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

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Introduction

99942 Apophis is a potentially hazardous NEA and a known planetary defense risk. The 2029 Earth encounter will amplify Apophis' orbital uncertainty, and affect future possibilities of impact [1].

Thermal effects, such as the YORP effect [2] induce dynamical perturbations that can be quantified by modeling Apophis's surface temperatures. Here, we develop a 3-d thermophysical model and also consider the exchange of radiation with Earth (spanning an angular size of ~20° at closest approach). Through visible and infrared radiation, 'Earthshine' could alter temperatures and YORP.

Our objectives are to:
1) Develop a 3-d thermophysical model to determine surface temperatures and dynamical effects
2) Perform thermophysical modeling of Apophis in the year leading up to the close approach
3) Estimate the effect of visible Earthshine flux on surface temperatures

Thermophysical Model

Results shown here use a 3-d thermophysical model in development for the Janus mission [3]. We begin by expanding the 1-d model from [4], which solves the heat diffusion equation.

This is coupled to an object's shape model. Here, we use the shape model from Pravec et al. (2014) [5] and step through the following process:
- Calculate diurnal fluxes incident on each facet for given orbital values (see Figure 1)
- Feed fluxes, orbital parameters and compositional parameters to model
- Model equilibrates for ≥ 1 year
- Surface and near subsurface temperatures are generated

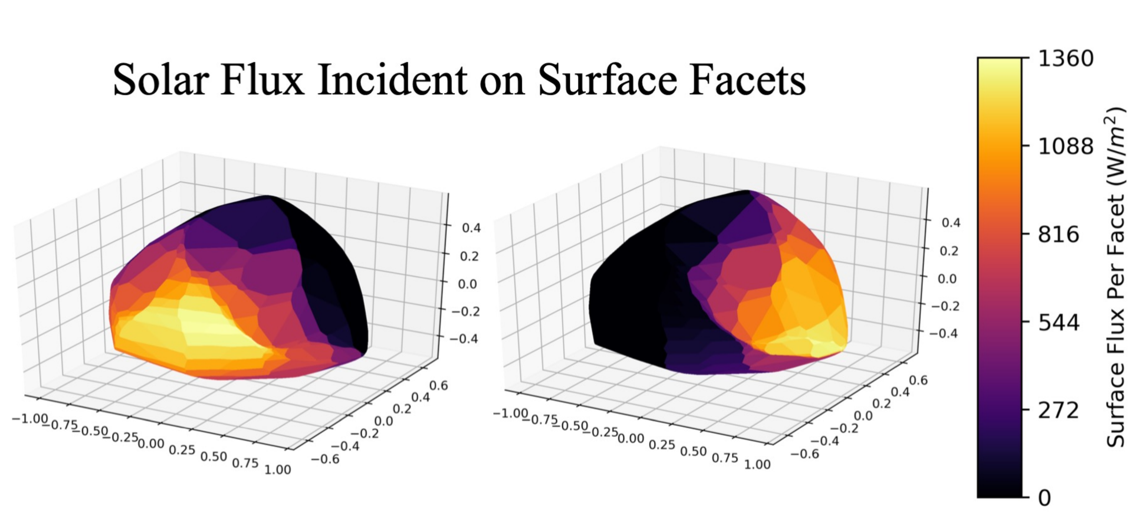

Figure 1: Sample flux values over a diurnal cycle for Apophis during the close approach

Apophis Model Results

Temperature Mapping

The model uses orbital and compositional parameters. Among others, we use:
- Thermal Inertia: 250-800 $J m^{-2} K^{-1} s^{-1/2}$; best guess at 600 $J m^{-2} K^{-1} s^{-1/2}$ [6]
- Spin period: 30.56 hr [5]
- Obliquity: 165˚ [5]
- Bond Albedo: 0.14 [6]

Table 1 shows equatorial diurnal temperature amplitudes and temperature extrema for various thermal inertias. Fig. 2 shows global surface temperatures. Note how higher thermal inertia dampens temperature amplitudes.

Table 1: Surface temperature metrics for various thermal inertias

Thermal Inertia $Jm^{-2} K^{-1} s^{-1/2}$	Equatorial Diurnal Amplitude	Global Minimum	Global Maximum
250	165 K	130 K	380 K
600	110 K	135 K	360 K
800	93 K	140 K	350 K

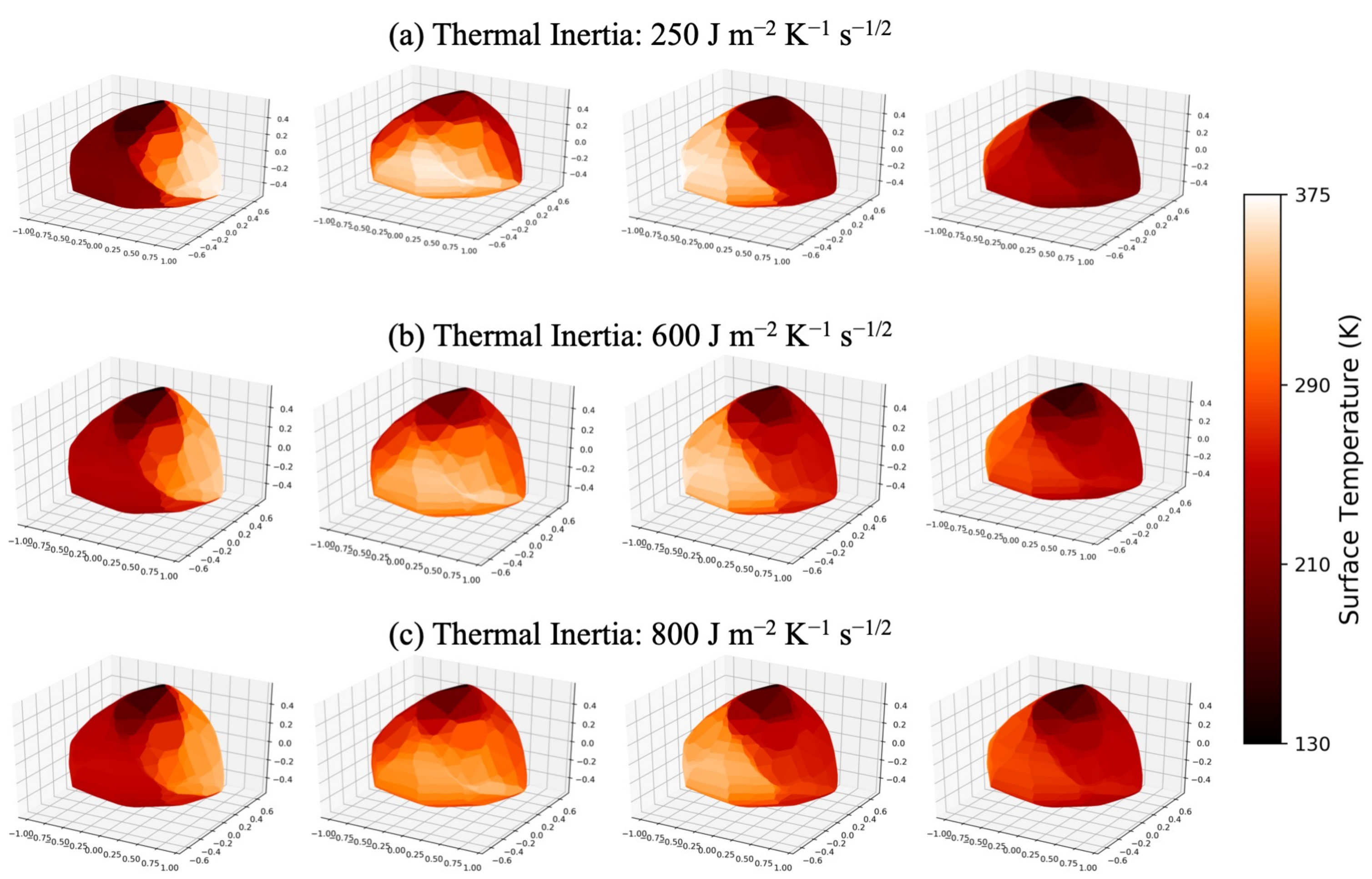

Figure 2: Surface temperature maps of Apophis during the close approach

Earthshine Effect

To study visible Earthshine (ES), we use the JPL Horizons system to get Earth-Sun, Apophis-Sun and Earth-Apophis vectors and solve for the Sun-Earth-Apophis phase angle. We solve for the fraction of the illuminated Earth visible to Apophis and calculate incoming ES flux incident on facets leading up to the close approach. These ES fluxes are fed to the model with the normal solar fluxes.

During the close approach, ES visible flux peaks at ~20 $W m^{-2}$, about a ~1.5% increase compared to local solar flux. Using a thermal inertia of 600 $J m^{-2} K^{-1} s^{-1/2}$ [4], we selected three representative shape model facets from the equator, mid-latitudes and pole. The model predicts an increase in surface temperature for all facets, but this increase is very small and of order **~0.1 K** at peak. Specific values for maximum temperatures with and without ES are shown below. No significant difference is observed for minimum values.

Table 2: Surface temperature predictions for varying latitudes both with and without Earthshine

Facet Location	Original Temp (K)	Earthshine Temp (K)	ΔT(K)
Equatorial	346.68	346.85	0.17
Mid-Latitude	334.47	334.63	0.16
Polar	234.37	234.47	0.10

Proposed Observations

We propose ground based observations to refine the thermal model and constrain the magnitude of thermal-dynamical effects. SOFIA's mid-IR FORCAST instrument [7] is one option. Predicted temperatures for Apophis indicate that FORCAST would obtain high-S/N measurements across the full range of available filters, from ~5.4 to 37.1 µm. Below is an example of FORCAST S/N estimates for the Apophis closest approach. Instruments such as AEOS or IRTF could also be used [8][9].

Fig. 4: SNR sensitivity cutoff for Apophis using SOFIA instrument specifications and a 1 s integration time. The required brightness temperature is T_b~ 150 K

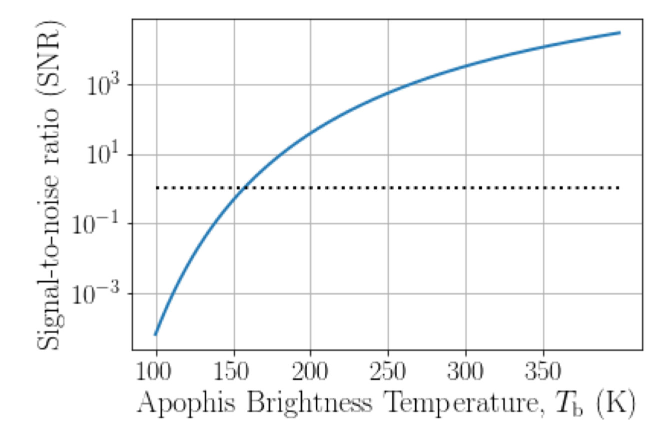

Figure 4: SNR cutoff for Sofia sensitivity

Fig 5: T_b of all facets on Apophis over 1 diurnal cycle. Red line shows the SNR cutoff T_b. Consistently ~90% of facets are sufficiently bright to observe.

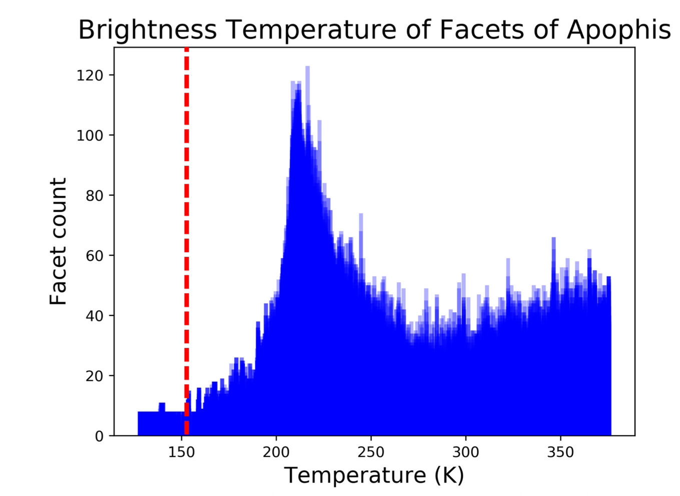

Figure 5: T_b values over diurnal cycle

Conclusions & Future Work

- As expected, higher thermal inertias mitigate temperature extremes and decrease the diurnal amplitude.
- Visible earthshine does not appear to have a substantial effect on Apophis's surface temperatures, and is unlikely to create measurable perturbations. Further study is needed to refine this and estimate the effect of IR radiation.
- Thermophysical model sensitive to changes in factors like obliquity, thermal inertia and albedo. As new observations occur, especially during the November 2020 to spring/summer 2021 window [10], we expect improvements in the model.
- **Future work**:
  - Estimation of changes in Yarkovsky and YORP effects following close approach
  - Refinement and testing of model using observational data taken before and during the 2029 close approach

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