THERMOPHYSICAL MODELING OF 99942 APOPHIS: ESTIMATIONS OF SURFACE TEMPERATURE DURING THE APRIL 2029 CLOSE APPROACH.

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Introduction: The April 13, 2029 close approach of the ~350-meter asteroid 99942 Apophis offers an unprecedented opportunity to observe a large near-Earth asteroid in detail with ground-based observatories. As one of the best-studied hazardous objects, with additional near-miss flybys in coming decades, it is crucial to planetary defense to understand its properties and potential perturbations to its orbit.

Apophis has been the subject of extensive study, and will continue to be so for years to come. This existing knowledge and the promise of new data makes it an excellent candidate for modeling subject to observational constraints. The 2029 close approach will have a sizable amplifying effect on Apophis' orbital uncertainty, so small dynamical perturbations will be required to understand both the conditions of the 2029 near miss and how these perturbations may affect future possibilities of impact [1]. Several of these perturbations are tied to thermal effects, potentially also influenced by radiative forcing from Earth itself (i.e., "earthshine").

We utilize a thermophysical model to calculate temperatures of the surface and near subsurface of Apophis in the year leading up to the close approach. We generate temperature maps of the surface at this time, and use the data to calculate possible temperature ranges, extremes and diurnal temperature amplitudes. Also included in our model is the exchange of radiation between Earth (spanning an angular size of ~20° at closest approach) and the asteroid in both the visible and infrared, which may contribute substantially to the surface energy budget. We propose the use of ground-based observatories to take thermal infrared measurements during the close encounter in order to validate our models and refine them for use on future close approaches and other potentially hazardous small bodies.

Refined understanding of the temperature distribution across Apophis's surface is critical to understanding the magnitude of certain dynamical effects, including the Yarkovsky effect.

Data and Methods: For modeling, we use the shape model generated from the data from Pravec et al. (2014) [2]. We also use a spin period of 30.56 hours and an obliquity of 165° [2]. Thermal inertia has been reported between 250 – 800 J m^{-2} K^{-1} $s^{-1/2}$, with a best estimate at 600 J m^{-2} K^{-1} $s^{-1/2}$ [3].

We use a 3-d thermophysical model developed for the Janus mission to binary asteroid systems [4] for the purposes of calculating temperatures and thermal IR fluxes. Our predictions for surface temperatures and dynamical effects will be directly testable during the Janus mission, with an anticipated launch date of 2022. Though the model was constructed with the intent of categorizing binary thermal and dynamical behaviors, including binary YORP [5][6], it is easily adaptable to solitary asteroids.

This model begins by coupling a 1-d thermophysical model [7] to a 3-d shape model and computing facet-by-facet temperatures of the surface and near subsurface during the time period of Apophis's 2029 close approach. To calculate temperatures, the model is given information about the incoming solar flux on each facet as a function of solar distance and is set to equilibrate for 1 year to allow for subsurface temperature settling. The thermophysical model is sensitive to changes in factors like obliquity, thermal inertia and albedo, so as new observations occur, especially during the November 2020 to spring/summer 2021 window [8], we expect improvements in the model.

Results: Figure 1 demonstrates the resulting temperature maps from running the thermal model with the aforementioned thermal inertia range during the April 2029 close approach. For the 'best estimate' thermal inertia of 600 J m^{-2} K^{-1} $s^{-1/2}$, we calculate the temperature range over the whole body to be ~140 K to 360 K, with a median diurnal amplitude of ~110 K at the equator. For the extremes, a lower-bound thermal inertia of 250 J m^{-2} K^{-1} $s^{-1/2}$ yields a temperature range over the whole body of ~120 K to 380 K, with a median equatorial diurnal range of ~170 K at the equator. The upper-bound thermal inertia of 800 yields a whole-body temperature range of ~140 K to 350 K, with a median equatorial amplitude of ~90 K.

Discussion and Proposed Observations: As expected, increasing thermal inertias has a dampening effect on the surface temperatures, mitigating the extremes and decreases the diurnal amplitude. The predicted temperature ranges for Apophis indicate it should be possible to measure thermal IR lightcurves using standard instruments with ground-based observatories. Further data collection and model development will allow us to refine our temperature measurements and use them to constrain the magnitude of effects like Yarkovsky and YORP. The Yarkovsky effect for Apophis has already been studied by Vokrouhlický et al. (2015). In particular, we plan to include the as-yet unstudied effects of earthshine and emitted IR radiation on the asteroid, which may affect surface temperatures and resulting dynamical effects. Though we plan to study these dynamical consequences, the primary focus is on refining and testing our thermophysical model using data and observations from the 2029 close approach. This will enable more accurate predictions for not only Apophis, but other hazardous asteroids.

We will consider the possibility of ground-based infrared observations of Apophis at the time of and in the time preceding the 2029 near-miss. Possible options for these observations could include using the mid-infrared capabilities of the Sofia Aircraft Observatory or the United States Air Force Advanced Electro-Optical System (AEOS) telescope, which has the capabilities to track fast moving low-Earth satellites. Future work could include sensitivity estimates and simulations of ground-based observational data based on our model calculations.

References: [1] Vokrouhlický, David, et al. (2015) *Icarus* 252, 277-283. [2] Pravec, P., et al. (2014) *Icarus* 233, 48-60. [3] Müller, T. G., et al. (2014), *Astronomy & Astrophysics* 566, A22. [4] Scheeres, D. J. et al. (2020), LPI, (2326), 1965. [5] Ćuk, M., and J. A. Burns (2005), *Icarus* 176.2, 418-431. [6] McMahon, J., and D. J. Scheeres. (2010), *Celestial Mechanics and Dynamical Astronomy* 106.3, 261-300. [7] Hayne, P. O. et al. (2017). *Journal of Geophysical Research: Planets*, *122*(12), 2371-2400. [8] Farnocchia, Davide, et al. (2013), *Icarus* 224.1, 192-200.

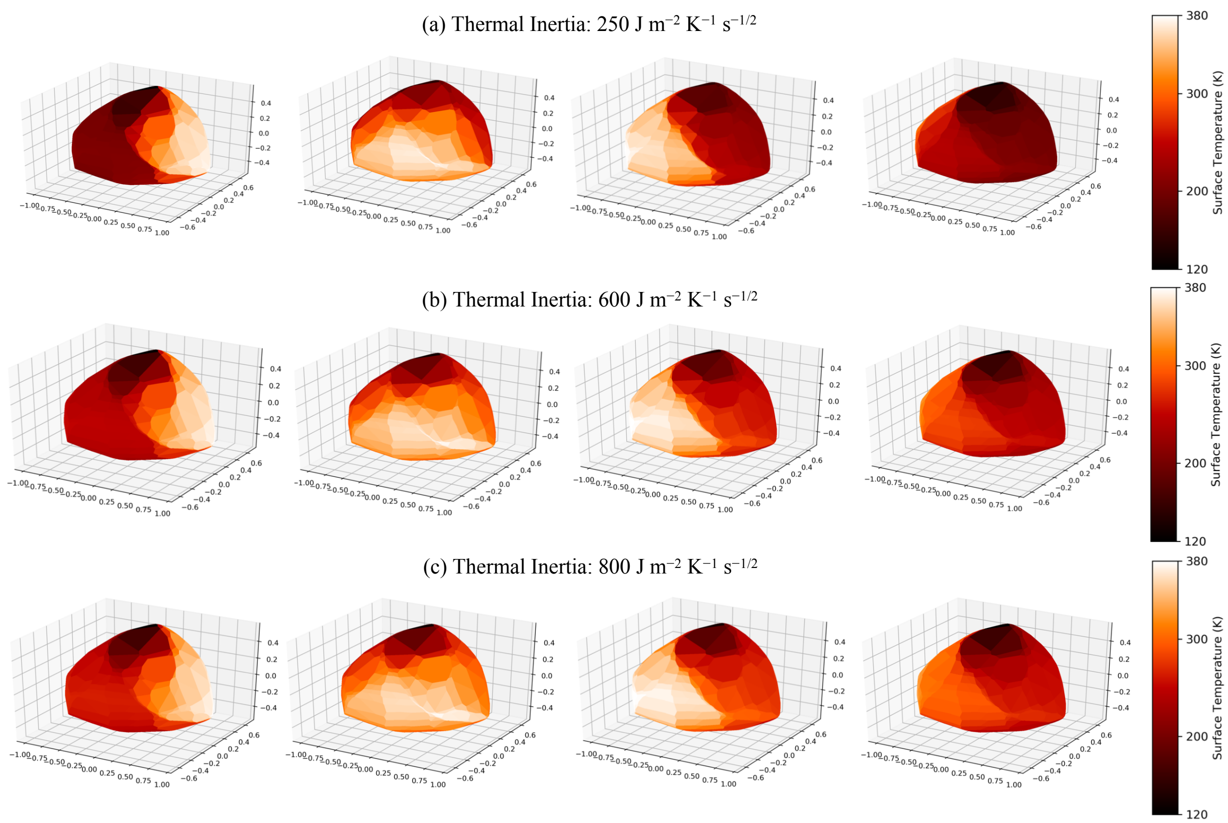

Figure 1: Diurnal temperature maps of 99942 Apophis at time of 2029 close pass using three different thermal inertias [3]. All colorbars on the right range from 120 K to 380 K. **(a)** With a thermal inertia of 250 J m^{-2} K^{-1} s$^{-1/2}$, the approximate temperature range is ~120 to 380 K. **(b)** With a thermal inertia of 600 J m^{-2} K^{-1} s$^{-1/2}$, the approximate temperature range is ~140 to 360 K. **(c)** A thermal inertia of 800 J m^{-2} K^{-1} s$^{-1/2}$ yields a temperature range of ~140 to 350 K.