YARKOVSKY EFFECT FOR TUMBLERS AND NON-CONVEX SHAPES: ASTEROID (99942) APOPHIS AS A TEST CASE. O. Golubov[1,2], A. V. Kopatko[1], A. Strelchenko[1], I. Kyrylenko[2], V. Unukovych[1], and Yu. N. Krugly[2], [1]V. N. Karazin Kharkiv National University, 4 Svobody Sq., Kharkiv, 61022, Ukraine, e-mail: oleksiy.golubov@karazin.ua, [2]Institute of Astronomy, Karazin National University, 35 Sumska Str., Kharkiv, 61022, Ukraine.

Introduction: Accounting for the Yarkovsky effect is crucial for precise determination of the trajectory of the hazardous asteroid (99942) Apophis and evaluation of its collision probability.

Presently, both the observed and computed values of its Yarkovsky force are very uncertain [1]. Still, we can expect that our knowledge of the asteroid orbit and its physical parameters will increase a lot after its Earth passages of 2021 and especially 2029. When these data become available, Apophis can serve as a good test case to assess the reliability of Yarkovsky effect theories in comparison with observations. Before this happens, it is worth getting prepared by advancing the existing theories in the directions that can potentially be important for precise simulation of Apophis.

Here we discuss such generalizations by investigating the effect of tumbling and non-convexity on the Yarkovsky effect. Tumbling of Apophis is an asserted fact [2], its non-convexity, although not yet measured in sufficient detail, is also inevitable. In the end, we perform orbit integration using different approaches to the Yarkovsky force computation, and find how much the collision probability is influenced by the studied effects.

The Yarkovsky effect for tumbling bodies: Apophis experiences tumbling motion [2], thus an extended theory and simulations are required for its Yarkovsky effect. Such simulations were conducted by [1], with the conclusion that tumbling does not strongly influence the Yarkovsky effect. Nevertheless, the question still remains whether this conclusion holds for different thermal inertias, asteroid shapes, and tumbling regimes.

To get a wider understanding of the effect that tumbling has on the motion of the asteroid, we use the methods by [3], but account for asteroid tumbling. In contrast to [1], this approach performs time averaging of the Yarkovsky effect prior to performing the surface integration over the asteroid. This allows us to understand how the relative contribution to the Yarkovsky effect from different parts of the asteroid changes as a result of tumbling. On the other hand, the applicability of this approach is limited to convex shapes, as for non-convex shapes the surface integral needs to always come first. This is not critical at the moment, as the best shape of Apophis obtained by light curve inversion techniques is convex anyway [4].

We apply the created code to conduct a parametric study of the Yarkovsky effect for tumblers. We investigate the parameter space, numerically compute the Yarkovsky effect in different cases, and construct analytic fits to the numeric results.

When more data on Apophis become available, they will allow us to test the presented theory at one single point, and thus to check our general understanding of the Yarkovsky effect on tumblers. Thus the tumbling of Apophis is not an obstacle but an opportunity to better understand the Yarkovsky effect.

The Yarkovsky effect for non-convex shapes: There is one more interesting extension to the Yarkovsky effect not discussed in the literature produced by self-shadowing of the surface even without thermal inertia.

Our toy model consists of the Rubincam propeller, which has no thermal inertia and thus instantly re-emits all the incident light (Figure 1) and creates a Yarkovsky force (Figure 2). In the evening, the wedges of the propeller absorb and re-emit light by their meridional sides (blue lines in Figure 2), and experience the recoil force acting in the equatorial plane. In the morning, they absorb and re-emit light by their tilted sides (yellow rectangles in Figure 2), and the tilt imposes a projection factor to the recoil force. Therefore, the force pushing the asteroid along its orbit in the morning is weaker than the force pushing it against its orbit in the evening, giving rise to a Yarkovsky effect.

Non-convexity is required for this effect to arise, but we do not have any information about the non-convexities of Apophis, thus we simulate the non-thermal Yarkovsky using radar shape models of other asteroids. We create a ray tracing computer program for these simulations. A non-convex shape model of tumbling asteroid (4179) Toutatis presents a particularly interesting application for the program, as it allows direct comparison of the effects of non-convexity and tumbling.

This non-thermal component of the Yarkovsky effect could operate even when the thermal Yarkovsky effect vanishes, e.g. for very slow or very fast rotators.

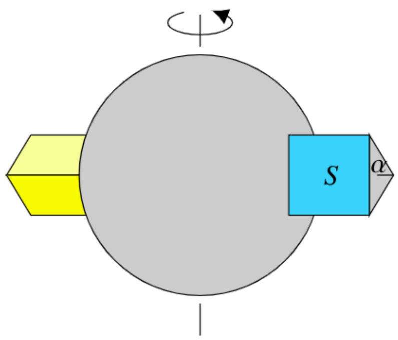

Fig. 1. Detailed view of the Rubincam propeller, used as an element in Figure 2..

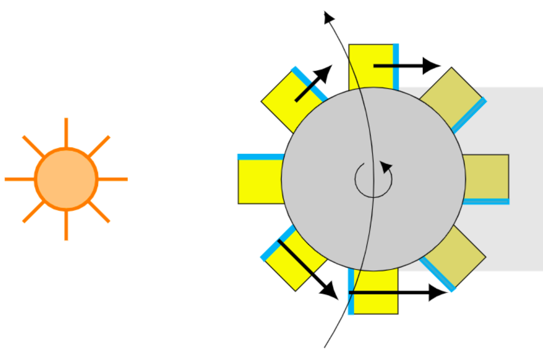

Fig. 2. Illustration of the Yarkovsky effect experienced by the Rubincam propeller. After averaging the force over the asteroid's rotation period, a net Yarkovsky force remains, which pushes the asteroid against its orbit.

Influence of the Yarkovsky effect on the collision probability: In the last part of our study, we perform numerical simulations of the orbit of Apophis to assess the influence of the Yarkovsky model on the collision probability.

We do this using a REBOUND software package that can model the motion of the asteroid, and takes into account the gravitational perturbations from other planets and major asteroids, as well as non-gravitational effects. Among all the integrators available within this package, we use IAS15 and MERCURIUS integrators which are designed for solving systems with close encounters.

We create an extension to REBOUND for computation of the keyholes in the *b*-plane, and use it to calculate the probability of the encounters with Apophis in different epochs. We study how the geometric structure of the keyholes and the values of the encounter probabilities change depending on the assumed model for the Yarkovsky effect. In particular, we evaluate the importance of the two discussed adjustments of the Yarkovsky effect, namely the tumbling and the non-convexity. The obtained results are compared with the previous analysis by [1] and [6].

Conclusion: At present, the available theory and observations of Apophis have already been exploited to the maximum possible extent. We expect much new data to come in the next decade, and we must get equipped with better theories for processing this data. We think that right now is the best time to develop new methods and study new concepts so when the 2019 data on Apophis appears we will be ready to utilize it in the most efficient ways.

Here we propose new numeric models for the Yarkovsky effect on tumblers and non-convex bodies, and apply them to asteroids (99942) Apophis and (4179) Toutatis.

References: [1] Vokrouhlicky D. et al. (2015) Icarus, 252, 277–283, [2] P. Pravec et al. (2014) Icarus, 233, 48-60, [3] Golubov O. et. al. (2016) MNRAS 3977-3989, [4] DAMIT, https://astro.troja.mff.cuni.cz/projects/damit/ [5] REBOUND, https://rebound.readthedocs.io/ [6] Farnocchia D. et al. (2013) Icarus, 224, 192–200.