Bower, J. M. Cordes, D. J. Champion, and H. Falcke, “Pulse Broadening Measurements from the Galactic Center Pulsar J1745-2900,” *ApJL*, vol. 780, p. L3, Jan. 2014.
- [116] G. C. Bower, A. Deller, P. Demorest, A. Brunthaler, R. Eatough, H. Falcke, M. Kramer, K. J. Lee, and L. Spitler, “The Angular Broadening of the Galactic Center Pulsar SGR J1745-29: A New Constraint on the Scattering Medium,” *ApJL*, vol. 780, p. L2, Jan. 2014.
- [117] R. C. Duncan, “Physics in ultra-strong magnetic fields,” in *Gamma-ray Bursts, 5th Huntsville Symposium* (R. M. Kippen, R. S. Mallozzi, and G. J. Fishman,

- eds.), vol. 526 of *American Institute of Physics Conference Series*, pp. 830–841, Sept. 2000.
- [118] C. Thompson and R. C. Duncan, “The soft gamma repeaters as very strongly magnetized neutron stars - I. Radiative mechanism for outbursts,” *MNRAS*, vol. 275, pp. 255–300, July 1995.
 - [119] T. G. Cowling, “The stability of gaseous stars,” *MNRAS*, vol. 94, pp. 768–782, June 1934.
 - [120] *Plasma astrophysics*, Jan. 1997.
 - [121] E. N. Parker, “Hydromagnetic Dynamo Models.,” *ApJ*, vol. 122, p. 293, Sept. 1955.
 - [122] C. Thompson and R. C. Duncan, “Neutron Star Dynamos and the Origins of Pulsar Magnetism,” *ApJ*, vol. 408, p. 194, May 1993.
 - [123] J. Braithwaite, “Axisymmetric magnetic fields in stars: relative strengths of poloidal and toroidal components,” *MNRAS*, vol. 397, pp. 763–774, Aug. 2009.
 - [124] P. Goldreich and A. Reisenegger, “Magnetic Field Decay in Isolated Neutron Stars,” *ApJ*, vol. 395, p. 250, Aug. 1992.
 - [125] A. Reisenegger, “Origin and evolution of neutron star magnetic fields,” *arXiv e-prints*, pp. astro-ph/0307133, July 2003.
 - [126] D. G. Yakovlev and D. A. Shalybkov, “Electrical Conductivity and Resistivity in Magnetized Cores of Neutron Stars,” *Soviet Astronomy Letters*, vol. 16, p. 86, Apr. 1990.
 - [127] K. Glampedakis, D. I. Jones, and L. Samuelsson, “Ambipolar diffusion in superfluid neutron stars,” *MNRAS*, vol. 413, pp. 2021–2030, May 2011.
 - [128] A. M. Beloborodov and X. Li, “Magnetar Heating,” *ApJ*, vol. 833, p. 261, Dec. 2016.
 - [129] A. Bransgrove, Y. Levin, and A. Beloborodov, “Magnetic field evolution of neutron stars - I. Basic formalism, numerical techniques and first results,” *MNRAS*, vol. 473, pp. 2771–2790, Jan. 2018.

- [130] P. B. Jones, “Nature of Fault Planes in Solid Neutron Star Matter,” *ApJ*, vol. 595, pp. 342–345, Sept. 2003.
- [131] Y. Levin and M. Lyutikov, “On the dynamics of mechanical failures in magnetized neutron star crusts,” *MNRAS*, vol. 427, pp. 1574–1579, Dec. 2012.
- [132] A. I. Chugunov and C. J. Horowitz, “Breaking stress of neutron star crust,” *MNRAS*, vol. 407, pp. L54–L58, Sept. 2010.
- [133] A. M. Beloborodov and Y. Levin, “Thermoplastic Waves in Magnetars,” *ApJL*, vol. 794, p. L24, Oct. 2014.
- [134] C. Thompson, M. Lyutikov, and S. R. Kulkarni, “Electrodynamics of Magnetars: Implications for the Persistent X-Ray Emission and Spin-down of the Soft Gamma Repeaters and Anomalous X-Ray Pulsars,” *ApJ*, vol. 574, pp. 332–355, July 2002.
- [135] A. M. Beloborodov, “Untwisting Magnetospheres of Neutron Stars,” *ApJ*, vol. 703, pp. 1044–1060, Sept. 2009.
- [136] M. Lyutikov, “Explosive reconnection in magnetars,” *MNRAS*, vol. 346, pp. 540–554, Dec. 2003.
- [137] D. A. Uzdensky, “Partial Field Opening and Current Sheet Formation in the Disk Magnetosphere,” *ApJ*, vol. 572, pp. 432–444, June 2002.
- [138] K. Parfrey, A. M. Beloborodov, and L. Hui, “Dynamics of Strongly Twisted Relativistic Magnetospheres,” *ApJ*, vol. 774, p. 92, Sept. 2013.
- [139] R. Perna and J. A. Pons, “A Unified Model of the Magnetar and Radio Pulsar Bursting Phenomenology,” *ApJL*, vol. 727, p. L51, Feb. 2011.
- [140] G. Hobbs, A. G. Lyne, and M. Kramer, “An analysis of the timing irregularities for 366 pulsars,” *MNRAS*, vol. 402, pp. 1027–1048, Feb. 2010.
- [141] P. Chatterjee, L. Hernquist, and R. Narayan, “An Accretion Model for Anomalous X-Ray Pulsars,” *ApJ*, vol. 534, pp. 373–379, May 2000.
- [142] M. A. Alpar, “On Young Neutron Stars as Propellers and Accretors with Conventional Magnetic Fields,” *ApJ*, vol. 554, pp. 1245–1254, June 2001.

- [143] D. N. C. Lin, S. E. Woosley, and P. H. Bodenheimer, “Formation of a planet orbiting pulsar 1829-10 from the debris of a supernova explosion,” *Nature*, vol. 353, pp. 827–829, Oct. 1991.
- [144] R. A. Chevalier, “Neutron Star Accretion in a Supernova,” *ApJ*, vol. 346, p. 847, Nov. 1989.
- [145] K. Menou, R. Perna, and L. Hernquist, “Stability and Evolution of Supernova Fallback Disks,” *ApJ*, vol. 559, pp. 1032–1046, Oct. 2001.
- [146] X.-D. Li, “The Nature of the Compact X-Ray Source in Supernova Remnant RCW 103,” *ApJL*, vol. 666, pp. L81–L84, Sept. 2007.
- [147] A. F. Illarionov and R. A. Sunyaev, “Why the Number of Galactic X-ray Stars Is so Small?,” *AAP*, vol. 39, p. 185, Feb. 1975.
- [148] H. Tong, W. Wang, X. W. Liu, and R. X. Xu, “Rotational Evolution of Magnetars in the Presence of a Fallback Disk,” *ApJ*, vol. 833, p. 265, Dec. 2016.
- [149] F. P. Gavriil, *Magnetar-like x-ray bursts from anomalous x-ray pulsars*. PhD thesis, McGill University, Canada, Jan. 2006.
- [150] V. M. Kaspi, F. P. Gavriil, D. Chakrabarty, J. R. Lackey, and M. P. Muno, “Long-Term Rossi X-Ray Timing Explorer Monitoring of the Anomalous X-Ray Pulsar 1E 1048.1-5937,” *ApJ*, vol. 558, pp. 253–262, Sept. 2001.
- [151] Z. Wang, D. Chakrabarty, and D. L. Kaplan, “A debris disk around an isolated young neutron star,” *Nature*, vol. 440, pp. 772–775, Apr. 2006.
- [152] S. O. Tagieva, E. Yazgan, and A. Ankay, “Do Young Neutron Stars Which Show Themselves as AXPs and SGRs Accrete?,” *International Journal of Modern Physics D*, vol. 12, pp. 825–831, Jan. 2003.
- [153] K. Y. Ekş1 and M. A. Alpar, “Can Thin Disks Produce Anomalous X-Ray Pulsars?,” *ApJ*, vol. 599, pp. 450–456, Dec. 2003.
- [154] J. Deeter and P. Boynton, “Timing Studies of X-ray Sources,” in *Proc. Inuyama Workshop, Nagoya Univ.*, p. 29, 1985.

- [155] M. E. Lower, M. Bailes, R. M. Shannon, S. Johnston, C. Flynn, S. Osłowski, V. Gupta, W. Farah, T. Bateman, A. J. Green, R. Hunstead, A. Jameson, F. Jankowski, A. Parthasarathy, D. C. Price, A. Sutherland, D. Temby, and V. Venkatraman Krishnan, “The UTMOST pulsar timing programme - II. Timing noise across the pulsar population,” *MNRAS*, vol. 494, pp. 228–245, Mar. 2020.
- [156] R. M. Shannon and J. M. Cordes, “Assessing the Role of Spin Noise in the Precision Timing of Millisecond Pulsars,” *ApJ*, vol. 725, pp. 1607–1619, Dec. 2010.
- [157] F. D’Alessandro, P. M. McCulloch, P. A. Hamilton, and A. A. Deshpande, “The timing noise of 45 southern pulsars,” *MNRAS*, vol. 277, pp. 1033–1046, Dec. 1995.
- [158] J. M. Cordes and G. S. Downs, “JPL pulsar timing observations. III. Pulsar rotation fluctuations.,” *ApJS*, vol. 59, pp. 343–382, Nov. 1985.
- [159] D. Çerri-Serim, M. M. Serim, Ş. Şahiner, S. Ç. Inam, and A. Baykal, “Pulse frequency fluctuations of magnetars,” *MNRAS*, vol. 485, pp. 2–12, May 2019.
- [160] M. A. Alpar, R. Nandkumar, and D. Pines, “Vortex creep and the internal temperature of neutron stars : timing noise in pulsars.,” *ApJ*, vol. 311, pp. 197–213, Dec. 1986.
- [161] D. M. Scott, M. H. Finger, and C. A. Wilson, “Characterization of the timing noise of the Crab pulsar,” *MNRAS*, vol. 344, pp. 412–430, Sept. 2003.
- [162] M. M. Serim, S. Ç. Inam, and A. Baykal, “Noise Strength Estimates of Three SGRs: Swift J1822.3-1606, SGR J1833-0832 and Swift J1834.9-0846,” in *Electromagnetic Radiation from Pulsars and Magnetars* (W. Lewandowski, O. Maron, and J. Kijak, eds.), vol. 466 of *Astronomical Society of the Pacific Conference Series*, p. 255, Dec. 2012.
- [163] R. C. Lamb, D. W. Fox, D. J. Macomb, and T. A. Prince, “Discovery of a Possible Anomalous X-Ray Pulsar in the Small Magellanic Cloud,” *ApJL*, vol. 574, pp. L29–L32, July 2002.

- [164] W. A. Majid, R. C. Lamb, and D. J. Macomb, “X-Ray Pulsars in the Small Magellanic Cloud,” *ApJ*, vol. 609, pp. 133–143, July 2004.
- [165] M. B. McGarry, B. M. Gaensler, S. M. Ransom, V. M. Kaspi, and S. Veljkovic, “X-Ray Timing, Spectroscopy, and Photometry of the Anomalous X-Ray Pulsar Candidate CXOU J010043.1-721134,” *ApJL*, vol. 627, pp. L137–L140, July 2005.
- [166] M. Durant and M. H. van Kerkwijk, “Possible Optical Detection of the Anomalous X-Ray Pulsar CXOU J010043.1-721134,” *ApJL*, vol. 628, pp. L135–L138, Aug. 2005.
- [167] W. Forman, C. Jones, L. Cominsky, P. Julien, S. Murray, G. Peters, H. Tananbaum, and R. Giacconi, “The fourth Uhuru catalog of X-ray sources,” *ApJS*, vol. 38, pp. 357–412, Dec. 1978.
- [168] M. Durant and M. H. van Kerkwijk, “Distances to Anomalous X-Ray Pulsars Using Red Clump Stars,” *ApJ*, vol. 650, pp. 1070–1081, Oct. 2006.
- [169] S. R. Oates, W. H. Baumgartner, A. P. Beardmore, S. Campana, N. Gehrels, E. A. Hovest, H. A. Krimm, V. Mangano, F. E. Marshall, A. Melandri, C. J. Mountford, K. L. Page, D. M. Palmer, P. Romano, C. J. Saxton, B. Sbarufatti, and G. Tagliaferri, “Swift detection of a SGR-like burst from the AXP 4U 0142+61,” *GRB Coordinates Network*, vol. 12209, p. 1, Jan. 2011.
- [170] S. D. Barthelmy, D. M. Palmer, and B. Sbarufatti, “Swift detection of 4U 1850-03,” *GRB Coordinates Network*, vol. 18675, p. 1, Jan. 2015.
- [171] A. J. van der Horst, V. Connaughton, C. Kouveliotou, E. Göğüş, Y. Kaneko, S. Wachter, M. S. Briggs, J. Granot, E. Ramirez-Ruiz, P. M. Woods, R. L. Aptekar, S. D. Barthelmy, J. R. Cummings, M. H. Finger, D. D. Frederiks, N. Gehrels, C. R. Gelino, D. M. Gelino, S. Golenetskii, K. Hurley, H. A. Krimm, E. P. Mazets, J. E. McEnery, C. A. Meegan, P. P. Oleynik, D. M. Palmer, V. D. Pal’shin, A. Pe’er, D. Svinkin, M. V. Ulanov, M. van der Klis, A. von Kienlin, A. L. Watts, and C. A. Wilson-Hodge, “Discovery of a New Soft Gamma Repeater: SGR J0418 + 5729,” *ApJL*, vol. 711, pp. L1–L6, Mar. 2010.

- [172] P. Esposito, G. L. Israel, R. Turolla, A. Tiengo, D. Götz, A. de Luca, R. P. Mignani, S. Zane, N. Rea, V. Testa, P. A. Caraveo, S. Chaty, F. Mattana, S. Mereghetti, A. Pellizzoni, and P. Romano, “Early X-ray and optical observations of the soft gamma-ray repeater SGR0418+5729,” *MNRAS*, vol. 405, pp. 1787–1795, July 2010.
- [173] M. A. Alpar, Ü. Ertan, and Ş. Çalışkan, “SGR 0418+5729—How does a Young Neutron Star Spin Down to a 9 s Period with a Dipole Field Less Than 10^{13} G?,” *ApJL*, vol. 732, p. L4, May 2011.
- [174] V. Soni, “Understanding the low magnetic field magnetar, SGR 0418+5279, from a magnetized core model,” *MNRAS*, vol. 425, pp. L15–L18, Sept. 2012.
- [175] M. Malheiro, J. A. Rueda, and R. Ruffini, “SGRs and AXPs as Rotation-Powered Massive White Dwarfs,” *PASJ*, vol. 64, p. 56, June 2012.
- [176] H. Tong and R. X. Xu, “SGR 0418+5729: A Small Inclination Angle Resulting in a Not So Low Dipole Magnetic Field?,” *ApJL*, vol. 757, p. L10, Sept. 2012.
- [177] S. D. Barthelmy, W. H. Baumgartner, A. P. Beardmore, D. N. Burrows, J. R. Cummings, P. A. Evans, N. Gehrels, O. Godet, C. Guidorzi, S. T. Holland, J. A. Kennea, V. Mangano, J. Mao, F. E. Marshall, P. T. O’Brien, J. P. Osborne, C. Pagani, K. L. Page, D. M. Palmer, M. Perri, T. Sakamoto, B. Sbarufatti, R. L. C. Starling, G. Stratta, T. N. Ukwatta, and L. Vetere, “New Soft Gamma Repeater SGR 0501+4516,” *The Astronomer’s Telegram*, vol. 1676, p. 1, Aug. 2008.
- [178] E. Gogus, P. Woods, and C. Kouveliotou, “Spin Period of New Soft Gamma Repeater SGR 0501+4516,” *The Astronomer’s Telegram*, vol. 1677, p. 1, Aug. 2008.
- [179] E. Göğüş, P. M. Woods, C. Kouveliotou, Y. Kaneko, B. M. Gaensler, and S. Chatterjee, “Spatial, Temporal, and Spectral Properties of X-ray Emission from the Magnetar SGR 0501+4516,” *ApJ*, vol. 722, pp. 899–908, Oct. 2010.
- [180] A. Camero, A. Papitto, N. Rea, D. Viganò, J. A. Pons, A. Tiengo, S. Mereghetti, R. Turolla, P. Esposito, S. Zane, G. L. Israel, and D. Götz, “Qui-

- escent state and outburst evolution of SGR 0501+4516,” *MNRAS*, vol. 438, pp. 3291–3298, Mar. 2014.
- [181] R. E. Rothschild, S. R. Kulkarni, and R. E. Lingenfelter, “Discovery of an X-ray source coincident with the soft γ -ray repeater 0525 - 66,” *Nature*, vol. 368, pp. 432–434, Mar. 1994.
- [182] A. Tiengo, P. Esposito, S. Mereghetti, G. L. Israel, L. Stella, R. Turolla, S. Zane, N. Rea, D. Götz, and M. Feroci, “Quiet but still bright: XMM-Newton observations of the soft gamma-ray repeater SGR0526-66,” *MNRAS*, vol. 399, pp. L74–L78, Oct. 2009.
- [183] S. R. Kulkarni, D. L. Kaplan, H. L. Marshall, D. A. Frail, T. Murakami, and D. Yonetoku, “The Quiescent Counterpart of the Soft Gamma-Ray Repeater SGR 0526-66,” *ApJ*, vol. 585, pp. 948–954, Mar. 2003.
- [184] T. Güver, E. Göğüş, and F. Özel, “On the cooling trend of SGR 0526-66,” *MNRAS*, vol. 424, pp. 210–216, July 2012.
- [185] F. P. Gavriil and V. M. Kaspi, “Anomalous X-ray Pulsars: Pulsed Flux Flares and Large Torque Variations in 1E 1048.1-5937,” in *AAS/High Energy Astrophysics Division #8*, vol. 8 of *AAS/High Energy Astrophysics Division*, p. 08.05, Aug. 2004.
- [186] R. F. Archibald, V. M. Kaspi, C. Y. Ng, P. Scholz, A. P. Beardmore, N. Gehrels, and J. A. Kennea, “Repeated, Delayed Torque Variations Following X-Ray Flux Enhancements in the Magnetar 1E 1048.1-5937,” *ApJ*, vol. 800, p. 33, Feb. 2015.
- [187] R. F. Archibald, P. Scholz, V. M. Kaspi, S. P. Tendulkar, and A. P. Beardmore, “Two New Outbursts and Transient Hard X-Rays from 1E 1048.1-5937,” *ApJ*, vol. 889, p. 160, Feb. 2020.
- [188] R. Dib, V. M. Kaspi, and F. P. Gavriil, “Rossi X-Ray Timing Explorer Monitoring of the Anomalous X-ray Pulsar 1E 1048.1 - 5937: Long-term Variability and the 2007 March Event,” *ApJ*, vol. 702, pp. 614–630, Sept. 2009.
- [189] R. C. Lamb and T. H. Markert, “X-ray emission from supernova remnants near gamma-ray sources,” *ApJ*, vol. 244, pp. 94–101, Feb. 1981.

- [190] F. Camilo, S. M. Ransom, J. P. Halpern, and J. Reynolds, “1E 1547.0-5408: A Radio-emitting Magnetar with a Rotation Period of 2 Seconds,” *ApJL*, vol. 666, pp. L93–L96, Sept. 2007.
- [191] J. P. Halpern, E. V. Gotthelf, J. Reynolds, S. M. Ransom, and F. Camilo, “Outburst of the 2 s Anomalous X-Ray Pulsar 1E 1547.0-5408,” *ApJ*, vol. 676, pp. 1178–1183, Apr. 2008.
- [192] S. Mereghetti, D. Götz, G. Weidenspointner, A. von Kienlin, P. Esposito, A. Tiengo, G. Vianello, G. L. Israel, L. Stella, R. Turolla, N. Rea, and S. Zane, “Strong Bursts from the Anomalous X-Ray Pulsar 1E 1547.0-5408 Observed with the INTEGRAL/SPI Anti-Coincidence Shield,” *ApJL*, vol. 696, pp. L74–L78, May 2009.
- [193] G. L. Israel, P. Esposito, N. Rea, S. Dall’Osso, F. Senziani, P. Romano, V. Mangano, D. Götz, S. Zane, A. Tiengo, D. M. Palmer, H. Krimm, N. Gehrels, S. Mereghetti, L. Stella, R. Turolla, S. Campana, R. Perna, L. Angelini, and A. de Luca, “The 2008 October Swift detection of X-ray bursts/outburst from the transient SGR-like AXP 1E1547.0-5408,” *MNRAS*, vol. 408, pp. 1387–1395, Nov. 2010.
- [194] Y. Kaneko, E. Göğüş, C. Kouveliotou, J. Granot, E. Ramirez-Ruiz, A. J. van der Horst, A. L. Watts, M. H. Finger, N. Gehrels, A. Pe’er, M. van der Klis, A. von Kienlin, S. Wachter, C. A. Wilson-Hodge, and P. M. Woods, “Magnetar Twists: Fermi/Gamma-Ray Burst Monitor Detection of SGR J1550-5418,” *ApJ*, vol. 710, pp. 1335–1342, Feb. 2010.
- [195] C. Y. Ng, V. M. Kaspi, R. Dib, S. A. Olausen, P. Scholz, T. Güver, F. Özel, F. P. Gavriil, and P. M. Woods, “Chandra and RXTE Observations of 1E 1547.0-5408: Comparing the 2008 and 2009 Outbursts,” *ApJ*, vol. 729, p. 131, Mar. 2011.
- [196] R. Dib, V. M. Kaspi, P. Scholz, and F. P. Gavriil, “RXTE Observations of Anomalous X-Ray Pulsar 1E 1547.0-5408 during and after its 2008 and 2009 Outbursts,” *ApJ*, vol. 748, p. 3, Mar. 2012.
- [197] L. Kuiper, W. Hermsen, P. R. den Hartog, and J. O. Urama, “Temporal and

Spectral Evolution in X- and γ -Rays of Magnetar 1E 1547.0-5408 since its 2008 October Outburst: The Discovery of a Transient Hard Pulsed Component after its 2009 January Outburst,” *ApJ*, vol. 748, p. 133, Apr. 2012.

- [198] F. Camilo, P. Scholz, J. Sarkissian, and J. Reynolds, “Radio and X-ray reactivation of magnetar PSR J1622-4950,” *The Astronomer’s Telegram*, vol. 10346, p. 1, May 2017.
- [199] P. Scholz, F. Camilo, J. Sarkissian, J. E. Reynolds, L. Levin, M. Bailes, M. Burgay, S. Johnston, M. Kramer, and A. Possenti, “Spin-down Evolution and Radio Disappearance of the Magnetar PSR J1622-4950,” *ApJ*, vol. 841, p. 126, June 2017.
- [200] P. M. Woods, C. Kouveliotou, J. van Paradijs, K. Hurley, R. M. Kippen, M. H. Finger, M. S. Briggs, S. Dieters, and G. J. Fishman, “Discovery of a New Soft Gamma Repeater, SGR 1627-41,” *ApJL*, vol. 519, pp. L139–L142, July 1999.
- [201] P. Esposito, G. L. Israel, S. Zane, F. Senziani, R. L. C. Starling, N. Rea, D. M. Palmer, N. Gehrels, A. Tiengo, A. de Luca, D. Götz, S. Mereghetti, P. Romano, T. Sakamoto, S. D. Barthelmy, L. Stella, R. Turolla, M. Feroci, and V. Mangano, “The 2008 May burst activation of SGR1627-41,” *MNRAS*, vol. 390, pp. L34–L38, Oct. 2008.
- [202] P. Esposito, M. Burgay, A. Possenti, R. Turolla, S. Zane, A. de Luca, A. Tiengo, G. L. Israel, F. Mattana, S. Mereghetti, M. Bailes, P. Romano, D. Götz, and N. Rea, “Spin-down rate and inferred dipole magnetic field of the soft gamma-ray repeater SGR1627-41,” *MNRAS*, vol. 399, pp. L44–L48, Oct. 2009.
- [203] H. Krimm, S. Barthelmy, S. Campana, J. Cummings, G. Israel, D. Palmer, and A. Parsons, “Swift/BAT detects a hard X-ray burst from AXP CXOU J164710.2-455216,” *The Astronomer’s Telegram*, vol. 894, p. 1, Sept. 2006.
- [204] G. L. Israel, S. Campana, S. Dall’Osso, M. P. Muno, J. Cummings, R. Perna, and L. Stella, “The Post-Burst Awakening of the Anomalous X-Ray Pulsar in Westerlund 1,” *ApJ*, vol. 664, pp. 448–457, July 2007.
- [205] H. An, V. M. Kaspi, R. Archibald, and A. Cumming, “Spectral and Timing

- Properties of the Magnetar CXOU J164710.2-455216,” *ApJ*, vol. 763, p. 82, Feb. 2013.
- [206] G. A. Rodríguez Castillo, G. L. Israel, P. Esposito, J. A. Pons, N. Rea, R. Turolla, D. Viganò, and S. Zane, “Pulse phase-coherent timing and spectroscopy of CXOU J164710.2-45521 outbursts,” *MNRAS*, vol. 441, pp. 1305–1316, June 2014.
- [207] V. Testa, R. P. Mignani, W. Hummel, N. Rea, and G. L. Israel, “VLT observations of the magnetar CXO J164710.2-455216 and the detection of a candidate infrared counterpart,” *MNRAS*, vol. 473, pp. 3180–3184, Jan. 2018.
- [208] W. Voges, B. Aschenbach, T. Boller, H. Bräuninger, U. Briel, W. Burkert, K. Dennerl, J. Englhauser, R. Gruber, F. Haberl, G. Hartner, G. Hasinger, M. Kürster, E. Pfeffermann, W. Pietsch, P. Predehl, C. Rosso, J. H. M. M. Schmitt, J. Trümper, and H. U. Zimmermann, “The ROSAT all-sky survey bright source catalogue,” *AAP*, vol. 349, pp. 389–405, Sept. 1999.
- [209] V. M. Kaspi, J. R. Lackey, and D. Chakrabarty, “A Glitch in an Anomalous X-Ray Pulsar,” *ApJL*, vol. 537, pp. L31–L34, July 2000.
- [210] V. M. Kaspi and F. P. Gavriil, “A Second Glitch from the “Anomalous” X-Ray Pulsar 1RXS J170849.0-4000910,” *ApJL*, vol. 596, pp. L71–L74, Oct. 2003.
- [211] S. Dall’Osso, G. L. Israel, L. Stella, A. Possenti, and E. Perozzi, “The Glitches of the Anomalous X-Ray Pulsar 1RXS J170849.0-400910,” *ApJ*, vol. 599, pp. 485–497, Dec. 2003.
- [212] R. Dib, V. M. Kaspi, and F. P. Gavriil, “Glitches in Anomalous X-Ray Pulsars,” *ApJ*, vol. 673, pp. 1044–1061, Feb. 2008.
- [213] P. Scholz, R. F. Archibald, V. M. Kaspi, C. Y. Ng, A. P. Beardmore, N. Gehrels, and J. A. Kennea, “On the X-Ray Variability of Magnetar 1RXS J170849.0-400910,” *ApJ*, vol. 783, p. 99, Mar. 2014.
- [214] F. Aharonian, A. G. Akhperjanian, U. Barres de Almeida, A. R. Bazer-Bachi, and e. a. Behera, “Discovery of a VHE gamma-ray source coincident with the supernova remnant CTB 37A,” *AAP*, vol. 490, pp. 685–693, Nov. 2008.

- [215] J. P. Halpern and E. V. Gotthelf, “An Energetic Magnetar in HESS J1713-381/CTB 37B,” *ApJ*, vol. 725, pp. 1384–1391, Dec. 2010.
- [216] T. Sato, A. Bamba, R. Nakamura, and M. Ishida, “Identification of CXOU J171405.7-381031 as a New Magnetar with XMM-Newton,” *PASJ*, vol. 62, pp. L33–L36, Oct. 2010.
- [217] J. A. Kennea, D. N. Burrows, C. Kouveliotou, D. M. Palmer, E. Göğüş, Y. Kaneko, P. A. Evans, N. Degenaar, M. T. Reynolds, J. M. Miller, R. Wijmands, K. Mori, and N. Gehrels, “Swift Discovery of a New Soft Gamma Repeater, SGR J1745-29, near Sagittarius A*,” *ApJL*, vol. 770, p. L24, June 2013.
- [218] R. Genzel, F. Eisenhauer, and S. Gillessen, “The Galactic Center massive black hole and nuclear star cluster,” *Reviews of Modern Physics*, vol. 82, pp. 3121–3195, Oct. 2010.
- [219] K. Mori, E. V. Gotthelf, S. Zhang, H. An, F. K. Baganoff, N. M. Barrière, A. M. Beloborodov, S. E. Boggs, F. E. Christensen, W. W. Craig, F. Dufour, B. W. Grefenstette, C. J. Hailey, F. A. Harrison, J. Hong, V. M. Kaspi, J. A. Kennea, K. K. Madsen, C. B. Markwardt, M. Nynka, D. Stern, J. A. Tomsick, and W. W. Zhang, “NuSTAR Discovery of a 3.76 s Transient Magnetar Near Sagittarius A*,” *ApJL*, vol. 770, p. L23, June 2013.
- [220] V. M. Kaspi, R. F. Archibald, V. Bhlerao, F. Dufour, E. V. Gotthelf, H. An, M. Bachetti, A. M. Beloborodov, S. E. Boggs, F. E. Christensen, W. W. Craig, B. W. Grefenstette, C. J. Hailey, F. A. Harrison, J. A. Kennea, C. Kouveliotou, K. K. Madsen, K. Mori, C. B. Markwardt, D. Stern, J. K. Vogel, and W. W. Zhang, “Timing and Flux Evolution of the Galactic Center Magnetar SGR J1745-2900,” *ApJ*, vol. 786, p. 84, May 2014.
- [221] F. Coti Zelati, N. Rea, A. Papitto, D. Viganò, J. A. Pons, R. Turolla, P. Esposito, D. Haggard, F. K. Baganoff, G. Ponti, G. L. Israel, S. Campana, D. F. Torres, A. Tiengo, S. Mereghetti, R. Perna, S. Zane, R. P. Mignani, A. Possenti, and L. Stella, “The X-ray outburst of the Galactic Centre magnetar SGR J1745-2900 during the first 1.5 year,” *MNRAS*, vol. 449, pp. 2685–2699, May 2015.

- [222] J. G. Laros, E. E. Fenimore, R. W. Klebesadel, J. L. Atteia, M. Boer, K. Hurley, M. Niel, G. Vedrenne, S. R. Kane, C. Kouveliotou, T. L. Cline, B. R. Dennis, U. D. Desai, L. E. Orwig, A. V. Kuznetsov, R. A. Sunyaev, and O. V. Terekhov, “A New Type of Repetitive Behavior in a High-Energy Transient,” *ApJL*, vol. 320, p. L111, Sept. 1987.
- [223] C. Kouveliotou, J. P. Norris, T. L. Cline, B. R. Dennis, U. D. Desai, L. E. Orwig, E. E. Fenimore, R. W. Klebesadel, J. G. Laros, J. L. Atteia, M. Boer, K. Hurley, M. Neil, G. Vedrenne, A. V. Kuznetsov, R. A. Sunyaev, and O. V. Terekhov, “SMM Hard X-Ray Observations of the Soft Gamma-Ray Repeater 1806-20,” *ApJL*, vol. 322, p. L21, Nov. 1987.
- [224] P. M. Woods, C. Kouveliotou, M. H. Finger, E. Göğüş, C. A. Wilson, S. K. Patel, K. Hurley, and J. H. Swank, “The Prelude to and Aftermath of the Giant Flare of 2004 December 27: Persistent and Pulsed X-Ray Properties of SGR 1806-20 from 1993 to 2005,” *ApJ*, vol. 654, pp. 470–486, Jan. 2007.
- [225] S. Mereghetti, A. Tiengo, P. Esposito, D. Götz, L. Stella, G. L. Israel, N. Rea, M. Feroci, R. Turolla, and S. Zane, “An XMM-Newton View of the Soft Gamma Repeater SGR 1806-20: Long-Term Variability in the Pre-Giant Flare Epoch,” *ApJ*, vol. 628, pp. 938–945, Aug. 2005.
- [226] A. Tiengo, P. Esposito, S. Mereghetti, N. Rea, L. Stella, G. L. Israel, R. Turolla, and S. Zane, “The calm after the storm: XMM-Newton observation of SGR 1806-20 two months after the Giant Flare of 2004 December 27,” *AAP*, vol. 440, pp. L63–L66, Sept. 2005.
- [227] S. Mereghetti, D. Cremonesi, M. Feroci, and M. Tavani, “BeppoSAX observations of SGR 1806-20,” *AAP*, vol. 361, pp. 240–244, Sept. 2000.
- [228] P. M. Woods, C. Kouveliotou, E. Göğüş, M. H. Finger, J. Swank, C. B. Markwardt, K. Hurley, and M. van der Klis, “Large Torque Variations in Two Soft Gamma Repeaters,” *ApJ*, vol. 576, pp. 381–390, Sept. 2002.
- [229] D. L. Kaplan, D. W. Fox, S. R. Kulkarni, E. V. Gotthelf, G. Vasisht, and D. A. Frail, “Precise Chandra Localization of the Soft Gamma-Ray Repeater SGR 1806-20,” *ApJ*, vol. 564, pp. 935–940, Jan. 2002.

- [230] S. Mereghetti, P. Esposito, and A. Tiengo, “XMM Newton observations of soft gamma-ray repeaters,” *APSS*, vol. 308, pp. 13–23, Apr. 2007.
- [231] P. Esposito, S. Mereghetti, A. Tiengo, S. Zane, R. Turolla, D. Götz, N. Rea, N. Kawai, M. Ueno, G. L. Israel, L. Stella, and M. Feroci, “SGR 1806-20 about two years after the giant flare: Suzaku, XMM-Newton and INTEGRAL observations,” *AAP*, vol. 476, pp. 321–330, Dec. 2007.
- [232] G. Younes, C. Kouveliotou, and V. M. Kaspi, “XMM-Newton Observations of SGR 1806-20 Over Seven Years Following the 2004 Giant Flare,” *ApJ*, vol. 809, p. 165, Aug. 2015.
- [233] A. I. Ibrahim, C. B. Markwardt, J. H. Swank, S. Ransom, M. Roberts, V. Kaspi, P. M. Woods, S. Safi-Harb, S. Balman, W. C. Parke, C. Kouveliotou, K. Hurley, and T. Cline, “Discovery of a Transient Magnetar: XTE J1810-197,” *ApJL*, vol. 609, pp. L21–L24, July 2004.
- [234] F. Camilo, I. Cognard, S. M. Ransom, J. P. Halpern, J. Reynolds, N. Zimmerman, E. V. Gotthelf, D. J. Helfand, P. Demorest, G. Theureau, and D. C. Backer, “The Magnetar XTE J1810-197: Variations in Torque, Radio Flux Density, and Pulse Profile Morphology,” *ApJ*, vol. 663, pp. 497–504, July 2007.
- [235] J. P. Halpern and E. V. Gotthelf, “The Fading of Transient Anomalous X-Ray Pulsar XTE J1810-197,” *ApJ*, vol. 618, pp. 874–882, Jan. 2005.
- [236] G. Israel, N. Rea, V. Testa, V. Mangano, N. Ageorges, W. Hummel, G. Lo Curto, O. Marco, and R. Mignani, “The likely IR counterpart to the Anomalous X-ray Pulsar XTE J1810-197,” *The Astronomer’s Telegram*, vol. 203, Nov. 2003.
- [237] F. Bernardini, G. L. Israel, S. Dall’Osso, L. Stella, N. Rea, S. Zane, R. Turolla, R. Perna, M. Falanga, S. Campana, D. Götz, S. Mereghetti, and A. Tiengo, “From outburst to quiescence: the decay of the transient AXP XTE J1810-197,” *AAP*, vol. 498, pp. 195–207, Apr. 2009.
- [238] F. Camilo, S. M. Ransom, J. P. Halpern, J. A. J. Alford, I. Cognard, J. E. Reynolds, S. Johnston, J. Sarkissian, and W. van Straten, “Radio Disappear-

ance of the Magnetar XTE J1810-197 and Continued X-ray Timing,” *ApJ*, vol. 820, p. 110, Apr. 2016.

- [239] P. A. Evans, J. D. Gropp, J. A. Kennea, N. J. Klingler, S. Laha, A. Y. Lien, K. L. Page, T. Sakamoto, A. Tohuvavohu, and Neil Gehrels Swift Observatory Team, “Swift-BAT trigger 960986: Swift detection of a new SGR Swift J1818.0-1607,” *GRB Coordinates Network*, vol. 27373, p. 1, Mar. 2020.
- [240] T. Enoto, T. Sakamoto, G. Younes, C.-P. Hu, W. C. G. Ho, K. Gendreau, Z. Arzoumanian, T. Guver, S. Guillot, D. Altamirano, P. S. Ray, M. Ng, D. Chakrabarty, G. K. Jaisawal, and S. Bogdanov, “NICER detection of 1.36 sec periodicity from a new magnetar, Swift J1818.0-1607,” *The Astronomer’s Telegram*, vol. 13551, p. 1, Mar. 2020.
- [241] D. Champion, I. Cognard, M. Cruces, G. Desvignes, F. Jankowski, R. Karuppusamy, M. J. Keith, C. Kouveliotou, M. Kramer, K. Liu, A. G. Lyne, M. B. Mickaliger, B. O’Connor, A. Parthasarathy, N. Porayko, K. Rajwade, B. W. Stappers, P. Torne, A. J. van der Horst, and P. Weltevrede, “High-cadence observations and variable spin behaviour of magnetar Swift J1818.0-1607 after its outburst,” *MNRAS*, vol. 498, pp. 6044–6056, Sept. 2020.
- [242] G. A. Kriss, R. H. Becker, D. J. Helfand, and C. R. Canizares, “G27.4+0.0 : a galactic supernova remnant with a central compact source,” *ApJ*, vol. 288, pp. 703–706, Jan. 1985.
- [243] W. W. Tian and D. A. Leahy, “The distances of supernova remnants Kes 69 and G21.5-0.9 from HI and ^{13}CO spectra,” *MNRAS*, vol. 391, pp. L54–L58, Nov. 2008.
- [244] G. Vasisht and E. V. Gotthelf, “The Discovery of an Anomalous X-Ray Pulsar in the Supernova Remnant Kes 73,” *ApJL*, vol. 486, pp. L129–L132, Sept. 1997.
- [245] S. Şaşmaz Muş, B. Aydın, and E. Göğüş, “A glitch and an anti-glitch in the anomalous X-ray pulsar 1E 1841-045,” *MNRAS*, vol. 440, pp. 2916–2921, June 2014.

- [246] H. An, R. F. Archibald, R. Hascoët, V. M. Kaspi, A. M. Beloborodov, A. M. Archibald, A. Beardmore, S. E. Boggs, F. E. Christensen, W. W. Craig, N. Gehrels, C. J. Hailey, F. A. Harrison, J. Kennea, C. Kouveliotou, D. Stern, G. Younes, and W. W. Zhang, “Deep NuSTAR and Swift Monitoring Observations of the Magnetar 1E 1841-045,” *ApJ*, vol. 807, p. 93, July 2015.
- [247] P. Zhou, Y. Chen, X.-D. Li, S. Safi-Harb, M. Mendez, Y. Terada, W. Sun, and M.-Y. Ge, “Discovery of the Transient Magnetar 3XMM J185246.6+003317 near Supernova Remnant Kesteven 79 with XMM-Newton,” *ApJL*, vol. 781, p. L16, Jan. 2014.
- [248] N. Rea, D. Viganò, G. L. Israel, J. A. Pons, and D. F. Torres, “3XMM J185246.6+003317: Another Low Magnetic Field Magnetar,” *ApJL*, vol. 781, p. L17, Jan. 2014.
- [249] E. P. Mazets, S. V. Golenetskij, and Y. A. Guryan, “Soft gamma-ray bursts from the source B1900+14,” *Soviet Astronomy Letters*, vol. 5, p. 343, Dec. 1979.
- [250] C. Kouveliotou, T. Strohmayer, K. Hurley, J. van Paradijs, M. H. Finger, S. Dieters, P. Woods, C. Thompson, and R. C. Duncan, “Discovery of a Magnetar Associated with the Soft Gamma Repeater SGR 1900+14,” *ApJL*, vol. 510, pp. L115–L118, Jan. 1999.
- [251] S. Mereghetti, P. Esposito, A. Tiengo, S. Zane, R. Turolla, L. Stella, G. L. Israel, D. Götz, and M. Feroci, “The First XMM-Newton Observations of the Soft Gamma-Ray Repeater SGR 1900+14,” *ApJ*, vol. 653, pp. 1423–1428, Dec. 2006.
- [252] P. Esposito, S. Mereghetti, A. Tiengo, L. Sidoli, M. Feroci, and P. Woods, “Five years of SGR 1900+14 observations with BeppoSAX,” *AAP*, vol. 461, pp. 605–612, Jan. 2007.
- [253] M. Stamatikos, D. Malesani, K. L. Page, and T. Sakamoto, “GRB 140705A: Swift detection of a short burst,” *GRB Coordinates Network*, vol. 16520, p. 1, Jan. 2014.
- [254] G. L. Israel, P. Esposito, N. Rea, F. Coti Zelati, A. Tiengo, S. Campana, S. Mereghetti, G. A. Rodriguez Castillo, D. Götz, M. Burgay, A. Possenti,

- S. Zane, R. Turolla, R. Perna, G. Cannizzaro, and J. Pons, “The discovery, monitoring and environment of SGR J1935+2154,” *MNRAS*, vol. 457, pp. 3448–3456, Apr. 2016.
- [255] G. Younes, C. Kouveliotou, A. Jaodand, M. G. Baring, A. J. van der Horst, A. K. Harding, J. W. T. Hessels, N. Gehrels, R. Gill, D. Huppenkothen, J. Granot, E. Göğüş, and L. Lin, “X-Ray and Radio Observations of the Magnetar SGR J1935+2154 during Its 2014, 2015, and 2016 Outbursts,” *ApJ*, vol. 847, p. 85, Oct. 2017.
- [256] G. Younes, T. Güver, C. Kouveliotou, M. G. Baring, C.-P. Hu, Z. Wadiasingh, B. Begiçarslan, T. Enoto, E. Göğüş, L. Lin, A. K. Harding, A. J. van der Horst, W. A. Majid, S. Guillot, and C. Malacaria, “NICER View of the 2020 Burst Storm and Persistent Emission of SGR 1935+2154,” *ApJL*, vol. 904, p. L21, Dec. 2020.
- [257] M. Morini, N. R. Robba, A. Smith, and M. van der Klis, “EXOSAT Observations of the Supernova Remnant G109.1-1.0 and the X-Ray Pulsar 1E 2259+586,” *ApJ*, vol. 333, p. 777, Oct. 1988.
- [258] P. M. Woods, V. M. Kaspi, C. Thompson, F. P. Gavriil, H. L. Marshall, D. Chakrabarty, K. Flanagan, J. Heyl, and L. Hernquist, “Changes in the X-Ray Emission from the Magnetar Candidate 1E 2259+586 during Its 2002 Outburst,” *ApJ*, vol. 605, pp. 378–399, Apr. 2004.
- [259] B. İçdem, A. Baykal, and S. Ç. Inam, “RXTE timing analysis of the anomalous X-ray pulsar 1E 2259+586,” *MNRAS*, vol. 419, pp. 3109–3114, Feb. 2012.
- [260] C. Malacaria, P. Jenke, O. J. Roberts, C. A. Wilson-Hodge, W. H. Cleveland, B. Mailyan, and GBM Accreting Pulsars Program Team, “The Ups and Downs of Accreting X-Ray Pulsars: Decade-long Observations with the Fermi Gamma-Ray Burst Monitor,” *ApJ*, vol. 896, p. 90, June 2020.
- [261] M. Revnivtsev and S. Mereghetti, “Magnetic Fields of Neutron Stars in X-Ray Binaries,” *SSR*, vol. 191, pp. 293–314, Oct. 2015.
- [262] L. Sidoli and A. Paizis, “An INTEGRAL overview of High-Mass X-ray Binaries: classes or transitions?,” *MNRAS*, vol. 481, pp. 2779–2803, Dec. 2018.

- [263] M. M. Serim, Ş. Şahiner, D. Çerri-Serim, S. Ç. İnam, and A. Baykal, “Comprehensive timing and X-ray spectral analysis of GX 1+4,” *MNRAS*, vol. 469, pp. 2509–2516, Aug. 2017.
- [264] A. Baykal, “The torque and X-ray flux changes of OAO 1657-415.,” *AAP*, vol. 319, pp. 515–524, Mar. 1997.
- [265] J. E. McClintock, H. V. Bradt, R. E. Doxsey, J. G. Jernigan, C. R. Canizares, and W. A. Hiltner, “Optical candidates for two X-ray bursters and an X-ray pulsar,” *Nature*, vol. 270, pp. 320–321, Nov. 1977.
- [266] M. Falanga, E. Bozzo, A. Lutovinov, J. M. Bonnet-Bidaud, Y. Fetisova, and J. Puls, “Ephemeris, orbital decay, and masses of ten eclipsing high-mass X-ray binaries,” *AAP*, vol. 577, p. A130, May 2015.
- [267] J. E. Deeter, P. E. Boynton, F. K. Lamb, and G. Zylstra, “VELA X-1 Pulse Timing. II. Variations in Pulse Frequency,” *ApJ*, vol. 336, p. 376, Jan. 1989.
- [268] A. Giménez-García, T. Shenar, J. M. Torrejón, L. Oskinova, S. Martínez-Núñez, W. R. Hamann, J. J. Rodes-Roca, A. González-Galán, J. Alonso-Santiago, C. González-Fernández, G. Bernabeu, and A. Sander, “Measuring the stellar wind parameters in IGR J17544-2619 and Vela X-1 constrains the accretion physics in supergiant fast X-ray transient and classical supergiant X-ray binaries,” *AAP*, vol. 591, p. A26, June 2016.
- [269] R. Giacconi, H. Gursky, E. Kellogg, E. Schreier, and H. Tananbaum, “Discovery of Periodic X-Ray Pulsations in Centaurus X-3 from UHURU,” *ApJL*, vol. 167, p. L67, July 1971.
- [270] E. Schreier, R. Levinson, H. Gursky, E. Kellogg, H. Tananbaum, and R. Giacconi, “Evidence for the Binary Nature of Centaurus X-3 from UHURU X-Ray Observations,” *ApJL*, vol. 172, p. L79, Mar. 1972.
- [271] W. Krzeminski, “The Identification and UBV Photometry of the Visible Component of the Centaurus X-3 Binary System,” *ApJL*, vol. 192, p. L135, Sept. 1974.
- [272] R. L. Kelley, S. Rappaport, G. W. Clark, and L. D. Petro, “Orbital period changes in Centaurus X-3,” *ApJ*, vol. 268, pp. 790–799, May 1983.

- [273] S. Suchy, K. Pottschmidt, J. Wilms, I. Kreykenbohm, G. Schönerr, P. Kretschmar, V. McBride, I. Caballero, R. E. Rothschild, and V. Grinberg, “Pulse Phase-Resolved Analysis of the High-Mass X-Ray Binary Centaurus X-3 over Two Binary Orbits,” *ApJ*, vol. 675, pp. 1487–1498, Mar. 2008.
- [274] M. H. Finger, R. B. Wilson, and G. J. Fishman, “Observations of accretion torques in Cen X-3,” in *The Second Compton Symposium* (C. E. Fichtel, N. Gehrels, and J. P. Norris, eds.), vol. 304 of *American Institute of Physics Conference Series*, pp. 304–308, Jan. 1994.
- [275] H. Tananbaum, H. Gursky, E. M. Kellogg, R. Levinson, E. Schreier, and R. Giacconi, “Discovery of a Periodic Pulsating Binary X-Ray Source in Hercules from UHURU,” *ApJL*, vol. 174, p. L143, June 1972.
- [276] A. P. Reynolds, H. Quaintrell, M. D. Still, P. Roche, D. Chakrabarty, and S. E. Levine, “A new mass estimate for Hercules X-1,” *MNRAS*, vol. 288, pp. 43–52, June 1997.
- [277] D. Gerend and P. E. Boynton, “Optical clues to the nature of Hercules X-1 / HZ Herculis,” *ApJ*, vol. 209, pp. 562–573, Oct. 1976.
- [278] R. Staubert, N. I. Shakura, K. Postnov, J. Wilms, R. E. Rothschild, W. Coburn, L. Rodina, and D. Klochkov, “Discovery of a flux-related change of the cyclotron line energy in Hercules X-1,” *AAP*, vol. 465, pp. L25–L28, Apr. 2007.
- [279] D. Klochkov, R. Staubert, K. Postnov, N. Shakura, and A. Santangelo, “Continuous monitoring of pulse period variations in Hercules X-1 using Swift/BAT,” *AAP*, vol. 506, pp. 1261–1267, Nov. 2009.
- [280] H. Oegelman, P. Kahabka, W. Pietsch, J. Truemper, and W. Voges, “35-DAY Cycle and the Rotation Period of HERCULES-X-1,” *SSR*, vol. 40, pp. 347–353, Feb. 1985.
- [281] R. Sunyaev, M. Gilfanov, E. Churazov, V. Loznikov, V. Efremov, A. Kaniovskiy, A. Kuznetsov, A. Melioranskiy, W. Voges, W. Pietsch, S. Doebereiner, J. Englhauser, C. Reppin, J. Truemper, H. Oegelman, E. Kendziorra, B. Mony, M. Maisack, R. Staubert, A. Smith, and A. N. Parmar, “Acceleration of Hercules X-1 pulsar rotation. The “Kvant” module observations in august 1987-

- july 1988.,” *Pisma v Astronomicheskii Zhurnal*, vol. 14, pp. 979–991, Nov. 1988.
- [282] E. K. Sheffer, I. F. Kopaeva, M. B. Averintsev, G. S. Bisnovaty-Kogan, I. M. Golynskaya, L. S. Gurin, A. V. Dyachkov, V. M. Zenchenko, V. G. Kurt, T. A. Mizyakina, E. N. Mironova, V. A. Sklyankin, A. S. Smirnov, L. G. Titarchuk, V. M. Shamolin, E. Y. Shafer, A. A. Shmelkin, and F. Giovannelli, “X-ray studies of the pulsar Hercules X-1 from the Astron space station,” *AZH*, vol. 69, pp. 82–105, Feb. 1992.
- [283] J. E. McClintock, G. R. Ricker, and W. H. G. Lewin, “Rapid Fluctuations in the High-Energy X-Ray Flux from a Source in Crux,” *ApJL*, vol. 166, p. L73, June 1971.
- [284] N. E. White, K. O. Mason, H. E. Huckle, P. A. Charles, and P. W. Sanford, “Periodic modulation of three galactic X-ray sources,” *ApJL*, vol. 209, pp. L119–L124, Nov. 1976.
- [285] D. T. Koh, L. Bildsten, D. Chakrabarty, R. W. Nelson, T. A. Prince, B. A. Vaughan, M. H. Finger, R. B. Wilson, and B. C. Rubin, “Rapid Spin-Up Episodes in the Wind-fed Accreting Pulsar GX 301-2,” *ApJ*, vol. 479, pp. 933–947, Apr. 1997.
- [286] L. Kaper, A. van der Meer, and F. Najarro, “VLT/UVES spectroscopy of Wray 977, the hypergiant companion to the X-ray pulsar GX301-2,” *AAP*, vol. 457, pp. 595–610, Oct. 2006.
- [287] V. Doroshenko, A. Santangelo, V. Suleimanov, I. Kreykenbohm, R. Staubert, C. Ferrigno, and D. Klochkov, “Is there a highly magnetized neutron star in GX 301-2?,” *AAP*, vol. 515, p. A10, June 2010.
- [288] A. Nabizadeh, J. Mönkkönen, S. S. Tsygankov, V. Doroshenko, S. V. Molkov, and J. Poutanen, “NuSTAR observations of wind-fed X-ray pulsar GX 301-2 during unusual spin-up event,” *AAP*, vol. 629, p. A101, Sept. 2019.
- [289] M. de Kool and U. Anzer, “A simple analysis of period noise in binary X-ray pulsars,” *MNRAS*, vol. 262, pp. 726–734, June 1993.

- [290] G. E. Parkes, P. G. Murdin, and K. O. Mason, “The optical counterpart of the binary X-ray pulsar 4U 1538-52.,” *MNRAS*, vol. 184, pp. 73P–77, Sept. 1978.
- [291] R. Giacconi, S. Murray, H. Gursky, E. Kellogg, E. Schreier, T. Matilsky, D. Koch, and H. Tananbaum, “The Third UHURU Catalog of X-Ray Sources,” *ApJS*, vol. 27, p. 37, Feb. 1974.
- [292] P. J. N. Davison, M. G. Watson, and J. P. Pye, “The binary X-ray pulsar 3U 1538-52.,” *MNRAS*, vol. 181, p. 73, Jan. 1977.
- [293] A. Baykal, S. Ç. Inam, and E. Beklen, “Recent timing studies on RXTE observations of 4U 1538-52,” *AAP*, vol. 453, pp. 1037–1040, July 2006.
- [294] K. Makishima, K. Koyama, S. Hayakawa, and F. Nagase, “Spectra and Pulse Period of the Binary X-Ray Pulsar 4U 1538-52,” *ApJ*, vol. 314, p. 619, Mar. 1987.
- [295] B. C. Rubin, M. H. Finger, D. M. Scott, and R. B. Wilson, “Observation of a Long-Term Spin-up Trend in 4U 1538-52,” *ApJ*, vol. 488, pp. 413–418, Oct. 1997.
- [296] J. E. McClintock, H. V. Bradt, R. E. Doxsey, J. G. Jernigan, C. R. Canizares, and W. A. Hiltner, “Optical candidates for two X-ray bursters and an X-ray pulsar.,” *Nature*, vol. 270, pp. 320–321, Nov. 1977.
- [297] S. Rappaport, T. Markert, F. K. Li, G. W. Clark, J. G. Jernigan, and J. E. McClintock, “Discovery of a 7.68 second X-ray periodicity in 3U 1626-67.,” *ApJL*, vol. 217, pp. L29–L33, Oct. 1977.
- [298] J. Middleditch, K. O. Mason, J. E. Nelson, and N. E. White, “4U 1626-67 : A prograde spinning X-ray pulsar in A 2500 S binary system.,” *ApJ*, vol. 244, pp. 1001–1021, Mar. 1981.
- [299] D. Chakrabarty, “High-Speed Optical Photometry of the Ultracompact X-Ray Binary 4U 1626-67,” *ApJ*, vol. 492, pp. 342–351, Jan. 1998.
- [300] N. S. Schulz, D. Chakrabarty, and H. L. Marshall, “Collisional Ionization in the X-ray Spectrum of the Ultracompact Binary 4U 1626-67,” *arXiv e-prints*, p. arXiv:1911.11684, Nov. 2019.

- [301] L. Bildsten, D. Chakrabarty, J. Chiu, M. H. Finger, J. M. Grunsfeld, T. Koh, T. A. Prince, and R. Wilson, “Change in accretion torque in the binary accreting pulsar 4U 1626-67,” in *The Second Compton Symposium* (C. E. Fichtel, N. Gehrels, and J. P. Norris, eds.), vol. 304 of *American Institute of Physics Conference Series*, pp. 294–298, Jan. 1994.
- [302] D. Chakrabarty, L. Bildsten, J. M. Grunsfeld, D. T. Koh, T. A. Prince, B. A. Vaughan, M. H. Finger, D. M. Scott, and R. B. Wilson, “Torque Reversal and Spin-down of the Accretion-powered Pulsar 4U 1626-67,” *ApJ*, vol. 474, pp. 414–425, Jan. 1997.
- [303] A. Camero-Arranz, M. H. Finger, N. R. Ikhsanov, C. A. Wilson-Hodge, and E. Beklen, “New Torque Reversal and Spin-up of 4U 1626-67 Observed by Fermi/Gamma-ray Burst Monitor and Swift/Burst Alert Telescope,” *ApJ*, vol. 708, pp. 1500–1506, Jan. 2010.
- [304] P. Esposito, G. L. Israel, R. Turolla, F. Mattana, A. Tiengo, A. Possenti, S. Zane, N. Rea, M. Burgay, D. Götz, S. Mereghetti, L. Stella, M. H. Wieringa, J. M. Sarkissian, T. Enoto, P. Romano, T. Sakamoto, Y. E. Nakagawa, K. Makishima, K. Nakazawa, H. Nishioka, and C. François-Martin, “Long-term spectral and timing properties of the soft gamma-ray repeater SGR 1833-0832 and detection of extended X-ray emission around the radio pulsar PSR B1830-08,” *MNRAS*, vol. 416, pp. 205–215, Sept. 2011.
- [305] D. Cerri, M. M. Serim, D. Yucalan, S. Sahiner, S. C. Inam, and A. Baykal, “The timing noise of Magnetars,” in *11th INTEGRAL Conference Gamma-Ray Astrophysics in Multi-Wavelength Perspective*, p. 68, Jan. 2016.
- [306] Y. E. Nakagawa, T. Mihara, A. Yoshida, K. Yamaoka, S. Sugita, T. Murakami, D. Yonetoku, M. Suzuki, M. Nakajima, M. S. Tashiro, and K. Nakazawa, “Suzaku Observations of SGR1900+14 and SGR1806-20,” *PASJ*, vol. 61, pp. S387–S393, Jan. 2009.
- [307] E. V. Gotthelf, J. P. Halpern, M. Buxton, and C. Bailyn, “Imaging X-Ray, Optical, and Infrared Observations of the Transient Anomalous X-Ray Pulsar XTE J1810-197,” *ApJ*, vol. 605, pp. 368–377, Apr. 2004.

- [308] E. V. Gotthelf and J. P. Halpern, “The Spectral Evolution of Transient Anomalous X-Ray Pulsar XTE J1810-197,” *ApJ*, vol. 632, pp. 1075–1085, Oct. 2005.
- [309] A. W. Hotan, S. R. Long, J. M. Dickey, and T. J. Dolley, “A Study of the Pulsed Radio Emission from XTE J1810-197,” *ApJ*, vol. 668, pp. 449–455, Oct. 2007.
- [310] D. Tsang and K. N. Gourgouliatos, “Timing Noise in Pulsars and Magnetars and the Magnetospheric Moment of Inertia,” *ApJL*, vol. 773, p. L17, Aug. 2013.
- [311] J. A. Pons and R. Perna, “Magnetars versus High Magnetic Field Pulsars: A Theoretical Interpretation of the Apparent Dichotomy,” *ApJ*, vol. 741, p. 123, Nov. 2011.
- [312] A. Baykal, M. Ali Alpar, P. E. Boynton, and J. E. Deeter, “The timing noise of PSR 0823+26, 1706-16, 1749-28, 2021+51 and the anomalous braking indices,” *MNRAS*, vol. 306, pp. 207–212, June 1999.
- [313] G. Hobbs, A. G. Lyne, M. Kramer, C. E. Martin, and C. Jordan, “Long-term timing observations of 374 pulsars,” *MNRAS*, vol. 353, pp. 1311–1344, Oct. 2004.
- [314] V. M. Kaspi, “Grand unification of neutron stars,” *Proceedings of the National Academy of Science*, vol. 107, pp. 7147–7152, Apr. 2010.
- [315] H. An, V. M. Kaspi, J. A. Tomsick, A. Cumming, A. Bodaghee, E. V. Gotthelf, and F. Rahoui, “Chandra Observations of SGR 1627-41 near Quiescence,” *ApJ*, vol. 757, p. 68, Sept. 2012.
- [316] E. Göğüş, L. Lin, Y. Kaneko, C. Kouveliotou, A. L. Watts, M. Chakraborty, M. A. Alpar, D. Huppenkothen, O. J. Roberts, G. Younes, and A. J. van der Horst, “Magnetar-like X-Ray Bursts from a Rotation-powered Pulsar, PSR J1119-6127,” *ApJL*, vol. 829, p. L25, Oct. 2016.
- [317] R. F. Archibald, M. Burgay, M. Lyutikov, V. M. Kaspi, P. Esposito, G. Israel, M. Kerr, A. Possenti, N. Rea, J. Sarkissian, P. Scholz, and S. P. Tendulkar, “Magnetar-like X-Ray Bursts Suppress Pulsar Radio Emission,” *ApJL*, vol. 849, p. L20, Nov. 2017.

- [318] R. F. Archibald, V. M. Kaspi, S. P. Tendulkar, and P. Scholz, “The 2016 Outburst of PSR J1119-6127: Cooling and a Spin-down-dominated Glitch,” *ApJ*, vol. 869, p. 180, Dec. 2018.
- [319] D. L. Kaplan, S. R. Kulkarni, M. H. van Kerkwijk, R. E. Rothschild, R. L. Lindegfelter, D. Marsden, R. Danner, and T. Murakami, “Hubble Space Telescope Observations of SGR 0526-66: New Constraints on Accretion and Magnetar Models,” *ApJ*, vol. 556, pp. 399–407, July 2001.
- [320] Ü. Ertan and Ş. Çalışkan, “Optical and Infrared Emission from the Anomalous X-Ray Pulsars and Soft Gamma-Ray Repeaters,” *ApJL*, vol. 649, pp. L87–L90, Oct. 2006.
- [321] S. Mereghetti, “The strongest cosmic magnets: soft gamma-ray repeaters and anomalous X-ray pulsars,” *AAPR*, vol. 15, pp. 225–287, July 2008.
- [322] V. Doroshenko, A. Santangelo, V. F. Suleimanov, and S. S. Tsygankov, “An observational argument against accretion in magnetars,” *AAP*, vol. 643, p. A173, Nov. 2020.
- [323] S. Rappaport, R. Doxsey, and W. Zaumen, “A Search for X-Ray Pulsations from Cygnus X-1,” *ApJL*, vol. 168, p. L43, Sept. 1971.
- [324] M. Oda, K. Takagishi, M. Matsuoka, S. Miyamoto, and Y. Ogawara, “Millisecond X-Ray Pulses from CYG X-1,” *PASJ*, vol. 26, p. 303, Jan. 1974.
- [325] M. Revnivtsev, E. Churazov, K. Postnov, and S. Tsygankov, “Quenching of the strong aperiodic accretion disk variability at the magnetospheric boundary,” *AAP*, vol. 507, pp. 1211–1215, Dec. 2009.
- [326] S. Scaringi, T. J. Maccarone, E. Kording, C. Knigge, S. Vaughan, T. R. Marsh, E. Aranzana, V. S. Dhillon, and S. C. C. Barros, “Accretion-induced variability links young stellar objects, white dwarfs, and black holes,” *Science Advances*, vol. 1, pp. e1500686–e1500686, Oct. 2015.



APPENDIX A

WEB LINKS FOR PRINTED VERSION

Table A.1: List of links for hyper-linked web addresses

Page	Short Name	Web Address
2	Lumen Learning: Astronomy	https://courses.lumenlearning.com/astronomy/chapter/pulsars-and-the-discovery-of-neutron-stars/
13	The Moscow Institute of Physics and Technology:X-ray pulsars	https://mipt.ru/english/news/x_ray_pulsars_fade_as_propeller_effect_sets_in
35	NASA:Solar Dynamo	https://solarscience.msfc.nasa.gov/dynamo.shtml
38	ESA/ATG medialab	https://sci.esa.int/web/xmm-newton/-/52773-artists-impression-of-magnetar-sgr-04185729
42 & 56	McGill Online Magnetar Catalog	http://www.physics.mcgill.ca/pulsar/magnetar/main.html
83 & 98	Fermi/GBM Pulsar Project	https://gammaray.nsstc.nasa.gov/gbm/science/pulsars.html
86 & 98	BATSE: Pulsars Project	https://gammaray.nsstc.nasa.gov/batse/pulsar/

