ORBITAL EVOLUTION OF (99942) APOPHIS DUE TO THE YARKOVSKY EFFECT.

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Introduction: The orbital evolution of Apophis is strongly affected by the Yarkovsky effect, which is a non-gravitational perturbation to the asteroid's trajectory caused by sunlight. We analyzed optical and radar astrometry of Apophis and measured the Yarkovsky drift rate. We place our results in the context of the largest set of Yarkovsky detections ever published [1] and compare Apophis to hundreds of other near-Earth asteroids.

Theory: The orbit-averaged Yarkovsky drift rate is

$$\langle \frac{da}{dt} \rangle = \pm\xi \frac{3}{4\pi}\frac{1}{\sqrt{a}}\frac{1}{(1-e^2)}\frac{L_\odot}{c\sqrt{GM_\odot}}\frac{1}{D\rho}$$

where a is semi-major axis, e eccentricity, c is the speed of light, G is the gravitational constant, $L_\odot$ and $M_\odot$ are the luminosity and mass of the Sun, D and ρ are the diameter and density of the asteroid, and ξ is the Yarkovsky efficiency [1]. The Yarkovsky efficiency is a fundamental quantity that describes the efficiency with which solar energy is converted into orbital energy. Any incorrect assumption about diameter, density, obliquity, albedo, and phase lag is absorbed in the Yarkovsky efficiency factor such that the orbit-averaged <da/dt> value, which is dictated by the astrometry, is not affected by these assumptions.

Astrometry: The optical and radar astrometry available as of August 22, 2020 includes 4522 optical observations (9044 measurements) spanning 2004–2020, 17 radar range measurements obtained during the 2005 and 2013 apparitions, and 29 radar Doppler measurements. Eleven range measurements have uncertainties smaller than 40 m, corresponding to fractional uncertainties of ~2 parts per billion.

Methods: Our methods are described by Greenberg et al. [1,3]. Briefly, we use software developed at UCLA to interface with a state-of-the-art astrodynamics platform, MONTE [2]. We considered the eight known planets and 24 of the most massive minor planets as gravitational perturbers. During close approaches to Earth, the integrator considers a detailed model of the planetary gravitational field. We also account for general relativistic effects. Our Yarkovsky detection metric relies on a rigorous analysis of variance.

Astrometric Fit: Our fit to the astrometry identifies <1% of optical observations as outliers and yields a root mean square (rms) of normalized optical residuals of 0.445. The largest normalized range residual is 0.73 and the rms of normalized range and Doppler residuals are 0.340 and 0.377, respectively. The overall sum of squares of residuals is 892 with 9005 degrees of freedom, i.e., a reduced chi-square ~0.1, indicating that measurements uncertainties are slightly over-estimated.

Results: We measured a Yarkovsky drift rate of (–23.43 +/– 12.4) x 10^{-4} au/My. The reliability of the detection is quantified by a p-value of 2.5 x 10^{-9}. Apophis's Yarkovsky efficiency estimated with a diameter D=340 m [4] and a density ρ=3.4 g/cm^3 [5, upper range of likely values] is ξ = 0.18. If the density were 2.3 g/cm^3, the Yarkovsky efficiency would be similar to the median value ξ = 0.12 of a sample of 247 near-Earth asteroids (Fig. 1).

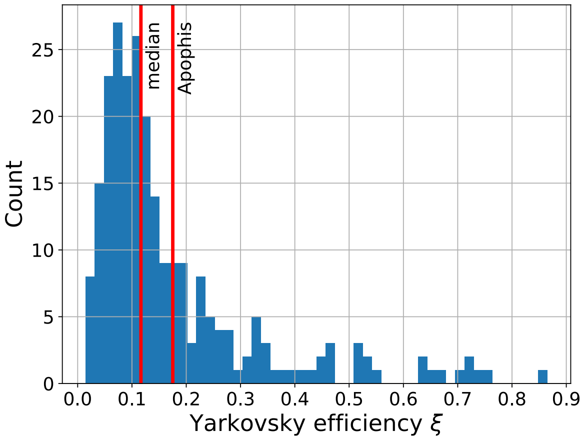

Figure 1: The distribution of Yarkovsky efficiencies ξ measured with a sample of 247 objects, adapted from [1]. The median efficiency, ξ = 0.12, and Apophis's efficiency, ξ = 0.18, are shown with red vertical lines.

Trajectory Predictions: With our Yarkovsky drift rate, we predict an Earth close approach (CA) time on April 13, 2029 of 21:46:07.03 UT. The CA time estimates change by +/– 1.43 s with the +/– 1 sigma range of Yarkovsky drift rate estimates, corresponding to approximately +/– 11 km along track. Trajectory predictions that neglect the Yarkovsky effect are off by +9.8 s or 72 km along track. The exact CA time in 2029 has a dramatic impact on the parameters of subsequent close approaches. The 2036 CA time is mispredicted by approximately one week when neglecting the Yarkovsky effect, and spans +/– 19 hours with the +/– 1 sigma range in the Yarkovsky drift rate. In comparison, the 2036 CA time is mispredicted by 8 minutes when neglecting the Earth's gravity field.

Importance of Radar Astrometry: Uncertainties on the Yarkovsky drift rate with optical-only solutions are about twice as large as those of the radar+optical solutions. The improvement factor due to radar observations is consistent with the approximate formula 2^{N-1}, where N is the number of apparitions with range astrometry [1].

References:

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