**PSR J1738+0333: a new gravitational laboratory**

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Abstract. We describe in this paper a new binary millisecond pulsar, PSR J1738+0333. Using Arecibo, we have achieved good timing accuracy for this object, about 220 ns for 1-hour integrations over 100 MHz. This allowed us to measure a precise proper motion, parallax and orbital parameters for this system. We highlight the system’s potential for constraining alternative theories of gravitation.

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**INTRODUCTION**

PSR J1738+0333 is a 5.85-ms pulsar in a binary system with an orbital period of 8.5 hours and a companion white dwarf (WD) with a mass of about 0.2 M$_\odot$. This millisecond pulsar (MSP) was found with the Parkes 64-m Radio Telescope in a 20-cm Multi-Beam search for pulsars in intermediate Galactic latitudes ($5° < |b| < 30°$) [1]; we have been timing it with Arecibo for the last 4 years using the Wide-band Arecibo Pulsar Processors (WAPPs, [2]). We have obtained a TOA residual rms of 220 ns per WAPP per hour. This pulsar will be used in the array that is being used to search for nano-Hertz gravitational waves.

**TIMING OF PSR J1738+0333**

Initially we sought to determine the companion and pulsar masses from a measurement of the Shapiro delay. Despite the high timing precision, the measurement was not possible given the system’s low orbital inclination.

Fortunately, it is possible to determine the masses of the components independently. This comes from recent optical work of Marten van Kerkwijk and one of us (BAJ). Using the Magellan telescope on Las Campanas, Chile, they detected the companion star and found its spectrum to be similar to that of the companion of PSR J1909–3744; which has as mass of 0.203 M$_\odot$, measured by Shapiro delay [3]. For this reason, and from here on, we assume that the companion of PSR J1738+0333 has mass ($m_2 = 0.20 \pm 0.05M_\odot$), but note that a precise estimate of this mass has not yet been made. This implies an orbital inclination of about 30°.

Introducing the Shapiro delay that corresponds to this companion mass and inclination, we obtain an eccentricity of $(8 \pm 16) \times 10^{-8}$, the lowest ever measured for any binary system. This opens up the possibility of greatly improved tests of the fundamental nature of spacetime, introducing the most stringent constraints ever on preferred-frame effects and non-conservation of momentum [4].

More recently, the radial-velocity curve was measured using Gemini South on Cerro Pachón (see Fig. 1). From this we can derive the mass ratio of the system, $R = 8.1 \pm 0.3$ (Van Kerkwijk, 2007, pers. comm.); therefore the pulsar mass is $m_1 = (1.7 \pm 0.4)M_\odot$. The error estimate for the companion mass assumed above is very conservative, it admits a wide possible range of companion and pulsar masses (see Fig. 2). It will certainly be measurable with better precision in the near future, as in the case of PSR J1911–5958A ([5, 6], see also Bassa et al.).

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FIGURE 1. Radial velocity measurements of the companion of PSR J1738+0333 as a function of orbital phase.
al. these proceedings).

A test of the Strong Equivalence Principle

The measurement of the masses of the components of important because it allows a (low-precision) estimate of the expected rate of orbital decay due to the emission of quadrupolar gravitational waves, as predicted by general relativity (GR): \( - (3.7^{+1.5}_{-1.3}) \times 10^{-14} \text{s/s} \). This period derivative is about 60 times smaller than what was measured for the Hulse-Taylor binary pulsar [7].

Fortunately, the timing precision for PSR J1738+0333 is such that we can already measure this value after four years of timing, although not with much significance: it is \((4.9 \pm 2.2) \times 10^{-14} \text{s/s}\). What is more important, the difference between the predicted value and the observed value (after acorrection for kinematic effects) is very small: \( \Delta (P_b) = (1.7 \pm 2.7) \times 10^{-14} (\text{<} 4.4 \times 10^{-14}) \).

This is the tightest limit ever on a possible contribution to the orbital decay by the emission of dipolar gravitational waves predicted by alternative theories of gravitation. As an example, in Brans-Dicke gravity, the emission of dipolar gravitational waves is given by:

\[
\left( \frac{\dot{P}_b}{P_b} \right)_D = - \frac{2}{2 + \omega_{BD}} (s_1 - s_2)^2 \left( \frac{2\pi}{P_b} \right)^2 m_2 R \frac{1}{R + 1} T_\odot, \quad (1)
\]

where \( T_\odot \) is the solar mass in time units, and \( \omega_{BD} \) is the Brans-Dicke constant; for GR this is infinite. The variable \( s_n \) is the fractional change of the gravitational binding energy (mass) of object \( n \) with a variation of the gravitational constant \( G (s_n = \partial \ln m_n / \partial \ln G) \) at a constant total number of baryons \( N \) (see e.g. [8]). For neutron stars, \( s_n \) depends on the equation of state, but generally it is of the order of 0.2. In double neutron star systems, we have \( s_1 \approx s_2 \), and therefore \((s_1 - s_2)^2 \approx 0\). This means that \( \left( \frac{\dot{P}_b}{P_b} \right)_D \) might be zero even if \( \omega_{BD} \) is finite. In the case of MSP-WD binaries like PSR J1738+0333, the binding
energy of the WD is many orders of magnitude smaller than the binding energy of the MSP, therefore \( s_2 \simeq 0 \) and \( (s_1 - s_2)^2 = s_1^2 \neq 0 \); for this reason they are called “asymmetric” binaries. This means that if \( \frac{\dot{P}_b}{P_b} |_D \) is very small (or zero), then \( \omega_{BD} \) must very large (or infinite).

Using \( \Delta (\frac{\dot{P}_b}{P_b}) |_D \), we obtain \( \omega > \sim 1300(s_1/0.2)^2 \) (85% C.L.). This is very similar to the limits derived from Arecibo timing of PSR J0751+1807 \([9]\). This is not as good as the result from the Cassini spacecraft \( \omega > 40,000, [10] \), but it is obtained in the strong-field regime, the only that can constrain all alternative theories of gravitation.

The main result of this study if that there is great potential for further improvement of this test. Over the next 5(10) years, the precision in the measurement of \( P_b \) will increase by a factor of 10(40). If the component masses are determined from the optical studies to a precision of 10%, or better, then the prediction of \( P_b \) will be accurate to \( 6 \times 10^{-13} \) s/s or better. This will be the limiting factor in the precision of this test. If the measured value conforms to the prediction, that will be equivalent to \( \omega > 15,000(s_1/0.2)^2 \), an order of magnitude improvement on all previous pulsar tests.

One of the advantages of the high timing precision of PSR J1738+0333 has been a precise measurement of the proper motion \((7.106 \pm 0.013 \text{ mas/yr in RA and } 4.83 \pm 0.04 \text{ mas/yr in Dec})\) and the parallax \((1.08 \pm 0.07 \text{ mas})\). This allows a very precise correction of the kinetic effects on the orbital period derivative.

Improving the mass ratio (definitely possible by averaging more radial velocity measurements) and using a precise measurement of the orbital decay will be used to determine the mass of the pulsar and the companion very accurately, assuming that general relativity applies. This might be also be used to help calibrate the optical methods for determining WD masses from their spectrum. If it is high, the pulsar mass might be important for the study of the equation of state for dense matter. PSR J1738+0333 might therefore be a great physics laboratory, relevant both for the study of gravitation and the study of the equation of state.

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REFERENCES

1. B. A. Jacoby, M. Bailes, S. M. Ord, H. S. Knight, and A. W. Hotan, Ap. J., Ap. J. 656, 408–413 (2007).
2. A. Dowd, W. Sisk, and J. Hagen, “The WAPP – Wideband Arecibo Pulsar Processor,” in Pulsar Astronomy - 2000 and Beyond, IAU Colloquium 177, edited by M. Kramer, N. Wex, and R. Wielebinski, Astronomical Society of the Pacific, San Francisco, 2000, pp. 275–276.
3. B. A. Jacoby, A. Hotan, M. Bailes, S. Ord, and S. R. Kuklarni, Ap. J. 629, L113–L116 (2005).
4. I. H. Stairs, Living Reviews in Relativity 6, 5 (2003).
5. C. G. Bassa, M. H. van Kerkwijk, D. Koester, and F. Verbunt, Ap. J., 456, 295–304 (2006).
6. G. Cocozza, F. R. Ferraro, A. Possenti, and N. D’Amico, Ap. J. Lett. 641, L129–L132 (2006).
7. J. M. Weisberg, and J. H. Taylor, “The Relativistic Binary Pulsar B1913+16,” in [11], pp. 93–98.
8. “Improved Bounds on Violation of the Strong Equivalence Principle,” in [11], pp. 69–74.
9. D. J. Nice, E. M. Splaver, I. H. Stairs, O. Löhmer, A. Jessner, M. Kramer, and J. M. Cordes, Ap. J. 634, 1242–1249 (2005).
10. B. Bertotti, L. Iess, and P. Tortora, Nature, 425, 374–376 (2003).
11. M. Bailes, D. J. Nice, and S. Thorsett, editors, Radio Pulsars, Astronomical Society of the Pacific, San Francisco, 2003.
