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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:

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

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:

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

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: 2) 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.

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:

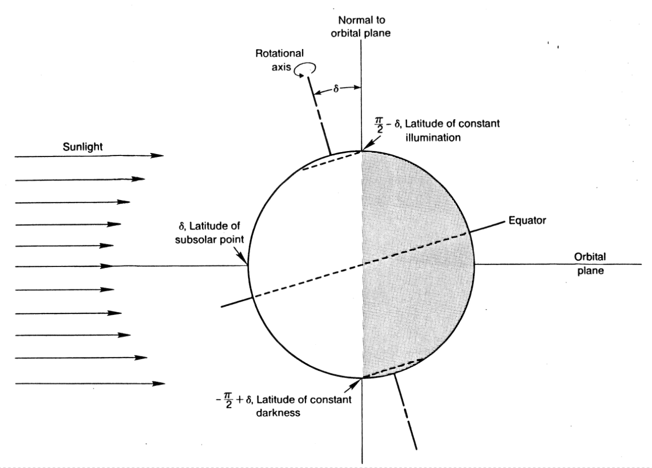


Figure 1: Representation of the obliquity with the orbital plane and the rotational axis

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.

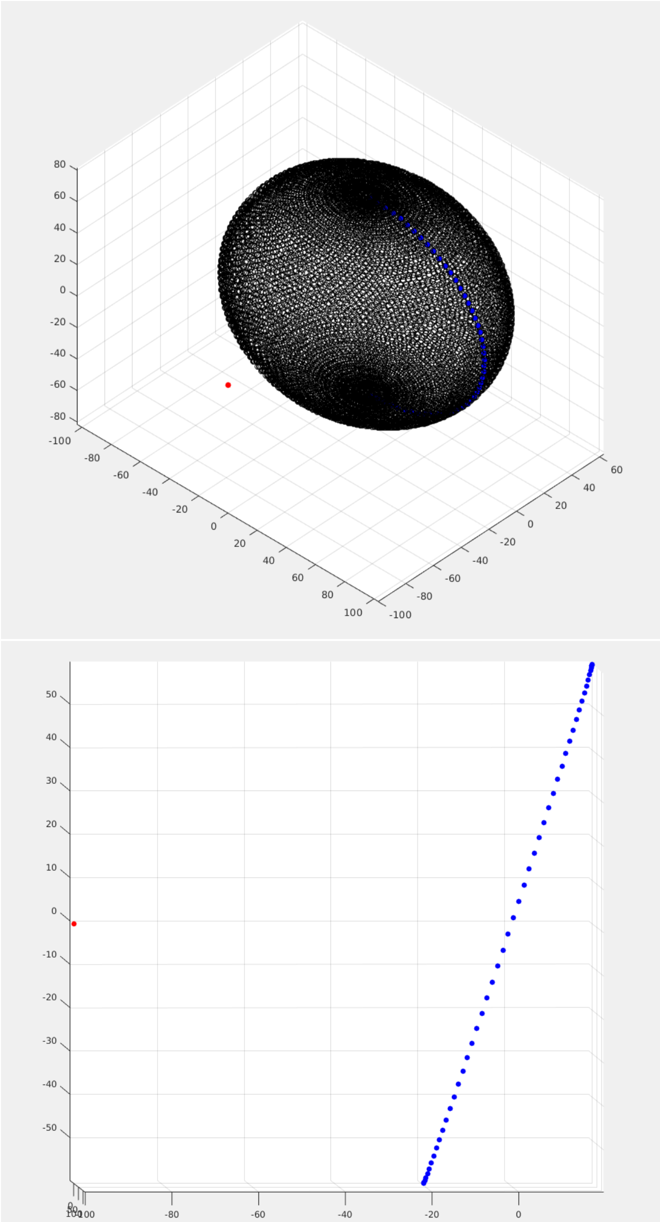


Figure 2: Implementation of the obliquity for the daily surface temperature variation at longitude = 0 degrees on Didymos' secondary. The spin axis is given as 171 ± 9 degrees. Here, the extreme case of 162 degrees has been taken. Black dots are the 80x63x63 meters ellipsoidal shape, blue dots are the meridian at longitude = 0 degrees and red dot is the Sun direction. The first image is the ellipsoidal shape without obliquity and the second image is the meridian tilted.

Simulations are executed at a fixed distance to the Sun with the asteroid rotating.

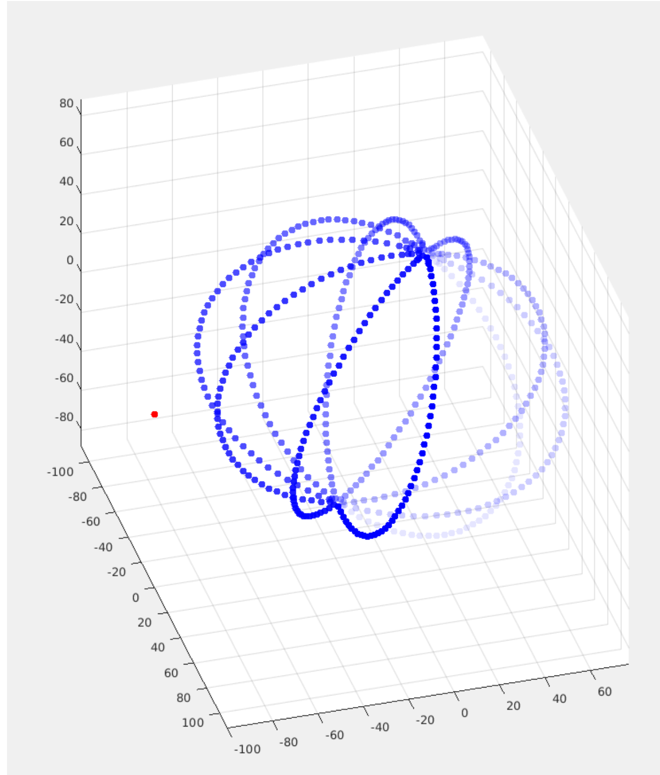
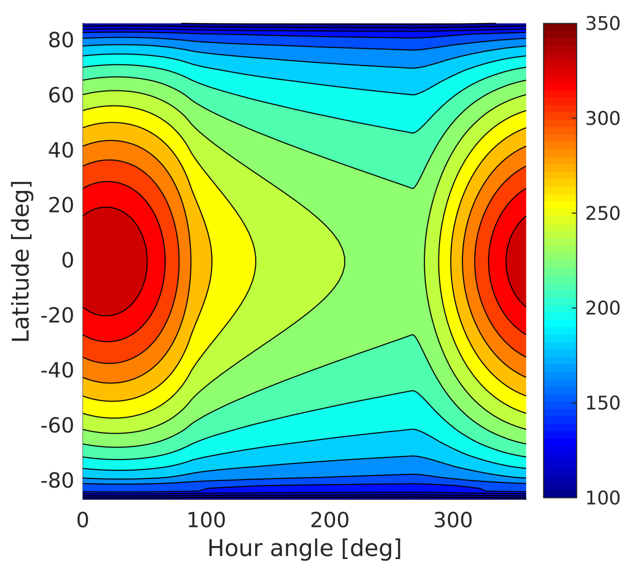


Figure 3: Implementation of the asteroid rotation. A full day represents 11.92 hours. On the figure is drawn the meridian during a full revolution at 10 different times.

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



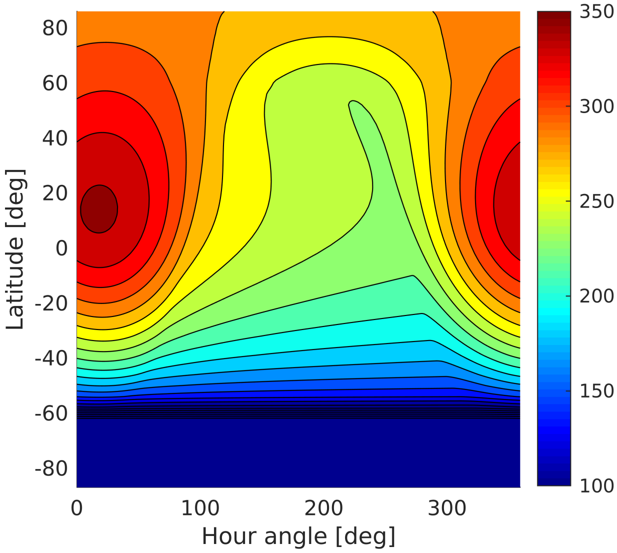


Figure 4: Contour maps of the daily surface temperature variation at longitude = 0 degree on Didymos' secondary for a thermal inertia of Γ = 500 $Jm^{-2}K^{-1}s^{-1/2}$, an heliocentric distance of 1.0748 AU and 162 degrees of obliquity.

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 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. We have take a Γ = 500, A= 0.07, C= 0.25;and rho= 2146; .

The particularity of this asteroid is their speed, we has a speed of v = . Study that asteroid has permit to understand why the speed impact the temperature.

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

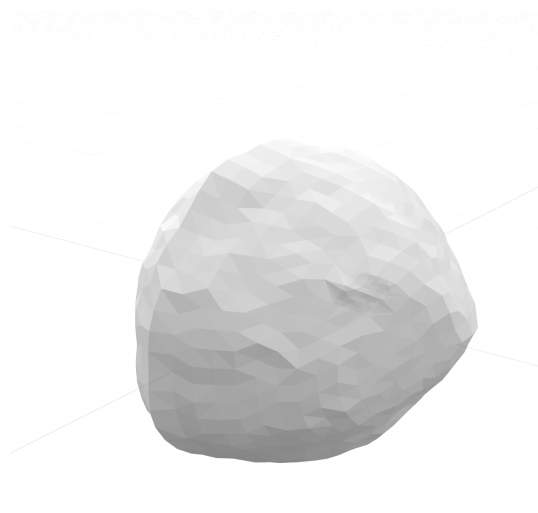
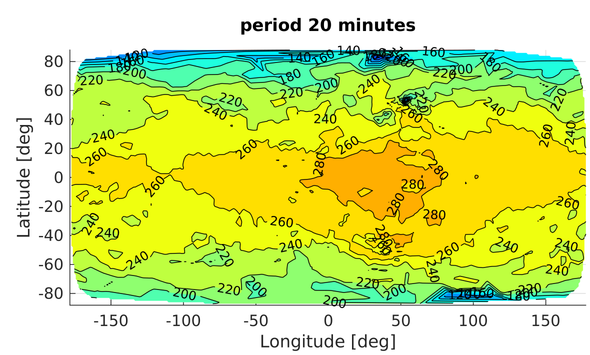


Figure 5: Shape model of HO3

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 will now tried to see the impact of the speed.For that we will take three different speed , and look at the thermal map.



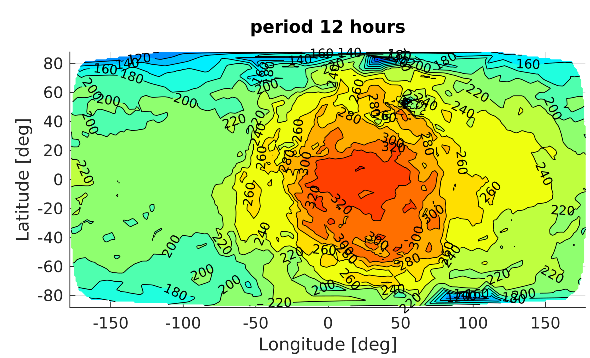


Figure 6: The first three images represent the asteroid with an orbital period fixed as $p_{orbital} = 20$ minutes and a $\Gamma = 500$, on the second line the other three images show an orbital period fixed as $p_{orbital} = 12$ hours and a $\Gamma = 500$

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

References

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