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Evidence of a metal-rich surface for the Asteroid (16) Psyche from interferometric observations in the thermal infrared ☆

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ABSTRACT

We describe the first determination of thermal properties and size of the M-type Asteroid (16) Psyche from interferometric observations obtained with the Mid-Infrared Interferometric Instrument (MIDI) of the Very Large Telescope Interferometer. We used a thermophysical model to interpret our interferometric data. Our analysis shows that Psyche has a low macroscopic surface roughness. Using a convex 3-D shape model obtained by Kaasalainen et al. (Kaasalainen, M., Torppa, J., Piironen, J. [2002]. Icarus 159, 369–395), we derived a volume-equivalent diameter for (16) Psyche of 247 ± 25 km or 238 ± 24 km, depending on the possible values of surface roughness. Our corresponding thermal inertia estimates are 133 or 114 J m^{-2} s$^{-0.5}$ K^{-1}, with a total uncertainty estimated at 40 J m^{-2} s$^{-0.5}$ K^{-1}. They are among the highest thermal inertia values ever measured for an asteroid of this size. We consider this as a new evidence of a metal-rich surface for the Asteroid (16) Psyche.

1. Introduction

Asteroids classified in the X-complex (in the taxonomies by Bus and Binzel (2002) and DeMeo et al. (2009)) are characterized by a visible and near-infrared reflectance spectrum that is essentially featureless and moderately red in the [0.3–2.5] μm region. The spectroscopic X-complex can be split into three taxonomic classes, E, M and P, according to albedo (Tholen, 1984). M-type asteroids are distinguished by exhibiting moderate geometric visible albedos of about 0.1–0.3. Due to the lack of absorption features in the spectrum of M-type asteroids, the nature of these objects remains uncertain. Historically, M-class asteroids were assumed to be the exposed metallic core of differentiated parent bodies that were catastrophically disrupted, and thus the source of iron meteorites (Bell et al., 1989; Cloutis et al., 1990). While the parent bodies of meteorites are usually assumed to have formed in the main belt, Bottke et al. (2006) showed that the iron-meteorite parent bodies most probably formed in the terrestrial planet region. Some of the metallic objects currently located in the main-belt may thus not be indigenous but rather remnants of the precursor material that formed the terrestrial planets including the Earth. Therefore, those objects play a fundamental role in the investigations of the Solar System formation theories. Radar observations provided strong evidences for the metallic composition of a least some M-type asteroids. Very high radar albedos have been measured for various asteroids of this class, consistent with high concentration of metal (Ostro et al., 1985; Shepard et al., 2008). Moreover, the average density of two multiple M-type asteroids, 3.35 g cm^{-3} (Descamps et al., 2008) for (22) Kalliope and 3.6 g cm^{-3} (Descamps et al., 2011) for (216) Kleopatra, appeared to be significantly larger than the density of C-type or S-type asteroids (Carry, 2012). This is a strong evidence of difference in internal composition between M and C-type asteroids. However, recent visible and near-infrared spectroscopic surveys on about 20 M-type asteroids, including those exhibiting high radar albedos, detected subtle spectral absorption features on most of them (Hardersen et al., 2005; Fornasier et al., 2010). The most common one being the 0.9 μm absorption feature, attributed to orthopyroxene, and thus indicating the presence of silicate on their surface. From a survey of the 3 μm spectrum of about 30 M-type asteroids, Rivkin et al. (1995, 2000) also found hydration features on a tens of them. On the basis of these observations, they suggested that the original "M" class should be divided into "M" asteroids that lack hydration features such as (16) Psyche and (216) Kleopatra, and "W" asteroids that are hydrated such as (21) Lutetia. All of that confirms that most of the objects defined by the Tholen M-class have not a pure

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metallic surface composition but contain other species including silicate minerals. Therefore, better compositional constraints for the spectrally featureless bodies like M-type asteroids are essential in order to understand and constrain the thermal, collisional, and migration history of Main-Belt Asteroids (MBAs). This includes the detection of additional absorption features in their reflectance spectra and the determination of their surface properties including surface roughness and in particular thermal inertia.

Thermal inertia (Γ) is a measure of the resistance of a material to temperature change. It is defined by $\Gamma = \sqrt{\rho\kappa c}$, where κ is the thermal conductivity, ρ the material density and c the specific heat. The value of thermal inertia thus depends on the material properties (see Mueller, 2007 and references therein for a table of the thermal inertia value of some typical materials). On one hand, it primarily informs us about the nature of the surface regolith: a soil with a very low value of Γ, for instance in the range between 20 and 50 J m^{-2} $s^{-0.5}$ K^{-1}, is covered with fine dust like on Ceres (Mueller and Lagerros, 1998); an intermediate value (150–700 J m^{-2} $s^{-0.5}$ K^{-1}) indicates a coarser, mm- to cm-sized, regolith as observed on (433) Eros (Veverka et al., 2001a; Veverka et al., 2001b) and (25143) Itokawa (Yano et al., 2006), respectively; solid rock with very little porosity is known to have thermal inertia values of more than 2500 J m^{-2} $s^{-0.5}$ K^{-1} (Jakosky, 1986). On the other hand, thermal inertia can represent a proxy for the surface composition, especially due to its dependency on thermal conductivity and specific heat. This is particularly important in the context of the M-type asteroids study since metal is an excellent thermal conductor, potentially leading to an enhanced thermal inertia. The study of Opeil et al. (2010) showed that thermal conductivity is significantly higher for iron meteorites than for non-metallic ones. This motivates our work of determining thermal inertia on M-type asteroids such as (16) Psyche to assess the change in thermal inertia for asteroids of different composition but having a similar size, knowing that the presence and thickness of the surface regolith is generally assumed to depend on the asteroid's size (see, e.g., Bottke et al., 2005).

The Asteroid (16) Psyche is the largest known M-type asteroid, with an IRAS diameter of 253 ± 4 km (Tedesco et al., 2002). Nevertheless, many size estimates have been reported during the last decade. Cellino et al. (2003) derived an area equivalent diameter of 288 ± 43 km based on speckle interferometry; Lupishko (2006) derived a diameter of 213 km based on considerations on its polarimetric albedo; from adaptive-optics imaging, Drummond et al. (2008) derived a volume equivalent diameter of 262 ± 6 km; Shepard et al. (2008) derived a volume equivalent diameter of 186 ± 30 km based on radar imaging; from the analysis of medium infrared data from the AKARI satellite by means of the Standard Thermal Model (Lebofsky et al., 1986), Usui et al. (2011) derived a diameter of 207 ± 3 km; finally, Durech et al. (2011) derived a volume equivalent diameter of 211 ± 21 km by combining a shape model derived by lightcurve inversion with occultation observations of (16) Psyche. In any case, Psyche appears to be significantly larger than the 30–90 km diameter expected for the metallic core of a differentiated asteroid (Rivkin et al., 2000), questioning a purely metallic nature for this asteroid. All those size measurements led to significant differences between the average bulk density estimations reported in the literature. They range from 1.8 ± 0.6 g cm^{-3} (Viateau, 2000) to 3.3 ± 0.7 g cm^{-3} (Drummond and Christou, 2006) and even 6.58 ± 0.58 g cm^{-3} (Kuzmanoski and Kovačević, 2002), value which is more in agreement with a metallic composition and a very low macroporosity. Nevertheless, by combining all the independent size and mass estimates, an average density of 3.36 ± 1.16 g cm^{-3} was found (Carry, 2012). This is comparable to the density estimates reported for other M-type asteroids like (22) Kalliope (Descamps et al., 2008) and (216) Kleopatra (Descamps et al., 2011). In addition, (Shepard et al., 2010) measured a high radar albedo of 0.42, which is indicative of a metal-rich surface. However, the detection of a 0.9 μm absorption feature suggested the presence of silicates on its surface (Hardersen et al., 2005). In this context, Hardersen et al. (2005) and Shepard et al. (2010) suggested that (16) Psyche may be a collisional aggregate of several objects, including partial or intact metallic cores that have retained a portion of their silicate-rich mantle.

To put tighter constrains on the nature of (16) Psyche, we used mid-infrared interferometry to determine the thermal properties of this asteroid, and refine its size measurements. Interferometry basically provides direct measurements of the angular extension of the asteroid along different directions (Delbo et al., 2009). Interferometric observations of asteroids in the thermal infrared, where the measured flux is dominated by the body's thermal emission, are sensitive to the surface temperature spatial distribution in different directions on the plane of the sky. The typical spatial resolution is about 0.06″ in the case of our Psyche observations. As the surface temperature distribution of atmosphereless bodies is affected by thermal inertia and surface roughness, interferometric thermal infrared data can be used to constrain these parameters. In particular, thermal infrared interferometry can help to remove the degeneracy existing between the effect of the thermal inertia and surface roughness in one single epoch (see Figs. 7 and 8 in Matter et al. (2011)), providing that we have several interferometric measurements with different projected baseline lengths and orientations, during the asteroid rotation. Thermal properties (thermal inertia and surface roughness) can thus be better constrained by thermal infrared interferometry in combination with the classical disk-integrated radiometry. In this context, we obtained interferometric data on (16) Psyche using the MIDI instrument combining two of the Auxiliary Telescopes (ATs) of the VLTI. As in Matter et al. (2011), a thermophysical model (TPM), taking into account the asteroid's orbit, spin, shape, and heat diffusion into the subsurface, was used for the analysis of the whole data set.

In Section 2 we report the observations and the data reduction process that we adopted; in Section 3 we briefly remind the principles of the thermophysical model used for the interpretation of MIDI data, and we detail the shape models that we used; in Section 4, we present our results, followed by a discussion in Section 5.

2. Observations and data reduction

2.1. Observations

The observations of (16) Psyche were carried out in visitor mode, on 2010 December 30. Two ATs were used in the E0–G0 configuration (baseline B = 16 m). Sky quality was relatively good and stable during those nights (see Table 1). We adopted the typical observing sequence of MIDI, which is extensively described by Leinert et al. (2004). For each of the five observing epochs of (16) Psyche (indicated in Table 1), we obtained one measurement of the total flux and of the interferometric visibility, both dispersed over the N-band, from 8 to 13 μm. We used the HIGH-SENS mode, where the total flux of the source is measured right after the fringe tracking and not simultaneously. To disperse the fringes, we used the prism of MIDI, which gives a spectral resolution of $\frac{\lambda}{\Delta\lambda} \approx 30$ at λ = 10 μm. Our observations also included a mid-infrared photometric and interferometric calibrator HD 29139, taken from the ESO database using the Calvin tool,[1] which is the calibrator selector for the VLTI instruments (MIDI and AMBER). We remind that interferometric calibrators are stars that have small and known angular diameter, so that their visibility is close to unity at all wavelengths. This calibrator was chosen to have a minimum angular separation

[1] Available at http://www.eso.org/observing/etc/.