Thermal Modeling of the Binary Asteroid Didymos

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Introduction

Thermal imaging is a powerful measurement technique to characterize the physical surface of airless bodies. Recently, the analysis of thermal images from the Thermal infrared imager (TIR) on-board the Hayabusa spacecraft, revealed the highly porous nature of the C-type asteroid 162173 Ryugu [9]. The upcoming HERA mission by ESA in 2024 will be the next small body mission equipped with a TIR instrument. Compared to Hayabusa, it will have better spatial and temporal coverage of the asteroid surface.

The target of the HERA mission is asteroid 65803 or Didymos (1996 GT), an Apollo-type near-Earth object (NEO). It is a binary asteroid: the primary body has a diameter of 775 m and a rotation period of 2.26 hours, whereas the secondary body (informally called Didymoon) has a diameter of 165 m and orbits the primary at a distance of 1.2 km in about 12 hours. The HERA observations will focus mainly on Didymoon which is the target of NASA's Dart impactor mission.

The thermophysical properties of the Didymoon surface govern the exchange of radiative energy between the asteroid and its environment, which drives the surface and subsurface temperature. Diurnal temperature changes are larger on fine soils (e.g. sand and highly porous rock) with lower thermal inertia, and smaller for dense rock with higher thermal inertia. Important properties that affect the thermal inertia include grain size, porosity, and packing of the surface material. Measuring the temperature variations of the asteroid allows to estimate the thermal inertia of its surface, providing constraints on these parameters.

Here, we present a thermophysical model of the Didymoon binary system, which includes two bodies and considers the obliquity of their spin axes. The model is used to predict surface temperature for different assumptions of surface thermal inertia.

Basic thermophysical model

The basic thermophysical model follows the work of Pelivan et al. 2017 [7] and Delbo et al. 2016 [2] and Michel et al. 2016 [6] and is extended with mutual and self heating (relevant to binary Didymos asteroid system) below. The basic thermophysical model uses only conductive heat transfer equation,

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2} \qquad \text{(Eq 1)}$$

where u is the temperature 1 dimensional temperature in space and time and α the diffusivity expressed as,

$$\alpha = \frac{k}{\rho c} \qquad \text{(Eq 2)}$$

where k is the conductivity, ρ is the density and c the heat capacity. The simple thermophysical model is stated as,

$$\begin{cases} u(x,0) = f(x), & \forall x \in [0, l_s] \\ \frac{\partial u}{\partial x}(0,t) = \frac{Q_{out} - Q_\odot}{k} & \forall t \geq 0 \\ \frac{\partial u}{\partial x}(l_s, t) = 0, & \forall t \geq 0 \end{cases} \qquad \text{(Eq 3)}$$

where f is the initialization of the temperature. The model is bounded on the surface by the balance between Solar heat flux and radiative losses into space. An adiabatic boundary condition is imposed about 4 skin depth below the surface. The second equation is the heat flux (Eq 1) at the asteroid surface and the third is an adiabatic boundary set at 4 thermal skin depth (Eq 6). Q_{out} the flux emitted from the asteroid, $Q_\odot$ the flux received from the sun, k the conductivity and l_s the thermal skin depth. The expression of Q_{out} is,

$$Q_{out} = \epsilon \sigma u^4 \qquad \text{(Eq 4)}$$

with ε the emissivity of the asteroid and σ the Stephan-Boltzman constant. $Q_\odot$ is stated as,

$$Q_\odot = \frac{S_\odot (1-A) \cos \varsigma}{r^2} \qquad \text{(Eq 5)}$$

where $S_\odot$ is the solar constant heat flux received at 1 AU, A the bond albedo of the asteroid, ς the incidence angle and r the heliocentric distance in AU. The thermal skin depth is defined as,

$$l_s = \sqrt{\alpha p / \pi} \qquad \text{(Eq 6)}$$

where p is the orbital period. We solve this model with a numerical method using second order finite-differences and an iterative Newton method. During this process, we define the stability parameter of the numerical method,

$$S = \alpha \frac{\Delta t}{\Delta x^2} \qquad \text{(Eq 7)}$$

This parameter should stay below 0.25 to ensure the convergence of the numerical method [1] [4].

Extended thermophysical model

The surface temperature of the secondary body also depends on the mutual heating by the primary. There are two effects, (1) the mutual diffuse heating which consist in the reflection of the heat flux of the Sun from the surface of the primary towards the surface of the secondary, and (2) the mutual direct heating which is the heat flux received from the primary behaving as a black body. The second equation of the system in (Eq 3) becomes,

$$Q_\odot + W_p + Q_p = \epsilon \sigma u^4 - k \frac{\partial u}{\partial x}\Big|_{x=0} \qquad \text{(Eq 8)}$$

where the mutual diffuse heating is defined as,

$$W_p = \sum_{i \neq j}^{N} V_{ij} \frac{S_\odot A \cos \varsigma_j}{r_H^2} \qquad \text{(Eq 9)}$$

where N is the total number of facets and V_{ij} is the view factor expressed as,

$$V_{ij} = \frac{a_i \cos \theta_i \cos \theta_j}{\pi r^2} \qquad \text{(Eq 10)}$$

where a_i is the surface area of the secondary, r the distance between facets i and j and θ the angle between the facet outward normal and the line from primary and secondary facets. The mutual direct heating,

$$Q_p = \sum_{i \neq j}^{N} V_{ij} \epsilon \sigma u_j^4 \qquad \text{(Eq 11)}$$

where u_j is the surface temperature of facet j. Finally, the surface temperature also depends on the self-heating produced by surface roughness and craters. To model this effect, the mutual heating equations are modified to represent interactions between facets of one body (Didymoon). The influence of this extension is about 5K inside craters.

Application to Didymoon

We considered the same parameters as in the reference model document of Didymos from ESA [3]. Predictions from the extended thermophysical model are shown in Figure 1 on the 3D shape model of Didymoon.

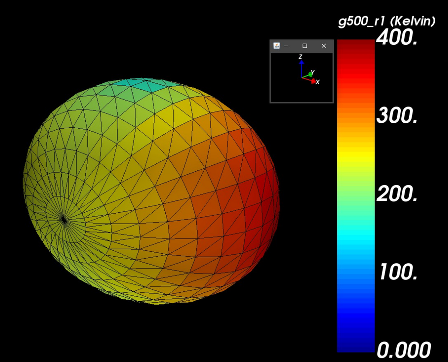


Figure 1 – Surface temperature on the ESA shape model of Didymoon

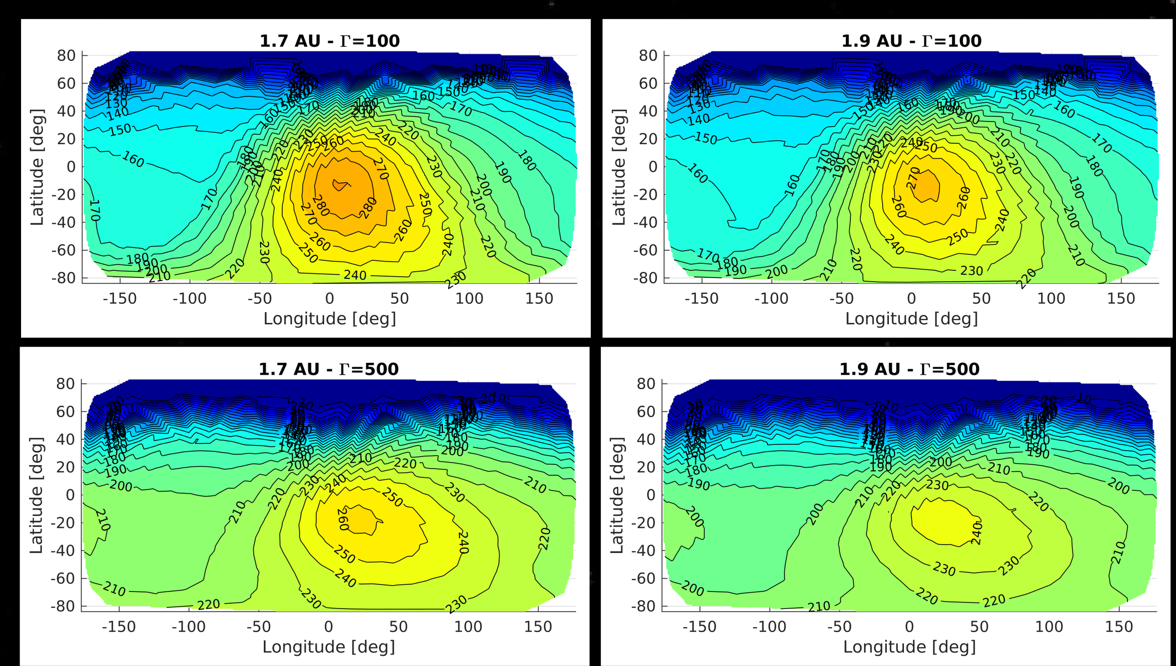
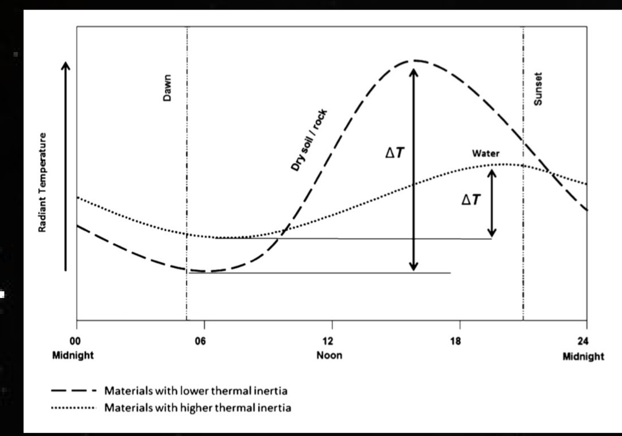


Figure 2 – Didymoon thermal map depending on the distance and thermal inertia (J.K-1.m-2.s-1/2) with an obliquity of 162° [5] [8].

The thermal inertia is the resistance of the asteroid surface to temperature changes (Figure 3). Observations of the minimal and maximal temperatures are useful to determine the thermal inertia of the body.

The model includes the influence of the obliquity, as seen from the subsolar point being shifted away from the equator. For the assumed position of Didymos with respect to the Sun, only the South pole is illuminated. The current shape model of Didymoon is a smooth ellipsoid, but in reality the surface could be rough and is expected to have an impact crater of the DART mission. Hence, we have implemented the self-heating on another shape model for example. As the shape model of Didymoon will be improved in the month to come, our model will be applied it.



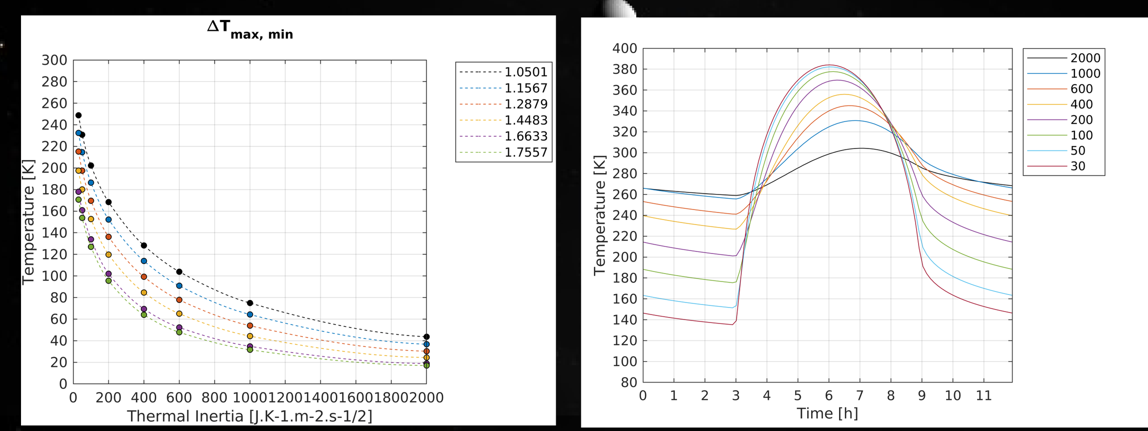


Figure 3 – Influence of the thermal inertia and heliocentric distance on the difference of temperatures

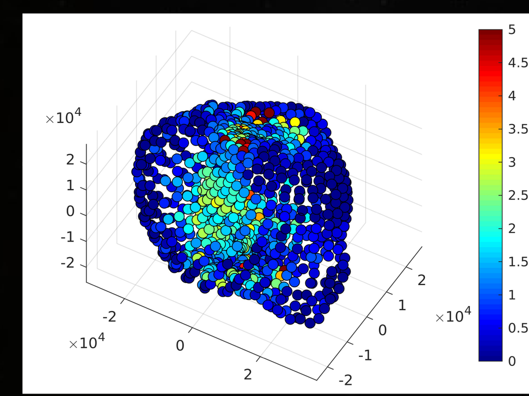


Figure 4 – Influence of the self heating for roughness surfaces

HERA predicted observations

To plan scientific observations using the TIR on the HERA spacecraft, the NASA/NAIF Spice database is a useful tool. We propose to study the future observations of the HERA spacecraft instruments with the objective to prepare as well as possible the mission. The current study will also help the proximity operations of HERA. The simulated thermal maps combined with orbital data and Instrument properties can be used to simulate. the thermal images that will be taken by the TIR instrument on-board HERA. A preliminary study will be done using the Cosmographia.

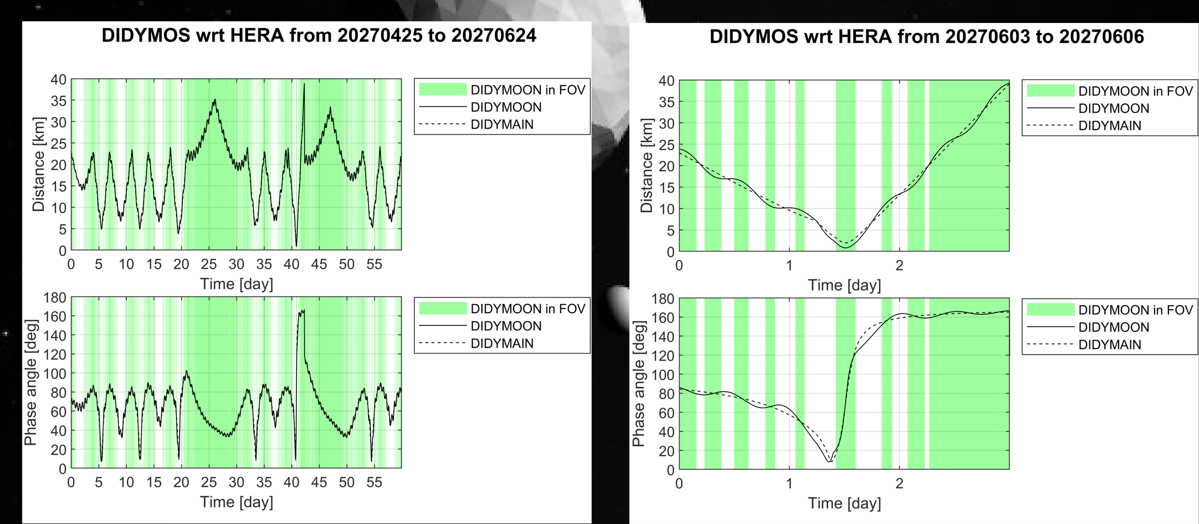


Figure 5 – Distance, phase angle (Sun & Hera) and FOV of Didymos with respect to Hera. DCP3 and very close flyby phases.

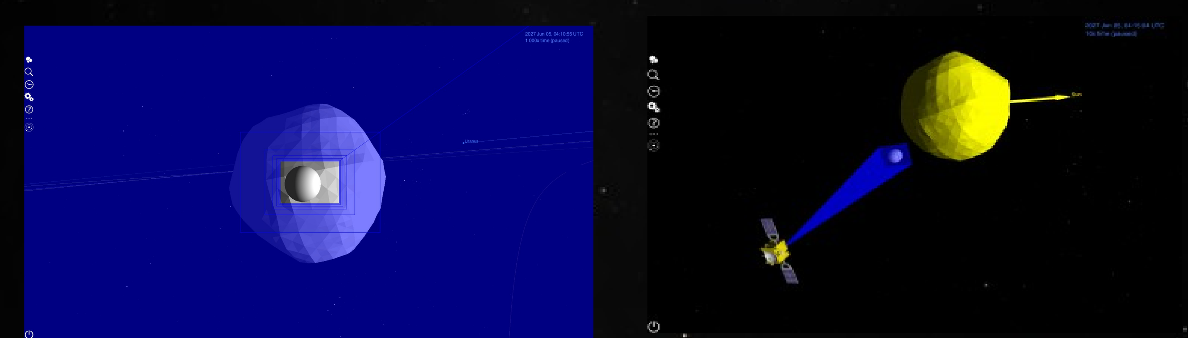


Figure 6 – FOV of Didymoon from Hera.

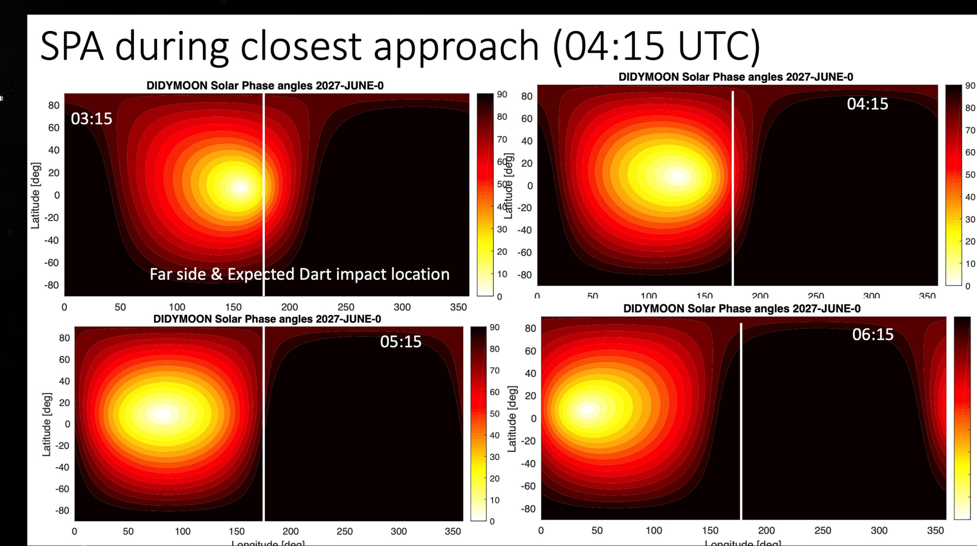


Figure 6 – Solar phase angle during closest flyby.

Conclusion and further works

A thermophysical model for the secondary in the Didymos system has been developed to explore the possible surface temperatures. The case study performed covers the extreme thermal inertia range of 30 – 2000 J.K-1.m-2.s-1/2 with different heliocentric distances.

Compared to the previous work, mutual heating from the primary and the secondary's self-heating are included in the model. In addition, the effect of obliquity is considered.
A low temperature region (T<100K) can be expected at the north pole depending on the obliquity of the binary system. At the equator the surface temperatures excursion between day and night can be more than 200K at 1 AU from Sun for a thermal inertia of 100 J.K-1.m-2.s-1/2. This diurnal temperature difference decreases as the distance from sun increases, reaching ~100 K at 1.9 AU.

The ongoing work to improve the model includes the modeling of surface roughness and lateral heat transfer.

A good thermophysical models for Didymoon is needed for the design and operation planning of TIR instrument and later for the data inversion. In addition, it provides the environmental conditions which are critical for survival of landers and their surface operations

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