On estimating the magnitude of perturbations in the rotational dynamics of asteroids approaching the Earth

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Abstract. In numerical experiments, the rotational dynamics of asteroids as they approach the Earth is considered. It is shown that close encounters can lead to noticeable perturbations in the asteroid's rotational speed and the orientation of the rotational axis. The influence of uncertainty in knowing the figure of an asteroid on the assessment of the magnitude of perturbations in its rotation has been studied. Estimates of perturbations in the rotational dynamics of the asteroid (99942) Apophis during its approach to the Earth in 2029 were obtained.

Introduction

In terms of asteroid-comet hazard, it is of great importance to study different aspects of near-Earth asteroids (NEAs) dynamics. Investigation of the dynamics of small (diameter 10–100 m) NEAs is of special interest since they engage frequently in close encounters with our planet at a distance of about 10 Earth radii (R_{E}). The rotational and orbital dynamics of an asteroid are closely interrelated and influence one another [1, 2]. In particular, perturbations in the rotation of an asteroid affect its orbital motion due to the changes in the value of the Yarkovsky effect [3, 4]. We have designed [4] numerical methods for modeling the rotational motion of an asteroid during its approach to the planet and investigated the dynamics of a number of small asteroids during their close encounters with the Earth. We present the main results of our numerical experiments with the following example of asteroid (99942) Apophis whose rotational dynamics during 2029 approach to the Earth was studied. By means of numerical experiments, the estimates of the change in the rotational period $\Delta P = P_{\mathrm{final}} - P_0$ and the angle between the rotational axis and the normal to the orbital plane $\Delta\gamma = \gamma_{\mathrm{final}} - \gamma_0$ were acquired, where P_0 and γ_0 are the values before the approach.

1. Influence of the orbit

An important issue is defining the size of an area of the space around the planet where disturbances in the rotational dynamics of an asteroid are significant. Figure 1 shows dependences of the magnitudes of perturbations in the rotation of Apophis on the parameters of its geocentric orbit (d, e), where $d = a(e-1)$ is the pericentric distance, a the semimajor axis and e the eccentricity. It can be seen that significant perturbations occur within $d \leq 10R_{\rm E}$, where $R_{\rm E}$ is the Earth radius. We made a similar conclusion from the analysis of the dynamics of other small NEAs ((367943) Duende, 2012 TC4, 2023 BU).

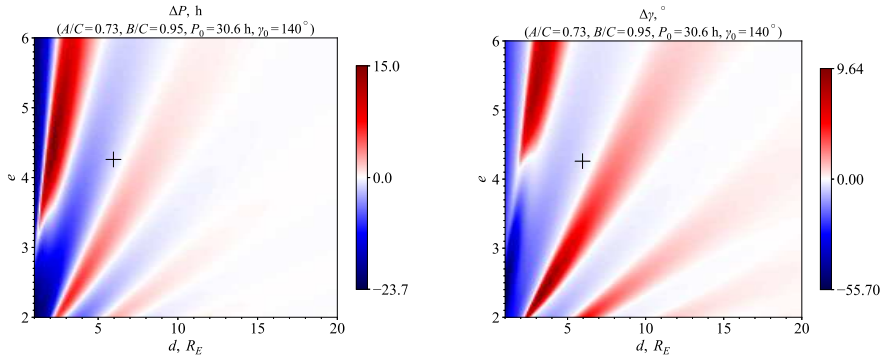

FIGURE 1. Dependences of ΔP and $\Delta\gamma$ for Apophis due to its approach to the Earth in 2029 on the orbital parameters $d = a(e-1)$ (within Earth's radii) and e. The cross indicates current position of Apophis [5]

2. Influence of the initial rotational state

The estimates of perturbations in the rotational dynamics of asteroids during approaches to the Earth have shown that for the asteroids with relatively slow rotation ($P > 5$ h) perturbations may be large. Figure 2 demonstrates the perturbations in the rotation of Apophis during its approach to the Earth in 2029. It can be seen that the rotational period may change by tens of hours, and variations in the orientation of the rotational axis may reach ten degrees. In case of the asteroids with extremely fast rotation ($P < 1$ h), which includes, for example, asteroids 2012 TC4 and 2023 BU, the perturbations in the rotational motion during approach to the Earth are negligibly small.

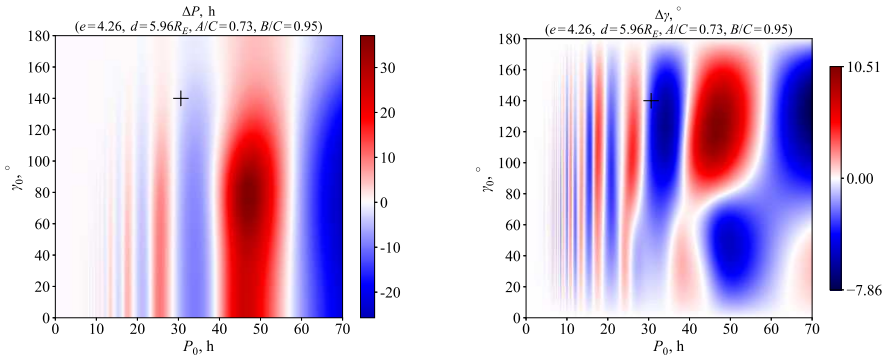

FIGURE 2. Dependences of ΔP and $\Delta\gamma$ for Apophis due to its approach to the Earth in 2029 on the possible initial (before the moment of approach) values of P_0 and γ_0. The cross indicates current position of Apophis [5]

3. Influence of the figure

The shape of small asteroids is usually unknown or poorly defined. We studied the influence of the asteroid's shape (which may be described through its moments of inertia $A < B < C$) on ΔP and $\Delta\gamma$. It follows from the example shown on Figure 3 that, in case of Apophis, the errors in determining the asteroid figure (which is approximated by a triaxial ellipsoid with the semi-axes $a > b > c$) may lead to significant underestimates of the values of perturbations. Similar results were obtained for other asteroids with slow rotation. In the case of asteroid with fast rotation, its shape has little influence on the estimates of the perturbation values.

Conclusion

Our numerical modeling of small asteroids approaching the Earth has shown that significant perturbations in the rotational dynamics of an asteroid take place only when it approaches the planet at a distance of less than 10 Earth radii. In case of asteroids with the rotational period $P > 5$ h encounters with the Earth may lead to noticeable changes in the rotational speed and the orientation of the rotational axis. In addition, precise knowledge of the asteroid figure is needed for the accurate estimation of the perturbation value. On the contrary, for the asteroids with fast rotation ($P < 1$ h) perturbations in the rotational motion are negligible, and the shape of an asteroid has little influence on their value.

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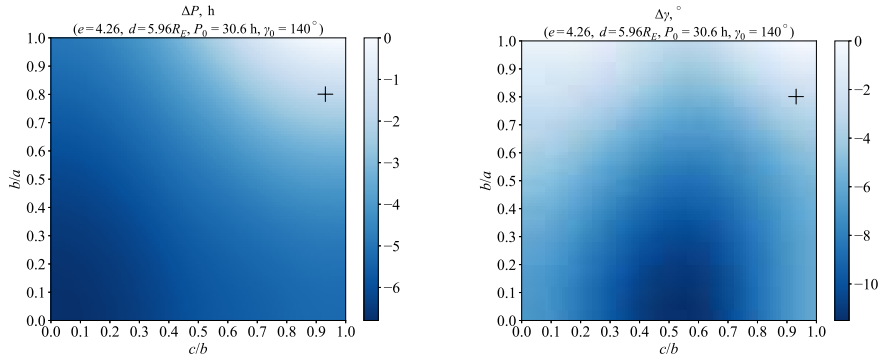

FIGURE 3. Dependences of ΔP and $\Delta\gamma$ for Apophis due to its approach to the Earth in 2029 on the parameters c/b and b/a, characterizing the figure of the asteroid. The cross indicates current position of Apophis [5]

References

[1] L.A.G. Boldrin, R.A.N. Araujo and O.C. Winter, *On the rotational motion of NEAs during close encounters with the Earth*, European Physical Journal Special Topics, v. 229, Issue 8, pp. 1391–1403, 2020.

[2] A.V. Melnikov, *Rotational dynamics of asteroids approaching planets*, Solar System Research, v. 56, Issue 4, pp. 241–251, 2022.

[3] A.A. Martyusheva and A.V. Melnikov, *Influence of planetary encounters on the magnitude of the Yarkovsky effect in asteroid dynamics*, Solar System Research, v. 57, Issue 5, pp. 486–494, 2023.

[4] K.S. Lobanova and A.V. Melnikov, *Disturbances in the rotational dynamics of asteroid (99942) Apophis at its approach to the Earth in 2029*, Solar System Research, v. 58, Issue 2, pp. 208–219, 2024.

[5] P. Pravec, P. Scheirich, J. Ďurech et al., *The tumbling spin state of (99942) Apophis*, Icarus, v. 233, pp. 48–60, 2014.

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