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MASTER PROJECT REPORT
Simulation of thermal camera images from a spacecraft around asteroid for the HERA mission

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Abstract

Didymoon is an asteroid of the binary system Didymos. It is orbiting around a bigger asteroid called Didymain for convenience. In order to prepare the defense of the Earth in the case of a direct impact of an asteroid, the Hera mission will initiate in the years to follow an impact onto Didymoon. The NASA is in charge of the collision with the asteroid. The ESA will study the outcomes of the impact. The spacecraft Hera will be equiped of sensors such as cameras. Studying the evolution of the temperature on Dydimoon will help us to understand what happened to after the collision. This work fits into the scheme of the simulations of thermal camera images from the spacecraft around the asteroid. This paper shows a method using asteroid thermophysical model, 3D numerical solver, NASA/NAIF SPICE and shape models.

1. The Hera mission

Cruising some 250 million kilometers around the Sun is an object first identified in 1996 as 1196G, by a Spacewatch survey at the University of Arizona. It was later named Didymos (Greek word for twin), after a smaller companion, Didymoon, was discovered orbiting it. Didymos is now classified as a potentially hazardous, near-Earth system.

Hera, named after the greek goddess of marriage, will be humanity's first probe to rendezvous with a binary asteroid system.

Hera is part of an international collaboration, alongside Nasa's DART which is due to deliver a kinetic impact Didymoon's surface, leading to to a deflection of its orbit around the bigger brother.

The mission's main objectives are to deepen our understanding of a planetary defense technique while also demonstrating numerous technologies, the likes of autonomous navigation around asteroids and gathering scientific data, further developping our understanding of asteroid compositions and structures.

Hera is set to launch in 2024, before traveling to Didymos where it will first focus on Didymoon for its study: High resolution mapping relying on Optical, radio and laser techniques.

In addition to planetary defense objectives, Hera will also carry two CubeSats on board, to be launched around the asteroid system for crucial scientific studies before touching down on their surface.

In this paper, we describe our contribution to the Hera Mission. Our work on the thermophysical model consists of taking into consideration the self heating (heat flux reflected from Didymoon's own 3D relief) and mutual heating (heat flux from Didymain) phenomena. Geometric considerations were further made to enrich the model such as true position, obliquity (with NASA/NAIF Spice) and shape models.

2. Current work

This paper is following the work of a previous document *Didymoon's surface thermal modeling*. The former presents a method to simulate the temperature at the surface of an asteroid. It describes in details the following thermophysical model and the numerical method:

$$\begin{cases} u(x,0) = f(x), & \forall x \in [0, l_s] \\ \dfrac{\partial u}{\partial x}(0,t) = \dfrac{Q_{out} - Q_{\odot}}{k} & \forall t \geq 0 \\ \dfrac{\partial u}{\partial x}(l_s,t) = 0, & \forall t \geq 0 \end{cases} \tag{1}$$

with u the 1 dimensional temperature in space and time, f a initial temperature repartition, Q_{out} the flux emitted from the asteroid, Q_{Sun} the flux received from the Sun, k the conductivity and l_s the annual thermal skin depth. The expression of Q_{out} is:

$$Q_{out} = \epsilon \sigma u^4 \tag{2}$$

with ϵ the emissivity of the asteroid and σ the Stephan-Boltzman constant. Q_{Sun} is stated as:

$$Q_{\odot} = \frac{S_{\odot}\,(1-A)\cos\varsigma}{r^2} \tag{3}$$

with $S_{\odot}$ the solar constant heat flux, A the bond albedo of the asteroid, ς the incidence angle and r the heliocentric distance in AU. The annual thermal skin depth is written as:

$$l_s = \sqrt{\alpha \pi p} \tag{4}$$

where α is the diffusivity and p is the orbital period. The diffusivity is expressed as:

$$\alpha = \frac{k}{\rho c} \tag{5}$$

where ρ is the density and c the heat capacity. The second equation of this thermophysical model is the heat flux at the surface of the asteroid and the third is an adiabatic condition set at several annual thermal skin depth. This model is based on the heat transfer equation:

$$\frac{\partial u}{\partial t} = \alpha \frac{\partial^2 u}{\partial x^2} \tag{6}$$

This ensures the conduction of the temperature inside the asteroid. To express the temperature from this equation, we used a second order finite-difference method and iterative techniques such as the Newton method. During the process, we defined the numerical stability parameter:

$$S = \alpha \frac{\Delta t}{\Delta x^2} \tag{7}$$

This parameter must remain lower than 0.25 for stability purposes. For the simulations, it is important to define the thermal inertia:

$$\Gamma = \sqrt{k\rho c} \tag{8}$$

3. Objectives

Following the former document, the main objectif of this paper is to have a more complex thermophysical model to get closer to the reality. The heat flux from the Sun is the main source of heating for asteroids but there are more phenomenons happening to implement and especially for a binary system of asteroid. The most important from the secondary effects is the mutual heating between the two bodies of the binary system. Another effect to implement for crateres or rough-shape asteroids is the self heating. This paper also aims to present a method to include the asteroid obliquity in our model. The document is mainly focused on the study of Didymos's secondary object Didymoon but it also presents another planetary defense mission with very different orbital and asteroid parameters which is interesting for comprehension purposes.

4. A thermophysical model for a binary system of asteroids

In this section, we present the implementation of the mutual heating. As Didymos is a binary system of asteroid, the current thermophysical model is not enough to fully describe the temperature at the surface of the asteroid. The Hera mission focuses on the secondary object in this binary system. Its surface temperature depends also on the primary object for two main reasons, firstly, the reflection of the Sun on the surface of the primary to the secondary, this phenomenon depends on the primary albedo and on its position with respect to the Sun and the secondary, and it is named the mutual direct heating, 2) the heat received from the primary itself, just as the Sun, considering it as a black body, it only depend on the distance and is called the mutual diffuse heating.

4.1. Theory

Didymos' secondary is modeled in a simplified manner due to the many unknowns and assumptions adopted in this study. This section deals with neglected effects thought to alter surface temperatures in certain cases.

A complete thermophysical model including the direct and diffuse mutual heating is (Pelivan et al., 2017):

$$Q_{Sun} + W_p + u_p + w_p = \epsilon\sigma u^4 + \kappa\frac{du}{dx}, \tag{9}$$

where the direct Q_{Sun} compute from Eq. 3.

For the current simplified model, the mutual heating from Didymain to Didymoon will be small due to the comparatively large distance of 1.18km **?** between the two bodies and enter through terms W_p, u_p and w_p. As defined in the reference model, the low albedo allow us to apply the single-scattering mode for which the diffuse thermal heating flux w_p can be neglected. However, this flux will be discussed in the next part.

Discretizing the two bodies into facets i for the secondary and j for the primary, the mutual heating from diffuse solar radiation from the primary can be compute using :

$$W_{p,j} = \sum_{i \neq j}^{N} V_{ij} \frac{S_{\odot} A cos\varsigma_j(t)}{r^2(t)} v_{j,sun}. \tag{10}$$

Where N is the total number of facets, $v_{j,sun}$ is the facet view factor to the Sun, and V_{ij} is the view factor.

The view factor is the numerical value between 0 and 1 representing the visibility of one facet to another as shown in Figure (**??**).

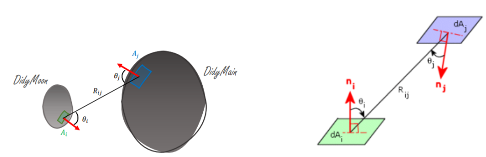


Figure 1: (a) View factor on Didymos system and (b) View factor schematic interpretation

Thus, this factor can be expressed as :

$$V_{ij} = \frac{a_i cos\theta_i cos\theta_j}{\pi r^2}. \tag{11}$$

a_i is the surface area of element i (In our model, we consider $a_i = 1$), r is the distance between facets i and j, and the angles θ are the angles between the facet outward normal and the line between facet centers. Using this factor, all facets with θ_i or $\theta_j \geq 90\,\mathrm{deg}$ are equals to 0 as they are not facing each other.

Considering now the direct thermal heating $u_{p,j}$ which is the largest flux from the primary due to the low albedo, we can write it as follow :

$$u_{p,j} = \sum_{i \neq j}^{N} V_{ij} \epsilon \sigma u_{s,j}^4. \tag{12}$$

Here, $T_{s,j}$ is the surface temperature of facet j.

In order to reduce computing time, temperatures of the primary are not computed, all facet temperatures $u_{s,j}$ from Eq. (12) are set to the same high value based on midday temperatures of the moon.In applying Eqs. (12) and (10) therefore an upper limit is derived for the occurring fluxes W_p and u_p. The temperature change due to heating from the primary is evaluated by applying Eq. (5) which for the night side and the eclipse periods of the moon reduces to :

$$W_p + u_p = \epsilon \sigma u^4 + \kappa \frac{du}{dx}, \tag{13}$$

Indeed, in addition to mutual heating implementation, we added the primary occultation on didymoon.

Using spice and *cspice_occult* function, we can determine if the moon is fully or partially in the shade of the primary body. During those phases, the algorithm avoid any direct solar flux and only compute mutual heating from the primary as shown in Eq. (13)

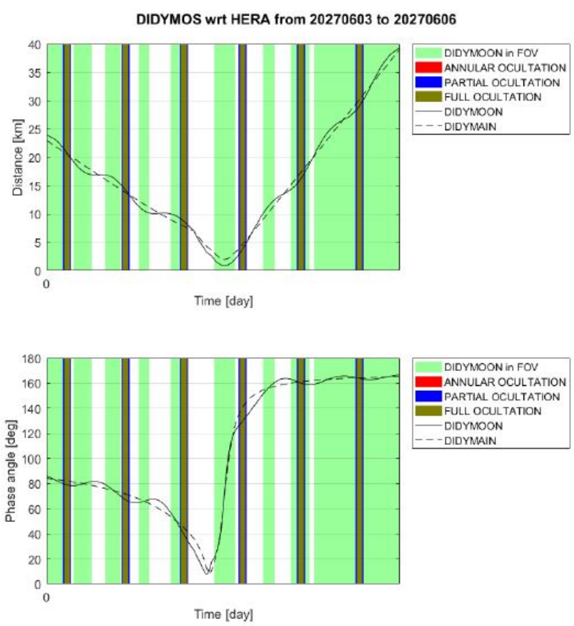


Figure 2: FOV, Phase angle and Occultation Considerations (Green means Didymoon is fully visible by HERA)

4.2. Integration

Using the Eq. (9), we implement the mutual heating to the current thermophysical model Eq. (1).

In order to check the result's consistency, several test has been performed in all possible configurations. As the algorithm takes every single facets of both primary and secondary bodies, we compute only the temperature for a single position at the equator.

The first test was performed using only the direct and indirect thermal from the primary, considering $Q_{Sun} = 0$ for a long time period, thus the temperature could converge. This test doesn't have physical meanings as the direct flux from the Sun cannot be null for a such a time period but was performed to see the influence of the mutual heating and check if this one create a significant thermal flux.

[TEST RESULTS WITH AND W/O QSUN]

We also performed several tests taking positions all around the equator, in the shade and in the normal axis to the Sun and everything was consistent.

Then, after a full integration and with the exact same parameters, we compute the difference between simulations including mutual heating and not including it.

Thus, we have the following result :

[DIFFERENCE BETWEEN WITH AND W/O MUTUAL HEATING]

5. Advanced thermophysical model for rough surface including cratere

In this section we present the implement of the self heating. A normal at the surface of an asteroid may appear to be hidden from the direct solar flux even if it situated in the day side, for instance inside a cratere. In this scenario, it is important to take in consideration what is called the self heating of the asteroid. Due to its albedo, the surface of the asteroid relfects sunlight rays and thus, if the asteroid is not pure smooth, some reflected rays might impact another location on the asteroid.

6. Another important celestial parameter: the obliquity

This section describes the implementation of the obliquity and the explanation of the impact on the surface temperature. The obliquity is defined as the angle of tilt of the body's axis of rotation. Thus, it has an immediat impact on the repartition of temperature on the body as this figure describes:

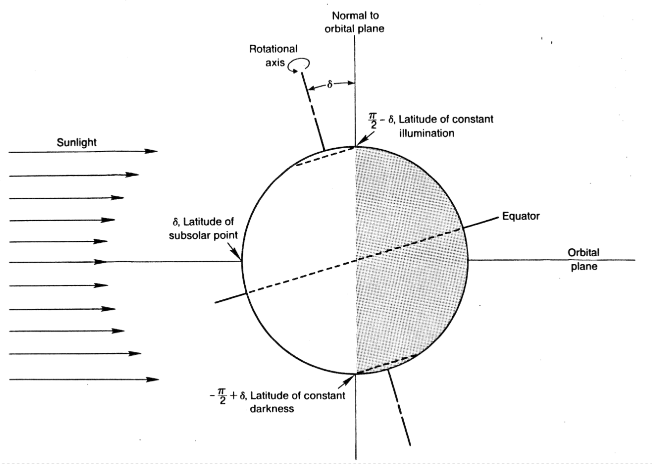
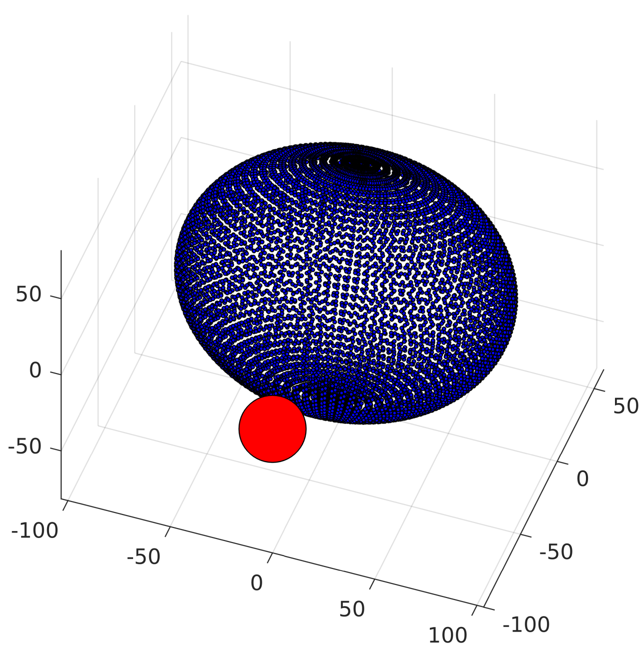
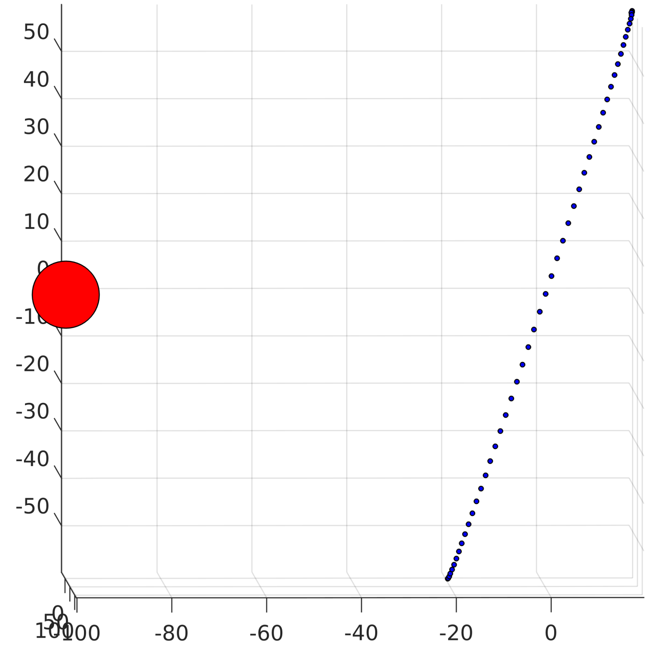


Figure 3: Representation of the obliquity with the orbital plane and the rotational axis

From the obliquity results two observable events. First, the subsolar point is not anymore located on the equator but on a point tilted from the equator as the figure shows above. Secondly, depending on the position of the asteroid on its orbit - i.e. depending on the seasons, only one pole is not receiving direct heating from the Sun whereas without obliquity both poles are not receiving the heat.

Before running the simulations presented in the previous sections, we implement the axial tilt on the shape model.





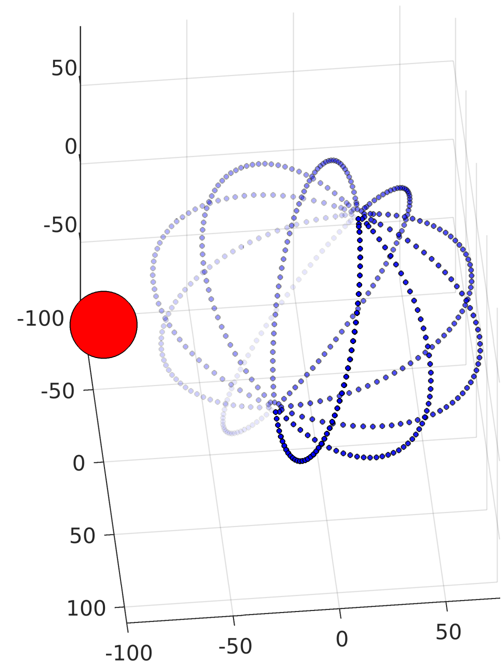


Figure 4: Implementation of the obliquity for the daily surface temperature variation at longitude = 0 degrees on Didymos' secondary. The spin axis is given as 171 $\pm$ 9 degrees. Here, the extreme case of 162 degrees has been taken. The first figure is Didymoon's shape with obliquity and the direction of the Sun. On the second image we show only the meridian at longitude 0. The third pictures the rotation of the meridian during a day.

Demonstration of the effects of the obliquity are performed for the temperature evolution of Didymos' secondary along a full day assuming an ellipsoidal shape.

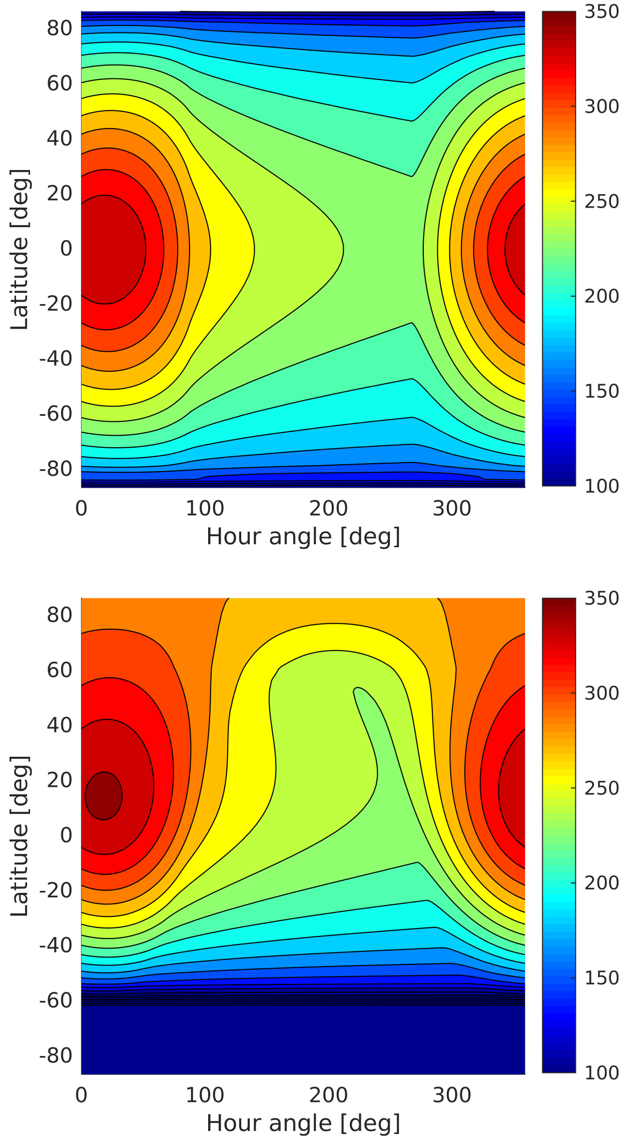


Figure 5: Contour maps of the daily surface temperature variation at longitude = 0 degree on Didymos' secondary for a thermal inertia of $\Gamma = 500 \ \mathrm{Jm^{-2}K^{-1}s^{-1/2}}$, an heliocentric distance of 1.0748 AU and 162 degrees of obliquity.

As expected, temperature peaks shift in latitudes depending on the obliquity and the south pole only is in the cold zone.

7. Another planetary defense mission: 2016 HO3

In this part we will look at the Asteroid HO3. We had to establish the thermophysical model of that asteroid.We have used the code used explain before and we have modified the differences value to fit with that asteroid.

(469219) Kamoʻoalewa, provisionally designated 2016 HO3, is a quasi-satellite of the Earth[3]. It was discovered on April 27, 2016 by the Pan-STARRS program at the Haleakalā observatory on the Hawaiian island of Maui. He has an excentricity e = 0,10414290 , a period of revolution of 20 minutes.

The particularity of this asteroid is their speed, he have a rotation period of 20 minutes which is fast, to compare with the one we have study in this paper he is 36 times faster. Study that asteroid has permit to understand why the speed of rotation as an impact on the temperature.

To implement the map of this asteroid on Matlab we had to create a shapmodel of HO3, for that we have used SBMT and recreate the asteroid with the real dimension.

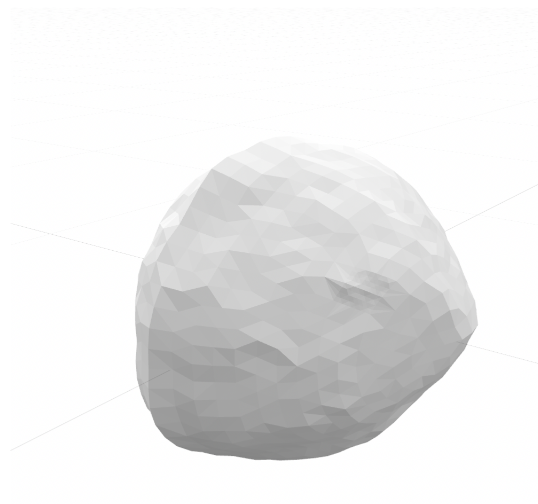
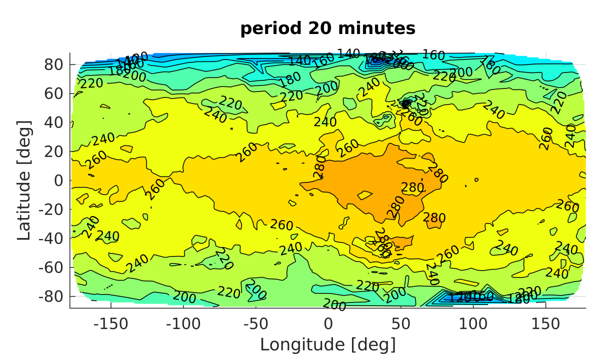


Figure 6: Shape model of HO3

We have used a know asteroid already implement called Bennu and we have changed the size, Bennu had quite the same asperity than HO3 and gave us a better shape model for the temperature.

We have used the Matlab code see in the previous part to create the thermal map, we have take a Γ = 500, A= 0.07, C= 0.25 and rho= 2146; .

We have plot 2 map, one with 20 minutes speed and the other one with 12 hours, in the next 2 figures you will se the temperatures.



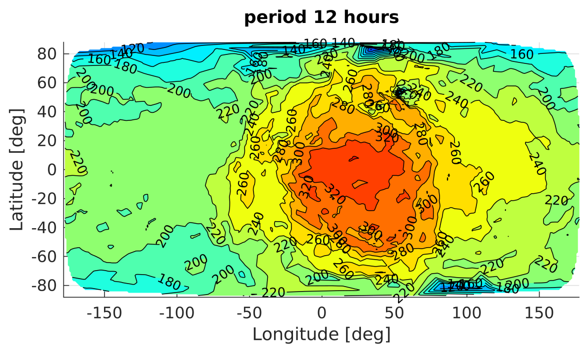


Figure 7: The first three images represent the asteroid with an orbital period fixed as $p_{orbital} = 20$ minutes and a $\Gamma = 500$, on the second line the other three images show an orbital period fixed as $p_{orbital} = 12$ hours and a $\Gamma = 500$

We will see how the speed has impact the values, the difference speed gives us an overview on how it works.

The most differences between this figures are the mid day temperature is higher with a faster rotation.Temperatures around mid day are much more stable on the axis of rotation with a delta of 20 degrees variation while for a period of 12 hours temperatures are colder around the mid day area.

More faster the asteroid his, higher are the temperature on a dedicate point. It's due that the rotation show to the sun more often their surfaces so they have higher temperature. When the asteroid is slower we see that only the obliquity axis have hight temperature. We have created our model as we have presented before.

To go through, we will look on why the thermal model map change.

When the asteroid is faster the pole on the obliquity axis stay more often on the view of the sun, it make that the temperature is higher on that point and colder on the extreme point.

When the asteroid is slower the temperature is distributed more uniformly over the whole of the asteroid, which means that we will find fairly hot temperatures on the skew axis but also cooler temperatures over the rest of the asteroid.

8. Further works

Hera we talk about the further works.

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