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J. Geogr. Inst. Cvijic. 2019, 69(3), pp. 265–269

Research note

UDC: 911.2:621.47
https://doi.org/10.2298/IJGI1903265J

Received: September 11, 2019
Reviewed: October 30, 2019
Accepted: November 10, 2019

CONSTRAINING YUKAWA GRAVITY FROM PLANETARY MOTION IN THE SOLAR SYSTEM

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Abstract: In this work we used the observed additional perihelion precession in the Solar System, obtained from the observations of planets and spacecrafts, to study the possible existence of Yukawa correction term to the Newtonian gravitational potential. Our study was motivated by previous analyses which indicated the possible discrepancies from Newtonian gravity in this form and at wide range of astrophysical scales. Yukawa gravity was introduced to cure some shortcomings of General Relativity (GR) at galactic and extragalactic scales. We demonstrated that this form of gravity can give the values for orbital precession which are comparable or even in better agreement with observations than the corresponding predictions of GR. The obtained results can be used for setting stronger constraints on variation of the gravitational constant G, as well as on the fundamental constant δ of Yukawa gravity. Moreover, Yukawa gravity could be used to improve the results for the motion of planets, other Solar System bodies, as well as spacecrafts, and as a consequence, it can help us to get more reliable predictions for natural hazards in the Solar System, such as potential impacts by near-Earth objects.

Keywords: modified theories of gravity; gravitational precession; experimental tests of gravitational theories; Solar System

Introduction

Different alternative gravity theories have been proposed like alternative approaches to Newtonian gravity (see e.g., Capozziello & Faraoni, 2011; Clifton, Ferreira, Padilla, & Skordis, 2012; Fischbach & Talmadge, 1999; Sotiriou & Faraoni, 2010 for reviews). These theories have to be also tested by astronomical observations taken at different scales such as Solar system, binary pulsars, spiral galaxies, clusters of galaxies (Capozziello & de Laurentis, 2011). In our previous work we performed such tests of different gravity theories in order to constrain their parameters at galactic (Borka, Capozziello, Jovanović, & Borka Jovanović, 2016; Borka, Jovanović, Borka Jovanović, & Zakharov, 2012, 2013; Capozziello et al., 2014; Dialektopoulos, Borka, Capozziello, Borka Jovanović, & Jovanović, 2019; Zakharov, Borka, Borka Jovanović, & Jovanović, 2014) and extragalactic scales (Borka Jovanović, Capozziello, Jovanović, & Borka, 2016; Capozziello, Jovanović, Borka Jovanović, & Borka, 2017). Among these theories, a special attention has been given to the gravity theories with Yukawa-like correction term (Fischbach, Sudarsky, Szafer, Talmadge, & Aronson, 1986; Fischbach &

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Talmadge, 1992; Hoyle et al., 2001; Iorio, 2007), and in our previous research we constrained parameters of Yukawa gravity at galactic scales (Borka et al., 2013; Zakharov et al., 2016, 2018).

On the other hand, the results of present high precision observational techniques and theories of planetary motions enable one to accurately study a variety of small effects in the Solar System, such as the presence of dark matter (Pitjeva & Pitjev, 2013) or possible deviations from Newtonian gravity (Adelberger, Gundlach, Heckel, Hoedl, & Schlamminger, 2009; Borka et al., 2013, Zakharov et al., 2016, 2018). Recently, discrepancies from the Newtonian potential in the form of Yukawa correction term have been tested at laboratory, geophysical and different astrophysical scales (Adelberger et al., 2009, Borka et al., 2013, Zakharov et al., 2016, 2018).

Here we use the observed additional perihelion precession of the planets with respect to the prediction of GR (Pitjeva & Pitjev, 2013), which is available for six planets up to Saturn, as well as for Pluto dwarf planet, and potentially hazardous near-Earth asteroid 99942 Apophis to constrain the Yukawa gravity and to study if it could be used to improve the results for the motion of the bodies and the prediction of hazards in the Solar System. Near-Earth asteroid 99942 Apophis is included in this study because the initial observations indicated a significant probability that it could hit Earth on April 13th 2029, although the additional observations provided improved predictions that eliminated the possibility of an impact on Earth or the Moon in 2029. However, a possibility remained that during the 2029 close encounter with Earth, Apophis will pass through a gravitational keyhole which could potentially cause a future impact. This possibility kept it at Level 1 on the Torino impact hazard scale until August 2006, and until now it is a subject of different observational and theoretical studies, such as e.g. the numerical simulations of the tidal encounter between Earth and Apophis in 2029 (DeMartini et al., 2019). In this study, we used the orbital elements for 99942 Apophis from NASA Jet Propulsion Laboratory Small-Body Database (Chamberlin et al., 1997) provided at: https://ssd.jpl.nasa.gov/sbdb.cgi?sstr=99942.

Method and results

Yukawa-like modification to the Newtonian gravitational potential is given by (see e.g., Borka et al., 2013):

$$\Phi(r) = -\frac{GM}{(1+\delta)r}\left[1+\delta e^{-\left(\frac{r}{\Lambda}\right)}\right], \tag{1}$$

where Λ is the range of interaction and δ is a new universal constant (for $\delta = 0$, $\Phi(r)$ reduces to the Newtonian potential). Orbital precession per orbital period induced by this potential is given by Zakharov et al. (2018):

$$\Delta\varphi_Y^{rad} \approx \frac{\pi\delta\sqrt{1-e^2}}{1+\delta}\frac{a^2}{\Lambda^2}, \quad a \ll \Lambda. \tag{2}$$

Based on some recent Solar System constraints (Adelberger et al., 2009), we assumed two small values of the universal constant $\delta = 10^{-11}$ and 10^{-10} and used the above expression to estimate the range of interaction Λ, so that the resulted orbital precession in Yukawa gravity is equal to the observed one (available for 6 planets up to Saturn), as well as to the Schwarzschild precession of elliptical orbits in GR (calculated for all 10 studied objects). The obtained results and the corresponding orbital elements (semi-major axes a and eccentricities e), are presented numerically in Table 1, and graphically in Figure 1a and 1b. By comparing the presented estimates for Λ with the corresponding recent experimental constraints at other scales given in Fig. 10 from Adelberger et al. (2009), it could be seen that the obtained results are in good agreement with these constraints. Moreover, assuming slightly different values of Λ, Yukawa gravity can recover both the observed and Schwarzschild orbital precessions, and thus, it could be used to improve the results for the motion of the bodies and spacecrafts in the Solar System. In a similar way, the obtained value for Λ in the case of 99942 Apophis could be used for improving its orbit and getting more reliable predictions for its potential future impacts on Earth.

Table 1
The estimated range of interaction Λ for two different values of δ, and in the case when the orbital precession in Yukawa gravity is equal to the observed one, as well as to the corresponding GR prediction

Body		Orbital elements		Precession		$\delta = 1 \times 10^{-10}$		$\delta = 1 \times 10^{-11}$	
No.	Name	*a* (AU)	*e*	GR ("/cy)	Observed ("/cy)	Λ_{GR} (10^6 m)	Λ_{obs} (10^6 m)	Λ_{GR} (10^6 m)	Λ_{obs} (10^6 m)
1	Mercury	0.3871	0.2056	42.9841	43.1000	0.40	0.40	0.13	0.13
2	Venus	0.7233	0.0068	8.6253	8.0000	1.05	1.09	0.33	0.34
3	Earth	1.0000	0.0167	3.8391	5.0000	1.71	1.50	0.54	0.47
4	Mars	1.5237	0.0934	1.3510	1.3624	3.19	3.18	1.01	1.00
5	Jupiter	5.2034	0.0484	0.0624	0.0700	20.22	19.09	6.39	6.04
6	Saturn	9.5371	0.0542	0.0137	0.0140	50.17	49.64	15.87	15.70
7	Uranus	19.1913	0.0472	0.0024	-	143.31	-	45.32	-
8	Neptune	30.0690	0.0086	0.0008	-	281.51	-	89.02	-
9	Pluto	39.4817	0.2488	0.0004	-	403.77	-	127.68	-
10	Apophis	0.9224	0.1912	4.8745	-	1.47	-	0.47	-

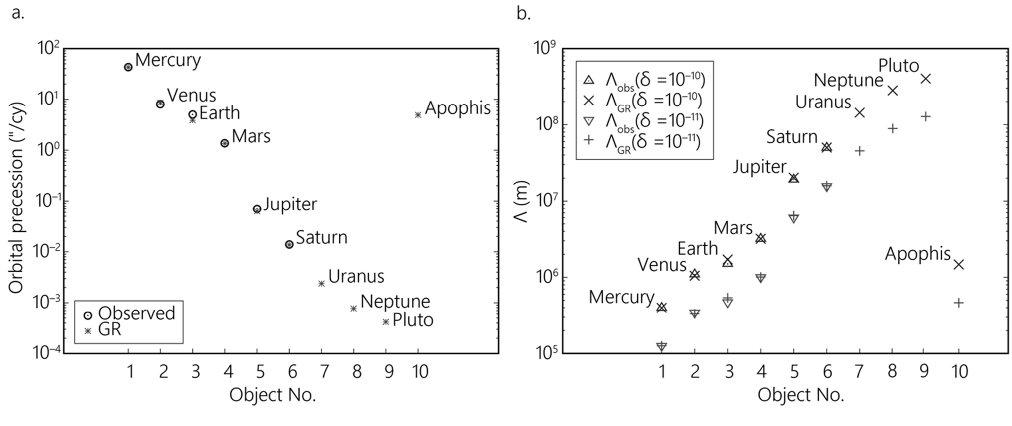

Figure 1. Comparison between the observed orbital precession of the selected Solar System bodies and the corresponding GR predictions (a); Constraints on range of interaction Λ in the case of $\delta = 10^{-11}$ and 10^{-10}, obtained from the observed orbital precession and its GR prediction (b).

Conclusion

We constrained the Yukawa gravity at the Solar System scales using the observed and Schwarzschild orbital precessions of the planets, Pluto dwarf planet, and potentially hazardous near-Earth asteroid 99942 Apophis. The obtained results show that Yukawa gravity could be used to improve the results for the motion of the Solar System bodies and spacecrafts, and thus to get more reliable predictions for potential hazards from the impacts by near-Earth objects. More precisely, we found that:

- Our estimates for the range of Yukawa interaction Λ are in good agreement with recent experimental constraints at different scales;
- There is a small, but significant difference between the values for Λ in the case of the observed orbital precession and the corresponding GR prediction (i.e., Schwarzschild precession);
- Assuming such slightly different values of Λ, this type of modified gravity can explain the observed additional perihelion precession of the planets without a dark matter hypothesis;
- Since it can significantly affect the orbits of all the bodies, Yukawa gravity could help us to get more reliable predictions for natural hazards in the Solar System, such as those from impacts by near-Earth objects.

Acknowledgements

This work is supported by Ministry of Education, Science and Technological Development of the Republic of Serbia, through the project 176003 "Gravitation and the Large Scale Structure of the Universe".

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