New insights on thermal properties of asteroids using IR interferometry

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Madrid, March 8th 2012
Thermal properties of asteroids

Physical parameters

Physical information

Scientific interest

Interferometry

Thermophysical modeling

Principle

Application: Main-belt asteroids (41) Daphne and (16) Psyche

Conclusion and perspectives
Introduction
Asteroids and the origin of our solar system

- Asteroids → debris of the planet formation process
- Small → little alteration → conserve pristine material
- Asteroids suffered collisional evolution
- Sizes, shapes, bulk densities, surface properties → collisional evolution
Introduction

Main-belt asteroids

Plot of the positions of the first 5000 asteroids

Size distribution

Bottke et al. (2005)

(1) Ceres

980 km

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Near-Earth asteroids (NEAs)

Location

Size distribution

Introduction

Doom:
- Crash into the Sun
- Ejection out of the solar system
- Impact on a planet

Origin:
- Some are from the main belt
- Some are dead comets
Thermal properties of asteroids
Thermal properties of asteroids: physical parameters

Thermal inertia

Measure of the resistance of a material to a temperature change

\[ \Gamma = \sqrt{\rho \kappa c} \]

in SI units: J.m\(^{-2}\).s\(^{-0.5}\).K\(^{-1}\)

Surface roughness

Surface parameter impacting the beaming effect

Modeled by adding hemispherical craters

\[ \gamma_c : \text{Opening angle} \]

\[ \rho_c : \text{Crater density} \]

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Thermal properties of asteroids: physical parameters

Effect on thermal emission

Thermal inertia

Surface roughness

Smoothing of the surface temperature distribution

Increase of the apparent temperature when surface is viewed at a small solar phase angle (thermal emission ‘beamed’ in the sunward direction)

Opposition effect in the visible (Eugene Cernan on the moon)

Midnight
Noon (insolation peak)


Credits: Michael Light

The opposition effect brightens the area around Eugene Cernan’s shadow due to retroreflective properties of lunar regolith.

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Thermal properties of asteroids: physical information

Thermal inertia

Presence (or absence), depth and thickness of regolith, and presence of exposed rocks on the surface of atmosphere–less bodies

<table>
<thead>
<tr>
<th>(25143) Itokawa</th>
<th>(433) Eros</th>
<th>The Moon</th>
<th>(21) Lutetia</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Gamma = 750$</td>
<td>$\Gamma = 150$</td>
<td>$\Gamma = 50$</td>
<td>$\Gamma = 20$</td>
</tr>
<tr>
<td>Coarse regolith and boulders</td>
<td>Finer and thicker regolith</td>
<td>Mature and fine regolith</td>
<td>Very fine regolith</td>
</tr>
</tbody>
</table>

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Thermal properties of asteroids: correlation with size

Inverse correlation size-thermal inertia

$$\Gamma \propto D^{-\xi}$$

- $$\xi_{small}$$
- $$\xi_{big}$$

NEAs and MBAs with $$D \leq 80-100 \text{ km}$$

MBAs with $$D \geq 80-100 \text{ km}$$
Thermal properties of asteroids: Scientific interest

Strenght of the Yarkovsky effect

Binzel et al. (2003)

\[
\frac{da}{dt} \propto D^{-1}
\]

Semi-major axis drift rate

Bottke et al. (2002)

\[
\Gamma = cte
\]

with D

\[
\frac{da}{dt} \propto D^{-1}
\]

Semi-major axis drift rate

Delbo&Tanga (2009)

\[
\Gamma \propto D^{-\xi}
\]

Size distribution of asteroids injected into the Near-Earth space is modified

Thermal inertia → impact prediction for hazardous asteroids

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Thermal properties of asteroids: Scientific interest

Refinement of size measurements

IR radiometry -> 140000 asteroids measured from simple thermal modeling of IR emission (See Mazieros et al. (2011))

IR flux

Thermal model
(spherical shape, zero thermal inertia)

Albedo size

If non-negligible thermal inertia

STM
Standard Thermal Model (Lebovski et al., 1986)

Diameter underestimation

Albedo overestimation

Spencer et al. (1989)

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Infrared Interferometry
IR interferometry: principle

Telescope plan

Beam collection

Combining plan (focal lab)

Detector

Dispersive element

Beam combination

Formation of interference fringes

\[ I(x, \lambda) = I_0[1 + \cos(a \frac{x}{\lambda})] \]
IR interferometry: principle

Telescope plan

Beam collection

Combining plan (focal lab)

Dispersive element

Detector

Formation of interference fringes

\[ I(x, \lambda) = I_0 [1 + C \left( \frac{B}{\lambda} \right) \cos \left( a \frac{x}{\lambda} + \varphi \left( \frac{B}{\lambda} \right) \right) ] \]

Fringes contrast (visibility) \( \rightarrow V(\lambda) \)

Fringes phase \( \rightarrow \varphi(\lambda) \)

Baseline B
IR interferometry: instrumentation

AMBER
3 telescopes
\[ \lambda \in [1.2 - 2.5] \mu m \]
\[ \theta \sim \frac{B}{\lambda} \in [3 - 25] \text{mas} \]

MIDI
2 télescopes
\[ \lambda \in [8 - 13] \mu m \]
\[ \theta \sim \frac{B}{\lambda} \in [15 - 100] \text{mas} \]

Sensitive enough for observation of MBAs (T \sim 250-300 K)

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Thermophysical modeling
Thermophysical modeling: principle

Shape model
- distances
- rotation axis
- shape and size
Thermophysical modeling: principle

Solar flux absorption

Heat conduction

Thermal re-emission

Temperature calculation

\[ \phi_N = -\kappa \nabla T \]

\[ F_{\text{incident}} \]

\[ F_{\text{emitted}} \]

\[ T_{\text{fac}} \]
Thermophysical modeling: principle

Creation of 2D mid-IR image (each \( \lambda \) and each epoch)

- Mid-IR flux \( \overline{I}(\lambda) \)
- Visibility \( \overline{V}(\lambda) \)
- Baseline B
Thermophysical modeling: principle

\[ \chi^2 = \frac{1}{N_e N_l} \sum_i \sum_j \chi_{i,j}^2 \]

**\( \chi^2 \) calculation**

- **Observations**: \( V(\lambda) \) et \( I(\lambda) \)
- **Model**: \( \overline{V}(\lambda) \) et \( \overline{I}(\lambda) \)
- **\( \chi_{i,j}^2 \)**

\[ \chi_{i,j}^2 = \left[ \frac{I_i(\lambda_j) - \overline{I}_i(\lambda_j)}{\sigma_{I_{i,j}}} \right]^2 + \left[ \frac{V_i(\lambda_j) - \overline{V}_i(\lambda_j)}{\sigma_{V_{i,j}}} \right]^2 \]

**Best-fit value for roughness model, thermal inertia, albedo, size**

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Thermophysical modeling: interest of interferometry

\[ I(\lambda) \propto D_{\text{proj}}^2 \]

\[ V(\lambda) = f(D_{\text{ang}}) \]

At one single epoch, flux + visibility \( \rightarrow \) strong constraint on thermal properties
Observing campaign performed in March 2008 with ATs (baseline = 16m) (four mid-IR visibility and flux measurements)

Big main-belt asteroid (D ~ 220 km)

Spectral properties (albedo) $\rightarrow$ **C-type asteroid** $\leftrightarrow$ primitive carbonaceous chondrite meteorites

**Thermophysical modeling: (41) Daphne**

**Non-convex model** (Carry, 2009)

Lightcurves observations and disk-resolved observations

Shape model
Shape model at the time of VLTI observations

MIDI measurements + best-fit model
Mid-IR Visibility + Flux → TPM

Moderate roughness

\[ 45^\circ \leq \gamma_c \leq 68^\circ \]
\[ 0.5 \leq \rho_c \leq 0.8 \]

(Moon and (1) Ceres → high roughness)

\[ \Gamma < 30 \text{J.m}^{-2}.\text{s}^{-1}.\text{K} \rightarrow \text{very fine regolith} \]

(Moon \approx 50 \text{J.m}^{-2}.\text{s}^{-1}.\text{K} and (1) Cérès \approx 15 \text{J.m}^{-2}.\text{s}^{-1}.\text{K})
Thermophysical modeling: (41) Daphne

Mid-IR Visibility + Flux → TPM

Mid-IR Flux → TPM

Strong constraints brought by IR interferometry

Matter et al., 2011, ‘Determination of physical properties of the asteroid (41) Daphne from interferometric observations in the thermal infrared’, Icarus
Thermophysical modeling: (16) Psyche

(16) Psyche

Main-belt asteroid

Visible and near-IR spectral properties (albedo) → **M-type asteroid** ↔ Ni-Fe or stony-iron meteorites (Hadersen et al., 1995; Ockert-Bell et al., 2010)

**Very high radar albedo** → strong evidence for a metal-rich surface regolith (Shepard et al., 2010)

**size estimates (~ 230-260 km) → densities ≤ 3 g/cm³ (silicate-rich) or densities ≥ 3.5 g/cm³ (metal-rich)** (Baer et al., 2008; Drummond & Christou, 2008)

Is M-type (16) Psyche a dense metal-rich asteroid?  
Origin: fragment of a differentiated body iron core?
New observing campaign performed in December 2010 with ATs (baseline = 16m) (five mid-IR visibility and flux measurements)
Thermophysical modeling: (16) Psyche

Shape model at the time of the VLTI observations

Visibilities and fluxes

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Thermophysical modeling: (16) Psyche

Mid-IR Visibility + Flux → TPM

\[ \gamma_c = 45^\circ \]
\[ \rho_c = 0.5 \]

Low roughness

Thermal inertia > 100 J.m\(^2\).s\(^{-1}\).K

Volume equivalent diameter → ~ 235 km
First conclusions

Smaller diameter (~ 235 km) → density ≥ 3.5 g/cm³

Dense structure

High thermal inertia values (> 100 J.m⁻².s⁻¹.K) → little porosity of the surface

High surface thermal conductivity

Metal-rich regolith and internal structure

In progress: refinement of the shape model + use of complementary data
Conclusion and perspectives
Summary

• First application of IR interferometry to the study of thermal properties of asteroids
  → (41) Daphne: First constraints on thermal inertia and surface roughness (Matter et al., 2011)
  → (16) Psyche: Preliminary results on size and thermal inertia → metallic composition

In progress

Perspectives

New VLTI instrument PRIMA

Larger panel of asteroids observable with MIDI
(expected gain of about 3 magnitudes in V)

Thermal properties    Internal structure
Thank you for your attention