ВАК 2024
MODERN ASTRONOMY:
FROM THE EARLY UNIVERSE TO EXOPLANETS AND BLACK HOLES
300 years Russian Academy of Sciences

Tidal changes in the rotational state of asteroids as evolution factor of the magnitude of the Yarkovsky effect

A. Melnikov[1], M. Khovrichev[1], I. Balyaev[1], and K. Lobanova[1,2]

[1] Pulkovo Observatory, 65/1 Pulkovskoye ave., Saint-Petersburg, 196140 Russia
[2] Saint Petersburg State University, 7/9 Universitetskaya emb., Saint-Petersburg, 199034 Russia

Abstract. We examined possible tidal-induced leaps in the rotational state parameters of the asteroids during their planet approaches. These dramatic changes in the rotational period and obliquity lead to significant changes in orbital dynamics due to the corresponding Yarkovsky acceleration A_2 leap. Our numerical simulations of asteroid rotational parameters evolution due to their planet encounters support the conclusion that significant A_2 changes can happen when planetocentric distance is less than ten planetary radii. We have found nine asteroids with anomalous A_2 values. However, there is no exact evidence that these A_2 discrepancies can be explained by tidal effects only.

Keywords: minor planets, asteroids: general

DOI: 10.26119/VAK2024.150

1 Introduction

The investigation of the Yarkovsky drift (Yarkovsky 1901) is significant for the understanding of the asteroid orbital evolution. The physical model of the Yarkovsky effect is well-developed (e.g. Vokrouhlicky et al. (2000)). It is customary to denote the nongravitational accelerations as A_1, A_2, A_3 according to Marsden et al. (1973). The A_2 value can be determined for the asteroids using the orbit improvement procedure.

The value of the considered effect depends on the rotational state of the body. Various physical phenomena can alter the rotation period (P) and axis orientation of asteroids. One such phenomenon is a tidal-induced leap in asteroid rotation during a close flyby of a planet. This paper aims to estimate the contribution of this phenomenon to the orbital dynamics of asteroids.

2 Numerical experiments

Numerical experiments were conducted to simulate the asteroid rotational dynamics during close encounters with planets (see Lobanova & Melnikov (2024)). It has been determined that under a rigid-body model, significant changes in P and γ (the angle between the axis of rotation and the normal to the orbital plane), leading to an anomalous change in A_2, can occur only during very close encounters ($d \leq 10R_{\mathrm{E}}$, where R_{E} is the radius of the Earth) and with a relatively slow initial rotation ($P > 5$ hours). Fig. 1 illustrates the relationship between the change in the P of the (99942) Apophis (ΔP) and the geocentric orbit parameters (d, e).

Among the numbered asteroids, there are some, like 1998 ST27, that can be described by the "rubble pile" model (Chapman 1977). For these asteroids, close encounters with planets can cause tidal deformation of their shape, resulting in a change in A_2. In Fig. 1 an example of changes in A_2 for a model asteroid similar to Apophis is shown. It is assumed that at the pericenter of the geocentric orbit, the asteroid undergoes deformation/destruction, causing changes in its inertial parameters: before approach $A/C = 0.73$, after — $A/C = 0.36$; $B/C = 0.95$ and remains unchanged. It is apparent that ΔA_2 is comparable to the current value (Pérez-Hernández et al. 2022) $A_2 = -2.9 \cdot 10^{-14}$ au/d^2 for Apophis. During tidal deformation, an asteroid's A_2 can change by a factor of 2 to 3 and even alter the direction of Yarkovsky drift.

3 Search for A_2 anomaly

Let's assume that the asteroid had the Yarkovsky parameter A_2 before its approach to the planet. Tidal effects during the approach to the planet changed the A_2 value.

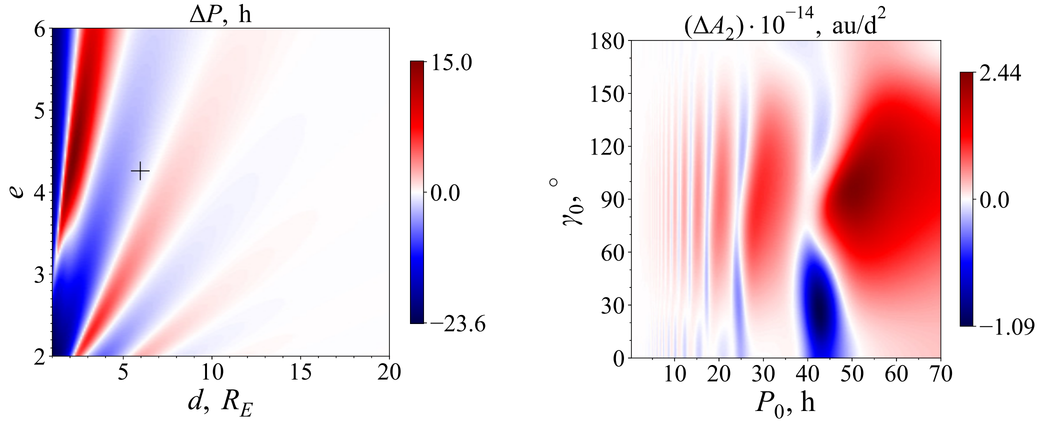

Fig. 1. The graph on the left shows how the change in the rotation period of the asteroid Apophis due to its approach to Earth in 2029 (denoted by ΔP) depends on the geocentric orbit parameters $d = a(e-1)$ and e; $A/C = 0.73$, $B/C = 0.95$, $P_0 = 30.6\,\mathrm{h}$, $\gamma = 140°$. The cross on the graph indicates the position of the asteroid (Pravec et al. 2014). The graph on the right illustrates how ΔA_2 depends on the initial values of the rotation period (P_0) and the angle (γ_0) between the axis of rotation and the normal to the orbital plane. In this case, the asteroid undergoes "deformation" at the point of approach. Before approaching, the ratio of moments of inertia is $A/C = 0.73$, but at the point of approach and beyond $A/C = 0.36$ and $B/C = 0.95$. The orbital parameters of the asteroid are the same as those of Apophis.

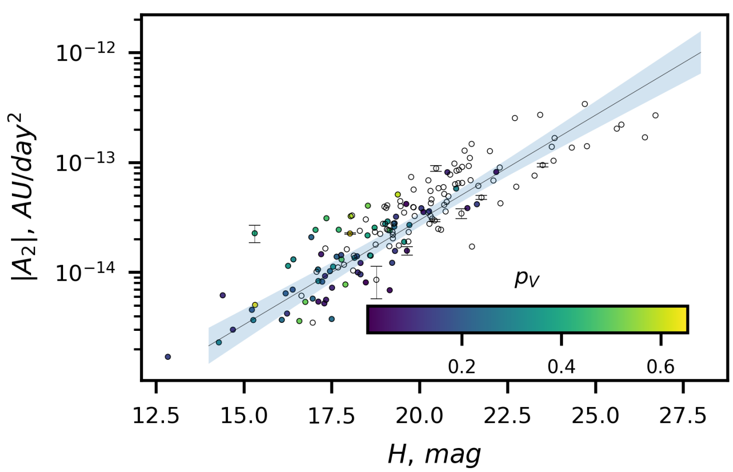

Fig. 2. A_2 as a function of H for asteroids with well-determined Yarkovsky acceleration. Error bars are shown for asteroids with the A_2 anomaly only.

Therefore, it can be expected that the A_2 estimate for the entire series of observations (usually 20–40 years), including astrometric measurements before and after the approach, will not correspond to the most probable value for asteroids with a certain absolute stellar magnitude (H) and albedo values p_v. Therefore, it was logical to try to search for asteroids with anomalous A_2 values.

Figure 2 demonstrates a well-known $A_2(H)$ relation in a logarithmic scale. We calculated the parameters of this ratio and detected 9 asteroids with A_2 value exceeding expected $A_2(H)$ in the 3σ sense. These asteroids are 2340 Hathor (1976 UA), 4179 Toutatis (1989 AC), 33342 (1998 WT24), 138175 (2000 EE104), 276033 (2002 AJ129), 363027 (1998 ST27), 437844 (1999 MN), 1995 CR and 2009 UG. The minimal geocentric distance within this list is 2.2 LD for 2002 AJ129. This significantly exceeds the effective planet-asteroid distance for the tidal-induced leap in the rotational state. Hence, there is no direct observational evidence for conducted simulation results. The A_2 anomaly for these asteroids may be explained by sublimation activity due to short perihelion distances.

4 Conclusions

Perturbations in the rotational motion of an asteroid can cause noticeable changes in the value of A_2 when the asteroid rotates relatively slowly (for periods of more than five hours) and comes close to a planet at a distance, ten times smaller than its radius. its radius. Asteroid A_2 value can change by a factor of 2 to 3 for the case of the tidal deformation. We have found nine asteroids with anomalous A_2 values. However, there is no exact evidence that these A_2 discrepancies can be explained by tidal effects only.

Funding

The study was funded by a Russian Science Foundation grant No 23-22-00306, https://rscf.ru/project/23-22-00306/.

References

Chapman C., 1977, IAU Colloquium, 39, p. 265
Lobanova K.S. and Melnikov A.V., 2024, Solar System Research, 58, 2, p. 208
Marsden B.G., Sekanina Z., and Yeomans D.K., 1973, Astronomical Journal, 78, p. 211
Pérez-Hernández J.A., Jorge A., and Benet L., 2022, Comm. Earth & Environ., 3, 1, id.10
Pravec P., Scheirich P., Ďurech J., et al., 2014, Icarus, 233, p. 48
Vokrouhlicky D., Milani A., and Chesley S.R., 2000, Icarus, 148, 1, p. 118
Yarkovsky I.O., 1901, The density of the light ether and the resistance it provides to movement, Bryansk: Yudin's typography