OBSERVING APOPHIS IN 2029: LESSONS FROM OTHER NEO FLY-BYS. N. A. Moskovitz[1], M. Devogèle[1], [1]Lowell Observatory, 1400 W. Mars Hill Road, Flagstaff, AZ 86004, USA, nmosko@lowell.edu.

Introduction: The near-Earth flyby of asteroid 99942 Apophis in April of 2021 will be an historic event due to the rarity of such a large body (D~300m) undergoing such a close encounter (altitude ~31,000 km or just under 5 Earth radii). However, encounters at such small separations are not rare. Since the discovery of Apophis in 2004, 21 near-Earth objects (NEOs) have experienced *closer* encounters with the Earth, albeit these were objects roughly two orders of magnitude smaller than Apophis. Nevertheless, such flybys provide important insight on the systems and formalisms needed to study these events, and into the physics of gravitational interactions between major and minor planets. We will discuss examples of recent NEO encounters and associated ground-based observational campaigns, lessons learned from these campaigns that are directly relevant to planning for Apophis, and an outline of infrastructure needs to maximize the scientific return from observations surrounding the Apophis flyby.

367943 Duende: In February of 2013 the 40-m x 20-m asteroid Duende experienced a near-Earth encounter at an altitude of 28,000 km. Lightcurve observations found that Duende is now in a non-principal axis rotation state with fundamental periods P_1 and P_2 equal to 8.7 and 23.7 hr respectively [1]. Available data and dynamical analyses suggest that Duende may have entered into this rotation state following an increase in its precessional rotation period (P_1) due to the planetary encounter [1,2]. This relatively slow tumbling state, a 2:1 axis ratio, and distance of the encounter are all good analogs to Apophis [3] and its encounter in 2029.

The primary limitation to assessment of Duende's possible change in rotation state was an incomplete and low quality data set prior to the planetary encounter. Similar challenges associated with Apophis (e.g. an outbound post-flyby trajectory at solar elongations <20°) will make it difficult to monitor the entirety of its flyby from ground-based facilities.

3200 Phaethon: The enigmatic asteroid-comet Phaethon seems to have experienced at least one recent fragmentation event [4] and displays short bursts of mass loss at perihelion [5], thus it is reasonable to suggest that Phaethon may have a complex, heterogeneous surface. In December of 2017 Phaethon approached the Earth at a distance of 0.07 AU (30x the Earth-Moon distance) and due to its large size (D~5 km) reached an apparent magnitude V~10, making it one of the brightest apparitions of any NEO over the past few decades. Multiple observational campaigns during this encounter focused on assessing the physical properties of this unusual object. Rotationally resolved spectroscopy indicated a spectrally uniform surface [6], while Doppler delay radar imaging revealed large-scale surface features including at least one crater and a radar-dark spot [7]. Polarimetric observations displayed rotationally-correlated variability at the level of 3% in relative polarization ratio, which is attributed to surface heterogeneity, either in albedo and/or regolith properties [8,9].

(155140) 2005 UD: The asteroid 2005 UD is dynamically associated with 3200 Phaethon suggesting that the two objects may be genetically related. Previous work found that the surface of 2005 UD displays color heterogeneity [10]. A favorable apparition in late 2018 provided an opportunity to further investigate the nature of 2005 UD. In addition to photometry and polarimetry, our group carried out a detailed campaign of spectroscopic observations aimed at sensitively probing for surface heterogeneity [11]. Visible spectroscopic observations were carried out over two full rotation periods. These data suggest no statistically significant variability in spectral slope with an average slope and 1-sigma variability of 2 ± 1% per 0.1 microns, implying a largely uniform surface as viewed during the 2018 apparition.

Preparing for Apophis: These case studies serve as important antecedents to the 2029 Apophis flyby. Observations of Apophis in 2029 – ground-based, space-based, or in situ – will undoubtedly focus on probing for rotational changes and/or changes is reflectivity caused by mobilization of surface regolith.

As with Duende, diagnosing rotational changes for Apophis will require extensive monitoring. The post-flyby rotation state of Duende was well constrained with ~2-3 days of nearly continuous lightcurve observations, roughly a factor of 3x the longest period in the system. Achieving similar coverage for Apophis, whose longest rotational mode is around 260 hours [3], will be a significant challenge requiring approximately a full month of observation.

As we learned from Phaethon and 2005 UD, probing for changes in surface reflectivity clearly revealed ~3% variability in polarization ratio [8.9] and constrained visible spectral slope at a 1-sigma precision of ~1% [11]. Carefully calibrated photometric images taken in different filters should be capable of diagnosing color changes at higher levels of precision. These polarimetric, spectroscopic, and photometric techniques will all require facilities and instruments capable of tracking Solar System objects at high non-sidereal rates. Additional consideration needs to be given to the instrumentation required to achieve high levels of stability for targets like Apophis. This is particularly true for ground-based facilities that will be sensitive to ever-changing atmospheric conditions. Simultaneous capture of complementary data products, e.g. broad band imaging in multiple filters or visible + near-IR spectra, can help to mitigate systematic effects that may obscure any underlying changes in the reflectance properties of Apophis induced during the planetary encounter.

Irrespective of instrumentation requirements, the geometry (i.e. solar elongation) of the Apophis flyby will preclude optical ground-based observations immediately following the Earth encounter. Significant post-flyby characterization with ground-based optical telescopes will have to wait until September 2029 when the solar elongation of Apophis reaches values higher than 90°. In this April – September window, reliance will be on space-based platforms to provide new data. Irrespective of any dedicated in situ spacecraft, consideration should be given to repurposing of existing flight assets (e.g. OSIRIS-Rex, Hayabusa 2, NEOCam) to specifically target Apophis during the months surrounding the 2029 flyby.

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