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Precision timing of PSR J1012+5307 and strong-field GR tests

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We report on the high precision timing analysis of the pulsar-white dwarf binary PSR J1012+5307. Using 15 years of multi-telescope data from the European Pulsar Timing Array (EPTA) network, a significant measurement of the variation of the orbital period is obtained. Using this ideal strong-field gravity laboratory we derive theory independent limits for both the dipole radiation and the variation of the gravitational constant.

Keywords: PSR J1012+5307; dipole radiation; gravitational constant variation.

1. Introduction

PSR J1012+5307 is a 5.3 ms pulsar in a low eccentricity binary system with orbital period of $P_b = 14.5$ h[1] and a low mass helium white dwarf (WD) companion.[2] Ref. 3 compared the measured optical luminosity of the WD to the value expected from WD models and calculated a distance of $d = 840 \pm 90$ pc. In addition they measured, a radial velocity component of 44 ± 8 km s^{-1} relative to the solar system barycentre (SSB), and the mass ratio of the pulsar and its companion $q = m_p/m_c = 10.5 \pm 0.5$. Finally they derived a companion mass of $m_c = 0.16 \pm 0.02\, M_\odot$, a pulsar mass of $m_p = 1.64 \pm 0.22\, M_\odot$ and an orbital inclination angle of $i = 52° \pm 4°$.

Ref. 4 presented the timing analysis of PSR J1012+5307 using 4 years of timing data from Effelsberg and 7 years from Lovell radio telescope. They derived the spin, astrometric and binary parameters for the system and they discussed the prospects of future measurements of a Post-Keplerian parameter (PK) which can contribute to the derivation of stringent limits on alternative gravity theories.

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2. Results

In this work PSR J1012+5307 has been revisited with seven more years of high-precision timing data and combined datasets from the EPTA telescopes (Effelsberg, Lovell, Nançay, Westerbork), at five different frequencies. The data have been analysed using the timing software TEMPO[a] and all the astrometric, spin and binary parameters of this system have been improved.

For the first time a parallax $\pi = 1.2 \pm 0.3$ mas has been measured for PSR J1012+5307. This corresponds to a distance of $d = 822 \pm 178$ pc which is consistent with the $d = 840 \pm 90$ pc measured from the optical observations.

As predicted by Ref. 4 a significant measurement of the change in the orbital period of the system, $\dot{P}_b = 5.0(1.4) \times 10^{-14}$, has been obtained for the first time. This is caused by the Doppler correction (which is the combined effect of the proper motion of the system[5] and a correction term for the Galactic acceleration) and by a contribution due to the quadrupole term of the gravitational wave emission, as predicted by general relativity (GR). After subtracting these two contributions from our measured value, the excess value of $\dot{P}_b^{exc} = (-0.4 \pm 1.6) \times 10^{-14}$ confirms the validity of GR for one more millisecond pulsar binary system.

All the terms mentioned above are the ones expected to contribute by using GR as our theory of gravity. However, there are alternative theories of gravity, that violate the strong equivalence principle (SEP) and predict extra contributions to the observed orbital period variation. One is the dipole term of the gravitational wave emission, which results from the difference in gravitational binding energy of the two bodies of a binary system. Thus PSR J1012+5307, a pulsar-WD system, is ideal for testing the strength of such emission. For small-eccentricity pulsar-WD systems, where the sensitivity s (related to the gravitational self-energy of a body) of the WD is much smaller than the one of the pulsar, one finds $\dot{P}_b^{dipole} = -4\pi^2 \frac{T_\odot \mu}{P_b} \kappa_D s_p^2$,[6] where $T_\odot = 4.9255 \,\mu s$ and μ is the reduced mass; s_p is the sensitivity of the pulsar and κ_D refers to the dipole self-gravitational contribution.

Another term is predicted by a hypothetical variation of the locally measured gravitational constant as the universe expands, $\dot{P}_b^{\dot{G}} = -2 \frac{\dot{G}}{G} \left[1 - \left(1 + \frac{m_c}{2M} \right) s_p \right] P_b$,[7,8] where M is the total mass of the system. It has been shown that there is no need to add these extra contributions to explain the variations of the orbital period, however the excess value has been used to set limits for a wide class of alternative theories of gravity.

PSR J1012+5307 is an ideal lab for constraining the dipole radiation term because the WD nature of the companion is affirmed optically, the mass estimates are free of any explicit strong-field effects and the mass of the pulsar is rather high, which is important in the case of strong field effects that occur only above a certain critical mass, like the spontaneous scalarisation.[9] Thus, by using the $\dot{G}/G = (4 \pm 9) \times 10^{-13} \,\mathrm{yr}^{-1}$ limit from the Lunar Laser Ranging (LLR)[10] the

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[a]http://www.atnf.csiro.au/research/pulsar/tempo/

$\dot{G}/G$ contribution has been calculated and subtracted from our excess value in order to finally obtain an improved generic limit for the dipole contribution of $\kappa_D = (0.2 \pm 2.4) \times 10^{-3}$ (95 per cent C.L.).

A generic test for $\dot{G}$ cannot be done with a single binary pulsar, since, in general, theories that predict a variation of the gravitational constant typically also predict the existence of dipole radiation. This degeneracy has been broken here in a joint analysis of PSR J1012+5307 and PSR J0437−4715,[11] two binary pulsar-WD systems with tight limits for $\dot{P}_b$ and different orbital periods. By applying Eq. 1

$$\frac{\dot{P}_b^{exc}}{P_b} = -2\frac{\dot{G}}{G}\left[1 - \left(1 + \frac{m_c}{2M}\right)s_p\right] - 4\pi^2\frac{T_\odot\mu}{P_b^2}\kappa_D s_p^2 \tag{1}$$

to both binary pulsars, and solving in a Monte-Carlo simulation this set of two equations, stringent and generic limits based purely on pulsar data and in the strong field regime have been obtained. With a 95 per cent C.L., $\frac{\dot{G}}{G} = (-0.7 \pm 3.3) \times 10^{-12}$ yr^{-1} and $\kappa_D = (0.3 \pm 2.5) \times 10^{-3}$. In the future, more accurate measurements of $\dot{P}_b$ and distance of the two pulsars and WDs could constrain even more our derived limits.

A more detailed work on this study of PSR J1012+5307 can be found in Ref. 12.

Acknowledgments

References

1. L. Nicastro, A. G. Lyne, D. R. Lorimer, P. A. Harrison, M. Bailes and B. D. Skidmore, *MNRAS* **273**, L68 (1995).
2. D. R. Lorimer, A. G. Lyne, L. Festin and L. Nicastro, *Nat.* **376**, 393 (1995).
3. P. J. Callanan, P. M. Garnavich and D. Koester, *MNRAS* **298**, 207 (1998).
4. C. Lange, F. Camilo, N. Wex, M. Kramer, D. Backer, A. Lyne and O. Doroshenko, *MNRAS* **326**, 274 (2001).
5. I. S. Shklovskii, *Soviet Ast.* **13**, 562 (1970).
6. C. Will, *Living Reviews in Relativity* **4**, 1 (2001), URL (Cited on 2006/02/01): http://www.livingreviews.org/Irr-2001-4.
7. T. Damour, G. W. Gibbons and J. H. Taylor, *Phys. Rev. Lett.* **61**, 1151 (1988).
8. K. Nordtvedt, *Phys. Rev. Lett.* **65**, 953 (1990).
9. T. Damour and G. Esposito-Farese, *Phys. Rev. Lett.* **70**, 2220 (1993).
10. J. G. Williams, S. G. Turyshev and D. H. Boggs, *Phys. Rev. Lett.* **93**, 261101 (2004).
11. J. P. W. Verbiest, M. Bailes, W. van Straten and et al., *ApJ* **679**, 675 (2008).
12. K. Lazaridis, N. Wex, A. Jessner and et al., *MNRAS* **400**, 805 (2009).