Timing the pulsar-main sequence binary PSR J1740-3052: effects of the companion wind and mass quadrupole

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PSR J1740-3052 is a young pulsar in orbit around a companion that is most likely a B-type main sequence star. Since its discovery a decade ago, data have been taken over several frequencies at the Green Bank, Jodrell Bank, and Parkes observatories. Data may also be available from the Westerbork Synthesis Radio Telescope. I intend to use the TEMPO or TEMPO2 timing software to analyze this data and investigate the effects of a mass quadrupole induced by the companion's rotation as well as tidal effects due to the pulsar. I will also study the effects of the companion's stellar wind on the scattering and dispersion of the pulsar beam. In order to do this, I will need to fit the pulse profiles for scattering in the interstellar medium and companion wind, which will require the use of the Fitscatter software to fit to the decaying "tail" characteristic of a scattered profile, and the modification of this software to accept the data formats I will be using. This software will also produce corrected pulse arrival times that I will use in my timing analysis.

I. MOTIVATION

Since their discovery four decades ago [5], pulsars have proven to be not only a fascinating pheonemon in their own right, but also one of nature's most useful tools. As some of the densest objects in the universe, they provide insights into the behaviour of matter condensed far beyond what is possible in laboratories on Earth. Their exceptionally strong gravitational fields allow for tests of Einstein's general theory of relativity and other theories of gravity, and have provided some of the best evidence so far for the existence of gravitational waves [8, 17]. Furthermore, their lighthouse-like pulses act as clocks with precision comparable to, or even exceeding, the best atomic clocks on Earth [10]. Careful timing of these pulses and their small variations can produce extremely precise measurements of a pulsar's position and motion, its magnetic field, the structure and density of the interstellar medium, and any other effects that might systematically alter the rate at which we receive pulses from the star.

As described below in Section II A, a pulsar is a rapidly rotating neutron star that emits strong radio beams at its magnetic poles, so that if the magnetic axis is not aligned with the rotation axis, it is possible to observe this radiation as a rapid and very regular series of pulses. The first pulsar discovery was made serendipitously in the late nineteen-sixties by Jocelyn Bell and Antony Hewish [5], and the connection to then-hypothetical neutron stars was made shortly thereafter [3].

Pulsars may be found in binary systems. Studies of the orbits and interactions in these systems can provide a great deal of information about neutron stars and their companions. About 5% of known pulsars are members of a binary system [6], although to date only four of these have as their companion a main sequence star. PSR J1740-3052 is one of these rare systems, discovered during the Parkes multibeam survey [15]. It is situated near the centre of the Galaxy, where much of the light at optical wavelengths is scattered or absorbed, but infrared observations revealed a main sequence star in the position on the sky at which the pulsar was observed. Careful analysis showed that this was almost certainly not the pulsar's companion, but rather a foreground star lying coincidentally along the line of sight to the pulsar [16]. More recent observations using adaptive optics imaging in the near infrared reveal a star that is a good candidate for the binary companion [1].

YYYY and collaborators have continued to ob-serve J1740-3052 using various instruments at the Green Bank, Jodrell Bank, and Parkes observatories, and this data is currently stored on the NANOGrav computer at UBC. Further data from Jodrell Bank and from Wester-bork Synthesis Radio Telescope may be sent to us in the near future. I propose to analyze these data using the technique of pulsar timing, examining in particular the effects of the companion's stellar wind on the dispersion and scattering of received pulse signals near *periastron*, or closest approach of the two stars, and the contribution of a mass quadrupole moment to precession of the binary orbit.

A good model of the companion's stellar wind will help to constrain the spectral class of the binary companion, currently thought to be a B-type star [15], which is several times hotter and more massive than the Sun. Furthermore, with an independent determination of the companion type, these data could be used to constrain the inclination of the orbit to our line of sight.

Determining the effects of a mass quadrupole induced by the rotation of the companion and tidal forces due to the pulsar may allow us, to some degree, to isolate general relativistic effects from those that are purely classical. These measurements could also put constraints on the angle between the companion's spin angular momen-

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tum and the orbital angular momentum, possibly providing insight into asymmetries in the supernova that produced the pulsar [14]. They may also provide further constraints on the system's orbital inclination.

II. THEORY

A. A basic pulsar model

While the detailed physics of pulsars are not yet fully understood, I present here a basic and widely agreed-upon model, similar to that proposed by Goldreich & Julian [4] shortly after the first pulsar was discovered.

A pulsar is a neutron star, which forms from the collapse of a main sequence star. A main sequence star is one, like the Sun, that withstands gravitational collapse by outward radiative pressure due to the nuclear fusion of hydrogen into helium in its core. A sufficiently massive star will, after burning up all of its hydrogen fuel, end in a supernova which leaves behind an object whose mass is great enough to overcome the degeneracy pressure of electrons, but is withheld from collapse into a black hole by the degeneracy pressure of neutrons. This is called a neutron star, and while it is as massive as a main sequence star (well-measured neutron stars range from 1.25 to 1.97 solar masses [2, 11]), it typically has a radius on the order of only 10 km [e.g. 12].

Neutron stars spin very fast when they are born and can have very strong magnetic fields. As illustrated in Figure 1, there is a distance from the star's rotation axis called the light cylinder beyond which anything corotating with the star would exceed the speed of light. Thus, a magnetic field line that extends beyond the light cylinder on its path between the star's magnetic poles will not close. Charged particles accelerating along these open field lines may be the cause of the radio beams emitted at the star's magnetic poles. If the magnetic and rotation axes of the neutron star are not aligned, then the beams will precess about the axis of rotation and can be seen by a well-aligned observer as weak, periodic pulses.

These pulses of light are usually seen from Earth as weak, periodic radio sources.

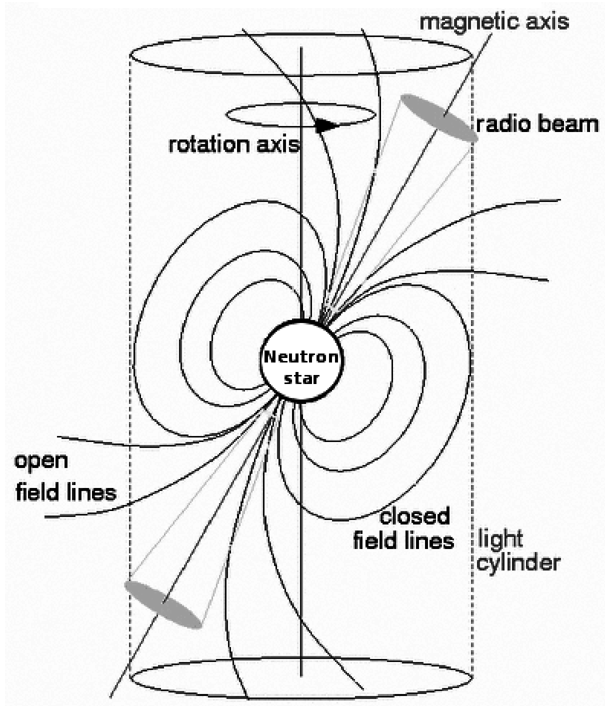

FIG. 1: A basic pulsar model. The light cylinder is a distance from the rotation axis such that anything corotating with the neutron star beyond this distance would be moving faster than light. Magnetic field lines that extend beyond the light cylinder thus cannot close, so that a narrow region at each magnetic pole is the source of open field lines. Charged particles that accelerate along these lines may be the source of radio beams emitted at the magnetic poles. A well-aligned observer will see these as regular pulses. Figure adapted from Lorimer & Kramer [12]

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B. Dispersion and scattering in the ISM and stellar wind

The vast stretches of space between our solar system and the other stars in the Galaxy are not merely empty vacuum. Indeed, interstellar space is rich in gases, dust, and ionized plasma. We call this the interstellar medium (ISM), and its presence cannot be ignored in pulsar observations where we are sensitive to tiny variations in the propagation of light. Although the ISM can be an obstacle in pulsar searches and observations, its effect on the shapes of pulse profiles and the times of arrival of pulses provides a very useful way to test models of the ISM itself.

Two consequences of the propagation of light through the ISM that will most concern my work on this project are *dispersion* and *scattering.* I will summarize these effects briefly, following the more detailed explanations in Lorimer & Kramer [12].

The ionized plasma of the ISM interacts with electromagnetic radiation such that we observe a frequency-dependent refractive index. Lower frequency radiation is more heavily refracted, an effect that becomes stronger as light approaches the *plasma frequency*, below which it cannot propagate at all. The plasma frequency increases as the square root of electron number density n_e and is typically about 1.5 kHz in the ISM.

An important quantity in pulsar observations is the *dispersion measure* (DM), defined as the integral of n_e along the line of sight to the pulsar and usually expressed in $\mathrm{cm}^{-3}\,\mathrm{pc}$. The difference in arrival time of the same pulse at two different frequencies f_1 and f_2 is proportional to $(f_1^{-2} - f_2^{-2}) \times \mathrm{DM}$. Therefore, if we measure

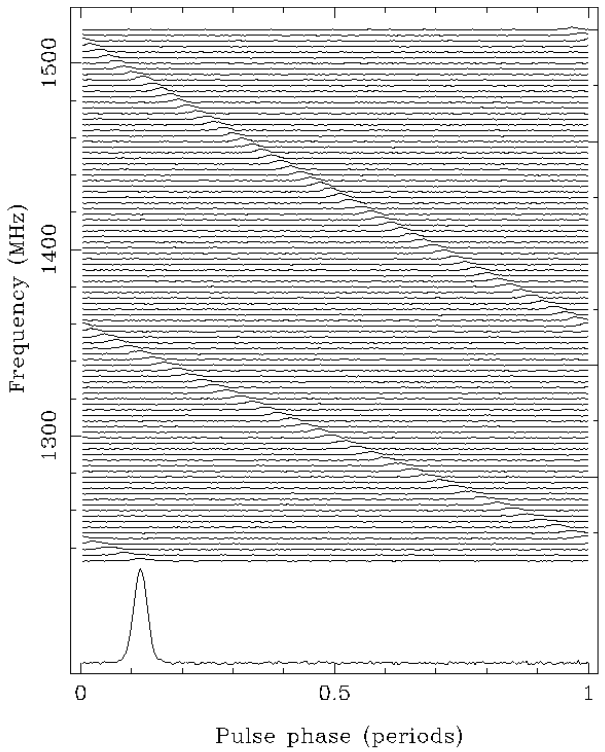

FIG. 2: An example of dispersion over one pulse period of PSR B1356-60. The interstellar medium imposes a frequency-dependent refractive index on the propagation of light, so that light from a single pulse will be delayed by a varying time at each frequency. The pulse profile at the bottom has been dedispersed (see text for details). If the individual bands were summed without being dedispersed, the profile would be spread across a whole period, making the data useless. Figure from Lorimer & Kramer [12]

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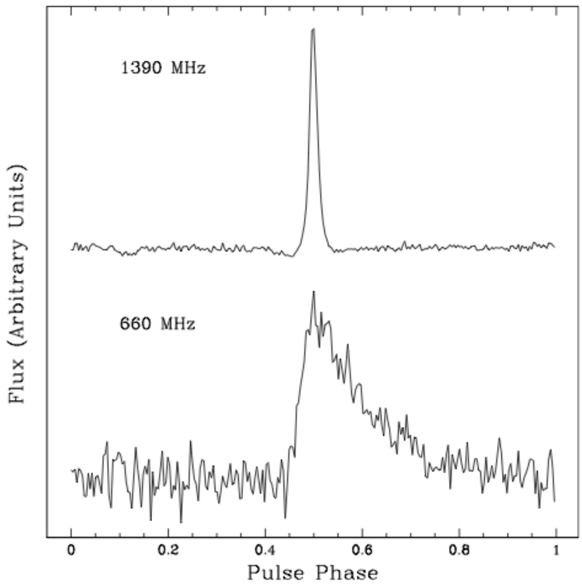

FIG. 3: Pulse profiles for PSR J1740-3052 taken at 1390 MHz and 660 MHz with the Parkes telescope. Note the long scattering tail at lower frequency. This can be modelled by a decaying exponential convolved with an unscattered profile. Figure from Stairs et al. [15]

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the pulse arrival times for at least two different frequencies, we can determine the DM and thus estimate the distance to the pulsar assuming a model for n_e, or conversely, we can determine the average value of n_e along the line of sight given an independent measure of the pulsar's distance, such as parallax.

Figure 2 illustrates the variation in pulse arrival times due to dispersion in the ISM. If a large bandwidth is used to observe a pulsar, smearing of the signal will result from the delays at various frequencies. The band may be divided into separate narrower bands that can be shifted relative to one another to correct for dispersion smearing. This is known as dedispersion [13].

The ISM has fluctuations across regions of space that change over time, and this causes further effects beyond dispersion. One such effect is scattering, which can be thought of as small random deflections of photons from the line of sight between the Earth and the pulsar. Some of these photons will be deflected at a later time back into our line of sight, so that they are still detected but at a slightly later time because of their longer path. The further the light is scattered off the straight path to our observatories, the less likely it is to be observed, and so the intensity of scattering-delayed light quickly drops off. The upshot of this is a decaying "tail" after a pulse, the intensity of which is well-modelled by

$$I(t) \propto e^{-\Delta t/\tau}, \tag{1}$$

where Δt is the time from the peak of a sharp pulse, and τ is known as the *scattering timescale.* In general, this shape is convolved with that of the unscattered pulse profile, producing the observed profile. This is seen most strongly at longer distances and lower frequencies. Figure 3 illustrates this effect.

The scattering timescale can be used to solve for fluctuations in the electron density Δn_e combined with the distance d over which these fluctuations occur and a typical size of density variations a by the equation

$$\tau = \frac{e^4}{4\pi^2 m_e^2}\,\frac{\Delta n_e^2}{a}\,d^2\,f^{-4}, \tag{2}$$

with e and m_e the electron charge and mass, and f the observing frequency [12].

In a pulsar-main sequence binary like J1740-3052, we expect additional pulse scattering and dispersion that varies over the period of the orbit due to the stellar wind of the main sequence companion. I will be assuming the model used by Kaspi et al. [9], in which the star loses mass in the form of ionized hydrogen at a constant rate so that $n_e(r)$ is proportional to $v(r)^{-1}r^{-2}$, where r is the radial distance from the centre of the companion star, and $v(r)$ is the wind speed at a distance r, given by

$$v(r) = v_\infty (1 - R_c/r)^{1/2}, \tag{3}$$

with v_∞ the terminal velocity and R_c the radius of the companion star.

C. Profiles and timing

Following the description in Lorimer & Kramer [12], I will proceed to explain the concepts of pulse profiles and pulsar timing.

While individual pulse signals from a pulsar are quite varied in shape and intensity, the average shape over many pulses is remarkably consistent. This is known as a *pulse profile*, obtained by "folding" together many consecutive pulses, usually while the data is being taken. Profiles representing up to several minutes of data are thus produced, with a timestamp at the centre of that data set. The key information needed for timing is the phase of the pulse at that time relative to an arbitrary fiducial point, which can be used to calculate a time of arrival (TOA) for a pulse.

Pulsar timing is a powerful tool that owes its strength to the precise regularity of a pulsar's rotation. Essentially, once the pulse period has been reasonably established, a model is built up to account for as many parameters as possible that could change the rate at which we observe the pulses on Earth. This includes the position and proper motion of the pulsar, orbital motion in a binary system, the interstellar medium, the gradual slowing of the pulsar's spin rate, and many other parameters including local effects such as the orbit of the Earth. This model aims to account for every single rotation of the neutron star so that it can predict precisely the pulse phase at a particular time. Thus, a model that accounts for everything should show no systematic behaviour in its residuals when compared with the observed pulse profiles. Different types of small errors can produce characteristic patterns in the residuals, as seen in Figure 4. A good timing solution should have the residuals randomly scattered about zero with a root mean square spread comparable to the TOA uncertainties [12].

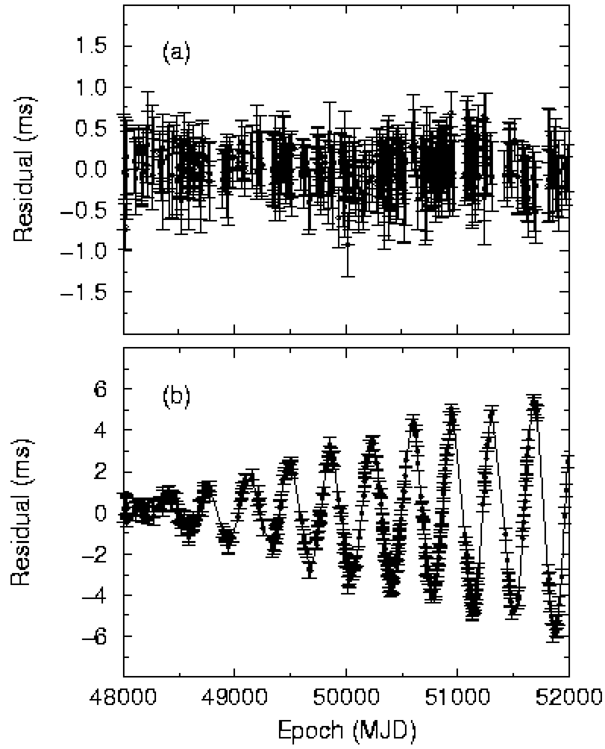

FIG. 4: Timing residuals for PSR B1133+16. The randomly scattered residuals in (a) are the result of a good timing model. The increasing oscillations in (b) come from neglecting the pulsar's motion across the sky, so that the observed pulse times fall in and out of phase with those predicted. The motion here is 380 milliarcsec/yr. Both plots cover the same period of time (about 11 years). Figure adapted from Lorimer & Kramer [12]

III. DETAILS ON PROPOSED EXPERIMENT

I will begin by familiarizing myself with the For-tran program Fitscatter, provided by XXXXXX of MPIfR, which takes as input an observed profile over some bandwidth that has undergone scattering due to the ISM and a scatter-free standard profile, and finds the value of τ for Equation 1 that best fits the observed data when the decaying exponential is convolved with the standard profile. If an ideal standard profile cannot be generated from the data, I can use a gaussian function of appropriate width to model the unscattered profile. The software is not written for the data formats I will be working with, so I will need to adapt it to read in and correctly use the J1740-3052 data. The output of this program is a file of TOAs of pulses, now shifted slightly to account for scattering, that can be read by the TEMPO or TEMPO2 timing software [7], as well as estimates of the scattering timescale τ.

After I have prepared the TOAs, I will move on to timing the pulsar. Although I will have corrected the TOAs for ISM scattering, there will still be changes in the dispersion measure with orbital phase because of the companion's stellar wind. I might be able to model this analytically using the simple model described at the end of Section II B and estimated parameters for the geometry of the orbit. If an analytical model does not seem feasible I will model the scattering changes numerically.

Once I have a satisfactory timing solution, I can use the change in dispersion measure and the scattering timescale τ via Equation 2 to determine Δn_e and Δn_e^2 over the time of the binary orbit, and can thus investigate the stellar wind of the pulsar's companion. I will also examine the timing parameters for effects due to a mass quadrupole of the companion, following the model of Wex [18].

IV. RESOURCES LIST

For this project, I will require the use of the NANOGrav computer which stores the data for PSR J1740-3052. I will also be using the TEMPO or TEMPO2 pulsar timing software.

V. PLANNED SCHEDULE

- **September–October:** Familiarize myself with the Fortran programming language and begin to modify the Fitscatter program that will be used to estimate τ and prepare the TOAs.
- **November:** Prepare and present my project proposal and then try to finish reworking Fitscatter so that I can run it on the BCPM data.
- **December:** Once I have Fitscatter producing TOAs, I will begin learning to use the TEMPO or TEMPO2 timing software so that I can use it to fit the BCPM data. I will also work on making Fitscatter work with the other data so that timing can be carried out on them. This will involve using the psrchive software to convert some of the data to an ASCII format that Fitscatter can read.
- **January:** Continue timing the BCPM data and try models of dispersion and scattering in stellar wind.
- **February:** Search for effects of stellar wind and mass quadrupole in timing parameters that have been fit at this point. Prepare and present progress report. Begin planning thesis.
- **Early March:** Carry on modelling the timing data set. Finish first draft of thesis.
- **Late March:** Write final draft of the thesis and submit it to supervisor at least two weeks before it is to be completed. Prepare and present my final report. Finalize the written thesis.

VI. ACKNOWLEDGEMENTS

I would like to thank my supervisor Dr. XXXX for her valuable comments on various drafts of this pro-posal, and for giving me the opportunity to do this re-search. I am also grateful to YYYYYat MPIfR for providing both the Fitscatter software and sample data so that I could figure out what it ought to be doing, and to Dr. Rob Kiefl for his guidance and examples in the Physics & Astronomy 449 course.

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