A New Probe of General Relativity Using Eclipses of the Double Pulsar PSR J0737−3039

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Abstract

The double pulsar, the first relativistic binary in which both neutron stars are observable radio pulsars, is a celebrated laboratory for testing general relativity in the strong-field regime via the precise timing of its radio pulses. A very fortunate alignment of our sight line with the orbital plane of this system allows us to observe eclipses when one of the pulsars passes behind its companion. These eclipses display a complex structure of flux modulations that would, according to a model proposed by Lyutikov and Thompson, originate from a varying optical depth induced by the rotation of the magnetosphere surrounding the companion pulsar. We present four years of eclipse monitoring conducted at the Green Bank Telescope, with which we tested this eclipse model. Our work not only accurately reproduces the eclipse light curves using the Lyutikov and Thompson model, but also provides a quantitative measurement of relativistic spin precession of the companion pulsar. This qualitatively new test of gravity in the strong-field regime agrees remarkably well the value predicted by general relativity.

1. Introduction

Binary radio pulsars are extraordinary tools for studying general relativity and alternative theories of gravity. They claim their success from a combination of physical and observational properties that make them nearly ideal laboratories for this type of study: 1) Pulsars are neutron stars and because they are extremely compact, they can be viewed as point-like particles. When two neutron stars orbit each other, the system is fully described by relatively clean dynamical equations and effects like tidal torques are negligible; 2) Radio pulsars emit pulses that can be timed to very high precision, sometimes rivaling with the stability of atomic clocks, and their orbital motion is easily monitored via the Doppler shift imprinted in their pulse arrival times.

Despite the fact that the tests of gravitational theories made using binary radio pulsars are currently limited compared to those of solar-system experiments, these measurements yield qualitatively different information since they are conducted in the environment of strong-field gravity [1]. Certain theories like general relativity predict that the behavior of gravity is independent of the nature of the bodies involved, however this might not generally be the case [2]. In this context, pulsars are privileged laboratories since their self-gravitation energy reach approximately 20% of their rest-mass energy.

2. The double pulsar

More than 30 years after the discovery of the first relativistic binary pulsar by Hulse and Taylor [3], about ten of these systems have been found. Generally consisting of a pulsar and a neutron star companion, they allow tests of gravitational theories from high-precision measurement of the orbital motion's departure from Newtonian orbit [see 4, for a review]. The most celebrated relativistic binary pulsar, PSR J0737−3039, is commonly known as the double pulsar because both neutron stars in this system are observable radio pulsars. The first member of this system, hereafter denoted pulsar A, is a 23-ms pulsar found in 2003 by Burgay et al. [5] in Parkes Multibeam Pulsar Survey data while pulsar B, the 2.8-s companion, went unnoticed for several weeks until its discovery by Lyne et al. [6]. The radio emission of pulsar B is very faint except in two well-defined regions of the orbit where it becomes brighter.

The potential of the double pulsar for testing gravity was immediately recognized. Its 2.4-hr orbital period is the shortest among relativistic binary pulsars and hence the strength of the observable relativistic effects is expected to scale accordingly. Indeed, it took only three years of double pulsar observations to supersede the precision achieved in other relativistic binary pulsars [7]. Five post-Keplerian parameters, describing relativistic corrections to the orbit, have been precisely measured from the radio timing. The addition of a second pulsar in the system allows the independent determination of the Keplerian parameter called the projected semi-major axis for each pulsar. In fact, their ratio provides a theory-independent constraint on their masses. Considering these measurements, the double pulsar permits four tests of theories of gravity. General relativity successfully passes all of them.

3. Unique double pulsar eclipses

In parallel to high-precision timing, the double pulsar offers a rich variety of phenomena to investigate. Perhaps one of the most intriguing are eclipses of pulsar A when it passes behind pulsar B at superior conjunction [6]. As a consequence of the fortunate alignment of our sight line with the orbital plane of the system, these eclipses are visible during a short 30-s interval each orbit. This duration implies an estimated size $\sim$14000 km at the distance of pulsar B from pulsar A, which is much larger than the typical 10-15 km neutron star radius. The eclipse region covers about 10% of pulsar B's light-cylinder, the fiducial region within which the co-rotation velocity is smaller than the speed of light in a vacuum and where its magnetic field lines are thought to close. Depending on their exact origin, the double pulsar eclipses potentially offer a unique way of probing the magnetosphere and environs of a pulsar.

A close look at the eclipse profile reveals a complex but intriguing phenomenology. Kaspi et al. [8] found that the eclipse duration is only slightly radio frequency dependent while McLaughlin et al. [9] discovered that the eclipse light curve is not smooth but in fact is punctuated with spectacular flux variations (see Figure 1). These flux variations are synchronized with the rotation of pulsar B (the pulsar that passes in front). This unexpected behavior indicates that pulsar B plays an active role in the eclipse mechanism.

4. Eclipse modeling

Lyutikov and Thompson proposed that the eclipses could originate from the magnetosphere of pulsar B [10]. The region of closed field lines of pulsar B is, in their model, filled by a plasma of hot, relativistic particles. In the ambient magnetic field, the synchrotron cross-section of electrons is very large and can efficiently absorb radio emission over a large range of radio frequencies. The geometry of the magnetosphere is chosen to be dipolar, a choice motivated by theoretical arguments; it has been a basic ingredient of the standard pulsar toy model since the discovery of pulsars 40 years ago. The key feature of the Lyutikov and Thompson model is that geometry can naturally reproduce the observed flux modulations: the sight line to pulsar A does not permanently intercept the closed field lines of pulsar B because the latter spins and the orbital motion changes their projected distance. In principle, successful modeling of the eclipse light curve should provide crucial information about the orientation of pulsar B with respect to its orbit.

We observed the double pulsar with the Green Bank Telescope in West Virginia regularly over a period of four years beginning a couple months after its discovery. Monitoring of the double pulsar was conducted at different radio frequencies but primarily at 820 MHz, with the SPIGOT instrument, because the pulsars are brighter in this part of the spectrum and the instrument's 50-MHz bandwidth is relatively clean of radio frequency interference (RFI). Our analysis includes a total of 63 eclipses.

For each data set, we generated an eclipse light curve and then fitted the Lyutikov and Thompson model. We concentrated our analysis on the three parameters relevant to the orientation of the magnetosphere. Two angles, the

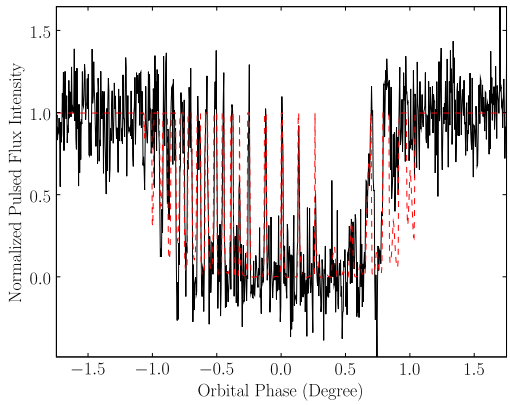

Figure 1: Eclipse profile for the eight eclipses observed at epoch MJD 54200 (black line) along with a sample model eclipse profile (red line). The pulsed flux intensity of pulsar A is normalized so that the average level outside the eclipse region is unity.

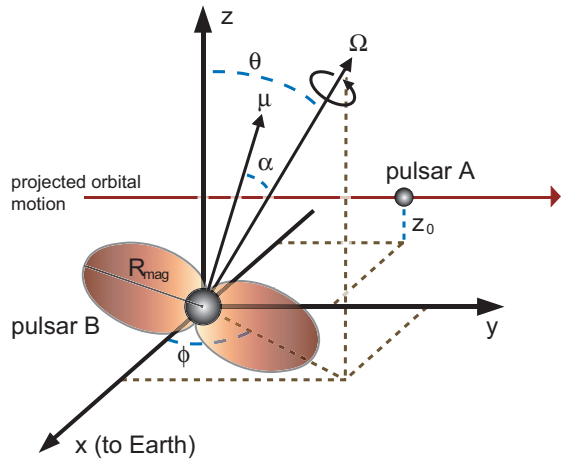

Figure 2: Schematic view of the double pulsar. The orbit is parallel to the $x-y$ plane, θ and ϕ describe the orientation of pulsar B's spin axis (Ω) and α is the misalignment of the magnetic axis (μ) with respect to Ω. The dipolar magnetosphere of pulsar B, truncated at radius $R_{\rm mag}$, is showed as a shaded red region.

colatitude (θ) and the longitude (ϕ) of pulsar B's spin axis, describe the orientation of the pulsar with respect to the orbit while another angle, the magnetic inclination (α), accounts for the misalignment of the magnetic dipole with respect to the spin axis (see Figure 2 for a schematic view of the system's geometry).

From the eclipse fitting, we obtained two sets of geometric configurations that produce the same light curves. This arises from the degeneracy associated with the unknown spin direction. We also find eclipse profile changes over the four-year monitoring campaign. The high quality of the fitted eclipse parameters enables us to quantify the observed changes in terms of physical quantities (see Figure 1 for a sample fit). Our derived geometry for pulsar B is consistent with no time variation of the magnetic inclination or of the colatitude of its spin axis, as expected from theory. However, the longitude of pulsar B's spin axis varies linearly with time. Such an evolution of the geometry of pulsar B, which was expected from Lyutikov and Thompson [10], can be attributed to precession of its spin axis around the system's total angular momentum.

5. A new test of general relativity

In general relativity and other theories of gravity, the spin axis of an orbiting body is not expected to remain fixed with respect to a distant observer. Relativistic precession naturally occurs from spin-orbit coupling [11] in a similar fashion to its quantum mechanical analogue. In the double pulsar system, the precession of pulsar B's spin axis can be interpreted as the consequence of two effects: 1) geodetic precession, which is induced by the parallel transport of the spin vector of pulsar B in a curved space time, and 2) frame-dragging, due to the motion of pulsar A around the center of mass of the system. These two effects couple and cannot be separated from each other.

Within the framework of generalized gravitational theories [12], the expression for the spin precession rate depends on the system's orbital angular momentum, L, the orbital eccentricity, e, the separation between the two bodies, a_R, and a general gravitational spin-orbit coupling constant, $\sigma_{\rm B}$, whose value is theory-dependent:

$$\Omega_{\rm B} = \frac{\sigma_B L}{a_R^3 (1-e^2)^{3/2}} \,. \tag{1}$$

There is no direct way to measure L and a_R, but several combinations of Keplerian and post-Keplerian parameters allows us to rewrite this equation in terms of observable quantities. One possible choice involves the orbital period of the system, $P_{\rm orb}$, the projected semi-major axis of each pulsar, x_A and x_B, and a post-Keplerian parameter

known as the Shapiro 'shape' parameter, s:

$$\Omega_{\rm B} = \frac{x_A x_B}{s^2} \frac{(2\pi)^3}{P_{\rm orb}^3 (1-e^2)} \frac{c^2 \sigma_B}{\mathcal{G}} \,, \tag{2}$$

where c is the speed of light and $\mathcal{G}$ is the generalized gravitational constant, which, in several theories like general relativity reduces to the standard value G. This particular form of the equation involves only measurable quantities and the ratio of two gravitational parameters ($\frac{c^2\sigma_{\rm B}}{\mathcal{G}}$). By deriving the precession rate from eclipse modeling, we can constrain the ratio of these two parameters. This demands, however, the measurement of both projected semi-major axes individually, a feature only possible in the double pulsar. Furthermore, any other combination of Keplerian and post-Keplerian parameters would introduce additional theory-dependent parameters [12] in the expression for the precession rate. It is therefore another fortunate coincidence that allows us to obtain a constraint on the ratio ($\frac{c^2\sigma_{\rm B}}{\mathcal{G}}$).

Our analysis agrees remarkably well with the value predicted by general relativity, with $\left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm obs} / \left(\frac{c^2\sigma_B}{\mathcal{G}}\right)_{\rm GR} = 0.94 \pm 0.13$ (68%-confidence, preliminary results). We expect the measurement precision to improve rapidly with the increasing observation baseline in the future.

6. Conclusions

Not only does the eclipse modeling offer a new way of quantitatively testing general relativity and alternative theories of gravity, it also provides tools for studying pulsars. For instance, the successful data modeling using the Lyutikov and Thompson model [10] provides strong empirical evidence that the magnetic field of pulsars is predominantly dipolar. Several aspects of pulsar theory, such as estimates of their ages and magnetic field strengths, are based on this simple assumption about the geometry of their magnetic field. Our knowledge of pulsar B's orientation with respect to its orbit brings valuable information for helping to understand the evolution of this system. Pulse profile changes in pulsar B have already been observed and are believed to be caused by the precession of its spin axis, making the emission cone intercept our sight line at different positions [13]. Indeed, pulsar B may completely disappear in the future. Finally, new instruments such as the Square Kilometer Array will provide much more sensitive observations that will permit a more detailed investigation of the plasma properties and the magnetosphere structure of pulsar B.

8. References

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