Modeling Tidally-Induced Resurfacing on 99942 Apophis During its 2029 Close Encounter with Earth.

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Introduction: In the taxonomic classification of asteroids, S- and Q-types have similar ordinary chondrite compositions but show slightly different absorption features and spectral slopes [1, 2]. While S-types show reddened surfaces indicative of space-weathering, Q-types have bluer surfaces, indicating relatively fresh surface materials. Although space weathering is a well-known process [3, 4], some resurfacing mechanisms have not yet been fully explored. Tidally induced resurfacing driven by close planetary encounters with terrestrial planets has been suggested as a critical contributor to reveal fresh materials beneath the weathered surfaces of some S-types, possibly driving a transition from S- to Sq- or Q-type. Earlier studies [5-8] support this hypothesis, statistically indicating that Q-types have experienced close encounters with terrestrial planets in their lifetimes. We believe (99942) Apophis – expected to have a close Earth flyby within 6 Earth radii on April 13, 2029 – represents a golden opportunity for the possible detection of tidal resurfacing on an S(q)-type asteroid during a close planetary encounter [9]. To this end, we have taken a joint approach of dynamic [10] and discrete element modeling [11] to numerically investigate the motion of surface grains due to tidal forces on Apophis during its Earth flyby. The results of this study may be important for indicating potential albedo changes after the encounter or identifying regions of interest to look for evidence of surface grain motion in potential missions going to Apophis either throughout or after the close encounter.

Numerical Models: We split the numerical modeling into two sections: dynamic modeling to determine slope evolution and accelerations felt by each surface patch on Apophis during the encounter, and discrete element modeling to track the specific motion of grains on a surface patch.

Dynamic Model. The dynamic model simulates the orbital and spin evolution of Apophis, using a recent best-fit shape model [12], and computes the surface slope evolution. The surface slope defines how a surface element normal is tilted with respect to the body center direction. The slope evolution indicates the change in slope in the direction of the net force (gravity, tidal, and rotational forces) acting on each facet.

Discrete Element Method (DEM). For the second stage of the simulations, we use the parallelized, *N*-body gravity tree code PKDGRAV to directly model the dynamics of grains in a surface patch on Apophis. PKDGRAV uses a soft-sphere DEM to model surface grains as individual spheres that feel interparticle and uniform gravity. The soft-sphere DEM also allows particles to slightly interpenetrate at the point of contact, using a restoring spring force to model the stiffness (akin to Young’s Modulus) of the material and apply normal and tangential damping and forces like interparticle friction [13].

Method/Approach: We begin our investigation by choosing an initial spin orientation and using the dynamic model to simulate the orbital and spin evolution of Apophis from 3 hrs before to 3 hrs after the closest encounter with a 1-min timestep. We then calculate the surface slope evolution for all 3996 patches on the surface of the body with the current best fit shape model [12], as well as the accelerations felt by each patch at every timestep.

The accelerations felt by individual patches are then handed off for the DEM simulations, where we choose a subset of interesting patches to model and uniformly apply the accelerations to a square, periodic patch of polydisperse, spherical particles. From the DEM modeling, we determine how many grains moved significantly (more than 1 particle radius) from the beginning to the end of the simulation.

We then associate the amount of grain motion on a subset of surface patches from the DEM simulations with the slope variations measured from the dynamic model and extrapolate statistics for tidal resurfacing across the entire body [14].

Simulation Details: For the dynamic models, we randomly choose 7 different initial spin orientations sampling from plausible spin states from the current uncertainties [12]. For these models, the bulk density is set as 2.0 g/cc, consistent with S-type asteroids. From these models, we retrieve the net gravitational, tidal, and rotational accelerations felt by each facet and hand them off to use in the DEM simulations.

For the DEM simulations, we choose 100 patches, with a range of initial slopes, but weighted toward more highly sloped regions (majority 25 – 35 degrees), and apply the dynamic model accelerations uniformly across an 8 × 8 × 3 cubic meter (length x width x depth), randomly packed, periodic patch of spherical particles with radii ranging from 6 to 18 cm. The grain density is 3.9 g/cc, and the initial bulk density in the patch is around 2 g/cc. The spring constant for the simulation is chosen such that the equivalent Young's modulus is between 1 MPa and 10 MPa, depending on particle radius, and friction values are chosen such that the friction angle for the material is about 35 degrees. Patches are slowly tilted up to their initial slopes and orientations to prevent significant flow before applying the time-varying accelerations across the same 6-hour window from the dynamic modeling, centered on the closest approach.

Results: Our preliminary results indicate that the main factors influencing the scale of resurfacing on Apophis as a result of the tidal encounter with Earth are the initial slope and slope variation of a given surface region and the orientation of the body during the encounter. One of the largest current uncertainties for the Apophis encounter is its spin state at the time of close approach. As shown in Fig. 1, when we model the same surface patch in different plausible orientations, the scale of the grain motion can vary widely. The spin orientation during perigee greatly influences the accelerations acting on a patch, and is thus one of the dominating factors for whether or not the patch will experience resurfacing.

We also find that patches with slope variations that increase the patch slope leading up to the closest encounter (a factor influenced by spin orientation and the patch location) are more likely to experience grain motion than those which show a slope decrease in the dynamic model, despite similar initial slopes and slope variation magnitudes. Figures 2 (a) and (b) show the results from modeling patches with a similar initial slope (~30 deg) and slope variation (~1 deg), but the patch with a decrease in slope before encounter has no grain motion in the DEM models. We confirm this behavior in the majority of cases, but have found some outliers which indicate that there are other important factors triggering grain motions, which we are still investigating. Finally, and importantly for potential in-situ missions, we find that most of the grain motion on patches that experience resurfacing occurs just prior to the closest approach, preceding the maximum slope change, and we generally see very little movement after perigee.

Acknowledgments: This work was supported in part by FINESST Award 80NSSC21K1531 and by Auburn University's Intramural Grant Program. DEM simulations were carried out at the University of Maryland on the deepthought2 supercomputing cluster administered by the Divison of Informational Technology. Analysis used MATLAB and Python's Numpy and SciPy modules.

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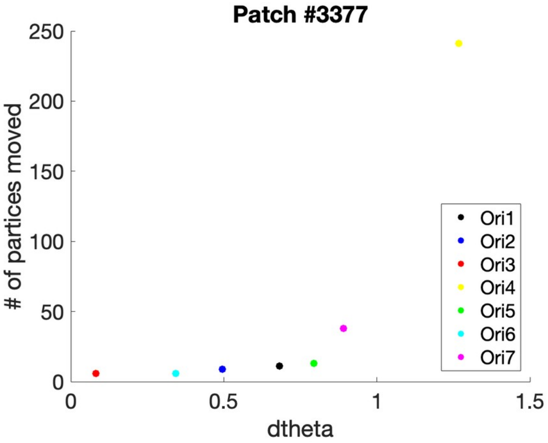

Figure 1: Total grain motion from DEM simulations on a patch with initial slope around 23 degrees using accelerations from 7 different encounter orientations (fig legend). Y-axis shows number of particles exhibiting significant motion across the encounter, x-axis shows slope variation from dynamic models.

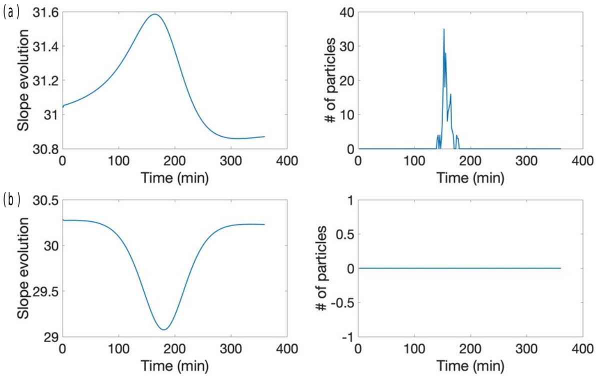

Figure 2: At left, changes in slope for patches in the dynamic models with generally increasing (a) and decreasing (b) slope in the time prior to the encounter. Y-axis is slope variation in degrees, x-axis is time elapsed in minutes with perigee at 180 min. At right, particle motion as a function of time. Y-axis is number of particles that move more than 1 particle radius between 1-minute timesteps, x-axis defined as in the left panels.