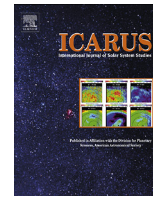
Icarus 252 (2015) 277–283

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus



The Yarkovsky effect for 99942 Apophis

David Vokrouhlický [a,*], Davide Farnocchia [b], David Čapek [c], Steven R. Chesley [b], Petr Pravec [c], Petr Scheirich [c], Thomas G. Müller [d]

[a] Institute of Astronomy, Charles University, V Holešovičkách 2, CZ-180 00 Prague 8, Czech Republic
[b] Jet Propulsion Laboratory/California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
[c] Astronomical Institute, Czech Academy of Sciences, Fričova 298, CZ-251 65 Ondřejov, Czech Republic
[d] Max-Planck-Institut für extraterestrische Physik, Giessenbachstrasse, Postfach 1312, D-85741 Garching, Germany

A R T I C L E   I N F O

Article history:
Received 24 October 2014
Revised 4 January 2015
Accepted 14 January 2015
Available online 31 January 2015

Keywords:
Celestial mechanics
Asteroids, dynamics
Asteroids, rotation

A B S T R A C T

We use the recently determined rotation state, shape, size and thermophysical model of Apophis to predict the strength of the Yarkovsky effect in its orbit. Apophis does not rotate about the shortest principal axis of the inertia tensor, rather its rotational angular momentum vector wobbles at an average angle of $\simeq 37^\circ$ from the body axis. Therefore, we pay special attention to the modeling of the Yarkovsky effect for a body in such a tumbling state, a feature that has not been described in detail so far. Our results confirm that the Yarkovsky effect is not significantly weakened by the tumbling state. The previously stated rule that the Yarkovsky effect for tumbling kilometer-size asteroids is well represented by a simple model assuming rotation about the shortest body axis in the direction of the rotational angular momentum and with rotation period close to the precession period is confirmed. Taking into account uncertainties of the model parameters, as well as the expected density distribution for Apophis' spectral class, we predict the secular change in the semimajor axis is $(-12.8 \pm 3.6) \times 10^{-4}$ au/Myr (formal 1σ uncertainty). The currently available astrometric data for Apophis do not allow an unambiguous direct detection of the Yarkovsky effect. However, the fitted secular change in semimajor axis of $(-23 \pm 13) \times 10^{-4}$ au/Myr is compatible with the model prediction. We revise the Apophis' impact probability information in the second half of this century by extending the orbital uncertainty derived from the current astrometric data and by taking into account the uncertainty in the dynamical model due to the thermal recoil accelerations. This is done by mapping the combined uncertainty to the close encounter in 2029 and by determining the statistical weight of the known keyholes leading to resonant impact orbits. Whereas collision with the Earth before 2060 is ruled out, impacts are still possible from 2060 with probabilities up to a few parts in a million. More definitive analysis will be available after the Apophis apparition in 2020–2021.

1. Introduction

There are few orbits among near-Earth asteroids that would be more remarkable than that of 99942 Apophis as far as efforts of their future propagation are concerned. The interest in Apophis is naturally powered by the impact threat of this asteroid in the second half of this century. The study of Apophis' hazard has already benefited from significant observational efforts, including dedicated radar and optical astrometry observations and efforts in understanding possible biases or local systematic errors in optical astrometry. The most important aspect of the Apophis orbit is an extraordinarily close approach to the Earth in April 2029 that will have a hugely amplifying effect on the orbital uncertainty. As a result, predicting Apophis' future orbit requires forefront techniques in modeling even very tiny perturbations in order to ascertain the circumstances of the 2029 encounter. Thus the Apophis case shares the same strict accuracy requirements on the dynamical model as other asteroids with known possibility of far-future impacts, e.g., (29075) 1950 DA (Giorgini et al., 2002; Farnocchia and Chesley, 2014), (101955) Bennu (Milani et al., 2009; Chesley et al., 2014) and (410777) 2009 FD (Spoto et al., 2014). And yet for Apophis the impact hazard lies decades rather than centuries in the future, and so the need to solve the problem soon is higher.

While the "standard artillery" of gravitational perturbations, including the relativistic effects and perturbations from massive asteroids, is being used in these highly-demanding cases, it has been also recognized that the main factor of uncertainty in the dynamical model arises from our inability to accurately model the non-gravitational effects. Of these, the Yarkovsky effect (e.g.,

* Corresponding author.
E-mail address: vokrouhl@cesnet.cz (D. Vokrouhlický).

http://dx.doi.org/10.1016/j.icarus.2015.01.011
0019-1035/

Bottke et al., 2006; Vokrouhlický et al., in press) plays the most important role. Chesley (2006) provides a very good introductory analysis of the Yarkovsky effect for Apophis, while more recent works of Giorgini et al. (2008), Chesley et al. (2009, 2010), and Farnocchia et al. (2013b) basically profit from longer astrometry databases, their better treatment or a more complete statistical analysis of the unknown parameters needed to estimate the strength of the Yarkovsky effect. Fundamental improvement in modeling the thermal accelerations is possible only after these parameters, such as the spin state, size, bulk density and surface thermal inertia, become well constrained.

Luckily, recent results from Pravec et al. (2014) and Müller et al. (2014) provide new physical constraints on Apophis, and the goal of this work is to use the new information for refinement of Apophis' orbit prediction, including revision of its future impact hazard. However, the solution is not as straightforward as it might look. This is because Pravec et al. (2014) found that Apophis does not rotate in the energetically lowest mode about the principal axis of inertia, but rather exhibits moderate tumbling. Since virtually all previous studies of the Yarkovsky effect assumed rotation about the principal body axis, we first need to describe in some detail how we deal with it in our approach[1] (Section 2). Next, we review the currently available astrometric observations of Apophis, both radar and optical, and apply up-to-date bias corrections to them. The dynamical model, completed by the thermal recoil accelerations, is then used for Apophis' orbit determination. This allows us to propagate its uncertainty to 2029, when Apophis encounters the Earth, and finally revise the impact threat in the second half of this century (Section 3).

2. Modeling the Yarkovsky effect for Apophis

The degenerate case of principal-axis rotation of an asteroid is characterized by a single (sidereal) rotation period in the inertial space. The general case of non-principal-axis rotation of an asymmetric body makes the description more complicated by involving two fundamental periods (e.g., Landau and Lifschitz, 1960). The first period, P_ψ, fully describes motion of the rotational angular momentum vector in the body fixed frame $\mathcal{B}$. Adopting the popular description of a transformation between the inertial space and $\mathcal{B}$ using a set of Euler angles (ϕ, θ, ψ) (see, e.g., Landau and Lifschitz, 1960; Kaasalainen, 2001), P_ψ sets the periodicity of the proper rotation angle ψ and the nutation angle θ. The second period, P_ϕ, describes the precession of $\mathcal{B}$ in the inertial space and it is needed to describe the Euler angle ϕ. Observationally, P_ψ and P_ϕ are the primary parameters set by the data analysis (e.g., Kaasalainen, 2001; Pravec et al., 2005). In a physical description of the rotation, they are however derived quantities depending on (i) the initial conditions, and (ii) parameters $I_a = A/C$ and $I_b = B/C$, where (A, B, C) are the principal moments of inertia. The fundamental periods P_ψ and P_ϕ could be obtained either by analytical formulas (e.g., Landau and Lifschitz, 1960, or Appendix B in Breiter et al., 2011, who use Andoyer canonical variables rather than Euler angles and their associated momenta). An alternative possibility is to use direct numerical integration of Euler kinematic equations (e.g., Landau and Lifschitz, 1960, or Appendix in Kaasalainen, 2001).

Apart from rotation, the asteroid undergoes also a translational motion in the inertial space. This is obviously its heliocentric motion, which is at the zero approximation (i.e., unperturbed orbit) characterized by the orbital period P_{orb}. This brings a third independent fundamental period to the problem. The rotation-related periods P_ψ and P_ϕ would set up what is known as the diurnal component of the Yarkovsky effect, while the translation-related period P_{orb} would yield the corresponding seasonal component. However, since we derive a fully numerical solution of the Yarkovsky effect here, we do not need to adopt any particular split of the complete effect (which would be anyway difficult, especially when P_ψ is not significantly smaller than P_{orb} as in the Apophis case).

Before we proceed with some details of our solution, we note that the method used to solve the heat diffusion problem requires that the solution be periodic in time. Strictly speaking, this occurs only when P_{orb} is an integer multiple of both P_ψ and P_ϕ. Despite the fact that this may not be exactly satisfied, we can adopt the following approximate scheme enforcing the above mentioned periodicity[2]:

(i) we slightly change some of the parameters determining P_ψ and P_ϕ such that their ratio is a rational number;
(ii) we slightly change the semimajor axis of the heliocentric orbit such that both P_{orb}/P_ψ and P_{orb}/P_ϕ are integer numbers.

A few comments are in order. The first step (i) is performed by a small redefinition of the I_a parameter within its uncertainty interval (for Apophis we use $|\delta I_a/I_a| \leqslant 0.5\%$, while the formal uncertainty of this quantity, as derived from observations, is $\simeq 10\%$; e.g., Pravec et al., 2014). There are obviously several solutions, so we choose those which then help to satisfy the second step (ii) with a minimum change of the orbital semimajor axis. Again for Apophis we use $|\delta a/a| \leqslant 1\%$. This is obviously more than the actual formal uncertainty in the semimajor axis determination. Henceforth, in a particular solution we redefine the solar constant, i.e., the solar radiation flux at a normalized heliocentric distance, such that the mean radiation flux over the true Apophis orbit is the same as the mean radiation flux over the "faked orbit" with a slightly redefined semimajor axis value. In order to justify our approach, we also compare at least two different variants of the solution (with two different rational values of P_ϕ/P_ψ). As expected, it turns out that the resulting mean semimajor axis change $\langle da/dt \rangle$, the most important effect in terms of orbit determination (e.g., Vokrouhlický et al., 2000), is insensitive to these details (see below).

Having discussed the issue of rotation modeling in some detail, we can now describe other components of our approach in a briefer way because they are rather standard (see, e.g., Čapek and Vokrouhlický (2005) or Čapek (2006) for more details). The asteroid shape is represented using a general polyhedron model with a typical number of surface facets ranging from hundreds to thousands. In the case of Apophis, the available model by Pravec et al. (2014) has 2024 surface facets. We consider the thermal history of each of the facets independently, not allowing a thermal communication between them by either conduction (e.g., Golubov and Krugly, 2012) or mutual thermal irradiation (e.g., Rozitis and Green, 2012, 2013). The space coordinate in the heat diffusion problem is simply vertical depth z below the facet, such that the space–time domain of the solution is in principle $(0, \infty) \times (0, P_{orb})$. In reality though, we set an upper limit Z on the depth, such that the true domain of

[1] In passing, we note that our method is similar, but refines the one we used in the case of (4179) Toutatis (e.g., Čapek and Vokrouhlický, 2005; Vokrouhlický et al., 2005). At that time the need to compute thermal accelerations for tumbling objects was rather an academic exercise without having significant practical importance. With Apophis, and possibly other similar cases in the future, we believe this situation has changed.

[2] Note that we implicitly use the same trick also in the case of the Yarkovsky solution for asteroids rotating in the principal-axis mode by modifying the rotation period P_{rot} such that the ratio P_{orb}/P_{rot} is integer. In this case, one can keep the orbit fixed and only slightly change the rotation period P_{rot} to satisfy the periodicity condition. Given typically short rotation periods of asteroids this usually involves a change in P_{rot} smaller than one per mille of its value, an insignificant change often within its uncertainty interval.