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APOPHIS' TUMBLING. P. Pravec[1], P. Scheirich[1], J. Pollock[2], P. Kušnirák[1], K. Hornoch[1], A. Galád[1], E. Jehin[3], J. Manfroid[3], C. Opitom[3], M. Gillon[3], J. Oey[4], J. Vraštil[1], D.E. Reichart[5], J.B. Haislip[5], K.M. Ivarsen[5], and A.P. LaCluyze[5]. [1]Astronomical Institute AS CR, Fričova 1, CZ-25165 Ondřejov, Czech Republic, [2]Physics and Astronomy Department, Appalachian State University, Boone, NC 28608, U.S.A., [3]Institut d'Astrophysique de l'Université de Liège, Allée du 6 Aout 17, B-4000 Liège, Belgium, [4]Leura Observatory, Leura, N.S.W., Australia, [5]Physics and Astronomy Department, UNC-Chapel Hill, Chapel Hill, NC 27599, U.S.A.

Introduction: The asteroid (99942) Apophis has been found to have a non-zero chance of impacting Earth on April 13, 2036 [1, 2]. The most significant uncertainty in the prediction is due to an unknown magnitude and sign of the Yarkovsky drift of the Apophis' orbit. The Yarkovsky drift depends on rotation state, angular momentum vector, and size of the asteroid. The favorable observing apparition of Apophis from December 2012 to April 2013 provided us a unique opportunity to take photometric observations to constrain the properties.

Observations: We observed Apophis photometrically from 2012 December 23 to 2013 April 15. The observations were taken with the 1.54-m Danish telescope on La Silla within our NEOSource project (data taken on 35 nights), the 0.41-m PROMPT 1 telescope on Cerro Tololo (30 nights), the 0.6-m TRAPPIST telescope on La Silla (4 nights), the 0.35-m telescope on Leura (3 nights), and the 0.65-m telescope in Ondřejov (1 linked night). The observations were performed and reduced using our standard techniques (see, e.g., [3]). The observations with the 1.54-m telescope were done in the Bessell R filter, supplemented with Johnson V band measurements, and calibrated in the Johnson-Cousins VR system using Landolt standards [4] with absolute accuracy around 0.01 mag. The PROMPT observations were done with Lum (IR block) filter and they were mutually linked in an instrumental magnitude system with an internal consistency of 0.02-0.03 mag. The TRAPPIST observations were done with the Exoplanet filter (blue cut at 450 nm) and calibrated in their Exo magnitude system. The Leura observations were done in Clear filter and calibrated in the Cousins R system using the asteroid's *(V-R)*. It was calibrated using solar colored comparison stars and *Rc* magnitude derived from 2MASS catalog with internal consistency of 0.02-0.03 mag [5]. The Ondřejov observations were done in the Bessell R filter. All the observations done and calibrated in the other filters/bands were converted to the Cousins R system using data overlapping with or close to the 1.54-m observations; an error of the conversion was estimated to be not greater than 0.03 mag for all the data subsets.

Results: Apophis is in a non-principal axis (NPA) rotation state. Our analysis of the data from the best covered interval 2013 January 7 to February 18, using the 2-period Fourier series method [6, 7], revealed that the main signal was in the 2nd and 1st harmonics of the main frequency f_1 = 1/30.56 h, and there was a comparatively lower signal (by factors 2-4) in the second apparent frequency of f_2 = 1/29.04 h and in the linear combinations of the two frequencies (2 f_1 - f_2) and (f_1 - 2 f_2). We have started physical modeling of the Apophis' spin state; if successful, we will resolve whether the second frequency of its NPA rotation is f_2 or some of the linear combinations of f_1 and f_2, and we will also estimate its angular momentum vector and ratios of the moments of inertia around the principal axes. Overall, the lightcurve (Fig. 1) resembles modeled lightcurves for a Short-Axis Mode (SAM) with the wobbling angle ß of about 20 to 25 degrees [8]; Apophis' spin state may be only moderately excited. The lightcurve amplitude was > 1.14 mag at solar phases 32-53 deg, revealing an elongated shape of Apophis. The amplitude was greater at higher solar phases (up to 78 deg) before and after the Jan7-Feb18 interval, likely due to the amplitude-phase effect that deepens lightcurve minima with shadowing effects of topography at the body's ends enhanced under oblique illumination.

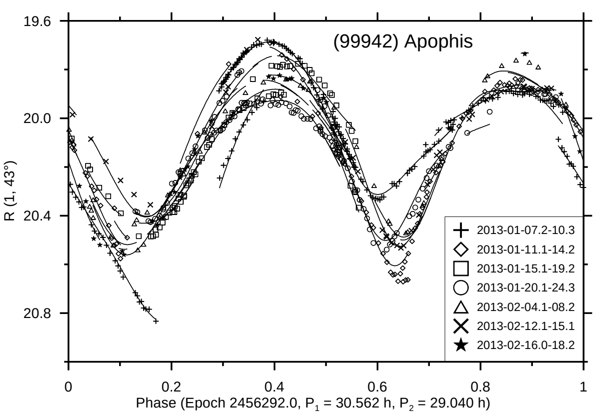

Fig. 1: Apophis lightcurve data from 2013 January 7 to February 18, folded with the main period. The curves are the 3rd order 2-period Fourier series fitted to the measurements.

The color index in the Johnson-Cousins VR system is $(V - R)$ = 0.453 ± 0.01, which is consistent with the SQ classification of Apophis. A slope of the phase relation has not been derived yet; assuming G = 0.24 ± 0.11 that is the range for SQ types [9], we estimate the Apophis' mean absolute magnitude H = 19.09 ± 0.19.

Assuming the geometric albedo p_V = 0.197 ± 0.051 for S type asteroids [10], we estimate the Apophis' mean effective diameter D = 0.46 ± 0.08 km.

The population of slow tumblers: It was no surprise to us when we found that Apophis is tumbling, given its position in the spin rate-diameter space. In Fig. 2, we plot Apophis together with more than a couple thousand asteroids with diameters 0.2 to 100 km and spin rates estimated with reliability code U >= 2 [9]. We highlighted there (in the range below the 45-Myr constant damping timescale line) asteroids that were reliably resolved as tumblers or non-tumblers from photometry. (We showed in [8] that the limiting wobbling angle ß for resolving a NPA rotation is ~15 deg.) Apophis lies in the range where tumblers predominate. Future studies will hopefully suggest whether the Apophis' rotation was excited by sub-catastrophic impacts [8], by an Earth's flyby [11], by the YORP effect [12], or by their combinations.

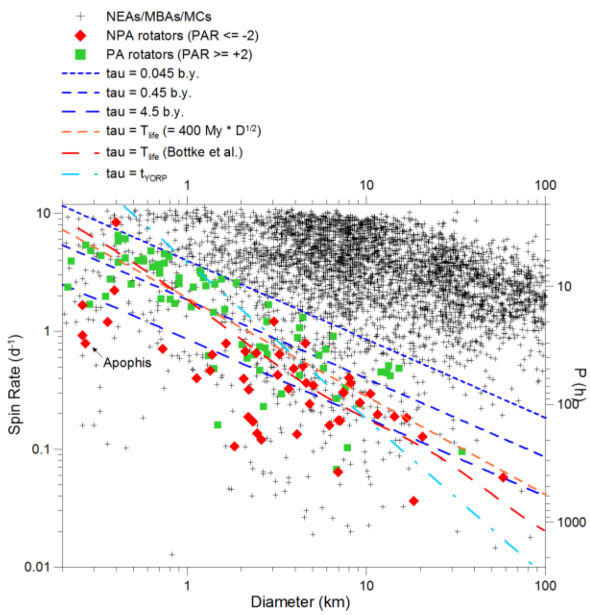

Fig. 2: Spin rate vs Diameter for asteroids with D = 0.2-100 km. Asteroids reliably resolved from photometric observations as tumblers or non-tumblers are highlighted with red diamonds and green squares, respectively.

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