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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:

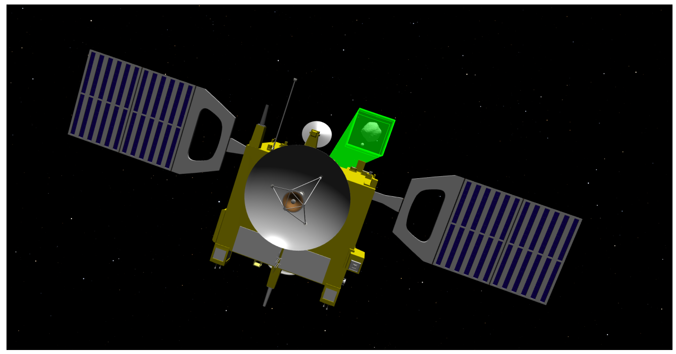


Figure 1: The binary system of asteroid Didymos viewed from the spacecraft Hera. The field of view of the AFC camera is in green.

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

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. $Q_{\odot}$ 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, and secondly, 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.

Figure 2: The binary system of asteroid Didymos

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):

$$Q_{\odot} + W_p + Q_p + W_m + Q_m = \epsilon \sigma u^4 - k \frac{\partial u}{\partial x}\Big|_{x=0} \tag{9}$$

where W_p stands for the mutual heating from diffuse solar radiation from the primary, Q_p corresponds to the direct thermal heating from the primary considered as a black body, W_m is the diffuse thermal self heating, Q_m is the direct thermal self heating and du/dx is the vertical temperature gradient with x positive upward.

For the current simplified model, the mutual heating from Didymain to Didymoon will be small due to the comparatively large distance of 1.18 km (mod, 2015) between the two bodies and enter through terms W_p and Q_p. As defined in the reference model, the low albedo allows us to apply the single-scattering mode for which the diffuse thermal self heating flux W_m can be neglected. Furthermore, considering the current shape of Didymoon, which is a simple ellipsoid, it is not necessary to include the term Q_m neither. However, these two flux will be discussed in the next part.

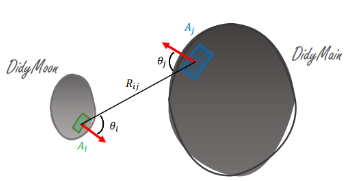
Discretizing the two bodies into facets i for the secondary and j for the primary, the mutual heating from diffuse solar radiation from the primary can be compute using:

$$W_p = \sum_{i \neq j}^{N} V_{ij} \frac{S_{\odot} A \cos \varsigma_j}{r_H^2} \tag{10}$$

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

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

where a_i is the surface area of the seconday, r is the distance between facets i and j and angles θ are the angles between the facet outward normal and the line between facet centers from primary and seconday. An angle of $\theta \geq 90$ degrees represents two facets not facing each other. The following schemes explain the situation:



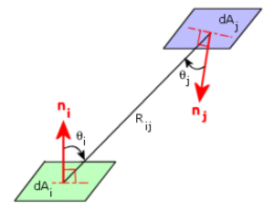


Figure 3: (1) View factor on Didymos system and (2) View factor schematic interpretation

Due to low aldbedo (both albedo of the primary and secondary are assumed identical) the direct thermal heating Q_p is the largest flux from the primary:

$$Q_p = \sum_{i \neq j}^{N} V_{ij} \epsilon \sigma u_j^4 \tag{12}$$

where u_j is the surface temperature of facet j. For computing time purposes, temperatures of the primary are not computed. All facets temperatures u_j are set to the highest midday temperature of the moon.

4.2. Integration

The Eq. 9 can now be implemented to the current thermophysical model in Eq. 1 to include the mutual heating from the primary body of the binary system of asteroid Didymos. Surface temperatures have been computed to each single node from the ESA shape models of the Didymos system asteroids.

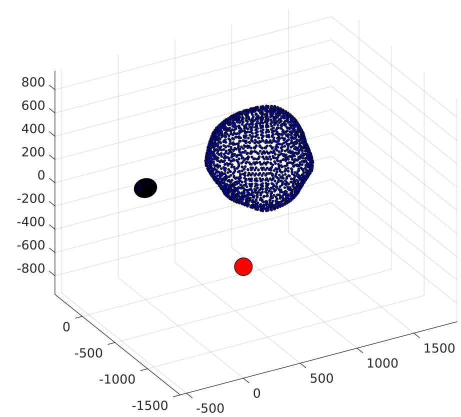


Figure 4: The binary system of asteroids Didymos with the Sun direction. Latest shape models of the ESA have been used in this simulation. The primary has a radius of 500 meters and the secondary 80 meters.

After implementation of the revolution of Didymoon, the following results are obtained for the surface temperatures of the secondary including the mutual heating from the primary:

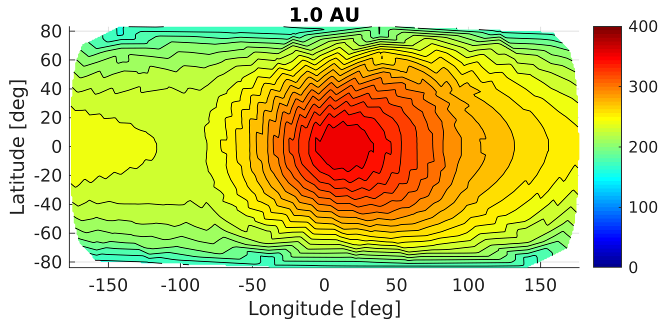


Figure 5: Thermal map of the secondary of the binary system of asteroids Didymos including the mutual heating from the primary using ESA shape models.

The computation were realized without the implementation of the obliquity, which is discussed in next parts. To compare with the previous implementation in Eq. 1, this graphs shows the benefits of including the mutual heating:

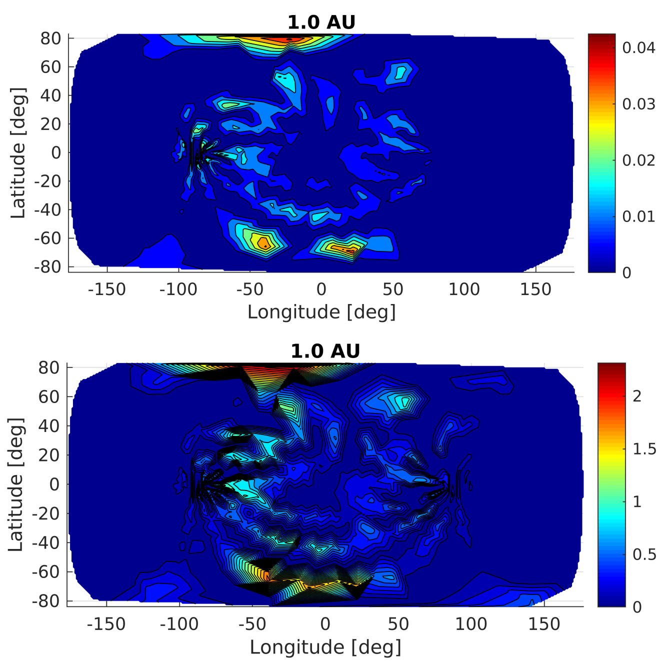


Figure 6: The two graphs shows the impact of including the mutual heating on the surface temperatures of Didymoon. The first figure shows the difference between the surface temperatures with the secondary diffuse mutual heating only (Eq. 10) and without it. The second image is the difference of temperature including the two equation of the mutual heating (Eq. 10 & Eq. 12) and without it.

The assumptions which consisted of considering the direct mutual heating as the largest flux of the mutual is confirmed with this graph. Furthermore, the Eq. 10 costs much more computational time rather than the Eq. 12, thus, and due to the present albedo, it might be more clever to not implement it. The first case suggests an increase of 0.05 K where the second case represents an increase of more than 2 K depending on the regions.

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 resulting in heating it up.

5.1. Theory

The implementation of the thermophysical model beaming into Didymoon, described above, had mutual-heating occurring between the two bodies of the Didymos system. However, this implementation neglected global self heating that can occur within large-scale concavities of an irregularly shaped asteroid.

Global self-heating provides a mechanism for heat to be transferred laterally across an asteroid surface. Fig. ??? demonstrates how global self heating can affect the thermophysical model and temperatures predictions for an asteroid with a large-scale concavity and an irregular shape. The large-scale concavity results in heat transfers that occur at certain geometries, where a facet is facing another one. In the absence of global self heating, those facets would receive only direct flux and mutual heating flux. However, if the facet receives reflected solar flux and emitted thermal radiation from the opposite side of the concavity that is illuminated, the temperature would be higher than expected. The aim of this section is to implement this phenomenon.

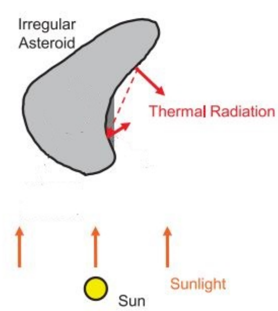


Figure 7: Schematic of global self-heating occurring inside a large concavity of an asteroid.

In the specific case of Didymoon, its shape model is still incredibly simple. The ESA's shape for Didymoon is smooth ellipsoid. This leads in the total absence of self heating. For this purpose, a more complex shape model has been taken, Mathilde:

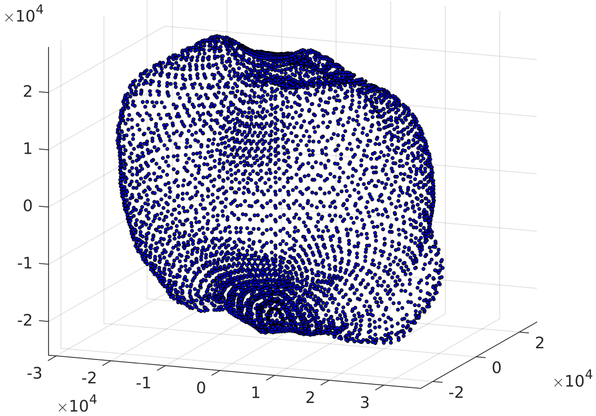


Figure 8: Shape model of the asteroid Mathilde. Dimensions: 66x48x46 km.

The two terms relative to the self heating in Eq. 9 are now considered following:

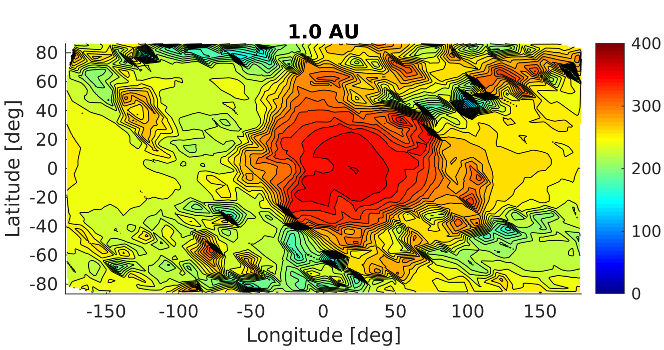
$$W_m = \sum_{i_1 \neq i_2}^{N} V_{i_1 i_2} \frac{S_{\odot} A \cos \varsigma_{i_2}}{r_H^2} \tag{13}$$

$$Q_m = \sum_{i_1 \neq i_2}^{N} V_{i_1 i_2} \epsilon \sigma u_{i_2}^4 \tag{14}$$

These two equations complete the model seen in Eq. 9. They very look like equations of the mutual, the only difference is the indices of the facets. Each surface node temperature is computed with respect to every other nodes on the asteroid excepting the current one. i_1 and i_2 belong to the asteroid. $V_{i_1 i_2}$ is computed as seen in Eq. 11. Same assumptions are taken for u_{i_2} as in the section 4.

5.2. Integration

To investigate in general on how global self heating within large concavities of asteroids influences thermophysical model, it is needed to first check the result's consistency, such as the surface temperature expected to be higher in a cratere. The implementation of the self heating on the shape model of the asteroid Mathilde results in the following thermal map:



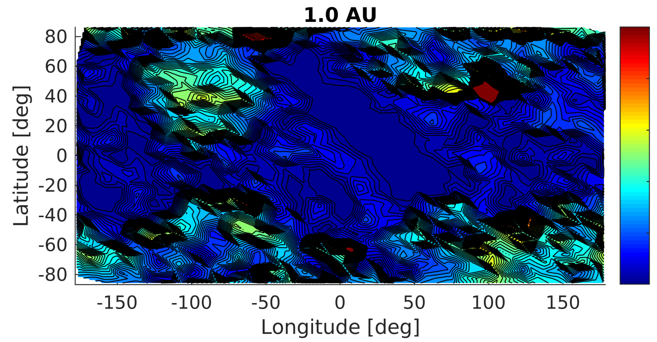


Figure 9: The first figure is the thermal map of the surface temperature of the asteroid Mathilde including its self heating. The second figure is the contribution of the self heating on thermal map. Orbital parameters and asteroid properties are taken as in section 4.

The contribution of the self heating may appear to be in some place higher than 5 Kelvins, as shown in the figure bellow, but this color axis has been chosen for reading purposes.

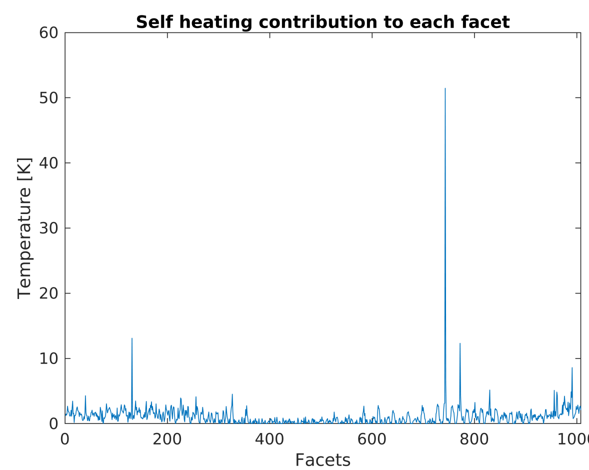
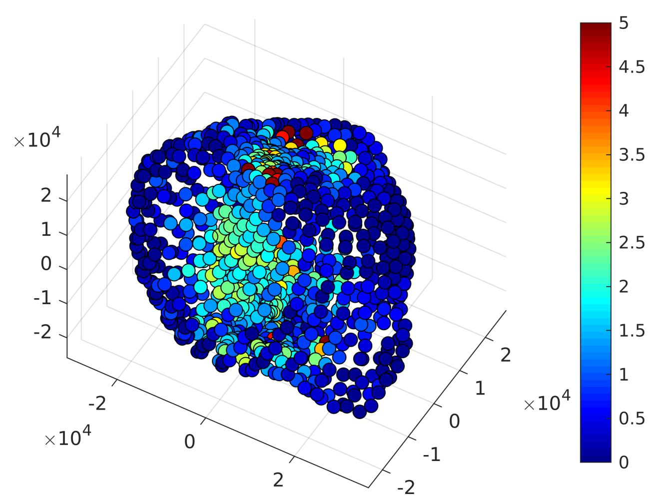


Figure 10: Self heating contribution for each facet. Most values are located between 0 and 5 Kelvin.

The results appears to be consistent as the following figures prove it, the self heating contribution is most essencially located in crateres.



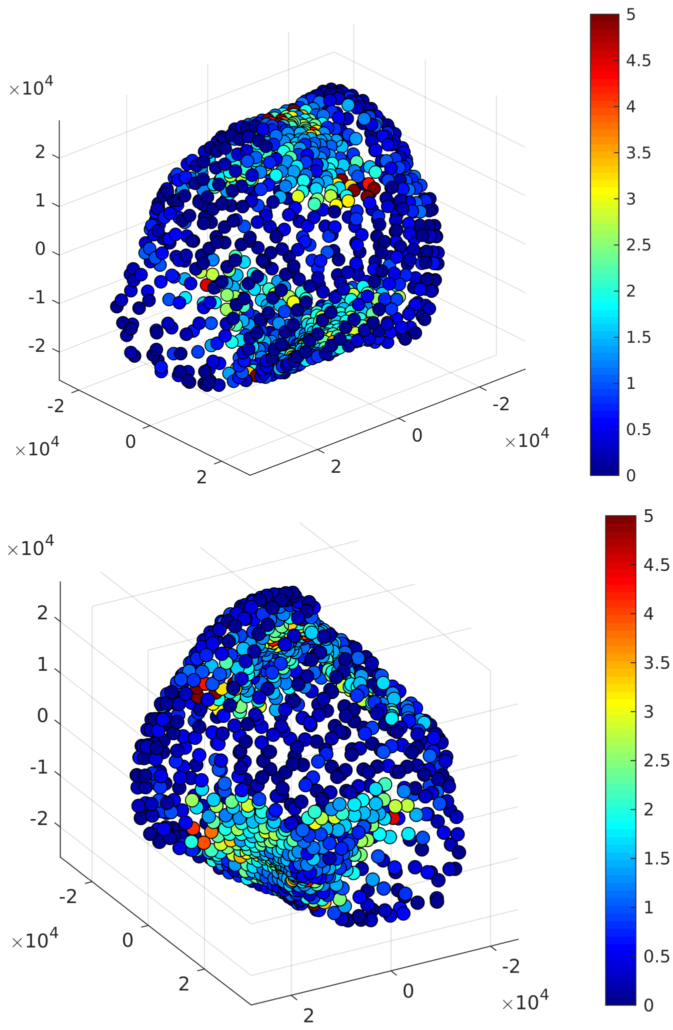


Figure 11: Self heating contribution displayed on the 3D shape model of the asteroid Mathilde.

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:

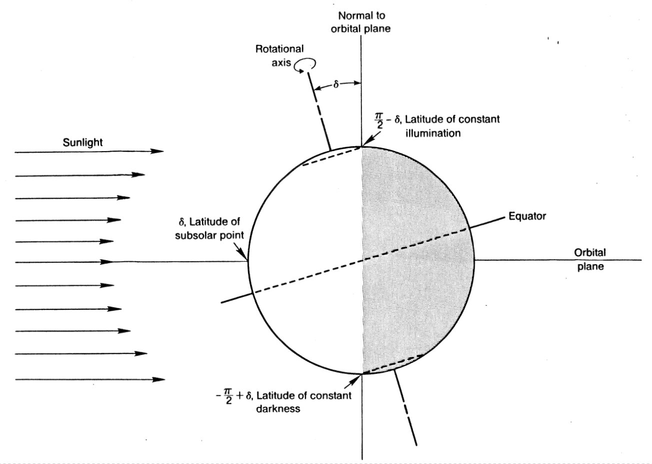
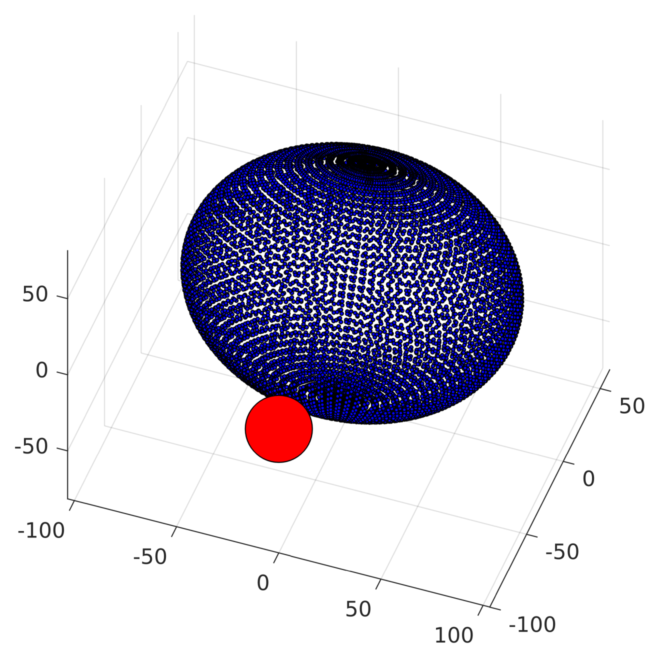


Figure 12: Representation of the obliquity with the orbital plane and the rotational axis

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.



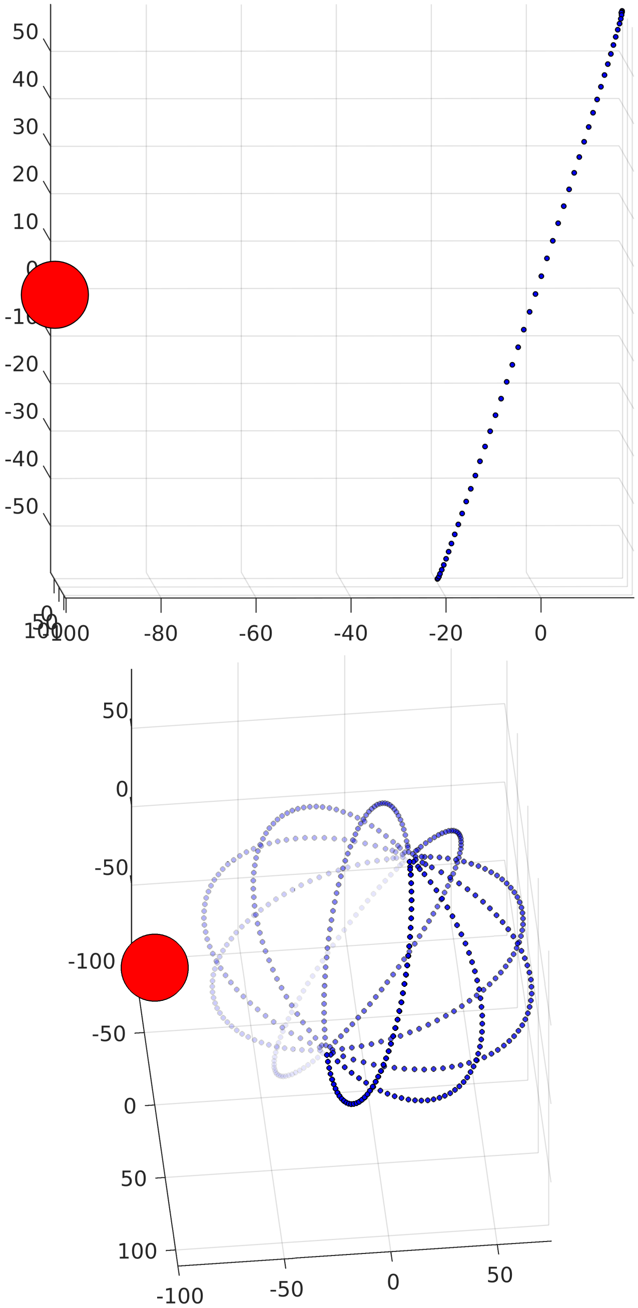


Figure 13: Implementation of the obliquity for the daily surface temperature variation at longitude = 0 degrees on Didymos' secondary. The spin axis is given as 171 ± 9 degrees. Here, the extreme case of 162 degrees has been taken. The first figure is Didymoon's shape with obliquity and the direction 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.

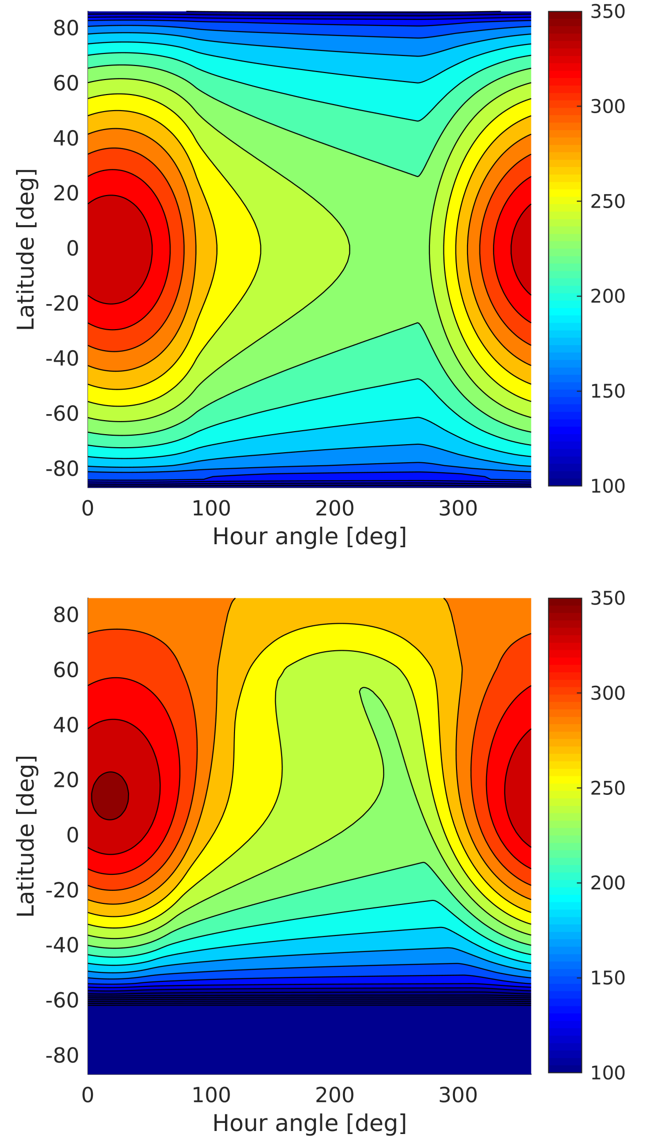


Figure 14: Contour maps of the daily surface temperature variation at longitude = 0 degree on Didymos' secondary for a thermal inertia of $\Gamma = 500\ \mathrm{Jm^{-2}K^{-1}s^{-1/2}}$, an heliocentric distance of 1.0748 AU and 162 degrees of obliquity.

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

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 Earth3. 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.

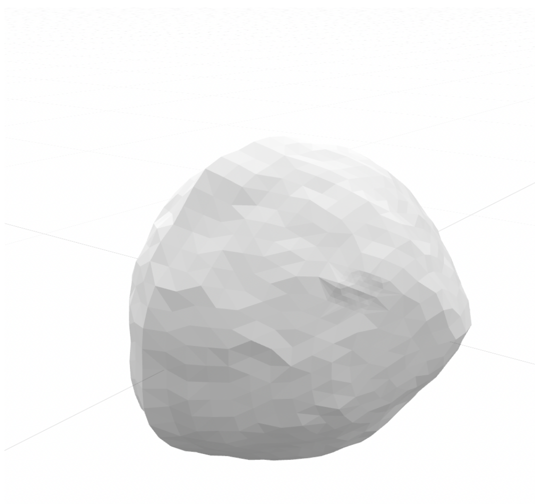
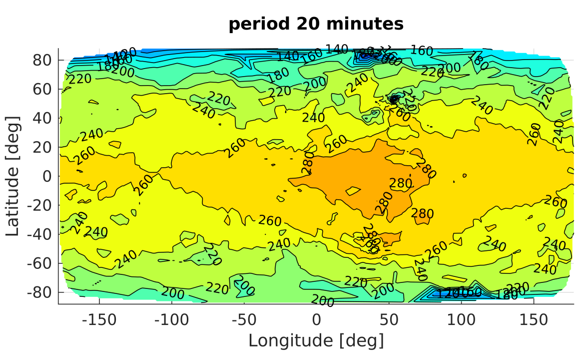


Figure 15: Shape model of HO3

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 see the temperatures.



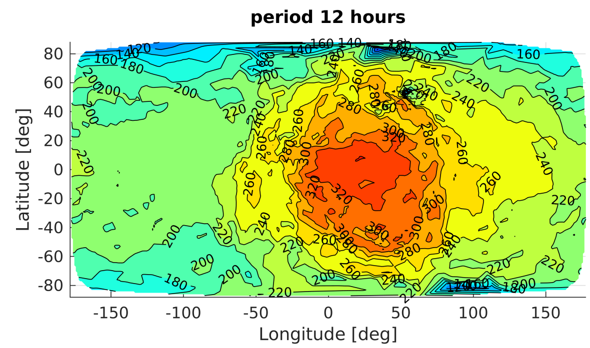


Figure 16: The first three images represent the asteroid with an orbital period fixed as $p_{orbital} = 20$ minutes and a $\Gamma = 500$, on the second line the other three images show an orbital period fixed as $p_{orbital} = 12$ hours and a $\Gamma = 500$

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.

We can apply a thermal map of her shap model using SMBT, using the value from Matlab it show us a 3D map.

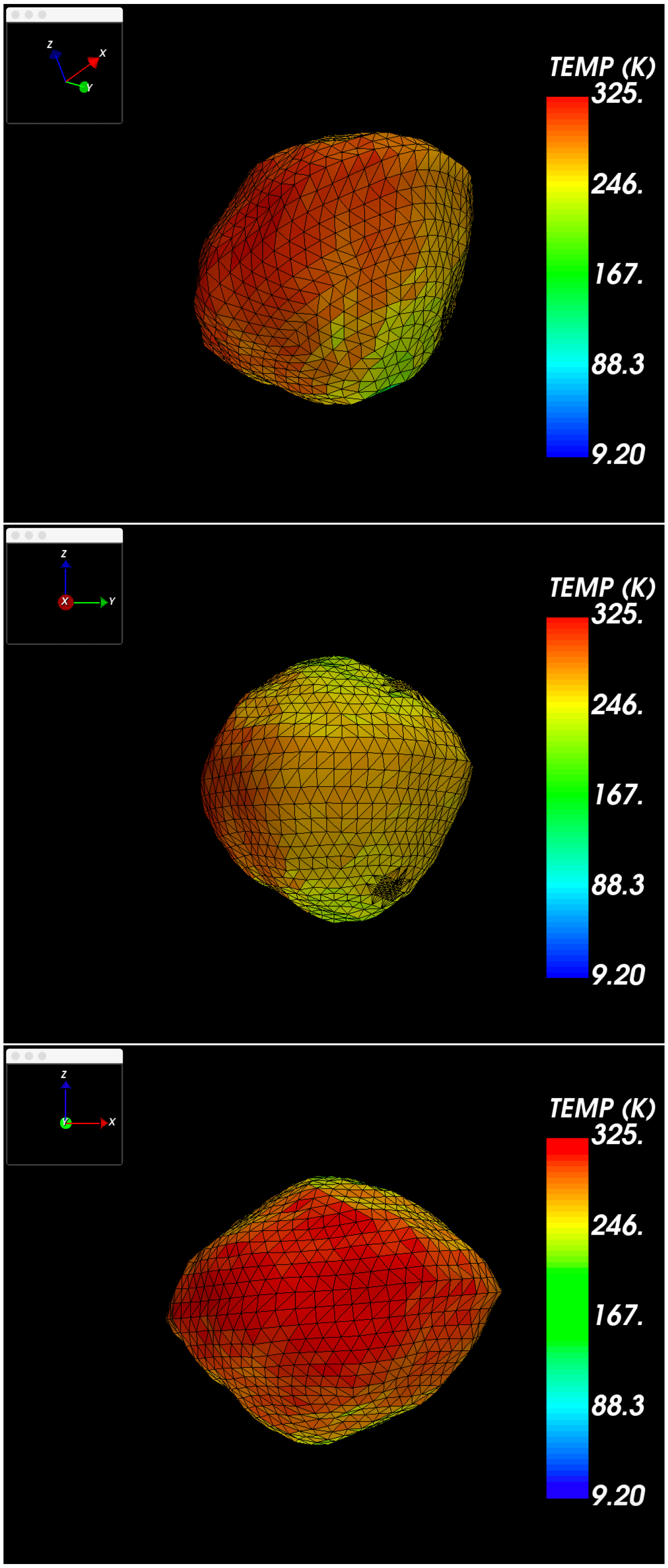


Figure 17: 3D thermal model

8. Surface covering

In order to get a more visual grasp on HERA's vision on Didymoon, we wanted to make use of the NASA/NAIF Spice database, coupled with Cosmographia.

Spice is an observation geometry information system designed by NASA's Navigation and Ancillary Information Facility (NAIF) to assist scientists in planning and interpreting scientific observations from space-based instruments aboard planetary spacecraft.

Cosmographia is an interactive tool used to produce 3D visualizations of planet, spacecraft and other objects in the solar system, while taking into account trajectories positions and orientations.

By combining known positions of Didymoon, Didymain, expected positions of HERA and the characteristics of the on-board AFC (Asteroid Framing Camera), we could recreate a visual representation of the visibility HERA will have on Didymoon during the various mission phases.

We relied on the FOV condition API set of functions (fovray) provided in the NAIF Spice toolkit which verifies if a ray is withing the boundaries of a specified instrument. By using this API, we are theoretically capable of determining which parts of Didymoon are visible at any moment in time.

9. Further works

Hera we talk about the further works.

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