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Thermal Inertia of Small Asteroids From Detailed Thermophysical Modeling

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Abstract

Thermal inertia is a key surface property of asteroids. So far, it has only been determined for large main-belt asteroids (MBAs). We report the thermal inertia of four near-Earth asteroids (NEAs) down to about 300m in diameter. Our results imply that, contrary to expectations, the surfaces of all target asteroids seem to be dominated by thermally-insulating dusty material (regolith), with possible implications to the planning of lander missions and to the magnitude of the Yarkovsky- and YORP-effects.

The derivation of thermal inertia requires a detailed thermophysical model, which is described; it allows not only the asteroid's thermal inertia, but also its size, albedo, and amount of surface roughness, to be determined. Effects due to thermal conduction and the asteroid shape, rotational state, and surface roughness ('beaming') are explicitly taken into account.

Thermal Inertia of Small Asteroids

Thermal inertia = resistance to temperature change

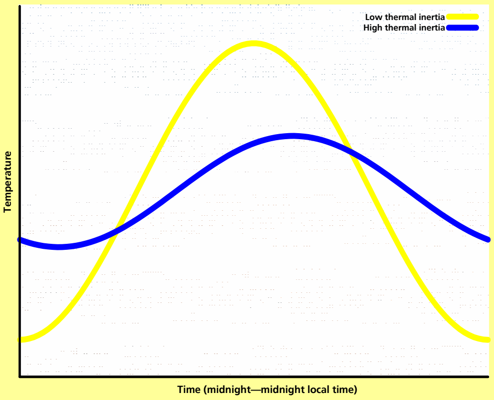

Fig. 1: Materials with a low thermal inertia, such as sand, are cold at night and hot in day-time. The temperature profile of high-thermal-inertia materials, such as the ocean, is much smoother; furthermore, the temperature curve 'lags behind' the insolation.

Significance to asteroid science:

- **Regolith:** The thermal inertia of bare rock is ~ 50 times that of regolith; one can easily tell rock from regolith if the thermal inertia is known. This is widely used in Martian geology; see, e.g., Jakosky 1986.
- **Lander missions:** Thermal inertia determines the temperature profile over a rotation period and thus the time range in which landers are operable.
- **Yarkovsky and YORP:** The afternoon-side is hotter than the morning-side; anisotropically emitted thermal photons carry away linear and angular momentum (Yarkovsky- and YORP-effects). Both effects vanish for very low or high thermal inertia.

Thermal inertia of small asteroids

Name	Thermal inertia ($J\ m^{-2}\ s^{-0.5}\ K^{-1}$)	Diameter (km)	Reference
(1580) Betulia	~ 180	4.57 ± 0.46	Harris et al. 2005
(433) Eros	150—250	~17	Mueller et al. 2005
(25143) Itokawa	~ 350	~ 0.3	Mueller et al. 2005
(33342) 1998 WT24	~ 150		Mueller et al. *in preparation*

For Comparison:

Lunar soil	~ 50		
Bare rock	> 2000		Jakosky 1986
Large MBAs	5—25	>100	Müller & Lagerros 1998

Discussion

- The derived thermal inertia of (433) Eros is consistent with Eros' surface being regolith-dominated and boulder-strewn as seen by NEAR.
- The thermal inertias of the studied small asteroids are higher than those of large MBAs by about an order of magnitude.
- They are consistent with the results of Delbó et al. (cf. Delbó's and Harris' talks): Typical thermal inertias of NEAs appear to be a few 100 $J\ m^{-2}\ s^{-0.5}\ K^{-1}$.
- This is consistent with surfaces dominated by dusty material (regolith) rather than bare rock – even down to some 300m in size. In the case of Itokawa, Hayabusa will soon provide ground-truth.
- Asteroids below an unknown threshold size should consist of bare rock – due to their low gravity they cannot retain collisional debris. Our results may indicate that this threshold size is below 300m, but more data are needed.

Current Spitzer observations

- Using the Spitzer Space Telescope we are observing an ultra-fast rotating small NEA, (54509) 2000 PH5, in order to determine its thermal inertia. Its diameter is ~180m, and its rotation period only about 12 minutes.
- On most of its surface, gravity can not match the centrifugal force, so the asteroid should display a high thermal inertia.
- If even this asteroid were to have a low thermal inertia, all asteroids as 'big' as 180m would be likely to be covered with regolith.

Detailed Thermophysical Modeling

What is a thermophysical model good for?

Most known asteroid diameters are derived from thermal-infrared observations, chiefly from IRAS-data. This requires an appropriate model to describe the thermal emission, which depends on the asteroid's size and other physical properties.

Many widely used thermal models, such as the 'Standard Thermal Model', describe the temperature distribution in a highly idealized way and contain empirical 'correction factors'; this leads to rather high systematic diameter uncertainties.

In a thermophysical model, on the other hand, a realistic description of the temperature distribution is aimed at, solely in terms of the asteroid's physical properties. This enables not only the diameter to be accurately determined, but also some physical surface properties, most prominently the thermal inertia.

Model overview

The model features a physical description of

- the asteroid's shape and spin state,
- thermal conduction causing thermal inertia, and
- 'beaming' due to surface roughness.

To calculate model fluxes, the contributions from all surface elements are summed up; local temperatures are determined using assumed values of size, albedo, thermal inertia, and surface roughness. These model parameters are varied until the best fit to the data is reached.

The model contains no empirical parameters; it can be used to consistently analyze multi-epoch data. It is similar to that proposed by Lagerros (1996, 1998), which was successfully used to describe the thermal emission of large MBAs. As opposed to MBAS, NEAs usually have rather irregular shapes (see, e.g., Fig. 2) and are often observed at large solar phase angles. This requires special care in the model implementation.

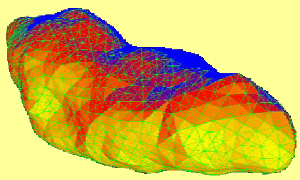

Fig. 2: Temperature distribution on an asteroid with irregular shape: Cold facets are blue, hot facets yellow.

Shape and spin state

The shape is modeled as a mesh of typically a few thousand triangular facets (see, e.g., Fig. 2); physical models of shape and spin state can be derived from the inversion of optical lightcurves, from radar observations, or from spacecraft imaging.

So far, only principal-axis rotation of convex asteroids is supported; a more general model is in preparation.

If the spin axis' orientation is ambiguous (prograde or retrograde), thermal-infrared studies can in principle resolve this ambiguity.

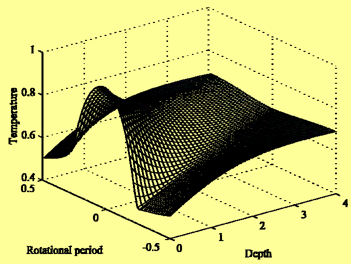

Fig. 3: Vertical temperature profile – the amplitude of the diurnal heat wave decreases with depth.

Thermal conduction

Heat is conducted into and from the sub-soil, leading to thermal inertia, see Fig. 3. On asteroids, the temperature is practically constant below a few centimeters. This *skin depth* is much smaller than the resolution of the shape models, so lateral heat conduction can be neglected.

On each facet the 1D heat diffusion equation is solved numerically using an assumed value of thermal inertia.

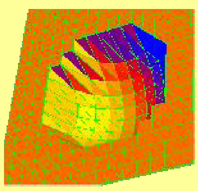

Fig. 4: Temperature distribution inside a crater; temperatures are color-coded as in Fig. 2.

Surface roughness

Roughness causes effects such as shadowing, mutual heating, and multiple reflection of both visible and thermal radiation.

We model surface roughness by cutting sections of hemispheres (craters) into each facet – see Fig. 4. Surface elements inside a crater exchange energy *(mutual heating):* They absorb and reflect radiation emitted or reflected by other surface elements. These effects are fully taken into account.

Variable model parameters are the crater density, i.e. the percentage of the surface covered with craters, and the crater opening angle.

So far, we use an approximation proposed by Lagerros (1998) to combine the effects of thermal conduction and surface roughness. An improved model is in preparation.

Summary

- A detailed thermophysical model has been developed and tested. It is similar to that by Lagerros (1996, 1998), but designed and tested for observations of small NEAs rather than large MBAs.
- The thermal inertias of four small NEAs down to about 300m in diameter have been determined by applying this model to new mid-infrared data.
- Their thermal inertias are significantly higher than those of large asteroids, but consistent with regolith-dominated surfaces.
- **The typical thermal inertia of NEAs appears to be a few hundred $J\ m^{-2}\ s^{-0.5}\ K^{-1}$.** Caveat: This is based on a small data-set.
- Using the Spitzer Space Telescope we are observing a 180m-sized asteroid, which we expect to consist of bare rock and thus to display a high thermal inertia. If regolith were to be found on our target this would suggest that all asteroids as 'big' as 180m are covered with regolith.

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