Building models and searching for signals:

pulsar glitches, solar flares, and continuous gravitational waves

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“A meaningful quote or special dedication”

Abstract

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Declaration

This page certifies that:

- This thesis contains only original work towards a Doctor of Philosophy, except where indicated in the preface.
- Due acknowledgement has been made in the text to all other material used.
- This thesis is fewer than 100 000 words in length, exclusive of tables, figures, bibliographies, and appendices.

Julian Brian Carlin

Preface

Here and henceforth "the author" refers to the author of this thesis, Julian Brian Carlin. This thesis is an original work by the author reporting research done alone or in collaboration with other authors. This section provides a chapter-by-chapter summary of the author's contributions and the publication status of all material.

Chapter 1 is a comprehensive literature review for the work in Chapters 2–6 written by the author for this thesis. It is an original work of the author and will not be submitted for publication.

Chapter 2 is published as Carlin and Melatos [1] in the Monthly Notices of the Royal Astronomical Society. This work was written primarily by the author, with scientific input and editing from A. Melatos. Some ideas in this chapter originally appeared in the thesis submitted for the degree of Master of Science (Physics) awarded to the author in 2018. Figure **??** originally appeared as figure 4.5 in the above-mentioned thesis. All figures and tables are the work of the author.

Chapter 3 is published as Carlin and Melatos [2] in the Monthly Notices of the Royal Astronomical Society. It was written primarily by the author, with scientific input and editing from A. Melatos. All figures and tables are the work of the author.

Chapter 4 is published as Carlin and Melatos [3] in The Astrophysical Journal. It was written primarily by the author, with scientific input and editing from A. Melatos. All figures are the work of the author.

Chapter 5 is submitted for publication in The Astrophysical Journal. It was written primarily by the author, with scientific input and editing from A. Melatos and M. Wheatland. Appendix **??** was written primarily by A. Melatos, but is included in this thesis for completeness. All figures and tables are the work of the author.

Chapter 6 is published as LVK [4] in Physical Review D on behalf of the LIGO-Virgo-KAGRA (LVK) collaboration. It was written primarily by the author, with scientific input and editing from A. Melatos, and other members of the LVK collaboration. According to LVK policies, all members of the collaboration are listed as authors on the publication, in alphabetical order. The author was responsible for selecting the targets for the search, developing the scripts to run the search pipeline (which was first developed by Suvorova et al. [5, 6]), running the search, constructing and testing validation procedures for outliers, and calculating upper limits on detectable strain. The analysis was reviewed internally to the collaboration by Pat Meyers and Evan Goetz. The followup search described in the final two paragraphs of Appendix **??** was performed by Rodrigo Tenorio and David Keitel using the PyFstat pipeline, thus those paragraphs were written by them, not the author. All figures and tables are the work of the author.

Chapter 7 summarizes the work in Chapters 2–6. It includes some exploratory future directions for the work in this thesis. It was written by the author, with editing from A. Melatos. All figures and tables are the work of the author.

During the author's PhD they also contributed to two other publications, which are not included in this thesis but are listed here for completeness.

- Millhouse et al. [7] studies how observed glitch rates scale with the spin frequency, spin frequency derivative (and combinations thereof). The author contributed edits to the manuscript, and scientific input regarding treatment of the likelihood function and related statistics.

- Jones et al. [8] presents a guide for two follow-up procedures for continuous gravitational wave candidates. The author contributed edits to the manuscript, and scientific input regarding the effective point spread function of the matched filtering statistic.

Acknowledgments

A long list of acknowledgements, inside jokes, etc

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CHAPTER 1

Introduction

1.1. What models and what signals?

Modern physics involves a constant iteration between theoretical model-building, new data collection, and the attempted falsification of models with that data. This thesis is concerned with pulsar glitches, solar flares, and continuously-emitted gravitational waves from neutron stars in accreting binary systems. While these topics are disparate, there is overlap in the methodology with which specific, bespoke models are built to test and explore the underlying physics. The connections are outlined diagramatically in Figure [**TODO**: ref].

Rapidly-rotating neutron stars are often seen as pulsars, with remarkably regular pulsed radio emission. The predictable spin of some pulsars is sporadically interrupted by timing irregularities known as "glitches". These glitches are suspected to arise from the sudden relaxation of steadily-built-up stress in the interior (or perhaps strain in the crust). An analogous phenomenon of stress build-up and release is believed to drive solar flares. The stable spin of neutron stars in binary systems is modulated due to accretion from a companion star, and possibly gravitational wave emission if such accretion builds a time-varying mass quadrupole.

This chapter serves as an introduction and literature review of the underlying theoretical physics and observational evidence of the above phenomena. In Section 1.2 we present a taxonomical overview of neutron stars from an observational perspective. In Section 1.3 we discuss pulsar timing and glitch detection. In Section 1.4 we review what is known about the structure of neutron stars, and how glitches are triggered. We shift focus to statistical models built to understand complex systems which undergo stress-accumulation and release in Section 1.5. We relate solar flares to the above topics in Section 1.6. In Sections 1.7 and 1.8 we introduce gravitational wave (GW) emission in general, and the specific case of continuous gravitational waves (CWs) respectively. Finally, in Section 1.9.

1.2. Observational taxonomy of neutron stars

A neutron star is the dense remnant of a massive star (with mass $9 \lesssim M/M_{\odot} \lesssim 25$, where $M_{\odot}$ is the mass of the Sun), after it has undergone a core collapse supernova [9]. First theorized to exist by Baade and Zwicky [10], direct observational evidence came over 30 years later with the discovery of a steadily pulsating radio source by then-PhD candidate Jocelyn Bell-Burnell and her supervisor Antony Hewish [11]. This object, the pulsar now known as PSR J1921+2153, was quickly designated as a rotating neutron star [12, 13], and many more pulsars were discovered soon after [14–18].

After 55 years of new discoveries, the variety of neutron stars with differing properties allows us to form a taxonomy broadly divided into two categories:

- **Isolated neutron stars** are seen most commonly as radio pulsars, but are also detected across the electromagnetic spectrum, e.g. optical, infrared, gamma-ray, and X-ray. Isolated pulsars are typically further classified into two main groups, so-called "rotation-powered" and "magnetars". The former have spin periods of $0.01 \lesssim P/\mathrm{s} \lesssim 10$, and time-derivative of their period of $10^{-16} \lesssim \dot{P} \lesssim 10^{-12}$. The latter are generally slower but spin down faster, with $P \gtrsim 1$ s and $\dot{P} \gtrsim 10^{-13}$ [19]. Some pulsars do not fit in the above two groups, for example if they only pulse intermittently, so-called "rotating radio transients" (RRATs) **[TODO: cite]**. Some isolated neutron stars do not exhibit pulsations at any wavelength, e.g. central compact objects (CCO, also called supernova remnants), which often have a black-body spectrum peaked in the X-rays **[TODO: cite]**. We discuss in Section 1.3 how pulsar timing is performed, and the timing irregularities, such as glitches, that are found in the process.

  The mechanism generating pulsed radio emission is an unsolved problem in the field (see Cerutti and Beloborodov [20] and Harding [21] and references therein). A recent critique by Melrose et al. [22] dismisses many of the currently favored models; the authors propose an alternative mechanism in Melrose et al. [23] (see also the work of Philippov et al. [24]). Whatever the emission mechanism, as the pulsed emission is coherent, the emission region must be small and offset from the rotation axis of the neutron star — leading to a "lighthouse effect" where the emission region must be offset from the pole of the rotation axis, and periodically enters our line-of-sight. Thermal emission at smaller wavelengths (e.g. X-ray) is explained as residual heat after the supernova that formed the object (typically observable for $\sim 10^5$ yr) [25].

- **Binary neutron stars** are also sometimes seen as radio pulsars, but are more often detected due to their X-ray emission (so-called "X-ray binaries"). This emission is thought to arise due to accretion from their companion star, the mass of which further categorizes X-ray binaries as either low-mass (LMXB, companion mass $M_c \lesssim M_{\odot}$), intermediate mass (IMXB, companion mass $1 \lesssim M_c/M_{\odot} \lesssim 10$), or high mass (HMXB, companion mass $M_c \gtrsim 10 M_{\odot}$) [26]. Some binary neutron stars are observed to have millisecond periods, and are thus called millisecond pulsars (MSPs). MSPs are seen to have quite low small period derivatives, $\dot{P} \lesssim 10^{-18}$, compared to standard rotation-powered pulsars. However, most X-ray binaries

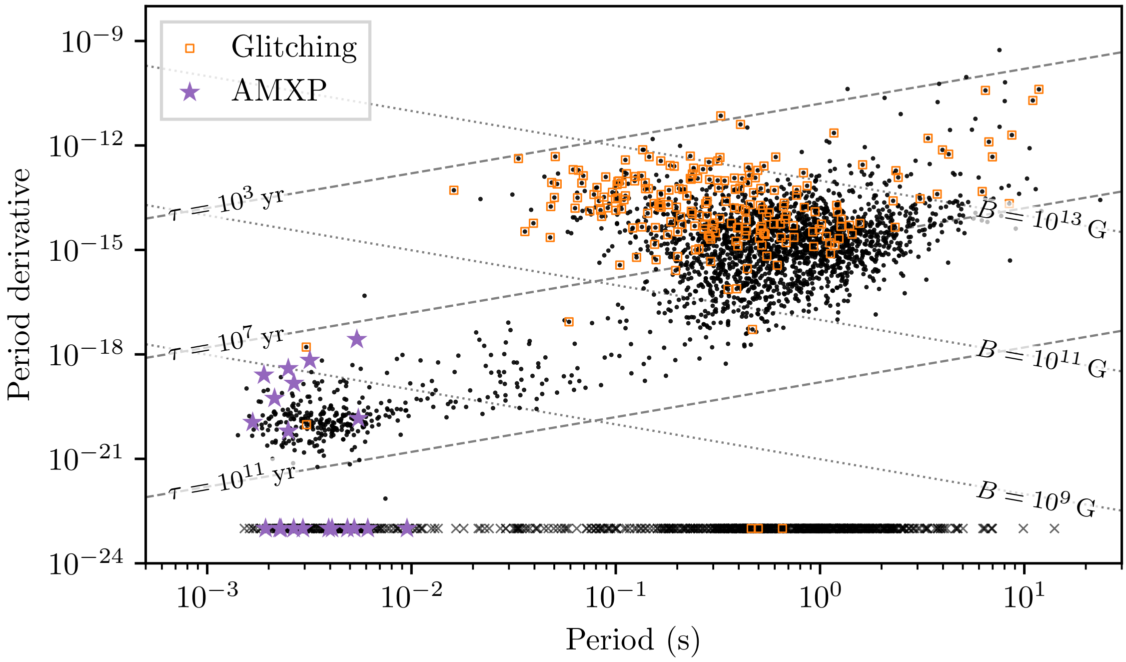

Figure 1.1: $P - \dot{P}$ diagram for over 3300 objects retrieved from the ATNF Pulsar Catalog. Black crosses sitting at the bottom of the figure are pulsars which do not have a recorded $\dot{P}$. Orange boxes indicate pulsars with at least one recorded glitch. Purple stars mark the known AMXPs. Dotted and dashed lines show lines of constant magnetic field at the poles and characteristic age respectively.

are not seen as pulsars, for example neither Scorpius X-1 nor Cygnus X-2 have detectable pulsations [27]. A small fraction of ultracompact (projected semi-major axis $a_0 \lesssim 2\,$lt-s) LMXBs intermittently go into outburst, where the X-ray flux is enhanced by ~two orders of magnitude for days to months (depending on the object) [28]. During these periods of outburst pulsations are sometimes detectable, which puts these objects in a separate class of "accreting millisecond X-ray pulsars" (AMXPs). We return to AMXPs in Section **[TODO**: sec].

The above taxonomy is driven by observations, and there are many systems that straddle the border between the outlined categories, or even move between categories [29]. For example, transitional millisecond pulsars, also known as redbacks, are sometimes observed as accretion-powered X-ray binaries, and then as rotation-powered radio pulsars [30]. Black widows are neutron stars that are ablating their companion due to strong outflows, perhaps explaining why some millisecond pulsars are seen without a companion. Magnetars and CCO are likely newly born neutron stars with differing birth magnetic fields [31]. The orientation of the emission region with respect to our line-of-sight could explain why some objects pulsate and some do not.

Typically, the pulsar population is visualized in a $P - \dot{P}$ diagram, such as Figure 1.1. Each black dot is a pulsar recorded in the Australian Telescope National Facility (ATNF) Pulsar Catalog [32][1]. Black crosses mark pulsars without a recorded period derivative.

[1]Accessed via `https://www.atnf.csiro.au/research/pulsar/psrcat/`.

The orange squares indicate that the object has at least one recorded glitch (see Section 1.4 for more on glitches). AMXPs are marked with a purple star. Lines of constant characteristic age τ and magnetic field strength at the poles B are shown as dashed and dotted lines respectively. These two quantities are calculated by modeling the pulsar as a simple rotating magnetic dipole [13, 33, 34] for which the electromagnetic power emitted is

$$\dot{E}_{\text{dipole}} = \frac{-4\pi^4 B^2 R^6 \sin^2\alpha}{3c^3 P^4}, \tag{1.1}$$

where R is the neutron star radius, α is the angle between the rotation and magnetic axes, and c is the speed of light. Combining Equation 1.1 with the rate of change of the rotational kinetic energy

$$\dot{E}_{\text{rot.}} = \frac{-4\pi^2 I\dot{P}}{P^3}, \tag{1.2}$$

where I is the moment of inertia of the neutron star, gives

$$B \approx 3.2 \times 10^{19}\,\text{G}\left(\frac{I}{10^{45}\,\text{g}\,\text{cm}^2}\right)^{1/2}\left(\frac{R}{10^6\,\text{cm}}\right)^{-3}\sin\alpha\sqrt{\dot{P}P}, \tag{1.3}$$

where we have included fiducial values for I and R, and set $\sin\alpha = 1$. The characteristic age is calculated by assuming that none of the parameters in Equation (1.3) vary in time from birth at $t = 0$ to the current age τ (besides P), and integrating to find

$$\tau = \frac{P^2 - P_0^2}{2\dot{P}P} \approx \frac{P}{2\dot{P}}, \tag{1.4}$$

where we assume the birth period $P_0 \ll P$.

Pulsars are almost certainly not perfectly rotating magnetic dipoles in a vacuum, and thus the above calculations are true only to zeroth order. They do apply remarkably well in some individual circumstances, e.g. the Crab pulsar (PSR J0537+2200) which is associated with a supernova remnant that was observed in 1054 AD by contemporary Chinese astronomers [35]. The current measurements of $P \approx 0.033\,\text{s}$ and $\dot{P} \approx 4.2\times10^{-13}$ [36] give $\tau \approx 1258\,\text{yr}$, only off from the true age by $\sim 300\,\text{yr}$. The power implied by Equation (1.2) of $\dot{E}_{\text{rot.}} \approx -4.5 \times 10^{38}\,\text{erg}\,\text{s}^{-1}$ (assuming $I = 10^{45}\,\text{g}\,\text{cm}^2$) is surprisingly comparable to the total energy requirements of the Crab nebula, $5 \times 10^{38}\,\text{erg}\,\text{s}^{-1}$ [37], implying that the energy lost due to rotation is likely absorbed and re-emitted by the nebula surrounding the pulsar.

1.3. Pulsar timing and glitch detection

There is a multi-stage process to "time" a pulsar, i.e. model and track the rotation over time. Most pulsars are not bright enough to resolve individual pulses, so the first stage is "folding" $5 - 30$ minutes (depending on the pulsar and observatory) of radio time-series data, i.e averaging the data modulo the fiducial rotation period of the pulsar [38].

In the second stage the folded data is correlated with a pulse shape template to generate a highly precise reference time for the observation, known as a time of arrival

(TOA). The TOA for an observation is defined as the time at which we have zero rotational phase, i.e. $\phi = 0$. A correction is applied to each TOA to subtract the effect of the motion of the observatory around the solar system barycentre.

In the third and final stage, a model is fit to a series of TOAs to model the phase as a function of time, noting that $\phi(t)$ must be an integer at each TOA. Traditionally, the phase is modelled as a simple Taylor series

$$\phi(t) = \phi(t_0) + \nu(t - t_0) + \frac{\dot{\nu}}{2}(t - t_0)^2 + \frac{\ddot{\nu}}{6}(t - t_0)^3 + \delta\phi(t), \tag{1.5}$$

where t_0 is an arbitrary reference time, $\nu = \frac{d\phi}{dt}\big|_{t=t_0}$, $\dot{\nu} = \frac{d^2\phi}{dt^2}\big|_{t=t_0}$, and $\ddot{\nu} = \frac{d^3\phi}{dt^3}\big|_{t=t_0}$. The phase residuals $\delta\phi(t)$ are studied for features of non-Gaussian noise, i.e. signatures of the Taylor series phase model not adequately explaining the data. Software such as TEMPO2 [39, 40] performs an iterated weighted-least-squares [41] procedure to calculate the values of various pulsar parameters which minimize $\delta\phi(t)$. These parameters include but are not limited to: ν, $\dot{\nu}$, $\ddot{\nu}$, right ascension and declination (henceforth RA and Dec. respectively), proper motion, and any relevant binary orbital elements.

Recent advances in modelling stochastic variations in $\delta\phi(t)$ have lead to extensions to TEMPO2, such as the software TEMPONEST [42] and the Hidden Markov Model (HMM) tracking described by Melatos et al. [43]. We discuss these approaches further in Sections 1.3.1 and 1.3.2 respectively.

1.3.1. *Timing noise*

The residuals $\delta\phi(t)$ often have a time-correlated structure that is not expected from measurement errors alone, or from unmodelled (deterministic) pulsar parameters [44, 45]. The power spectrum of such residuals is red, with a mixture of random walks in ν and $\dot{\nu}$, alongside discrete jumps in ϕ, explaining so-called "timing noise" [46, 47]. Timing noise makes precision timing experiments such as pulsar timing arrays (PTAs) difficult [48–51]. The Bayesian inference software TEMPONEST performs parameter inference on not just the deterministic pulsar parameters, but also estimates the level of timing noise by simultaneously modelling a red noise process in the frequency domain.

However, while such an approach can model the aggregate statistical properties of the residuals, it explicitly does not model the observed instantiation of the stochastic process. On the other hand, one may treat ϕ, ν, and potentially $\dot{\nu}$, as hidden random variables that are estimated via a hidden Markov model (HMM) [43]. We summarize the work of Melatos et al. [43] in the context of glitch detection in the following subsection, and discuss the mathematical formulation of a HMM in the context of searches for gravitational waves in Section 1.8.

The mechanism causing timing noise is uncertain. What follows is a non-exhaustive list of the various mechanisms posited in the literature: i) free precession [52–54], ii) undetected debris or planetary companions [55, 56], iii) unmodelled pulse shape changes [57, 58], iv) magnetospheric state switching [59, 60], v) superposition of small rotational glitches [61, 62], vi) superfluid turbulence [63–65], vii) variations in external torques [66, 67], or viii) variations in the coupling between internal components and the crust [68].

In some contexts, including CW searches (discussed in more detail in Section 1.8), timing noise is referred to as "spin-wandering" [5, 69–71]. Spin-wandering is typically, but not always, attributed to stochastic variations in the mass accretion rate $\dot{M}$. Coincident measurements of the instantaneous spin frequency of a pulsar from both a CW detection and electromagnetic observations would allow estimates of various coupling parameters between the crust (to which the electromagnetic frequency is bound) and core (to which the gravitational wave frequency is bound) [72, 73]. The degree of spin-wandering in Scorpius X-1 is estimated by Mukherjee et al. [71] to limit the coherence time for a CW search to $\lesssim 10\,\mathrm{d}$. Spin-wandering has not been estimated quantitatively in other accreting systems, although recent advances in the state-space formulation of the problem could enable these estimates in the future [74].

1.3.2. Glitch detection

A sudden discontinuity in the phase residuals points to the occurance of a rotational glitch. For example, if a glitch involves only a jump in spin frequency, the phase residuals will show a linear ramp, while a change in the spin frequency time derivative would result in parabolic phase residuals. We discuss the broad phenomonelogy of glitches further in Section 1.5.3. Traditionally, these discontinuities are discovered by eye, and two glitchless phase models, i.e. Equation (1.5), are fit to TOAs before and after the glitch epoch to define the parameters of the glitch. Both timing noise, and long, irregular gaps between TOAs can lead to imprecise or degenerate estimates of glitch parameters [75]. Recent advances in Bayesian model selection techniques, i.e. TEMPONEST, may help, but are not yet mature enough to deploy without human supervision [76].

An automated pipeline that fits phase residuals within a sliding window, and flags deviations from a polynomial regression, is implemented at the Ooty Radio Telescope [77].The HMM-based method outlined by Melatos et al. [43] simultaneously models the secular and stochastic behaviour of the phase. It determines if a glitch is present in the data by comparing the Bayesian evidence for models that do and do not include a glitch. Due to the computational efficiency of the method, and its automated nature, it is possible to quantitatively assess the upper limit smallest detectable glitch, at a given confidence level. For the set of 282 pulsars timed in the UTMOST [78] pulsar timing programme the mean upper limit on the glitch size, as a fraction of the spin frequency, is 1.9×10^{-8}, at 90% confidence.

1.4. Neutron star structure

1.4.1. Equation of state

1.4.2. Superfluidity and superconductivity

1.4.3. Glitch trigger mechanisms

1.5. Stress accumulation and relax

1.5.1. Self-organized criticality and sandpiles

1.5.2. Phenomenological models

1.5.3. Glitch models and observations

1.6. Solar flares

Our sun is a main sequence star about halfway through its life, at the end of which it will become a red giant, and then a white dwarf. It is not massive enough to become a neutron star.

1.6.1. Underlying mechanism

1.6.2. Statistical modeling

1.7. Gravitational waves

1.8. Continuous gravitational waves

1.9. Thesis outline

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