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Perturbations in the rotational dynamics of small asteroids when approaching the Earth

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Abstract. Using numerical modeling, perturbations that occur in the rotational motion of small (10–50 m in diameter) asteroids during their close approaches to the Earth (at distances of the order of several Earth radii) are considered. For a number of asteroids (Duende, 2012 TC4 and 2023 BU), estimates of possible changes in the rotational period P and the orientation of the rotational axis due to approach to the Earth were obtained. It has been established that in the case of fast rotation of an asteroid ($P < 1$ h), perturbations in its rotational motion that arise during approach are negligible. With a relatively slow rotation of the asteroid ($P > 5$ h), perturbations can be significant: changes in P may reach several hours, and deviations of the rotation axis from the initial position may amount to tens of degrees. Such perturbations influence further orbital dynamics of a slowly rotating asteroid by changing the magnitude of the Yarkovsky effect.

Keywords: celestial mechanics; minor planets, asteroids: general; methods: numerical

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1 Introduction

One of the important characteristics of an asteroid is its rotational state. More than 60% of currently known near-Earth asteroids are small bodies (diameter $D <$ 100 m)[3]. The period P of the asteroid's own rotation is related to the size of the asteroid (see, for example, Pravec & Harris (2000); Fenucci et al. (2024)). Among small asteroids, objects with fast ($P < 5$ h) rotation predominate. Periods $P = 5$–100 h are typical for larger asteroids ($D >$ 100–1000 m). Asteroids with $D \sim 10$ m, which are probably monolithic bodies, can have very fast rotation with $P < 1$ h. During the secular orbital evolution of a number of small asteroids, close encounters with the Earth at distances of several radii of our planet ($R_{\rm E}$) take place. Such approaches cause perturbations in the rotation of the asteroid (Scheeres et al. 2000; Boldrin et al. 2020; Melnikov 2022) and influence its further orbital dynamics (Martyusheva & Melnikov 2023; Lobanova & Melnikov 2024). Within the framework of the problem of asteroid-comet hazard, the study of the influence of close encounters with the Earth on the rotational dynamics of an asteroid is of great importance.

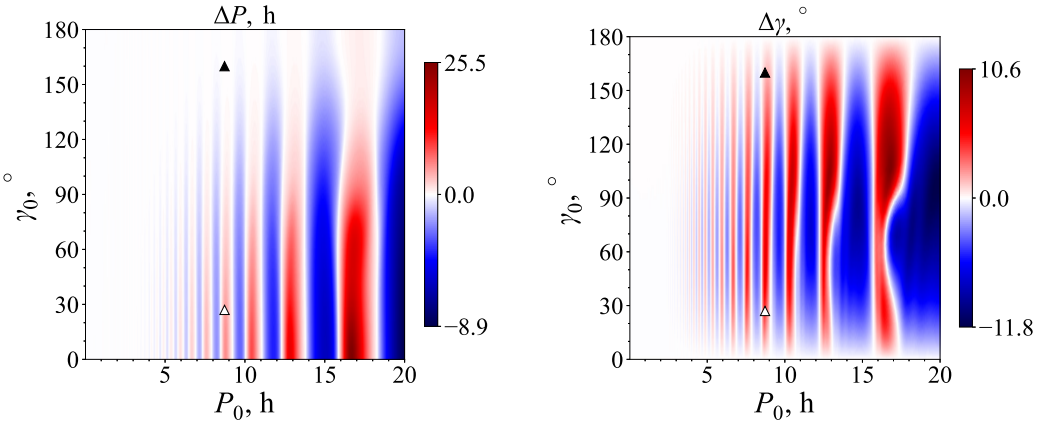
2 Problem statement and method

Using numerical experiments to model a close ($< 10R_{\rm E}$) approach to the Earth, the influence of the rotational speed and orientation of the asteroid's rotational axis on the magnitude of perturbations in its rotational dynamics was studied. In accordance with the methodology presented in Lobanova & Melnikov (2024), the dynamics of three small asteroids was considered: (367943) Duende ($D \approx 30$ m, $P \approx 8$ h), 2012 TC4 ($D \sim 10$ m, $P \approx 12$ min) and 2023 BU ($D \sim 10$ m, $P \approx 2$ min). On the set of initial values (before approach) of the asteroid's rotational period P_0 and the angle between the rotational axis and the normal to the orbital plane γ_0, the values $\Delta P = P_{\rm final} - P_0$ and $\Delta\gamma = \gamma_{\rm final} - \gamma_0$ were determined, where $P_{\rm final}$ and $\gamma_{\rm final}$ represent the values acquired after approach to the Earth.

3 Perturbations in asteroid rotation

Figure 1 shows diagrams of $\Delta P(P_0, \gamma_0)$ and $\Delta\gamma(P_0, \gamma_0)$, constructed for the approach of Duende to the Earth in 2013. The diagrams show the position of Duende for two models (Benson et al. 2020) of its rotation after approach ($P_0 = 8.7$ h; $\gamma_0 = 27°, 160°$). From Fig. 1 it follows that for the first model ($P_0 = 8.7$ h, $\gamma_0 = 27°$) we have: $\Delta P \approx 4$ h, $\Delta\gamma \approx 4°$, for the second model the perturbations are somewhat smaller.

[3] https://cneos.jpl.nasa.gov/stats/size.html



a) b)

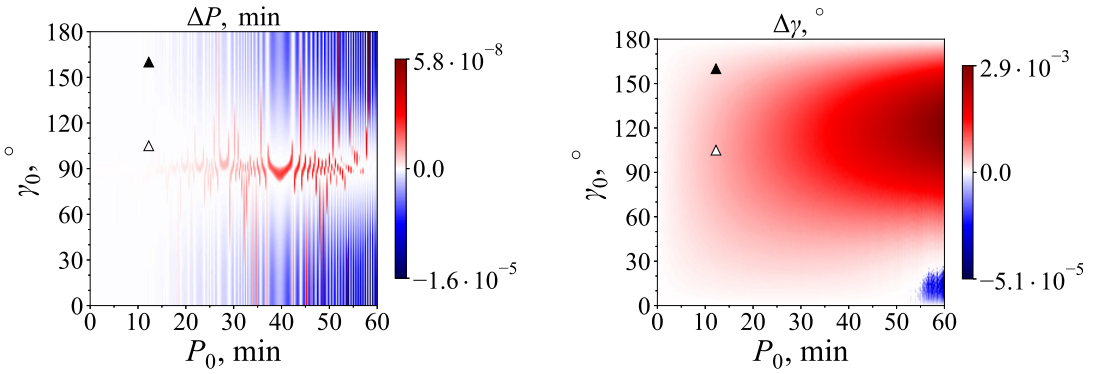
Fig. 1. a) Dependence of the change in the rotational period ΔP of the asteroid Duende due to its approach to the Earth in 2013 on the possible initial (before the moment of approach) values of P_0 and γ_0. b) Dependence of the change $\Delta\gamma$ in angle characterizing the deviation of the rotation axis of the asteroid Duende from the normal to the orbital plane on P_0 and γ_0. Accepted orbital and inertial parameters of the asteroid Duende: $e = 4.22$, $d = 5.34R_{\rm E}$, $A/C = 0.25$, $B/C = 0.85$. Triangles indicate possible positions of the asteroid (according to Benson et al. (2020)).

Taking into account the results of our earlier (Lobanova & Melnikov 2024) modeling of the rotational dynamics of the asteroid Apophis ($D \approx 340$ m, $P \approx 30$ h) during its approach to the Earth in 2029, we can assume that asteroids with relatively slow rotation ($P > 5$ h) are characterized by significant perturbations in rotation. For example, in the cases of Apophis and Duende, when approaching the Earth, the values of $|\Delta P|$ are from a few to tens of hours, and the value of $|\Delta\gamma|$ reaches tens of degrees.

Figure 2 shows diagrams constructed for the approach of asteroid 2012 TC4 to the Earth in 2017. Analysis of the diagrams showed that perturbations for small asteroids with very fast rotation ($P < 1$ h) should be negligible: in the case of 2012 TC4 $|\Delta P| < 10^{-5}$ min, $|\Delta\gamma| < 0.01°$. For the asteroid 2023 BU, the identified magnitude of possible perturbations was even smaller.

4 Influence of perturbations on the Yarkovsky effect

In the orbital dynamics of small asteroids, a significant role is played by the Yarkovsky effect (YE) (Vokrouhlický et al. 2000), leading to a secular change in the semimajor axis of the asteroid's orbit. We studied the influence of perturbations in the rotation



a) b)

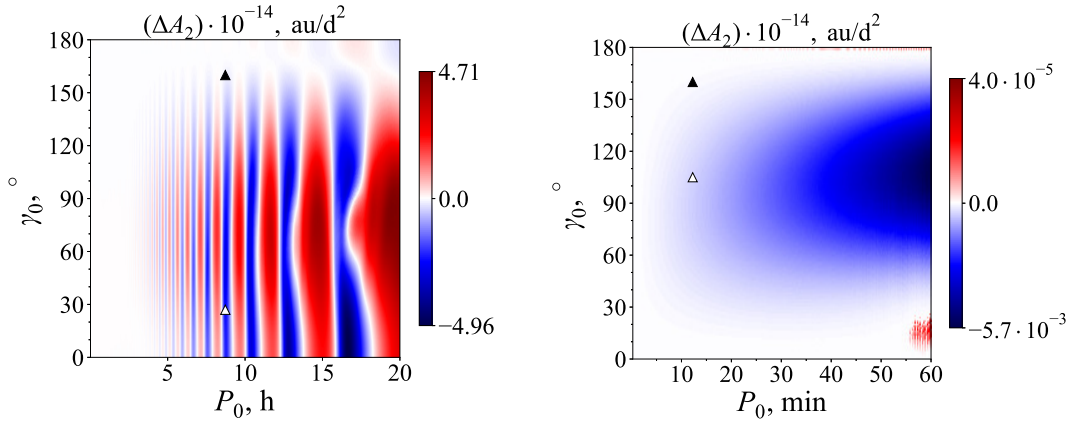
Fig. 2. a) Dependence of the change in the rotational period ΔP of the asteroid 2012 TC4 due to its approach to the Earth in 2017 on the possible initial (before the moment of approach) values of P_0 and γ_0. b) Dependence of the change $\Delta\gamma$ in angle characterizing the deviation of the rotation axis of the asteroid 2012 TC4 from the normal to the orbital plane on P_0 and γ_0. Accepted orbital and inertial parameters of the asteroid 2012 TC4: $e = 6.36$, $d = 7.86 R_{\rm E}$, $A/C = 0.42$, $B/C = 0.81$. Triangles indicate possible positions of the asteroid (according to Lee et al. (2021)).

of asteroids due to close encounters with the Earth on the value of the parameter A_2 (Marsden et al. 1973), which characterizes the YE. Based on the obtained estimates of ΔP and $\Delta\gamma$ for all studied asteroids, the values of the YE before ($A_2^{\rm before}$) and after ($A_2^{\rm after}$) approaching the Earth were calculated.

Figure 3 for asteroids Duende and 2012 TC4 shows $\Delta A_2(P_0, \gamma_0)$ diagrams, where $\Delta A_2 = A_2^{\rm after} - A_2^{\rm before}$. It can be seen that in the case of Duende, for the adopted rotational parameters (Benson et al. 2020) there is a slight change in ΔA_2. In the case of Apophis, an almost 30% change in A_2 is possible (see Lobanova & Melnikov (2024) for more details). Close encounters with the Earth can noticeably change the magnitude of the YE in the case of small asteroids with relatively slow rotation. For asteroids with fast rotation (such as 2012 TC4 and 2023 BU), perturbations that occur in the rotational dynamics due to close encounters with the Earth have no noticeable effect on their A_2 values.

5 Summary

In this work, through numerical experiments, the perturbations arising in the rotational dynamics of small asteroids during their close approaches to the Earth were studied. It was shown that:



a) b)

Fig. 3. a) Dependence of the parameter ΔA_2, which characterizes the change in the magnitude of the YE, on the possible initial (before the moment of approach) values of P_0 and γ_0 for Duende during its approach to the Earth in 2013. b) The same for asteroid 2012 TC4 during its approach to the Earth in 2017. The triangles indicate possible positions of asteroids (according to Benson et al. (2020); Lee et al. (2021)).

1. For asteroids with very fast rotation ($P < 1$ h), perturbations in the rotational speed (the value of the period P) and the orientation of the rotational axis (the angle γ which characterizes the orientation of the rotational axis relative to the normal to the orbital plane) are very small. The perturbations do not affect further dynamics of the asteroid.
2. For small asteroids with relatively slow rotation ($P > 5$ h), perturbations in the rotational speed and orientation of the rotational axis can be significant: changes in P reach several to tens of hours, and changes in γ reach tens of degrees. Such perturbations must be taken into account when studying further asteroid dynamics.
3. Perturbations in rotation (in P and γ) arising due to the approach to the Earth will affect the magnitude of the Yarkovsky effect for asteroids with slow rotation and will be unnoticeable in the case of asteroids with very fast rotation.

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