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First preliminary tests of the general relativistic gravitomagnetic field of the Sun and new constraints on a Yukawa-like fifth force from planetary data

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Abstract

The general relativistic Lense–Thirring (LT) precessions of the perihelia of the inner planets of the Solar System amount to $\lesssim 10^{-3}$ arcseconds per century. Recent improvements in planetary orbit determination may yield the first observational evidence of such a tiny effect. Indeed, corrections to the known perihelion rates of -0.0036 ± 0.0050, -0.0002 ± 0.0004 and 0.0001 ± 0.0005 arcseconds per century ($''\,\mathrm{cy}^{-1}$) were recently estimated by E.V. Pitjeva for Mercury, the Earth and Mars, respectively, on the basis of on the EPM2004 ephemerides and a set of more than 317,000 observations of various kinds. The predicted relativistic LT precessions for these planets are -0.0020, -0.0001 and $-3 \times 10^{-5}{}''\,\mathrm{cy}^{-1}$, respectively, and are compatible with the determined perihelia corrections. The relativistic prediction fits better than the zero-effect hypothesis, especially if a suitable linear combination of the perihelia of Mercury and the Earth, which a priori cancels out any possible bias due to the solar quadrupole mass moment, is considered. However, the overall errors are still large. Also the latest data for Mercury processed independently by Fienga et al. with the INPOP ephemerides yield preliminary insights about the existence of the solar LT effect. The data from the forthcoming planetary mission BepiColombo will improve our knowledge of the orbital motion of this planet and, consequently, the precision of the measurement of the LT effect. As a by-product of the present analysis, it is also possible to constrain the strength of a Yukawa-like fifth force to a $10^{-12} - 10^{-13}$ level at scales of about one Astronomical Unit (10^{11} m).

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1. Introduction

A satisfactorily empirical corroboration of a fundamental theory requires that as many independent experiments as possible are conducted by different scientists in different laboratories. Now, the general relativistic gravitomagnetic Lense–Thirring (LT) effect is difficult to test, also in the weak-field and slow-motion approximation, valid in our Solar System, both because such a relativistic effect is very small and the competing classical signals are often quite larger. Until now, a preliminary 6% LT test has recently been conducted in the gravitational field of Mars by using the data of the Mars Global Surveyor (MGS) spacecraft; other tests accurate to about[1] 10% have been performed by a different team in the gravitational field of the Earth by analyzing the data of the LAGEOS and LAGEOS II artificial satellites (see Section 1.2). We think it is worthwhile to further extend these efforts trying to use different laboratories, i.e. other gravitational fields, even if the outcomes of such tests should be less accurate than those conducted so far. To this aim, in this paper we

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[1]Other estimates point towards a 15 – 20% error.

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investigate the LT effect induced by the Sun on the orbital motion of the inner planets of the Solar System in the context of the latest results in the planetary ephemerides field.

1.1. The LT effect

According to Einstein, the action of the gravitational potential U of a given distribution of mass–energy is described by the coefficients $g_{\mu\nu}$, $\mu, \nu = 0, 1, 2, 3$, of the space–time metric tensor. They are determined, in principle, by solving the fully non-linear field equations of the Einsteinian general theory of relativity (GTR) for the considered mass–energy content. These equations can be linearized in the weak-field ($U/c^2 \ll 1$, where c is the speed of light in vacuum) and slow-motion ($v/c \ll 1$) approximation (Mashhoon et al., 2001; Ruggiero and Tartaglia, 2002), valid throughout the Solar System, and look like the equations of the linear Maxwellian electromagnetism. Among other things, a non-central, Lorentz-like force

$$\boldsymbol{F}_{\mathrm{LT}} = -2m\left(\frac{\boldsymbol{v}}{c}\right) \times \boldsymbol{B}_{\mathrm{g}} \quad (1)$$

acts on a moving test particle of mass m. It is induced by the post-Newtonian component $\boldsymbol{B}_{\mathrm{g}}$ of the gravitational field in which the particle moves with velocity $\boldsymbol{v}$. $\boldsymbol{B}_{\mathrm{g}}$ is related to the mass currents of the mass–energy distribution of the source and comes from the off-diagonal components $g_{0i}, i = 1, 2, 3$ of the metric tensor. Thanks to such an analogy, the ensemble of the gravitational effects induced by mass displacements is also named gravitomagnetism. For a central rotating body of mass M and proper angular momentum $\boldsymbol{L}$ the gravitomagnetic field is

$$\boldsymbol{B}_{\mathrm{g}} = \frac{G[3\boldsymbol{r}(\boldsymbol{r} \cdot \boldsymbol{L}) - r^2\boldsymbol{L}]}{cr^5}. \quad (2)$$

One of the consequences of Eqs. (1) and (2) is a gravitational spin–orbit coupling. Indeed, if we consider the orbital motion of a particle in the gravitational field of a central spinning mass, it turns out that the longitude of the ascending node Ω and the argument of pericentre ω of the orbit of the test particle are affected by tiny secular advances $\dot{\Omega}_{\mathrm{LT}}$, and $\dot{\omega}_{\mathrm{LT}}$ (Ashby and Allison, 1993; Barker and O'Connell, 1974; Cugusi and Proverbio, 1978; Iorio, 2001; Lense and Thirring, 1918; Soffel, 1989)

$$\dot{\Omega}_{\mathrm{LT}} = \frac{2GL}{c^2a^3(1-e^2)^{3/2}}, \quad \dot{\omega}_{\mathrm{LT}} = -\frac{6GL\cos i}{c^2a^3(1-e^2)^{3/2}}, \quad (3)$$

where a, e and i are the semimajor axis, the eccentricity and the inclination, respectively, of the orbit and G is the Newtonian gravitational constant. Note that in their original paper Lense and Thirring (1918) used the longitude of pericentre $\varpi \equiv \Omega + \omega$.

The gravitomagnetic force may have strong consequences in many astrophysical and astronomical scenarios involving, e.g., accreting disks around black holes (Stella et al., 2003; Thorne et al., 1986), gravitational lensing and time delay (Sereno, 2003, 2005a, b). Unfortunately, in these contexts the knowledge of the various competing effects is rather poor and makes very difficult to reliably extract the genuine gravitomagnetic signal from the noisy background. E.g., attempts to measure the LT effect around black holes are often confounded by the complexities of the dynamics of the hot gas in their accretion disks. On the contrary, in the solar and terrestrial space environments the LT effect is weaker but the various sources of systematic errors are relatively well known and we have the possibility of using various artificial and natural orbiters both to improve our knowledge of such biases and to design suitable observables circumventing these problems, at least to a certain extent.

1.2. The performed and ongoing tests

Up to now, all the performed and ongoing tests of gravitomagnetism were implemented in the weak-field and slow-motion scenarios of the Earth and Mars gravitational fields.

As far as the Earth is concerned, in April 2004 the GP-B spacecraft (Everitt, 1974; Everitt, 2001; Fitch et al., 1995) was launched. Its aim is the measurement of another gravitomagnetic effect, i.e. the precession of the spins (Pugh, 1959; Schiff, 1960) of four superconducting gyroscopes carried onboard. The level of accuracy obtained so far is about 256–128% (Muhlfelder et al., 2007), with the hope of reaching[2] $\approx 13\,\%$ in December 2007. In regard to the LT effect on the orbit of a test particle, the idea of using the LAGEOS satellite and, more generally, the Satellite Laser Ranging (SLR) technique to measure it in the terrestrial gravitational field with the existing artificial satellites was put forth for the first time by Cugusi and Proverbio (1978). Attempts to practically implement such a strategy began in 1996 with the LAGEOS and LAGEOS II satellites (Ciufolini et al., 1996). The latest test was performed by Ciufolini and Pavlis (2004). They analyzed the data of LAGEOS and LAGEOS II by using an observable independently proposed by Pavlis (2002), Ries et al. (2003a, b) and Iorio and Morea (2004). The error claimed by Ciufolini and Pavlis (2004) is 5–10% at 1–3 sigma, respectively. The assessment of the total accuracy of such a test raised a debate (Ciufolini and Pavlis, 2005; Iorio, 2005a, b, 2006a, 2007; Lucchesi, 2005).

Recently, a preliminary 6% LT test on the orbit of the MGS spacecraft in the gravitational field of Mars has been reported (Iorio, 2006b); indeed, the predictions of general relativity are able to accommodate, on average, about 94% of the measured residuals in the out-of-plane part of the MGS orbit over about five years.

Finally, it must be noted that, according to Nordtvedt (2003), the multidecade analysis of the Moon'orbit by means of the Lunar Laser Ranging (LLR) technique yields a

[2]See on the WEB StanfordNews 4/14/07 downloadable at http://einstein.stanford.edu/.