Available online at www.sciencedirect.com

ScienceDirect

Advances in Space Research 61 (2018) 2697–2706

ADVANCES IN SPACE RESEARCH (a COSPAR publication)

www.elsevier.com/locate/asr

A possible flyby anomaly for Juno at Jupiter

L. Acedo *, P. Piqueras, J.A. Moraño

Instituto Universitario de Matemática Multidisciplinar, Building 8G, Access C, 2º Floor, Camino de Vera, Universitat Politécnica de Valéncia, 46022 Valencia, Spain

Received 17 July 2017; received in revised form 20 September 2017; accepted 27 February 2018
Available online 7 March 2018

Abstract

In the last decades there have been an increasing interest in improving the accuracy of spacecraft navigation and trajectory data. In the course of this plan some anomalies have been found that cannot, in principle, be explained in the context of the most accurate orbital models including all known effects from classical dynamics and general relativity. Of particular interest for its puzzling nature, and the lack of any accepted explanation for the moment, is the flyby anomaly discovered in some spacecraft flybys of the Earth over the course of twenty years. This anomaly manifest itself as the impossibility of matching the pre and post-encounter Doppler tracking and ranging data within a single orbit but, on the contrary, a difference of a few mm/s in the asymptotic velocities is required to perform the fitting.

Nevertheless, no dedicated missions have been carried out to elucidate the origin of this phenomenon with the objective either of revising our understanding of gravity or to improve the accuracy of spacecraft Doppler tracking by revealing a conventional origin.

With the occasion of the Juno mission arrival at Jupiter and the close flybys of this planet, that are currently been performed, we have developed an orbital model suited to the time window close to the perijove. This model shows that an anomalous acceleration of a few mm/s^2 is also present in this case. The chance for overlooked conventional or possible unconventional explanations is discussed.

Keywords: Juno mission; Tidal perturbations; Jupiter's gravity model; Flyby anomaly

1. Introduction

A key step towards interplanetary space exploration was achieved by the theoretical work of Minovitch (Minovitch, 1961b,a) and Flandro (Flandro, 1966). In the early sixties of the past century these authors proposed the use of the gravitational assist manoeuvre to increase the energy of spacecraft in the Solar System barycenter, allowing for fast reconnaissance missions to the outer planets from Jupiter to Neptune (Butrica, 1998). Since then, many gravity assist, flyby or slingshot manoeuvers (as this manoeuver can be equally be named) have been programmed in the course of missions to the inner planets (Mariner, Messenger), outer planets (Pioneer, Voyager, Galileo, Cassini, New Horizons, Juno) or asteroids (NEAR). The objective of many of these flybys is to obtain data from the planets as they flyby them and to take advantage of the energy transfer obtained during the flyby (Anderson et al., 2007).

Apart from the obvious contribution to planetary science, these missions have provided an excellent framework to perform tests of General Relativity and to improve the accuracy of trajectory determination systems. As soon as 1976, the Viking mission allowed for the verification of Shapiro's echo delay prediction of an increase in a time taken for a round-trip's light signal to travel between the Earth and Mars as a consequence of the curvature of space-time by the Sun (Reasenberg et al., 1979). More recently, Everitt et al. (2011) have tested the geodetic and frame-dragging effects. Also, the analysis of the data from the Messenger mission to Mercury is now used for improving the accuracy of ephemeris as they also put a stringent

* Corresponding author.
E-mail address: luiacrod@imm.upv.es (L. Acedo).

https://doi.org/10.1016/j.asr.2018.02.037
0273-1177/

test on the parameters in the post-newtonian formalism (Verma et al., 2013, 2014). With such an ongoing interest in fundamental aspects of spacecraft dynamics and gravity it is, perhaps, not surprising that some anomalies have showed up in the years passed since the beginning of the space age. Among them, the so-called Pioneer anomaly stands out as a particularly interesting case. As it has become common lore within the space physics community, the Pioneer anomaly consist on a trend detected on the Doppler data for the Pioneer 10 and Pioneer 11 spacecraft as they travel beyond Jupiter. This trend was consistent with an, almost constant, acceleration of $a_P = (8.74 \pm 1.33) \times 10^{-8}\ \mathrm{cm/s^2}$ directed, approximately, towards the Sun (Lämmerzahl et al., 2008; Anderson et al., 2002). Despite the many suggestions for new physics (Turyshev and Toth, 2010), the problem was finally settled, after the careful retrieval of the whole telemetry dataset, as originating from the anisotropic emission of heat from the radioactive sources on the thermoelectric generators (Rievers and Lämmerzahl, 2011; Turyshev et al., 2012; Bertolami et al., 2010).

Even more intriguing is the flyby anomaly, i. e., the unexplained difference among the post-encounter and the pre-encounter Doppler residuals of a spacecraft in a gravity assist manoeuver around the Earth (Anderson et al., 2008). The first detection of the effect occurred during the first Galileo flyby of the Earth on December, 8th, 1990. In this case the discrepancy was interpreted as an anomalous increase of 3.92 mm/s in the post-encounter asymptotic velocity. It is important to emphasize that this anomaly is also observed in the ranging data and cannot be attributed to a conventional or unconventional issue related entirely to the Doppler tracking. A primary evaluation of the possible conventional physical effects with could be contributing to the anomaly was carried out by Lämmerzahl et al. (Lämmerzahl et al., 2008). Ocean tides and a coupling of the spacecraft to the tesseral harmonic terms in the geopotential model have also recently been studied (Acedo, 2016). Atmospheric friction can also be dismissed except for flybys at altitudes of 300 km or lower (Acedo, 2017b). The same can be said of the corrections corresponding to General Relativity (Iorio, 2009; Hackmann and Laemmerzahl, 2010), thermal effects (Rievers and Lämmerzahl, 2011) or other (Atchison and Peck, 2010).

The absence of any convincing explanation have motivated many researchers to undertake the task of looking for models beyond standard physics. An early work by Adler (Adler, 2010, 2011) presented a model in which a halo of dark matter coalesces around the Earth and its interactions would explain away the flyby anomaly. Anaway, these interactions would verify very stringent conditions. We have also many models which refer to extensions of General Relativity or modifications of standard newtonian gravity: extensions of Whitehead's theory of gravity (Acedo, 2015; Acedo and Bel, 2017), topological torsion (Pinheiro, 2014, 2016), retardation effects (Hafele, 2009), motion in conformal gravity (Varieschi, 2014) or some *ad hoc* modifications of the Newtonian potential (Nyambuya, 2008; Wilhelm and Dwivedi, 2015; Bertolami et al., 2016). In the work of Bertolami et al. (2016) several ungravity inspired modifications of the Newtonian potential through couplings of the stress-energy tensor or the baryonic current with a rank-2 tensor are considered. However, the authors conclude that no modifications of the classical Newtonian potential of this kind can account for the anomalous energy changes detected during the flybys. Consequently, dissipative or velocity-dependent effects accounting for an energy transfer from the spacecraft to the planet should be considered in future studies if the anomalies persist after rigorous analysis. One of the objectives of the present paper is to develop a method from which, in principle, we can infer the form of the perturbation from the trajectory. This way we can test if the perturbation is compatible with a conservative force of takes another form as proposed by Bertolami et al. (2016) and other authors (Acedo, 2015).

This top-down approach from new theoretical models to fit the data for the anomaly is unlikely to be successful at the present state of research in this area. Although the observations of the anomaly are clear in some cases, it is still on the threshold of detectability (or it is simply absent) from other flyby manoeuvers (such as the Juno flyby of the Earth on October, 2013 (Jouannic et al., 2015; Thompson et al., 2014)). It seems more reasonable to improve the analysis of the flyby trajectories performed around the Earth and to carry out more analysis of other flyby manoeuvers in the future. This would help to clarify the existence of such an anomaly, its relation to standard gravity and its manifestation in missions to other planets. The very nature of this anomaly, with its variations in sign and magnitude from flyby to flyby, has made very difficult to find a consistent pattern among them (Anderson et al., 2008) in order to settle its characteristics and phenomenology.

This could have been done by a dedicated science mission such as the, now cancelled, Space–Time Explorer and Quantum Equivalence Principle Space Test (STE-QUEST) spacecraft (Páramos and Hechenblaikner, 2013). But, as gravity assist manoeuvers are almost routine in every interplanetary mission, we can expect that the necessary data to establish the undeniable existence of the phenomenon and its anomalous nature, i.e., the lack of explanation within the current paradigm of physics. To achieve this objective, it would be highly useful to find that similar anomalies are found in the flybys of other planets. If these anomalies are revealed in this situation, and as Lämmerzahl et al. have already claimed (Lämmerzahl et al., 2008), we will have an important science case. Nowadays, the Juno spacecraft is orbiting around Jupiter in a highly elliptical orbit with perido 53.5 days after the successful orbit insertion on past July, 4th, 2016. After a failed period reduction manoeuver in its second perijove, the spacecraft is now planned to complete a total of 12 orbits of which six have now been completed. The interesting fact, in connection with out problem, is that Juno is achieving its periapsis at only 4200 km over the pla-