THE RECENTLY DETERMINED ANOMALOUS PERIHELION PRECESSION OF SATURN

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ABSTRACT

The astronomer E. V. Pitjeva, by analyzing with the EPM2008 ephemerides a large number of planetary observations including also two years (2004–2006) of normal points from the Cassini spacecraft, phenomenologically estimated a statistically significant nonzero correction to the usual Newtonian/Einsteinian secular precession of the longitude of the perihelion of Saturn, i.e., $\Delta \dot{\sigma}_{\text{Sat}} = -0.006 \pm 0.002 \text{ cy}^{-1}$; the formal, statistical error is 0.0007. It can be explained neither by any of the standard classical and general relativistic dynamical effects mismodeled/unmodeled in the force models of the EPM2008 ephemerides nor by several exotic modifications of gravity recently put forth to accommodate certain cosmological/astrophysical observations without resorting to dark energy/dark matter. Both independent analyses by other teams of astronomers and further processing of larger data sets from Cassini will be helpful in clarifying the nature and the true existence of the anomalous precession of the perihelion of Saturn.

Key words: celestial mechanics – ephemerides – gravitation – planets and satellites: individual (Saturn) – relativity

1. INTRODUCTION

At present, the best theory of the gravitational interaction available to us is the Einsteinian General Theory of Relativity (GTR) which has passed so far many observational tests concerning orbital motions and propagation of electromagnetic waves in the (inner) solar system with excellent results (Ni 2005; Will 2006; Turyshhev 2008). Deviations from the expected behavior have been detected in the hyperbolic motions of the Pioneer 10/11 spacecraft after they passed the threshold of approximately 20 Astronomical Units (AU) (Anderson et al. 1998), but it is unlikely that the Pioneer anomaly may be ascribed to long-range modifications of the known laws of gravitation (Iorio 2007a). The so-called flyby anomaly (Anderson et al. 2008) consists of a small but unexplained increase in the velocity of several interplanetary probes (e.g., Galileo; NEAR; Rosetta) moving along their hyperbolic orbits at their closest approaches to the Earth; at present, no conventional explanations in terms of known physics have been found. Another anomalous effect which has recently attracted attention is the secular increase of the Astronomical Unit (Krasinsky & Brumberg 2004; Standish 2004). For an overview of such topics see Lämmerzahl et al. (2008).

In this paper, I will focus on a recently detected nonstandard feature of the motion of Saturn which, if confirmed as a genuine dynamical effect by further, independent analyses, may be added to the list of the solar system anomalies not explained by known mundane causes.

The astronomer E. V. Pitjeva has recently processed a huge data set (1913–2007) of planetary observations of various kinds also including three-dimensional normal point observations of the Cassini spacecraft (2004–2006) with the refined dynamical models of the EPM2008 ephemerides (Pitjeva 2008a). They also encompass the action of Eris, the other 20 largest trans-Neptunian objects, disfavoring the possibility that the real uncertainty can be as large as 0.007 cy$^{-1}$. $\Delta \dot{\sigma}_{\text{Sat}}$ takes into account, by construction, any unmodeled/mismodeled dynamical effects affecting the orbit of Saturn. Previous estimates based on the EPM2006 ephemerides, which did not include the Cassini data, yielded (Pitjeva 2006)

$$\Delta \dot{\sigma}_{\text{Sat}} = -0.006 \pm 0.002 \text{ arcsec century}^{-1} (\text{"cy}^{-1}); \quad (1)$$

it is not compatible with zero at 3σ level. Concerning the quoted uncertainty of 0.002 cy$^{-1}$, it is important to note that it is not the formal error which is, instead, three times smaller and amounts to 0.0007 cy$^{-1}$ (E. V. Pitjeva 2008, private communication). There should also be considered the possibility that the realistic uncertainty may be up to 10 times the formal one (E. V. Pitjeva 2008, personal communication), but I believe that until no other independent determinations to be compared with the one of Equation (1) will be available, this cannot be decided. Thus, throughout the paper I will rest upon the result of the fit of Equation (1). However, in Section 2, I will present some considerations, based on the action of the trans-Neptunian objects, favoring the possibility that the real uncertainty can be as large as 0.007 cy$^{-1}$. $\Delta \dot{\sigma}_{\text{Sat}}$ takes into account, by construction, any unmodeled/mismodeled dynamical effects affecting the orbit of Saturn. Previous estimates based on the EPM2006 ephemerides, which did not include the Cassini data, yielded (Pitjeva 2006)

$$\Delta \dot{\sigma}_{\text{Sat}} = -0.92 \pm 0.29 \text{ "cy}^{-1} \text{ (formal error)}; \quad (2)$$

Waiting for independent confirmations of Equation (1) by other teams of astronomers and further data analysis including, hopefully, more Cassini normal points, in this paper, I will address the following questions. (1) May some known standard physical effects, not properly modeled, or unmodeled at all, be the cause of the estimated anomalous retrograde precession of Saturn? (2) Could some of the recently proposed modified theories of gravity, not modeled in the EPM2008 ephemerides, account for $\Delta \dot{\sigma}_{\text{Sat}}$?

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would imply modeled action of the TNOs, such a positive apsidal precession about 70% of the entire population of the TNOs obtained by its orbit with respect to the Sun’s equator in deg, and $P_0$ is its orbital period in yr.

Table 1
Orbital Parameters of Saturn at the Epoch J2000 with Respect to the Mean Ecliptic and Equinox of J2000

| $a$ (AU) | $e$ | $i$ (deg) | $P_0$ (yr) |
|---------|-----|---------|---------|
| 9.53707032 | 0.05415060 | 4.6655 | 29.453 |

Notes. $a$ is the semimajor axis in AU, $e$ is the eccentricity, $i$ is the inclination of its orbit with respect to the Sun’s equator in deg, and $P_0$ is its orbital period in yr.

2. POSSIBLE EXPLANATIONS OF THE ANOMALOUS PERIHELION PRECESSION OF SATURN

In Table 2, I quote the analytical expressions and the nominal values of the secular perihelion precessions of Saturn due to the known dynamical effects of classical and relativistic origin, along with some exotic forces recently proposed to explain, e.g., the Pioneer anomaly (Anderson et al. 1998), the cosmological expansion without resorting to dark energy (Dvali et al. 2000) and the flat rotation curves of galaxies (Milgrom 1983) without invoking dark matter; also the actions of a spherically symmetric distribution of dark matter (Khriplovich & Pitjeva 2006) and the cosmological constant (Kerr et al. 2003) in the solar system are considered. It turns out that the majority of the considered effects, modeled or not in the EPM2008 routines, cannot explain both the sign and the magnitude of $\Delta \dot{\sigma}_{\text{Sat}}$ because they induce prograde perihelion precessions. In particular, since the modeling of the TNOs is certainly not yet complete, it may be argued that the uncertainty in their total mass can induce prograde perihelion precession of Saturn large enough to explain Equation (1). Although it is reasonable to assume the modeling of the action of the TNOs as still preliminary, it seems difficult to attribute the determined anomalous apsidal precession of Saturn to them because the perihelion precession due to them is prograde (Iorio 2007b). Note that if one assumes for the uncertainty in $\Delta \dot{\sigma}_{\text{Sat}}$ the value 0.007 cy$^{-1}$, i.e., 10 times the formal, statistical error, a prograde extra-precession of +0.001 cy$^{-1}$ would be allowed. If attributed to a still imperfectly modeled action of the TNOs, such a positive apsidal precession would imply $\dot{m}_{\text{TNOs}} = 0.01 M_\oplus$; it is just the nominal value of the Classical Kuiper Belt Objects (CKBOs) which constitutes about 70% of the entire population of the TNOs obtained by Bernstein et al. (2004) with nondynamical techniques. This would be in contrast to the fact that Pitjeva did actually model the action of the 20 largest TNOs and of a massive ring, i.e., it is difficult to believe that a mismodeling as large as 100% may have occurred given the exquisite level of modeling of the EPM ephemerides. The general relativistic gravitoelectric Schwarzschild-like force of the order $O(c^{-2})$ has been modeled in EPM2008. Since the resulting perihelion precession can be written in terms of the standard Eddington–Robertson–Schiff PPN parameters $\beta$ and $\gamma$ (Will 1993) as

$$\dot{\sigma}_{\text{GE}} = \frac{nGM}{c^2 a(1 - e^2)},$$

with $n = \sqrt{GM/a^3}$ Keplerian mean motion and

$$v = \frac{2 + 2\gamma - \beta}{3},$$

it may be argued that, in principle, $\Delta \dot{\sigma}_{\text{Sat}}$ may be explained in terms of a deviation $\Delta \nu$ of $\nu$ from its general relativistic value $v_{\text{GTR}} = 1$. However, this would imply

$$\Delta \nu = -0.428 \pm 0.142,$$

(5)

which is contradicted by several other independent determinations of $\beta$ and $\gamma$ throughout the Solar System (Ni 2005; Will 2006; Turgshev 2008).

Concerning the forces able to induce a negative perihelion precession, the Newtonian $N$-body interactions with the major planets yield the largest retrograde effect; since it is mainly due to Jupiter, the uncertainty in its mass might, in principle, induce a mismodeled precession able to accommodate Equation (1). In fact, the answer is negative because the mass of Jupiter is presently known with a relative accuracy of $1 \times 10^{-8}$ (Pitjeva 2008b) which yields a mismodeled precession 2 orders of magnitude smaller than Equation (1). The retrograde perihelion precession of order $O(c^{-2})$ due to the general relativistic gravitomagnetic Lense–Thirring force generated by the Sun’s rotation (Lense & Thirring 1918), not modeled in the EPM2008 ephemerides, is smaller than $\Delta \dot{\sigma}_{\text{Sat}}$ by 4 orders of magnitude. With regards to the putative exotic forces considered here, the Dvali–Gabadadze–Porrati (DGP) modified gravity (Dvali et al. 2000) predicts a negative secular perihelion precession (Lue & Starkman 2003) of $-0.0005$ cy$^{-1}$; it is too small to explain Equation (1) which rules out its existence at 2.75$\sigma$ level. Incidentally, let us note that the positive value of the DGP effect, related to the self-accelerated branch of the cosmic expansion, is ruled out at 3.25$\sigma$ level. The anomalous acceleration experienced by the Pioneer 10/11 probes at the Saturn orbit (Nieto & Anderson 2005), if attributed to a constant and uniform extra-force directed toward the Sun acting also on the planets, induces a retrograde secular perihelion precession of the perihelion of Saturn 4 orders of magnitude larger than Equation (1). The force quadratic in the radial velocity considered in Standish (2008) as a possible explanation of the Pioneer anomaly induces a retrograde precession of the perihelion which, for Saturn, is 1 order of magnitude larger than Equation (1) being incompatible with it at 11$\sigma$ level; in Iorio (2009) it was still compatible with less recent determinations of $\Delta \dot{\sigma}_{\text{Sat}}$. Also MOdified Newtonian Dynamics (MOND) (Milgrom 1983) causes retrograde secular perihelion precessions; however, in the case of Saturn they are either too small or too large with respect to Equation (1) by several orders of magnitude.

It may be argued that some mutual cancellations among different unmodeled/mismodeled effects may have conspired to yield just the estimated value of $\Delta \dot{\sigma}_{\text{Sat}}$, but an inspection of Table 2 shows that this seems to be a very unlikely possibility.

The detected anomalous perihelion precession of Saturn may be used to phenomenologically constrain the existence of an unknown constant and uniform acceleration directed toward the Sun continuously existing in the spatial regions swept by the Saturn’s orbital motion during the time interval spanned by the data set used (1913–2007) covering about four orbital revolutions of Saturn. It is

$$A_{\text{Sat}} = -(9.14 \pm 3.04) \times 10^{-14} \, \text{m} \, \text{s}^{-2}.$$  

(6)

However, its existence in the inner regions of the solar system is ruled out by the estimated corrections to the Newtonian–Einsteinian perihelion precessions of Venus, Earth, and Mars, as shown in Table 3. Concerning Equation (6), it must be noted that it could not be reproduced by a Yukawa-like term

$$A_{\text{Yuk}} = -\frac{GM\alpha}{r^2} \left(1 + \frac{r}{\lambda}\right) \exp \left(\frac{-r}{\lambda}\right),$$

(7)

They used the ACS camera of the Hubble Space Telescope (HST).
evaluated at the Saturn’s orbit. Indeed, in Iorio (2008) it has been shown that the estimated corrections to the standard precessions of the perihelia of the inner planets constrain \( \alpha \) and \( \lambda \) to \( \alpha \leq 4 \times 10^{-11}, \lambda \leq 0.18 \) AU; such values in Equation (7) yield for Saturn

\[
A_{Yak} = -2 \times 10^{-15} \text{ m s}^{-2}.
\]

On the other hand, typical values for \( \alpha \) and \( \lambda \) able to fit astrophysical observations of distant galaxies, i.e. \( \alpha = -3 \times 10^{-8}, \lambda = 33,000 \) AU (Moffat & Toth 2007), would yield for Saturn

\[
A_{Yak} = 1.98 \times 10^{-12} \text{ m s}^{-2}.
\]

3. DISCUSSION AND CONCLUSIONS

Based on the analysis presented, summarized by Table 2, I conclude that the recently estimated anomalous retrograde apsidal precession of Saturn \( \Delta \tilde{\sigma}_{Sat} \) cannot be explained by any of those standard Newtonian and Einsteinian dynamical effects which have been mismodeled (or unmodeled at all) in the force models of the EPM2008 ephemerides. The same also holds for many exotic modifications of gravity proposed in the recent past to explain various kinds of cosmological/astrophysical observations. In particular, the DGP braneworld model is ruled out at about 3\( \sigma \) level, while the existence of the force quadratic in the radial velocity proposed to explain the Pioneer anomaly must be excluded, at least in the spatial regions swept by the Saturn’s orbit, at 11\( \sigma \) level. Table 2 also shows that a finely tuned cancellation of several unmodeled/mismodeled effects yielding just the estimated \( \Delta \tilde{\sigma}_{Sat} \) is unlikely. Both independent analyses by other teams of astronomers will be important in order to clarify the nature and the genuine existence of the anomalous behavior of the Saturnian perihelion. Moreover, it will be important for further studies to include the largest number of normal points as possible from spacecraft-based missions—in particular Cassini—covering the largest portion as possible of a full orbital revolution of Saturn.

Table 2

Nominal Values, in \( \text{cy}^{-1} \), of the Secular Precessions of \( \tilde{\sigma}_{Sat} \) due to Known Classical and Relativistic Effects and by Some Nonstandard Forces

| Dynamical Effect | Analytical Expression | \( \tilde{\sigma} \) (\( \text{cy}^{-1} \)) |
|------------------|-----------------------|---------------------|
| \( N \)-body* | Numerical integration | -1508.313 |
| Solar quadrupole* \( J_2^Q \) | \( \frac{3}{2} \frac{m_p}{M_\odot} \left( \frac{r}{a} \right)^2 \left( 1 - \frac{3}{2} \sin^2 i \right) \) | \( 3 \times 10^{-7} \) |
| Small asteroid ring* | \( \frac{1}{3} \sqrt{\frac{G}{M_\odot}} \left( \frac{r}{a} \right)^3 \) | \( 1 \times 10^{-5} \) |
| TNOs* | \( \frac{3}{2} \sqrt{\frac{G}{M_\odot}} \left( \frac{r_{\text{ring}}}{a} \right)^3 \) | >0 |
| Schwarzschild* | \( \frac{3}{2} \frac{\rho}{\sqrt{G M_\odot}} \left( \frac{r}{a} \right)^3 \) | 0.014 |
| Lense–Thirring | \( \left[ \frac{4G}{c^4} \frac{R_{\odot}}{r^2} \right] \) | \( -1 \times 10^{-7} \) |
| DGP | \( \pm \frac{3}{n_0} \) | \( \pm 0.0005 \) |

Notes. The integrated \( N \)-body precession can be retrieved at http://ssd.jpl.nasa.gov/txt/p_elem_t1.txt. I have assumed for the quadrupole mass moment of the Sun \( J_2^Q = 2 \times 10^{-7} \) (Pireaux et al. 2007) and for its angular momentum \( S_2 = 190.0 \times 10^{39} \) kg m\(^2\) s\(^{-1}\) (Pijpers 1998). The precession by the small asteroid ring has been computed according to Fienga et al. (2008) with \( r_{\text{ring}} = 0.34 \times 10^{-10} \) M\(_\odot\) and \( r_{\text{ring}} = 2.8 \) AU. TNOs are the trans-Neptunian objects modeled as a ring of mass \( m_{\text{TNOs}} \) and inner and outer radii \( r_{\text{min}} \) and \( r_{\text{max}} \), respectively (Iorio 2007b). DGP is the Lue & Starkman (2003) perihelion precession in the Dvali–Gabadadze–Porrati (Dvali et al. 2000) multidimensional braneworld model; \( r_0 \approx 5 \) Gpc. Pioneer (Saturn) is the Pioneer anomaly at the Saturn’s orbit \( A_{Pio} = -(1.8 \pm 6.4) \times 10^{-10} \) m s\(^{-2}\) (Nieto & Anderson 2005). Pioneer \((|v|)\) and Pioneer \((v^2)\) are the velocity-dependent forces proposed in Standish (2008); for them I used \( K = 7.3 \times 10^{-14} \) s\(^{-1}\) and \( H = 6.07 \times 10^{-18} \) m s\(^{-1}\). The effect of a spherically symmetric distribution of dark matter has been worked out in, e.g., Khriplovich & Pitjeva (2006), while that of MOND is due to Sereno & Jetzer (2006) with \( \Lambda_{\text{MOND}} = \sqrt{GM_\odot/a_0} \). The apsidal precession induced by the cosmological constant \( \Lambda \approx 10^{-52} \) m\(^2\) s\(^{-2}\) is due to Kerr et al. (2003). The other parameters used are \( a, e, i, \) semimajor axis, eccentricity and inclination, respectively, of the planetary orbit, \( n = \sqrt{GM_\odot/a^3} \) Keplerian mean motion, \( M_\odot, R_\odot \) mass and equatorial radius, respectively, of the Sun, \( G \) Newtonian gravitational constant, and \( c \) is the speed of light in vacuum. \*The effects with \* have been modeled in EPM2008.
Table 3
First Row: Estimated Corrections to the Standard Perihelion Precessions of Mercury (Pitjeva 2005), Venus (E. V. Pitjeva 2008, private communication), Earth (Pitjeva 2005), and Mars (Pitjeva 2005), in ”cy-1

|       | Mercury | Venus | Earth | Mars |
|-------|---------|-------|-------|------|
| Δcy-1 | -0.0036 ± 0.0050 | -0.0004 ± 0.0005 | -0.0002 ± 0.0004 | 0.0001 ± 0.0005 |
|       | -0.0011 |       |       |      |

Notes. *The quoted errors are realistic. Second row: anomalous perihelion precessions, in ”cy-1, of Mercury, Venus, Earth, and Mars induced by Equation (6).

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