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Constraining the cosmological constant and the DGP gravity with the double pulsar PSR J0737-3039

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We consider the double pulsar PSR J0737-3039A/B binary system as a laboratory to locally test the orbital effects induced by an uniform cosmological constant Λ in the framework of the known general relativistic laws of gravity, and the DGP braneworld model of gravity independently of the cosmological acceleration itself for which they were introduced. We, first, construct the ratio $R = \Delta\dot{\omega}/\Delta P$ of the discrepancies between the phenomenologically determined periastron rate $\dot{\omega}$ and orbital period P_b and their predicted values from the 1PN $\dot{\omega}_{1PN}$ approximation and the third Kepler law $P^{(0)}$. Then, we compare its value $|R| = (0.3 \pm 4) \times 10^{-11}$ s^{-2}, compatible with zero within the errors, to the ratios R_Λ and R_{DGP} of the effects induced on the apsidal rate and the orbital period by Λ and the DGP gravity; we find them neatly incompatible with R being $R_\Lambda = (3.4 \pm 0.3) \times 10^{-8}$ s^{-2} and $R_{DGP} = (1.4 \pm 0.1) \times 10^{-7}$ s^{-2}, respectively. Such a result, which for the case of Λ is valid also for any other Hooke-like exotic force proportional to r, is in agreement with other negative local tests recently performed in the Solar System with the ratios of the non-Newtonian/Einsteinian perihelion precessions for several pairs of planets.

1. Introduction

Since, at present, the only reason why the cosmological constant[1] Λ is believed to be non-zero relies upon the observed acceleration of the universe (Riess et al., 1998; Perlmutter et al., 1999), i.e. just the phenomenon for which Λ was introduced (again), it is important to find independent observational tests of the existence of such an exotic component of the spacetime.

In this paper we wish to put on the test the hypothesis that $\Lambda \neq 0$, where Λ is the uniform cosmological constant of the Schwarzschild-de Sitter (Stuchlík and Hledík, 1999) (or Kottler (Kottler, 1918)) spacetime, by suitably using the latest determinations of the parameters (see Table 1) of the double pulsar PSR J0737-3039A/B system (Burgay et al., 2003). The approach followed here consists in deriving analytical expressions $\mathcal{O}_\Lambda$ for the effects induced by Λ on some quantities for which empirical values $\mathcal{O}_{meas}$ determined from fitting the timing data exist. By taking into account the known classical and relativistic effects $\mathcal{O}_{known}$ affecting such quantities, the discrepancy $\Delta\mathcal{O} = \mathcal{O}_{meas} - \mathcal{O}_{known}$ is constructed and attributed to the action of Λ, which was not modelled in the pulsar data processing. Having some $\Delta\mathcal{O}$ and $\mathcal{O}_\Lambda$ at hand, a suitable combination $\mathscr{C}$, valid just for the case $\Lambda \neq 0$, is constructed out of them in order to compare $\mathscr{C}_{meas}$ to $\mathscr{C}_\Lambda$: if the hypothesis $\Lambda \neq 0$ is correct, they must be equal within the errors. Here we will use the anomalistic period P_b and the periastron precession $\dot{\omega}$ for which purely phenomenological determinations exist in such a way that our $\mathscr{C}$ is the ratio of $\Delta\dot{\omega}$ to ΔP_b; as we will see, this observable is independent of Λ but, at the same time, it retains a functional dependence on the system's parameters peculiar to the Λ-induced force and of any other Hooke-like forces.

This work complements (Iorio, 2008) in which a similar test was conducted in the Solar System by means of the latest determinations of the secular precessions of the longitudes of the perihelia of several planets. The result of Iorio (2008) was negative for the Schwarzschild-de Sitter spacetime with uniform Λ; as we will see, the same conclusion will be traced out of this paper in Section 2.1.

A complementary approach to explain the cosmic acceleration without resorting to dark energy was followed by Dvali, Gabadadze and Porrati (DGP) in their braneworld modified model of gravity (Dvali et al., 2000). Among other things, it predicts effects which could be tested on a local, astronomical scale. In (Iorio, 2008) a

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[1] See Calder and Lahav (2008) and references therein for an interesting historical overview.

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Table 1
Relevant Keplerian and post-Keplerian parameters of the binary system PSR J0737-3039A/B (Kramer et al., 2006)

P_b (d)	x_A (s)	x_B (s)	e	$\dot{\omega}$ (deg year^{-1})	s	r (μs)
0.10225156248(5)	1.415032(1)	1.5161(16)	0.0877775(9)	16.89947(68)	0.99974(39)	6.21(33)

The orbital period P_b is measured with a precision of 4×10^{-6} s. The projected semi-major axis is defined as $x = (a_{bc}/c)\sin i$, where a_{bc} is the barycentric semi-major axis, c is the speed of light and i is the angle between the plane of the sky, perpendicular to the line-of-sight, and the orbital plane. The eccentricity is e. The best determined post-Keplerian parameter is, to date, the periastron rate $\dot{\omega}$ of the component A. The phenomenologically determined post-Keplerian parameter s, related to the general relativistic Shapiro time delay, is equal to $\sin i$; we have conservatively quoted the largest error in s reported in (Kramer et al., 2006). The other post-Keplerian parameter related to the Shapiro delay, which is used in the text, is r.

negative test in the Solar System was reported; as we will see in Section 3, PSR J0737-3039A/B confirms such a negative outcome at a much more stringent level.

The conclusions are in Section 4.

2. The effect of on the periastron and the orbital period

The Schwarzschild-de Sitter metric induces an extra-acceleration[2] (Rindler, 2001)

$$\mathbf{A}_\Lambda = \frac{1}{3}\Lambda c^2 \mathbf{r}, \tag{1}$$

where c is the speed of light; eq. (1) in view of the extreme smallness of the assumed non-zero value cosmological constant ($\Lambda \approx 10^{-52}$ m^{-2}), can be treated perturbatively with the standard techniques of celestial mechanics. In (Kerr et al., 2003) the secular precession of the pericentre of a test particle around a central body of mass $\mathfrak{M}$ was found to be

$$\dot{\omega}_\Lambda = \frac{\Lambda c^2}{2n^{(0)}}\sqrt{1-e^2}, \tag{2}$$

where

$$n^{(0)} = \sqrt{\frac{G\mathfrak{M}}{a^3}} \tag{3}$$

is the Keplerian mean motion; a and e are the semi-major axis and the eccentricity, respectively, of the test particle's orbit. Concerning a binary system, in (Jetzer and Sereno, 2006) it was shown that the equations for the relative motion are those of a test particle in a Schwarzschild-de Sitter space–time with a source mass equal to the total mass of the two-body system, i.e. $\mathfrak{M} = \mathfrak{m}_A + \mathfrak{m}_B$. Thus, Eq. (2) is valid in our case; a is the semi-major axis of the relative orbit.

Following the approach by Jetzer and Sereno, 2006, we will now compute P_Λ, i.e. the contribution of Λ to the orbital period. One of the six Keplerian orbital elements in terms of which it is possible to parameterize the orbital motion in a binary system is the mean anomaly $\mathcal{M}$ defined as $\mathcal{M} \equiv n(t - T_0)$, where n is the mean motion and T_0 is the time of pericenter passage. The mean motion $n \equiv 2\pi/P_b$ is inversely proportional to the time elapsed between two consecutive crossings of the pericenter, i.e. the anomalistic period P_b. In Newtonian mechanics, for two point-like bodies, n reduces to the usual Keplerian expression $n^{(0)} = 2\pi/P^{(0)}$. In many binary systems, as in the double pulsar one, the period P_b is accurately determined in a phenomenological, model-independent way, so that it accounts, in principle, for all the dynamical features of the system, not only those coming from the Newtonian point-like terms, within the measurement precision.

The Gauss equation for the variation of the mean anomaly, in the case of an entirely radial disturbing acceleration A like Eq. (1), is

$$\frac{d\mathcal{M}}{dt} = n - \frac{2}{na}A\left(\frac{r}{a}\right) + \frac{(1-e^2)}{nae}A\cos f, \tag{4}$$

where f is the true anomaly, reckoned from the pericenter. Using the eccentric anomaly E, defined as

$$\mathcal{M} = E - e\sin E, \tag{5}$$

turns out to be more convenient. The unperturbed Keplerian ellipse, on which the right-hand-side of Eq. (4) must be evaluated, is

$$r = a(1 - e\cos E); \tag{6}$$

by using Eq. (1) and

$$\begin{cases} \frac{d\mathcal{M}}{dE} = 1 - e\cos E, \\ \cos f = \frac{\cos E - e}{1 - e\cos E}, \end{cases} \tag{7}$$

Eq. (4) becomes

$$\frac{dE}{dt} = \frac{n^{(0)}}{(1-e\cos E)}\left\{1 - \frac{\Lambda c^2}{3{n^{(0)}}^2}\left[2(1-e\cos E)^2 - \frac{(1-e^2)}{e}(\cos E - e)\right]\right\}. \tag{8}$$

Since $\Lambda c^2/3{n^{(0)}}^2 \approx 10^{-29}$ from Eq. (8) it can be obtained

$$P_b \simeq \int_0^{2\pi}\frac{(1-e\cos E)}{n^{(0)}}\left\{1 + \frac{\Lambda c^2}{3{n^{(0)}}^2}\left[2(1-e\cos E)^2 - \frac{(1-e^2)}{e}(\cos E - e)\right]\right\}dE, \tag{9}$$

which integrated yields that

$$P_b = P^{(0)} + P_\Lambda \tag{10}$$

with

$$P_\Lambda = \frac{\pi\Lambda c^2(7+3e^2)}{3{n^{(0)}}^3}. \tag{11}$$

2.1. Combining the periastron and the orbital period

The general relativistic expressions of the post-Keplerian parameters r, s and $\dot{\omega}$ are

$$\begin{cases} r = T_\odot m_B, \\ s = x_A\left(\frac{P_b}{2\pi}\right)^{-2/3} T_\odot^{-1/3} M^{2/3} m_B^{-1}, \\ \dot{\omega}_{1PN} = \frac{3}{(1-e^2)}\left(\frac{P_b}{2\pi}\right)^{-5/3}(T_\odot M)^{2/3}, \end{cases} \tag{12}$$

where

$$T_\odot = \frac{G\mathfrak{M}_\odot}{c^3} \tag{13}$$

and $M = m_A + m_B$ in units of solar masses. By means of

$$a = \frac{c}{s}(x_A + x_B) \tag{14}$$

[2] The present test is valid for all exotic Hooke-type forces of the form Cr (Calder and Lahav, 2008), with C arbitrary non-zero constant.