Icarus 309 (2018) 297–337

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Thermophysical modeling of main-belt asteroids from WISE thermal data

J. Hanuš[a,*], M. Delbo'[b], J. Ďurech[a], V. Alí-Lagoa[c]

[a] Astronomical Institute, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, Prague 18000, Czech Republic
[b] CNRS–Lagrange, Observatoire de la Côte d'Azur, Université Côte d'Azur, CS 34229, F 06304 NICE Cedex 4, France
[c] Max-Planck-Institut für extraterrestrische Physik, Giessenbachstraße, Postfach 1312, Garching 85741, Germany

ARTICLE INFO

Article history:
Received 24 July 2017
Revised 9 March 2018
Accepted 14 March 2018
Available online 15 March 2018

Keywords:
Asteroids
Asteroids, surfaces
Asteroids, composition
Infrared observations
Photometry

ABSTRACT

By means of a varied-shape thermophysical model of Hanuš et al. (2015) that takes into account asteroid shape and pole uncertainties, we analyze the thermal infrared data acquired by the NASA's Wide-field Infrared Survey Explorer of about 300 asteroids with derived convex shape models. We utilize publicly available convex shape models and rotation states as input for the thermophysical modeling. For more than one hundred asteroids, the thermophysical modeling gives us an acceptable fit to the thermal infrared data allowing us to report their thermophysical properties such as size, thermal inertia, surface roughness or visible geometric albedo. This work more than doubles the number of asteroids with determined thermophysical properties, especially the thermal inertia. In the remaining cases, the shape model and pole orientation uncertainties, specific rotation or thermophysical properties, poor thermal infrared data or their coverage prevent the determination of reliable thermophysical properties. Finally, we present the main results of the statistical study of derived thermophysical parameters within the whole population of main-belt asteroids and within few asteroid families. Our sizes based on TPM are, in average, consistent with the radiometric sizes reported by Mainzer et al. (2016). The thermal inertia increases with decreasing size, but a large range of thermal inertia values is observed within the similar size ranges between $D \sim 10$–100 km. We derived unexpectedly low thermal inertias (< 20 J m^{-2} s$^{-1/2}$ K^{-1}) for several asteroids with sizes $10 < D < 50$ km, indicating a very fine and mature regolith on these small bodies. The thermal inertia values seem to be consistent within several collisional families, however, the statistical sample is in all cases rather small. The fast rotators with rotation period $P \lesssim 4$ h tend to have slightly larger thermal inertia values, so *probably do not have* a fine regolith on the surface. This could be explained, for example, by the loss of the fine regolith due to the centrifugal force, or by the ineffectiveness of the regolith production(e.g., by the thermal cracking mechanism of Delbo' et al. 2014).

1. Introduction

The recent availability of thermal infrared data obtained by the NASAs Wide-field Infrared Survey Explorer (WISE, Wright et al., 2010) opens exciting possibilities of determining surface characteristics of thousands of minor bodies of our solar system (Mainzer et al., 2011a). This characterisation can be performed by the analysis of WISE data by thermophysical models (hereafter TPM, see Section 3). WISE observations changed asteroid thermophysical modeling from being limited by the availability and accuracy of thermal infrared data to being limited by the availability of the *a priori* information required by the TPMs, namely the spin and shape solutions (Koren et al., 2015). This is why early TPM analyses of WISE data focused on a small number of objects: of near-Earth asteroids (NEAs) (341843) 2008 EV5 (Alí-Lagoa et al., 2014) and (29075) 1950 DA (Rozitis et al., 2014), and four main-belt asteroids (MBAs), four NEAs and 1 Trojan (Hanuš et al., 2015).

The main object characteristics that one aims to determine are thermal inertia Γ, Bond albedo A (or geometric visible albedo p_V), surface roughness $\overline{\theta}$ and volume-equivalent diameter (i.e., the diameter of a sphere with the same volume as of the asteroid shape model). The *shape* can be elongated and in general quite different compared to a sphere. Surface roughness at a scale bigger than the typical diurnal heat propagation distance (few mm to few cm) causes a surface to emit thermal radiation in a non Lambertian way (Lagerros, 1998; Rozitis and Green, 2011; Delbo' et al., 2015). In particular, the absorbed solar flux is preferentially radiated back to the sun, a phenomenon that is called thermal infrared beam-

* Corresponding author.
E-mail address: pepa@sirrah.troja.mff.cuni.cz (J. Hanuš).

https://doi.org/10.1016/j.icarus.2018.03.016
0019-1035/

ing. Thermal inertia is defined as a function of the density of the surface regolith ρ, thermal conductivity κ, and heat capacity C: $\Gamma = (\rho\kappa C)^{1/2}$, and measures the resistance of a material to temperature change, and thus controls the temperature distribution of the surface of an atmosphere-less body. Non-zero thermal inertia breaks the symmetry of the temperature distribution on asteroids. So, Γ directly controls the strength of the Yarkovsky effect, which is the rate of change in the semi-major axis of the orbit of an asteroid ($\mathrm{d}a/\mathrm{d}t$) due to the recoil force of the thermal photons (see, e.g., Bottke et al., 2006; Vokrouhlický et al., 2015).

In the case of asteroids, values between almost zero or below 10 to almost 1000 J m^{-2} s$^{-1/2}$ K^{-1} have been derived (see Table A.2). The lowest values are typical for very large asteroids ($D > 100$ km, Mueller, 2012), large Trojans (Mueller et al., 2010; Horner et al., 2012) and large trans-Neptunian objects (TNOs) (Lellouch et al., 2013). These low thermal inertia values have been interpreted as due to very fine and mature regolith or even fluffy surfaces with extremely high porosities (e.g., Vernazza et al., 2012; Lellouch et al., 2013). Most $D > 100-200$ km MBAs have a thermal inertia of the order of few tens of J m^{-2} s$^{-1/2}$ K^{-1}. On the other hand, much smaller NEAs (sizes from several hundred meters to few kilometers) have thermal inertia values of the order of several hundreds (Delbo' et al., 2015). However, there are almost no thermal inertia determinations for MBAs in a size range of 10–100 km. Our current study fills this gap.

The findings concerning different thermal inertia values between small and large asteroids were later confirmed by the work of Gundlach and Blum (2013): in particular, asteroids with sizes smaller than 100 km in diameter were found to be covered by relatively coarse regolith grains with typical particle sizes in the millimeter to centimeter regime, whereas large asteroids (with diameters bigger than 100 km) possess very fine regolith with grain sizes between 10 and 100 microns. Modeling by Rozitis et al. (2014) suggested a lunar-like thermal inertia characteristic of fine surface regolith on a 1-km NEA. Presence of cohesion forces could prevent the escape of the fine particles driven by the solar wind pressure and the centrifugal force from the surface. So, thermal inertia correlates with the regolith grain size (Gundlach and Blum, 2013). Particularly, objects covered with a very fine regolith (for instance, grain sizes between 10 and 100 microns on asteroids larger than 100 km) have typical values of thermal inertia of the order of 10 J m^{-2} s$^{-1/2}$ K^{-1} (see the compilation in Table A.2 for several examples). On the other hand, coarse regolith grains with typical particle sizes of millimeters to centimeters implies thermal inertia values of several hundred J m^{-2} s$^{-1/2}$ K^{-1} (typical for NEAs).

The database of the WISE thermal infrared asteroid observations, with their unprecedented *photometric* accuracy (often better than 1%) not achievable by current ground-based telescopes and with no contamination by Earth's atmosphere, can be analyzed by means of a TPM in order to derive thermal inertias for several hundreds of asteroids with known shapes models. Typically, shape models are based on radar imaging or on inversion of photometric lightcurves. The lightcurve-based shape models are stored in the public Database of Asteroid Models from Inversion Techniques (DAMIT,[1] Ďurech et al., 2010).

Classically, a TPM is used with an a priori knowledge of the shape and the rotational state of the asteroid. However, the high precision of WISE data introduces a new challenge: as it was already noticed, the shape model plays a crucial role in the derivation of the asteroid physical parameters (Alí-Lagoa et al., 2014; Emery et al., 2014; Rozitis and Green, 2014). This motivated our recent study (Hanuš et al., 2015), where we introduced a *varied shape* TPM scheme (VS-TPM) that takes into account asteroid shape and pole uncertainties, and where we demonstrated its reliability on nine asteroids. Here we apply the VS-TPM method to all main-belt asteroids with lightcurve-based shape models and sufficient amount of thermal infrared data in WISE filters W3 and W4 (see Section 2.1).

We describe the thermal infrared fluxes obtained by the WISE satellite in Section 2.1 and the shape models and the optical lightcurves used for their determination in Section 2.2. The VS-TPM is described in Section 3 and applied to three hundred asteroids in Section 4. In Section 5, we present the main findings of the statistical study of thermophysical parameters within the whole population of MBAs and within few asteroid families. We conclude our work in Section 6.

2. Data

2.1. Thermal infrared fluxes

We make use of the data acquired by the WISE satellite (Wright et al., 2010), in particular the results of the NEOWISE project dedicated to the solar system bodies (see, e.g., Mainzer et al., 2011a). The thermal infrared data were downloaded from the WISE All-Sky Single Exposure L1b Working Database via the IRSA/IPAC archive[2] and processed in the same way as data used in our previous studies focused on asteroid (341843) 2008 EV$_5$ (Alí-Lagoa et al., 2014) and nine asteroids (Hanuš et al., 2015). Bellow, we briefly summarize our procedure, additional details can be found in papers mentioned above.

We consider only thermal data from filters W3 and W4 (isophotal wavelengths at 12 and 22 µm) from the fully cryogenic phase of the mission, because these data are thermal-emission dominated, whilst the fluxes in filters W1 and W2 (isophotal wavelength at 3.4 and 4.6 µm) usually at least partially consist of reflected sunlight for typical main-belt objects.

Our selection criteria are based on a combination of criteria from Mainzer et al. (2011b), Masiero et al. (2011), and Grav et al. (2012). We obtained the reported observation tracklets from the Minor Planet Center (MPC) and used them for a cone search radius of 1″ around the MPC ephemeris of the object when querying the IRSA/IPAC catalogs. We only consider data with artifact flags p, P, and 0, quality flags A, B, and C, and data with a magnitude error bars smaller than 0.25 mag. Moreover, we require the IRSA/IPAC modified Julian date to be within four seconds of the time specified by the MPC and that the data are not partially saturated. A positive match from the WISE Source Catalog within 6.5″ around the tracklet indicates that there is an inertial source at a distance smaller than the point-spread function width of the W1 band. We consider that these data are contaminated if the inertial source fluxes are greater than 5% of the asteroid flux and we remove them. We implement the correction to the red and blue calibrator discrepancy in W3 and W4 filters (Cutri et al., 2012).

We selected only datasets where we had at least 5 points in both W3 and W4 filters. Similarly as in Hanuš et al. (2015), we increased the nominal error bars of the fluxes by factors 1.4 and 1.3 for the W3 and W4 data, respectively. To be more specific, we studied the consistency of the error bars within two WISE measurements of the same source in frames obtained 11 s apart from each other. Such double measurements were allowed due to a 10% field overlap between two subsequent frames. Because 11 s is not enough time for rotation to explain the differences in the observed fluxes, the uncertainties are clearly underestimated and thus we should consider them. To account for that, we decided to enlarge the uncertainties the way they roughly followed the nor-

[1] http://astro.troja.mff.cuni.cz/projects/asteroids3D

[2] http://irsa.ipac.caltech.edu/Missions/wise.html