APOPHIS TRAJECTORY, IMPACT HAZARD, AND SENSITIVITY TO SPACECRAFT CONTACT.

D. Farnocchia[1] and S. R. Chesley[1], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109, USA, Davide.Farnocchia@jpl.nasa.gov.

Introduction: Near-Earth asteroid (99942) Apophis was discovered on 2004 June 19 by Tucker, Tholen, and Bernardi at Kitt Peak, Arizona [1]. Telescope scheduling and poor observing conditions prevented additional observations on the following nights. Apophis was serendipitously re-observed in December 2004 by Gordon Garradd at Siding Spring Observatory [2], when it became clear that the asteroid would come extraordinarily close to Earth in April 2029. The possibility of an impact in 2029 was only ruled out in late December 2004, when precovery data from Spacewatch on March 2004 were reported [3].

Observational dataset: Apophis has been extensively tracked since discovery. The observational dataset includes ~8000 optical astrometric observations from 2004 to 2021 [4], 30 radar delay and 20 radar Doppler measurements from Arecibo and Goldstone in 2005, 2006, 2012, 2013, and 2021 [5,6,7], and even occultations in March and April 2021 [8].

Trajectory and impact hazard: The trajectory of Apophis is extremely well constrained until the 2029 encounter, when the asteroid will reach a geocentric distance of 38,012 ± 4 km at 2029-April-13 21:46 TDB. The average time interval between Earth encounters within this distance by asteroids with an absolute magnitude brighter than that of Apophis is 7500 years [9]. The close encounter will significantly perturb the orbit of Apophis, e.g., the semimajor axis will increase from 0.92 au to 1.10 au and, as a result, Apophis will transition from an Aten to an Apollo type asteroid. Besides changing the orbit itself, such a close approach invariably causes increased uncertainty for post-encounter trajectory predictions. As a consequence, until 2021 the post-2029 trajectory of Apophis remained challenging to predict and resonant returns [10] opened the possibility of later impacts, especially in 2036 and 2068 [11, 12, 13]. Thanks to data collected during the 2020-2021 apparition, the trajectory of Apophis is now deterministic until 2116 and any impact over the next century is ruled out [14].

Yarkovsky effect: Given the small orbital uncertainty and the scattering effect of the 2029 encounter, small perturbations can be significant. In particular, the Yarkovsky effect, a subtle nongravitational acceleration related to the anisotropic emission of thermal radiation that causes a semimajor axis drift [15], is a key consideration in modeling the trajectory of Apophis. Before the 2020-2021 apparition, the Yarkovsky effect could not be measured from the optical and radar astrometric dataset and was therefore constrained using a thermophysical model based on known physical properties of Apophis [13]. However, extending the data arc into 2021 yields a semimajor axis drift estimate of -199 ± 1 m/yr, which is the second highest signal-to-noise ratio Yarkovsky detection in the catalog after Bennu [16]. During the 2029 encounter Apophis is likely to experience changes in its rotation state [17] and, in turn, the Yarkovsky effect.

Spacecraft Perturbations: The 2029 Earth encounter of Apophis represents a great scientific opportunity to study a relatively large asteroid at an extraordinarily close distance to Earth. A possible mission to Apophis, e.g., [18, 19, 20], would call for interaction or even contact between spacecraft and the asteroid, thus slightly perturbing the motion of Apophis. Given the stiff dynamics driving the trajectory of Apophis and the presence of future planetary encounters, it is important to ensure that Apophis is not deflected onto an impact trajectory. In general, any contact taking place pre-perigee in 2029 would be greatly amplified by the 2029 encounter, while those taking place post-perigee would have a dramatically reduced effect on the trajectory. In this presentation, we will study the sensitivity on small perturbations during the 2029 encounter of the future trajectory of Apophis.

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References: [1] MPS 109613 (2004) [2] MPEC 2004-Y25 (2004). [3] MPEC 2004-Y70 (2004). [4] https://bit.ly/3I35eUJ [5] Giorgini et al. (2008) *Icarus, 193,* 1-19. [6] Brozović et al. (2018) *Icarus, 300*, 115–128. [7] https://go.nasa.gov/37nG0nf [8] https://bit.ly/3q3qN14 [9] Farnocchia and Chodas (2021) *RNAAS, 5,* 257. [10] Milani et al. (1999) *Astron. Astrophys. 346*, L65–L68. [11] Chesley (2006) *IAU Symp. 229,* 215-228. [12] Farnocchia et al. (2013) *Icarus, 224,* 192–200. [13] Vokrouhlický et al. (2015) *Icarus, 252,* 277–283. [14] https://go.nasa.gov/3686w3F [15] Vokrouhlický et al. (2015) *Asteroids IV*, 509. [16] Farnocchia et al. (2021) *Icarus, 369,* 114594. [17] Scheeres et al. (2005) *Icarus, 178,* 281-283. [18] Daly et al., LPI Contributions, 2242:2043 (2020) [19] Lauretta et al., LPI Contributions, 2242:2008 (2020) [20] Raymond et al., LPI Contributions, 2242:2048 (2020).