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# A new method to determine the grain size of planetary regolith

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ABSTRACT

Airless planetary bodies are covered by a dusty layer called regolith. The grain size of the regolith determines the temperature and the mechanical strength of the surface layers. Thus, knowledge of the grain size of planetary regolith helps to prepare future landing and/or sample-return missions. In this work, we present a method to determine the grain size of planetary regolith by using remote measurements of the thermal inertia. We found that small bodies in the Solar System (diameter less than ~100 km) are covered by relatively coarse regolith grains with typical particle sizes in the millimeter to centimeter regime, whereas large objects possess very fine regolith with grain sizes between 10 μm and 100 μm.


## 1. Introduction

Planetary surfaces are exposed to a continuous flux of impactors of various sizes, which have, due to the hyper-velocity nature of the impacts, ground down the initially rocky material to ever finer particle sizes (Chapman, 1976; Housen and Wilkening, 1982). Thus, airless bodies in the Solar System (e.g., Mercury, the Moon, planetary moons, and asteroids) are covered by planetary regolith, a granular material consisting of distinct solid grains (Chapman, 2004). Each hyper-velocity impact causes the ejection of material from the forming crater, which can partly be re-captured by the planetary body if its gravitational escape speed exceeds the ejection velocity (Housen and Wilkening, 1982; Cintala et al., 1978). Fragments with higher velocities are lost into interplanetary space.

Laboratory experiments (Fujiwara and Tsukamoto, 1980; Nakamura and Fujiwara, 1991; Nakamura, 1993; Nakamura et al., 1994) and studies of the crater structures on the Moon (Vickery, 1986, 1987) have shown that hyper-velocity impacts accelerate small fragments to higher velocities than large ones so that we expect that larger planetary bodies possess a finer average regolith grain size than small bodies (Cintala et al., 1978). However, the mean particle size of planetary regolith has, except for the Moon (Duke et al., 1970; McKay et al., 2009), not been measured directly.

In this work, we present a new method to determine the grain size of planetary regolith from remote or in situ thermal inertia measurements (see Section 2 and Fig. 1). Using literature data of the heat conductivity of lunar regolith (Cremers et al., 1971; Cremers and Birkebak, 1971), sampled by the Apollo 11 and 12 astronauts, we fit our published heat-conductivity model of granular material (Gundlach and Blum, 2012, see Section 3) to the lunar regolith and show that the resulting characteristic grain size agrees with the regolith size distribution measured for the Moon (McKay et al., 2009, see Section 4). We confirm the expected anti-correlation between the regolith grain size and the gravitational acceleration of the planetary body for a large number of asteroids, the Moon, the martian moons and Mercury with diameters between 0.3 km and 4,880 km (see Sections 5–8). Our results can help to prepare future landing and sample-return missions to primitive bodies of the Solar System (see Section 9).

## 2. Strategy

To determine the particle size of planetary regolith (see Fig. 1 for a flow chart of our approach), we used literature data of thermal inertiae measured for different airless bodies in the Solar System (see Section 5). The thermal inertia,

$$\Gamma = \sqrt{\lambda C}, \quad (1)$$

describes the resistance of the near surface material of a Solar System body to follow diurnal changes in the irradiation and depends on the heat conductivity $\lambda$ and the volumetric heat capacity of the bulk regolith, respectively. The volumetric heat capacity can be expressed by $C = \phi\rho c$, with the packing fraction $\phi$, the mass density $\rho$, and the specific heat capacity $c$ of the regolith particles. Thus, the thermal inertia depends on the material properties of the regolith and the degree of compaction of the regolith particle layers. We also expect that the heat conductivity depends on the size of the regolith particles as suggested by Gundlach and Blum (2012). With the knowledge of the thermal inertia, the surface-material properties and assumptions about the packing density of the regolith particles, one can thus derive the particle size of the surface regolith.

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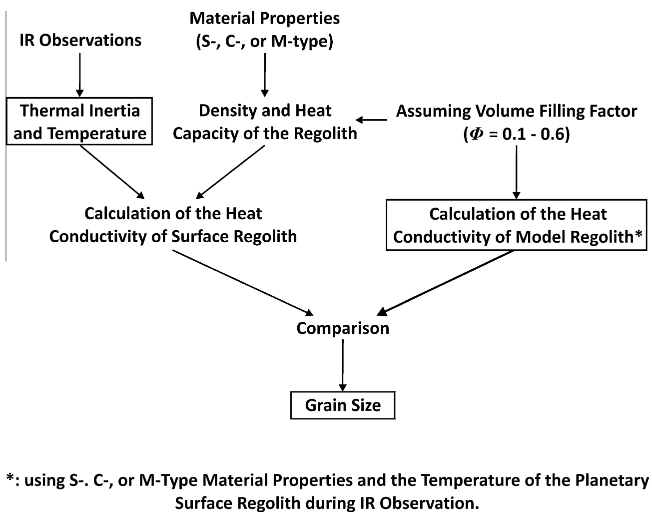


**Fig. 1.** Strategy for the grain size determination of planetary regolith using thermal-inertia measurements.

For the estimation of the mass density and the specific heat capacity of the regolith material, we divided the analyzed bodies into stony (S), carbonaceous (C), and metallic (M) objects (see Section 5). For each of the three classes, the mass density and heat capacity of the material were approximated by the laboratory measurements of these properties of representative meteorites (Opeil et al., 2010), i.e. Cronstad and Lumpkin (S), Cold Bokkeveld and NWA 5515 (C) and Campo del Cielo (M) (see Section 3). In order to take different degrees of compaction of the regolith into account, we treated the volume filling factor (or packing fraction) of the material as a free parameter and varied it between $\phi = 0.1$ and $\phi = 0.6$ in intervals of $\Delta\phi = 0.1$. For each of the six packing densities, we thus arrive at a heat conductivity value. In general, the heat capacity and the thermal conductivity are temperature dependent. Thus, we also derived the surface temperatures of the celestial bodies in our sample at the time of observation of their thermal inertiae. The mean grain size of the planetary regolith can then be determined from a comparison with a modeled heat conductivity of granular materials in vacuum (Gundlach and Blum, 2012, see Section 6).

## 3. The heat conductivity model

The heat conductivity model for regolith in vacuum used in this work was introduced by Gundlach and Blum (2012) and is an extension of the model by Chan and Tien (1973). Regolith is a packing of individual solid particles, in which heat can be transported through the solid network of grains and due to radiation inside the pores of the material. Due to the relatively small contact areas between neighboring regolith particles, the heat conductivity through the particle network is generally much lower than the heat conductivity of the solid material the particles consist of. Radiative heat conduction is favored by large void spaces between the regolith particles, i.e. by a large mean free path of the photons.

The heat conductivity of a granular packing of equal-sized spheres with radii $r$ temperature $T$ and packing fraction $\phi$ is given by

$$\lambda(r,T,\phi) = \lambda_{\mathrm{solid}}(T)\ H(r,T,\phi) + 8\sigma\epsilon T^3 \Lambda(r,\phi) \quad (2)$$

and consists of a conductive (first term on the rhs of Eq. (2)) and a radiative term (second term on the rhs of Eq. (2)). It relates the granular heat conductivity to that of the solid material of the regolith particles, $\lambda_{\mathrm{solid}}$ through the dimensionless Hertz factor $H(r,T,\phi)$ (describing the reduced heat flux through the contacts between the regolith particles) and the mean free path $\Lambda(r,\phi)$ of the photons within the pore space of the granular material. Here, $\sigma$ and $\epsilon$ denote the Stefan–Boltzmann constant and the material emissivity of the regolith grains, respectively. The mean free path of the photons can be expressed by

$$\Lambda(r,\phi) = e_1 \frac{1-\phi}{\phi} r, \quad (3)$$

with $e_1 = 1.34 \pm 0.01$ (Dullien, 1991; Gundlach and Blum, 2012). Thus, the radiative heat conductivity is proportional to the regolith grain size.

Due to the expected smallness of the regolith particles and the low gravity environment for asteroids, the inter-particle forces in the uppermost regolith layers are dominated by mutual van der Waals attraction between the regolith grains and not by the particle weight. Thus, the Hertzian dilution factor for such a granular packing can be expressed by (Gundlach and Blum, 2012)

$$H(r,T,\phi) = \left[\frac{9\pi}{4}\frac{1-\mu^2}{E}\frac{\gamma(T)}{r}\right]^{1/3} \cdot (f_1\ \exp[f_2\phi]) \cdot \chi. \quad (4)$$

The first of the three dimensionless factors on the rhs of Eq. (4) describes the heat-flux reduction due to the neck between the particles caused by the van der Waals force. Here, $\mu$, $E$, and $\gamma(T)$ are Poisson's ratio, Young's modulus, and the specific surface energy of the grain material, respectively. The derivation of this first dimensionless factor is based on the solution of the heat transfer equation for solid spheres in contact. Chan and Tien (1973) extended this to a network of monodisperse spheres in contact. The resulting dilution factor depends on the external applied force acting on the particles. This force determines the Hertzian contact area between the particles and, hence the efficiency of the heat conduction through the network of particles. For large particles on Earth ($r \gtrsim 50$ µm), the heat conductivity can be derived using the weight of the particles. However, for small particles ($r \lesssim 50$ µm) on Earth, the adhesion force (e.g., van der Waals bonding) between the particles is much larger than their weight. For asteroids, for which the gravitational force is comparatively small, adhesion between the particles is always the dominant force in the first few regolith particle layers, determining the contact area between the regolith particles. In order to implement the adhesive force between the particles into the model, we used the JKR theory (Johnson et al., 1971) for the calculation of the force between particles in contact. Using the model by Chan and Tien (1973) and replacing the external force by the internal JKR force, yields the first dimensionless factor on the rhs of Eq. (4).

The second factor on the rhs of Eq. (4) contains the structural information about the particle chains inside the regolith, which can transport heat, with $f_1 = (5.18 \pm 3.45) \times 10^{-2}$ and $f_2 = 5.26 \pm 0.94$ being empirical constants (Gundlach and Blum, 2012).

Finally, the factor $\chi$ describes the reduction of the heat conductivity when the model assumption of monodisperse spherical particles is relaxed towards irregular polydisperse grains of a real regolith. This factor is determined by the calibration of the heat conductivity model using lunar regolith (see Section 4).

Using Eqs. (2)–(4), the heat conductivity of regolith in vacuum can be expressed as

$$\lambda(r,T,\phi) = \lambda_{\mathrm{solid}}(T) \cdot \left[\frac{9\pi}{4}\frac{1-\mu^2}{E}\frac{\gamma(T)}{r}\right]^{1/3} \cdot (f_1\ \exp[f_2\phi]) \cdot \chi + 8\sigma\epsilon T^3 e_1 \frac{1-\phi}{\phi} r. \quad (5)$$

Eq. (5) shows the dependence of the heat conductivity on the grain size of the regolith, which is the only free parameter of the model if the material properties, the regolith temperature, and the volume