GENERIC GRAVITY TESTS WITH THE DOUBLE PULSAR

NORBERT WEX* and MICHAEL KRAMER

Max-Planck-Institut für Radioastronomie,
Auf dem Hügel 69, D-53121 Bonn, Germany
**E-mail: wex@mpifr-bonn.mpg.de*

Presently the double pulsar allows for the measurement of six post-Keplerian parameters. In addition, its double-line nature gives access to the projected semi-major axes of both orbits. We use this wealth of information to pose some very general restrictions on a wide class of conservative and semi-conservative theories of gravity.

Keywords: double pulsar; gravity tests; preferred-frame effects.

Among the most well-known uses of pulsars has been their role in tests of theories of gravity, in particular in the experimental verification of general relativity (GR).[1] In 2003 a binary system was discovered where both members were identified as radio pulsars.[2,3] Both pulsars, now known as PSR J0737–3039A (23 ms) and PSR J0737–3039B (2.8 s), A and B hereafter, orbit each other in 2.45 hours in a slightly eccentric orbit. As a result, the system is not only the first and, thus far, only double neutron star system where both neutron stars are visible as active radio pulsars, but it is also the most relativistic binary pulsar known to date. By measuring the radial motion of the two pulsars, we obtain a precise measurement of the mass ratio m_A/m_B.[4] In addition, a total of six post-Keplerian (PK) parameters has been measured. Five arise from four different relativistic effects visible in pulsar timing (Ref. 5), while a sixth one can be determined from the effects of geodetic precession on the observed radio eclipses (Ref. 6). The measurement of the mass ratio and six PK parameters, including the relativistic spin precession of B, makes the double pulsar (DP) the most constrained binary pulsar known. This allows for much more general statements about alternative theories of gravity than it has been possible before the discovery of this system.

Testing conservative theories of gravity

Will (Ref. 7) and Damour and Taylor (Ref. 8) have generalized the Lagrangian of the post-Newtonian orbital dynamics to the strong-field regime, for fully conservative theories of gravity. Therein, strong-field effects (SFEs) in the orbital motion of a binary system that consists of two compact bodies are accounted for by three SFE parameters: $\mathcal{G}$ (effective gravitational constant), ε, and ξ. Possible SFEs in the spin–orbit interaction are described by two coupling functions Γ_A^B and Γ_B^A.[8]

In GR $\mathcal{G} = G$, $\varepsilon = 3$, $\xi = 1$, and $\Gamma_A^B = \Gamma_B^A = 2G$. In alternative theories of gravity these quantities are functions of the parameters of the theory and of the structure of each body. For neutron stars these parameters can deviate significantly from their values in GR, even if their weak-field limit agrees with GR.[7,9]

The fact that in any Lorentz-invariant theory of gravity the DP gives access to the mass ratio through its 'double-line' nature (Ref. 4) and the inclination of the orbit with respect to the line of sight via the shape of the Shapiro delay (Refs. 7,8), allows us to determine theory independent values for the effective gravitating masses of the system: $\mathcal{G}m_A = 1.339 \pm 0.003\, GM_\odot$ and $\mathcal{G}m_B = 1.250 \pm 0.002\, GM_\odot$, where $M_\odot$ is the mass of the Sun.[10]

Since the PK parameters of the Damour–Deruelle timing model can be expressed as a function of the Keplerian parameters, the effective gravitating masses, and the SFE parameters (Ref. 8), we can use the measured PK parameters to generically constrain the SFE parameters for the DP system:[10]

$$\begin{array}{llllll}
\dot\omega & \Rightarrow & 2\varepsilon - \xi & = & 4.998 \pm 0.008 & [0.2\%] \\
\gamma & \Rightarrow & \mathcal{G}_{B0}/\mathcal{G} + \mathcal{K}_A^B & = & 1.005 \pm 0.010 & [1.0\%] \\
r & \Rightarrow & (\mathcal{G}_{B0}/\mathcal{G})(\varepsilon_{B0} + 1) & = & 4.04 \pm 0.22 & [5.4\%] \\
\Omega_B & \Rightarrow & \Gamma_B^A/\mathcal{G} & = & 1.88 \pm 0.26 & [13\%]
\end{array}$$

which is in full agreement with GR. Index $B0$ indicates the SFE parameter for the interaction between the compact body B and a photon. The parameter $\mathcal{K}_A^B$ accounts for a possible change of the moment of inertia of pulsar A due to the changing distance to the compact companion B. This parameter is zero in GR.

We would like to emphasize that currently the DP is the only system that allows for the test of the effacement property of a spinning body, i.e. the fact that the spin-precession of a body does not depend on its internal structure (up to a certain post-Newtonian level).[11–13]

Testing preferred-frame effects

The generic tests of the previous section can be extended to semi-conservative gravity theories, i.e. the DP can even be used to derive general restrictions on theories in which gravity is not boost invariant. Such theories predict that the Universe's global matter distribution selects a preferred rest frame for local gravitational physics. A binary pulsar that moves with respect to this preferred frame would show characteristic variations in the eccentricity and orientation of its orbit, which can be used to test strong-field preferred-frame effects (PFEs).[14]

The existence of a preferred frame for gravity would lead to a characteristic signature in the timing data of the DP, as PFEs impose periodic changes on the orbital parameters with periods of 21.30 and 10.65 years.[15] Therefore the DP has the potential to uniquely identify PFEs, if present at a measurable level. Moreover, in the absence of PFEs the DP can be used to determine limits for the strong-field PFE parameters α_1^* and α_2^*, corresponding to the 21.30 and 10.65 year period respectively, for nearly any direction in the sky. Using the published timing data (Ref. 5), one finds for a preferred frame at rest with respect to the cosmic microwave background:[a] $-0.3 < \alpha_1^* < 0.2$, $-0.6 < \alpha_2^* < 0.3$. These limits are clearly less stringent than present limits for α_1^* from small-eccentricity binary pulsars.[14,16] However, these

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[a] Here we assume that the kinetic PFE parameters are equal to one, as in GR. Limits for the full PFE parameters, including the kinetic contributions, can be found in Ref. 15.

results are based on timing observations which span only a small fraction of the PFE periods given above, and therefore show very strong correlations between the PFE amplitudes and other orbital parameters. Simulations show that these correlations will reduce considerably once the advance of periastron approaches 180°. Hence, an analysis including all the new data is expected to provide limits that are better by about three orders of magnitude. Furthermore, we would like to emphasize that preferred-frame tests with the DP are qualitatively different from those in pulsar white-dwarf binaries, since it probes effects that are only present in the interaction of two compact bodies.[7,15,17]

References

1. J. H. Taylor, *Binary pulsars and relativistic gravity*, in: Les Prix Nobel, Norstedts Tryckeri, Stockholm, 1994, pp. 80.
2. M. Burgay, N. D'Amico, A. Possenti, R. N. Manchester, A. G. Lyne, B. C. Joshi, M. A. McLaughlin, M. Kramer, J. M. Sarkissian, F. Camilo, V. Kalogera, C. Kim and D. R. Lorimer, *Nature* **426** 531–533 (2003).
3. A. G. Lyne, M. Burgay, M. Kramer, A. Possenti, R. N. Manchester, F. Camilo, M. A. McLaughlin, D. R. Lorimer, N. D'Amico, B. C. Joshi, J. Reynolds and P. C. C. Freire, *Science* **303** 1153–1157 (2004).
4. T. Damour, *Binary Systems as Test-beds of Gravity Theories*, in: M. Colpi *et al.* (Eds.), A Century from Einstein Relativity: Probing Gravity Theories in Binary Systems, Springer, 2007, (arXiv:0704.0749).
5. M. Kramer, I. H. Stairs, R. N. Manchester, M. A. McLaughlin, A. G. Lyne, R. D. Ferdman, M. Burgay, D. R. Lorimer, A. Possenti, N. D'Amico, J. M. Sarkissian, G. B. Hobbs, J. E. Reynolds and P. C. C. Freire, F. Camilo, *Science* **314** 97–102 (2006).
6. R. P. Breton, V. M. Kaspi, M. Kramer, M. A. McLaughlin, M. Lyutikov, S. M. Ransom, I. H. Stairs, R. D. Ferdman, F. Camilo and A. Possenti, *Science* **321** 104–107 (2008).
7. C. M. Will, *Theory and Experiment in Gravitational Physics*, Cambridge University Press, Cambridge, 1993.
8. T. Damour and J. H. Taylor, *Phys. Rev. D* **45** 1840–1868 (1992).
9. T. Damour and G. Esposito-Farese, *Phys. Rev. D* **54** 1474–1491 (1996).
10. M. Kramer and N. Wex, *Class. Quantum Grav.* **26** 073001 (2009).
11. T. Damour, *The problem of motion in Newtonian and Einsteinian gravity*, in: S. Hawking and W. Israel (Eds.), 300 Years of Gravitation, Cambridge University Press, Cambridge, 1987, pp. 128.
12. K. S. Thorne and J. B. Hartle, *Phys. Rev. D* **31** 1815–1837 (1985).
13. S. Kopeikin and I. Vlasov, *The effacing principle in the post-Newtonian Celestial Mechanics*, in: H. Kleinert, R.T. Jantzen and R. Ruffini (Eds.), Proc. 11th Marcel Grossmann Meeting, part C, World Scientific, 2008, pp. 2475.
14. T. Damour and G. Esposito-Farèse, *Phys. Rev. D* **46** 4128–4132 (1992).
15. N. Wex and M. Kramer, *MNRAS* **380** 455–465 (2007).
16. N. Wex, *Small-eccentricity binary pulsars and relativistic gravity*, in: M. Kramer, N. Wex, and R. Wielebinski (Eds.), Pulsar Astronomy – 2000 and Beyond, IAU Colloquium 177, Astronomical Society of the Pacific, San Francisco, 2000, pp. 113.
17. T. Damour and G. Esposito-Farèse, *Phys. Rev. D* **53**, 5541–5578 (1996).