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The influence of uncertainty in the shape of an asteroid on the estimate of perturbation magnitudes in its rotational dynamics when approaching the Earth

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Abstract. The shape of the vast majority of small asteroids is unknown. There are only estimates of the average diameter obtained for them on the basis of absolute magnitude and albedo under a number of assumptions. To estimate the magnitude of perturbations in the rotational dynamics of an asteroid that arise when approaching the Earth by means of numerical modeling, it is necessary to know its moments of inertia, determined, among other things, by the shape of the asteroid. By conducting massive numerical experiments to simulate a close approach of an asteroid to the Earth, the influence of the figure's parameters on the magnitude of perturbations in the rotational dynamics of the asteroid was studied. It has been established that with very fast rotation (period $P < 1$ hour), even significant errors in knowledge of the asteroid's figure do not have a significant effect on the estimate of the magnitude of the perturbations. On the contrary, with a relatively slow rotation of the asteroid ($P > 5$ hours), inaccurate specification of the parameters of the asteroid's figure can lead to a significant underestimation of the perturbation values in numerical experiments. For example, for the asteroid Apophis ($P = 30.6$ hours), the error in the estimation of the rotational period after its close approach to the Earth in 2029 can be several hours, and the uncertainty in knowledge of the orientation of the rotational axis can be tens of degrees.

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

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1 Introduction

The rotational and orbital dynamics of the asteroid are closely interrelated. Planetary encounters that take place in the orbital dynamics of asteroids affect their rotational dynamics (Scheeres et al. 2000). In turn, through the Yarkovsky effect, rotation affects the orbital dynamics of the asteroid. An important task is the numerical modeling of the rotational dynamics of near-Earth asteroids. Perturbations that arise in the dynamics of an asteroid during approach can lead to a catastrophic collision in subsequent returns (Giorgini et al. 2008; Sokolov et al. 2012).

When numerically modeling the rotational dynamics of an asteroid during approach, its shape is usually approximated by a triaxial ellipsoid with semi-axes $a > b > c$ (see, for example, Pravec et al. 2014; Melnikov 2022). The moments of inertia of the asteroid ($A < B < C$), knowledge of which is necessary for modeling the gravitational interaction of the asteroid and the planet during approach, under the assumption of uniform density of the asteroid, are associated with the parameters of the figure:

$$\frac{c}{b} = \sqrt{\frac{A+B-C}{A-B+C}}, \quad \frac{b}{a} = \sqrt{\frac{A-B+C}{-A+B+C}}, \tag{1}$$

The figures of asteroids are usually known with large errors. For most asteroids, there are only estimates of diameter obtained from the absolute magnitude of the asteroid under certain simplifications. The purpose of this work was to study the influence of uncertainty in the knowledge of asteroid's figure (c/b, b/a) on the estimates of perturbations in its rotational dynamics obtained from numerical modeling of the asteroid's approach to the Earth.

2 Numerical experiments

According to the methodology described in (Lobanova & Melnikov 2024), numerical experiments were carried out to simulate asteroids approaching the Earth: (99942) Apophis (diameter $D \approx 340$ m, rotational period $P \approx 30$ hours), (367943) Duende ($D \approx 30$ m, $P \approx 8$ hours), 2012 TC4 ($D \approx 10$ m, $P \approx 12$ min) and 2023 BU ($D \sim 10$ m, $P \approx 2$ min). For all considered asteroids, $\Delta P(c/b, b/a)$ and $\Delta\gamma(c/b, b/a)$ diagrams were constructed and analyzed. The values of ΔP and $\Delta\gamma$ characterize the magnitude of perturbations in the rotational dynamics of the asteroid arising due to its approach to the Earth (for more details, see Melnikov 2022), namely: ΔP corresponds to the change in the rotational period of the asteroid, $\Delta\gamma$ corresponds

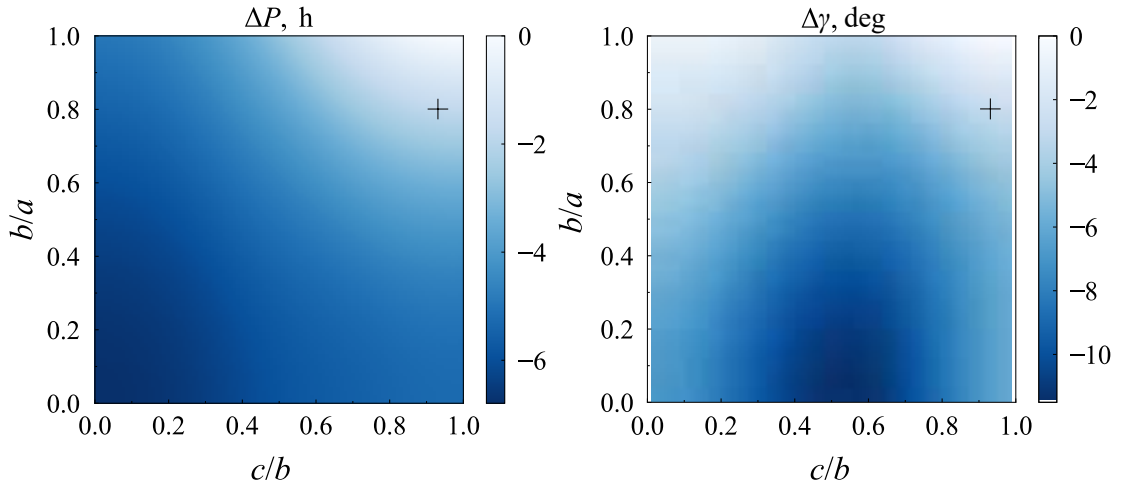

Fig. 1. Dependences of ΔP change in rotational period and $\Delta\gamma$ change in angle characterizing the deviation of the rotational axis from the normal to the orbital plane for the asteroid Apophis ($e = 4.26$, $d = 5.96\,R_E$, $P_0 = 30.6$ hours, $\gamma_0 = 140°$) due to its approach to the Earth in 2029 from the parameters c/b and b/a, characterizing the figure of the asteroid. The cross indicates the possible position of the asteroid (see Pravec et al. 2014).

to the change in the angle between the asteroid's rotational axis and the normal to the plane of its orbit.

Figures 1 and 2 show examples of diagrams for Apophis and 2012 TC4. The figures show the accepted initial (before approach) values of the period P_0 and the angle γ_0 between the axis of rotation of the asteroid and the normal to the orbital plane, and the parameters of the geocentric orbit (e, $d = a(e-1)$, where e is the eccentricity, a is the semi-major axis). It can be seen that in the case of Apophis, uncertainties in knowledge of the figure can lead to errors in the estimate of ΔP amounting to several hours; when estimating $\Delta\gamma$ the error can reach ten degrees. We made a similar conclusion from the analysis of diagrams for Duende. Fig. 2 shows that for 2012 TC4, the values of ΔP and $\Delta\gamma$ are extremely small. Therefore, uncertainties in knowledge of the 2012 TC4 figure do not affect estimates of the magnitude of perturbations that arise in the rotational dynamics due to its approach to the Earth. We obtained results similar to 2012 TC4 for the asteroid 2023 BU.

3 Summary

We studied the influence of knowledge of the parameters of the asteroid's figure on the estimates of the magnitude of perturbations that arise in the rotational dynamics

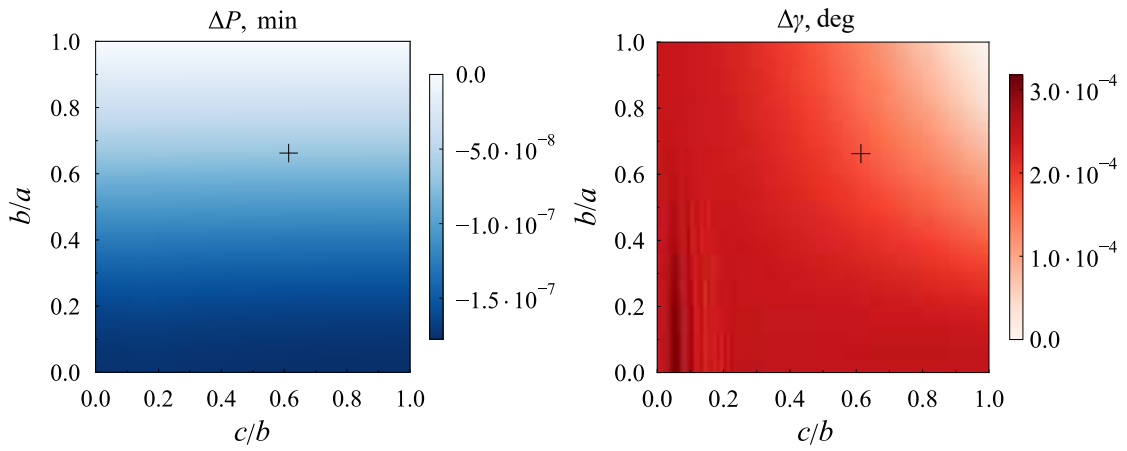

Fig. 2. The same for asteroid 2012 TC4 ($e = 6.36$, $d = 7.86\,R_E$, $P_0 = 12.25$ min, $\gamma_0 = 160°$) during its approach to the Earth in 2017. The cross indicates the possible position of the asteroid (see Lee et al. 2021).

when it approaching the Earth. It is shown, that for the asteroids Apophis and Duende with relatively slow rotation ($P > 5$ hours), errors in the determination of the parameters of the figure can lead to noticeable inaccuracies in the estimation of magnitude of perturbations: for changes in P they reach from a few to tens of hours, and for changes in γ they reach tens of degrees. For asteroids 2012 TC4 and 2023 BU with very fast rotation ($P < 1$ hour), the uncertainty in knowledge of the figure does not affect the assessment of perturbations in its rotational dynamics. Note that the amplitude of perturbations itself is small in this case.

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