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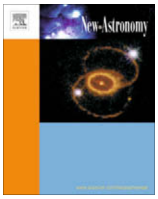

Juno, the angular momentum of Jupiter and the Lense–Thirring effect

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The recently approved Juno mission will orbit Jupiter for 1 year in a highly eccentric ($r_{\min} = 1.06R_{\rm Jup}, r_{\max} = 39R_{\rm Jup}$) polar orbit ($i = 90^\circ$) to accurately map, among other things, the jovian magnetic and gravitational fields. Such an orbital configuration yields an ideal situation, in principle, to attempt a measurement of the general relativistic Lense–Thirring effect through the Juno's node Ω which would be displaced by about 570 m over the mission's duration. Conversely, by assuming the validity of general relativity, the proposed test can be viewed as a direct, dynamical measurement of the Jupiter's angular momentum S which would give important information concerning the internal structure and formation of the giant planet. The long-period orbital perturbations due to the zonal harmonic coefficients $J_\ell, \ell = 2, 3, 4, 6$ of the multipolar expansion of the jovian gravitational potential accounting for its departures from spherical symmetry are, in principle, a major source of systematic bias. While the Lense–Thirring node rate is independent of the inclination i, the node zonal perturbations vanish for $i = 90$. In reality, the orbit injection errors will induce departures δi from the ideal polar geometry, so that, according to a conservative analytical analysis, the zonal perturbations may come into play at an unacceptably high level, in spite of the expected improvements in the low-degree zonals by Juno. A linear combination of Ω, the periJove ω and the mean anomaly $\mathscr{M}$ cancels out the impact of J_2 and J_6. A two orders of magnitude improvement in the uncanceled J_3 and J_4 would be needed to reduce their bias on the relativistic signal to the percent level; it does not seem unrealistic because the expected level of improvement in such zonals is three orders of magnitude. More favorable conclusions are obtained by looking at single Doppler range-rate measurements taken around the closest approaches to Jupiter; numerical simulations of the classical and gravito-magnetic signals for this kind of observable show that a 0.2–5% accuracy would be a realistic goal.

1. Introduction

Recently, NASA approved the Juno[1] mission (Matousek, 2007) to Jupiter. Juno is a spinning, solar powered spacecraft to be placed in a highly eccentric polar orbit around Jupiter (see Table 1 for its relevant orbital parameters) specifically designed to avoid its highest radiation regions. Understanding the formation, evolution and structure of Jupiter is the primary science goal of Juno. It will carry onboard a dual frequency gravity/radio science system, a six wavelength microwave radiometer for atmospheric sounding and composition, a dual-technique magnetometer, plasma detectors, energetic particle detectors, a radio/plasma wave experiment, and an ultraviolet imager/spectrometer. The nominal mission's lifetime is 1 year. Juno is aimed, among other things, at accurately mapping the gravitational field of Jupiter (Anderson, 1976) with unprecedented accuracy (Anderson et al., 2004) by exploiting the slow apsidal precession of its 11-day orbit.

In this paper we wish to explore the possibility offered by Juno to perform a test of general relativity by directly measuring the gravito-magnetic Lense–Thirring effect; its basics are reviewed below. Even putting aside the more or less successful attempts so far performed with other natural and artificial test particles orbiting different central bodies of the solar system, it must be recalled that a satisfactorily empirical corroboration of a fundamental theory like general relativity requires that as many independent experiments as possible are conducted by different scientists in different laboratories; thus, it is worthwhile to try to use different gravitational fields to perform such a test of intrinsic gravito-magnetism. Conversely, since, as we will see, the Lense–Thirring precessions are due to the proper angular momentum $\boldsymbol{S}$ of the orbited central body, one may also assume the existence of the general relativistic gravito-magnetism and consider such a test as a direct, dynamical measurement of the Jupiter's angular momentum through the Lense–Thirring effect; this would yield further, important information concerning the interior of Jupiter. Indeed, the moment of

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[1] See on the WEB http://juno.wisc.edu/index.html.

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Table 1
Planetocentric nominal orbital parameters of Juno. a, e, i are the semi-major axis (in jovian radii $R = 71492$ km), the eccentricity and the inclination (in °) to the Jupiter's equator, respectively. P is the orbital period (in days). T is the mission duration (in years).

a (R)	e	i (°)	P (d)	T (year)
20.03	0.947	90	11	1

inertia ratio C/MR^2 entering S is a measure of the concentration of mass towards the center of the planet (Irwin, 2003). Such a figure, together with the measured values of the zonal[2] coefficients of the gravity field accounting for its deviations from spherical symmetry may be fitted with internal models that model how the density, pressure, temperature and composition vary with depth (Irwin, 2003; Guillot, 2005; Hori et al., 2008). Moreover, a dynamical, model-independent determination of S would be important also for a better knowledge of the history and formation of Jupiter (Machida et al., 2008).

Let us, now, briefly review the basics of the Lense–Thirring effect (Lense and Thirring, 1918; Zel'dovich and Novikov, 1971; Soffel, 1989). In its weak-field and slow-motion approximation, the field equations of general relativity get linearized looking like those of the Maxwellian electromagnetism. Analogously with the magnetic field generated by moving electric charges, mass-energy currents give rise to a gravito-magnetic field $\boldsymbol{B}_{\rm g}$ (Mashhoon, 2007); far from an isolated spinning body of mass M and proper angular momentum $\boldsymbol{S}$ it is (Lichtenegger and Iorio, 2007)

$$\boldsymbol{B}_{\rm g} = -\frac{G}{cr^3}[\boldsymbol{S} - 3(\boldsymbol{S}\cdot\hat{\boldsymbol{r}})\hat{\boldsymbol{r}}], \tag{1}$$

where G is the Newtonian gravitational constant and c is the speed of light in vacuum. $\boldsymbol{B}_{\rm g}$ exerts the non-central Lorentz-like acceleration (Soffel, 1989; Mashhoon, 2007)

$$\boldsymbol{A}^{\rm GM} = -\frac{2}{c}\boldsymbol{v}\times\boldsymbol{B}_{\rm g}, \tag{2}$$

upon a test particle moving with velocity $\boldsymbol{v}$. For ordinary astronomical bodies like, e.g., a planet, $A^{\rm GM}$ is many orders of magnitude smaller than the Newtonian monopole $A^{\rm N} = GM/r^2$, so that it can be considered as a small perturbation. As a result, the longitude of the ascending node Ω and the argument of pericentre ω of a test particle undergo small secular precessions (Lense and Thirring, 1918)

$$\dot{\Omega}_{\rm LT} = \frac{2GS}{c^2a^3(1-e^2)^{3/2}}, \tag{3}$$

$$\dot{\omega}_{\rm LT} = -\frac{6GS\cos i}{c^2a^3(1-e^2)^{3/2}}. \tag{4}$$

Concerning a direct measurement of the Lense–Thirring effect, attempts have been recently performed with the LAGEOS satellites in the gravitational field of the Earth (Cugusi and Proverbio, 1978; Ciufolini and Pavlis, 2004; Ries et al., 2008), the Mars Global Surveyor probe orbiting Mars (Iorio, 2006, 2010a) and some of the inner planets of the Solar System (Iorio, 2008). The evaluation of the total accuracy of the LAGEOS (Ciufolini and Pavlis, 2005; Iorio, 2007a) and MGS (Krogh, 2007; Iorio, 2010a) tests has raised a debate in the recent past because of the difficulty of realistically assessing the impact of certain competing dynamical effects acting as sources of systematic errors; for example, the total accuracy of the LAGEOS test may be as large as some tens percent (Iorio, 2010b); similar shortcomings may affect also the approved LARES mission (Iorio, 2009a,b). For an overview of several theoretical and experimental features of gravito-magnetism see, e.g., Iorio (2007b). Concerning the jovian scenario, Lense and Thirring (1918) originally proposed to use the orbital precessions of the Galilean satellites; such a possibility has been recently investigated by Iorio and Lainey (2005), but it seems to be still premature. Haas and Ross (1975) proposed a spacecraft-based experiment in the gravitational field of Jupiter to measure another gravito-magnetic effect, i.e. the precession of a gyroscope (Pugh, 1959; Schiff, 1960). It is also one of the goals of the GP-B mission (Everitt, 1974) whose target was a ≈1% measurement of such an effect with four superconducting gyroscopes carried onboard by a low-altitude polar spacecraft in the gravitational field of the Earth, but it is still unclear if it will be finally possible to meet the original accuracy because of some unexpected systematic aliasing effects occurred during the mission[3] (Conklin et al., 2008; Everitt et al., 2009). A test of gravito-magnetism[4] concerning the deflection of electromagnetic waves by Jupiter in its orbital motion has been performed in a dedicated radio-interferometric experiment (Fomalont and Kopeikin, 2008). With regard to other suggested non-gravito-magnetic tests of general relativity in the jovian gravitational field, Hiscock and Lindblom (1979) proposed to measure the much larger gravito-electric Einstein pericenter precessions (Einstein, 1915) of the natural satellites of Jupiter and Saturn. There exist also plans for performing a test of the light bending due to the Jupiter's monopole and quadrupole mass moments with the forthcoming astrometric mission GAIA (Crosta and Mignard, 2006).

The Jupiter's proper angular momentum amounts to (Soffel et al., 2003)

$$S \approx 6.9\times10^{38}\ \text{kg m}^2\ \text{s}^{-1}. \tag{5}$$

Table 1 and Eq. (5) yield for Juno

$$\dot{\Omega}_{\rm LT} = 68.5\ \text{mas year}^{-1}, \tag{6}$$

$$\dot{\omega}_{\rm LT} = 0. \tag{7}$$

which correspond to a shift Δv of the cross-track component of the planetocentric position (Christodoulidis et al., 1988)

$$\Delta v_{\rm LT} = a\sqrt{1+\frac{e^2}{2}}\sin i\Delta\Omega_{\rm LT} = 572\ \text{m}\ (T = 1\ \text{year}), \tag{8}$$

over the entire duration of the mission. A total accuracy of the order of 1–10 m with respect to the km-level of the past Jupiter missions in reconstructing the Juno's orbit in a planetocentric frame does not seem an unrealistic target, although much work is clearly required in order to have a more firm answer. Note that a 1–10 m accuracy implies a 0.2–2% error in measuring the gravito-magnetic shift.

The fact that the possibility of detecting the Lense–Thirring effect with Juno's orbit seems worth of further consideration can be preliminarily shown also with a different approach with respect to the cumulative measurement over the full mission duration previously outlined. Indeed, a gravity-science pass for Juno is defined by a continuous, coherent Doppler range-rate measurement plus and −3 h of closest approach; in practice, most of the Lense–Thirring precession takes place just during such a 6 h pass, a near optimum condition. Another crucial factor is the orientation of the Earth to the Juno's orbit: our planet will be aligned 67° from the probe's orbital plane at approximately two degrees south latitude on the jovian equator. Preliminary numerical simulations of the Juno's Lense–Thirring Doppler range-rate signal show that such an orbital geometry represent a perfect compromise for measuring both the Jupiter's even zonal harmonics and the gravito-magnetic signal itself. Indeed, it turns out that the maximum Lense–Thirring Doppler

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[2] They preserve the axial symmetry.

[3] See on the WEB http://einstein.stanford.edu/.

[4] In this case, the mass currents inducing a gravito-magnetic action are not those related to the Jupiter's proper rotation (intrinsic gravito-magnetism), but are due to its translational orbital motion (extrinsic gravito-magnetism).