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Thermal conductivity measurements of porous dust aggregates: I. Technique, model and first results

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ABSTRACT

We present a non-invasive technique for measuring the thermal conductivity of fragile and sensitive materials. In the context of planet-formation research, the investigation of the thermal conductivity of porous dust aggregates provide important knowledge about the influence of heating processes, like internal heating by radioactive decay of short-lived nuclei, e.g. ^{26}Al, on the evolution and growth of planetesimals. The determination of the thermal conductivity was performed by a combination of laboratory experiments and numerical simulations. An IR camera measured the temperature distribution of the sample surface heated by a well-characterized laser beam. The thermal conductivity as free parameter in the model calculations, exactly emulating the experiment, was varied until the experimental and numerical temperature distributions showed best agreement. Thus, we determined for three types of porous dust samples, consisting of spherical, 1.5 μm-sized SiO_2 particles, with volume filling factors in the range of 15–54%, the thermal conductivity to be 0.002–0.02 $W\,m^{-1}\,K^{-1}$, respectively. From our results, we can conclude that the thermal conductivity mainly depends on the volume filling factor. Further investigations, which are planned for different materials and varied contact area sizes (produced by sintering), will prove the appropriate dependencies in more detail.

1. Introduction

In the field of planet-formation research, the investigation of the physical properties of porous dust aggregates – as analogs for protoplanetary bodies – is of great importance for understanding the evolution of solid matter in young planetary systems. The evolution of the size (distribution) of dust aggregates depends heavily on the collision properties of these particles (see Zsom et al., 2010; Güttler et al., 2010). For larger dust aggregates, other properties become also relevant. Here, we will discuss the thermal conductivity of macroscopic dust aggregates with various packing densities and try to figure out to what extent heating processes can alter their internal structure. Beside globally elevated temperatures in protoplanetary disks and episodic heating events, internal heating of larger bodies by radioactive decay of short-lived nuclei, e.g. ^{26}Al, can lead to significant structural metamorphism of planetesimals (Göpel et al., 1994; Trieloff et al., 2003; Kleine et al., 2008; Prialnik and Podolak, 1999; Prialnik et al., 2008).

Planetesimals are initially highly porous and fragile bodies. As high porosity bodies have only few contacts between neighboring monomers of the material and/or very small contact areas between them, a lower thermal conductivity is expected than in more compact bodies. If a porous body is heated from inside by radioactive decay, sintering between monomer grains in contact can occur. By the formation of inter-particle necks due to the sintering process, the contact areas between the single particles will be enlarged and thus the material solidifies (Poppe, 2003). The larger contact areas of the sintered material would imply a higher thermal conductivity and as a consequence a more efficient and faster heat transport to the surface of the body. The intimate interplay between heating due to low thermal conductivity and an increase in heat flow caused by sintering is a yet unsolved problem in planet-formation research. The question whether these two counteracting effects lead to a complete or partial melting of the body during growth and how such effects influence the further growth and the structural and physico-chemical evolution of planetesimals are yet to be answered.

Although the thermal conductivity of porous media is an important quantity for heat transfer in many other disciplines, like e.g. geology and engineering (e.g. van Antwerpen et al., 2010; Masamune and Smith, 1963), comparable thermal conductivity measurements for highly porous matter do not exist, which vary the bulk porosity and packing structure, use particle sizes in the order of few micrometers, and are performed under vacuum conditions. Most of the literature about heat conduction of particulate materials deals with gaseous or fluid transport through the voids,

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whereas typical gas pressures in protoplanetary disks or (at a later stage) debris disks are so low that the heat transport through the pore space of dust aggregates by gas molecules can be neglected (see also Section 6). Comparable measurements under vacuum conditions or at low atmospheric pressures found in the literature mostly concentrate on larger particle sizes and higher (and often inhomogeneous) packing densities (e.g. Huetter et al., 2008; Kührt et al., 1995, 1969).

The presumably most unaltered protoplanetary material available in the Solar System can be found in comet nuclei, and recent infrared measurements of Comet 9P/Tempel 1 have shown that the thermal inertia $I = \sqrt{k\rho C}$, with k, ρ, and C being the heat conductivity, the density, and the specific heat capacity, respectively, is as small as $I < 50\ \mathrm{W\,K^{-1}\,m^{-2}\,s^{1/2}}$ (Groussin et al., 2007). Assuming $\rho = 100\text{–}1000\ \mathrm{kg\,m^{-3}}$ and $C = 700\text{–}1400\ \mathrm{J\,kg^{-1}\,K^{-1}}$, a thermal conductivity of $k < 1.8 \times 10^{-3}\text{–}3.6 \times 10^{-2}\ \mathrm{W\,m^{-1}\,K^{-1}}$ can be derived. Mind, that the low thermal-inertia values derived by Groussin et al. (2007) are in conflict with a different analysis of the same data by Davidsson et al. (2009), who yield thermal inertias of wide surface ranges of Comet 9P/Tempel 1 of $1000\text{–}3000\ \mathrm{W\,K^{-1}\,m^{-2}\,s^{1/2}}$, whereas only small fractions of the comet surface possess low thermal inertias of $40\text{–}380\ \mathrm{W\,K^{-1}\,m^{-2}\,s^{1/2}}$. The measurement of the thermal conductivity of porous dusty media can, thus, provide information about the morphology and structure of the surface material of comets. Such results are not only important for the early evolution of small Solar System bodies, but also for thermal processes in evolved systems, e.g. for heating and implicit activity of comets with their porous ice structure and dust mantles during passage through the inner Solar System, or the Yarkovsky effect for asteroids that may have regolith on their surfaces.

The thermal conductivity of porous media is affected by a large range of parameters: the bulk material in general (pure or mixed), the temperature, the porosity, the shape of monomers, the size distribution of the grains (mono- or polydisperse), the number of contact points between the particles, the size distribution of the contact area (potentially changed by sintering effects, see Kossacki et al., 1994; Seiferlin et al., 1995), and the structure of the bulk matrix. The latter can be disordered or ordered, and in the ordered case can additionally be divided into isotropic (with simple or complex structure) and anisotropic (isotropic in one plane or not isotropic in any plane).

Many models to describe the evolution of planetesimals or parent bodies of meteorites use thermal conductivity values derived by measurements of chondrites (Miyamoto et al., 1981; Ghosh and McSween, 1998; McSween et al., 2002; Ghosh et al., 2003, 2006; Merk and Prialnik, 2003, 2006; Hevey and Sanders, 2006). However, this material has already undergone several thermally and mechanically induced structural modifications and, thus, cannot correctly represent the primary highly porous state of these bodies. Even an often used correction or reduction factor for the heat conductivity to account for the porosity or the cohesiveness of the bulk material cannot describe the complex correlation between the thermal conductivity and the inner structure of the material to the full extent (e.g. Capria et al., 2002; Seiferlin et al., 1996; Paton et al., 2010). For many decades, extensive studies have been made to describe the relationship between the thermal conductivity and the porosity of two-phase mixtures and porous materials (see reviews by Progelhof et al. (1976) and Cheng and Vachon (1970)). All the semi-empirical equations mentioned in the literature are based on well-defined material configurations and environmental conditions and thus are restricted to specific application problems. In addition to that, most of these formulae consider the porosity as the most important parameter defining the thermal conductivity without including the influence of pore size, pore shape, material structure, etc. In this work, the numerical model reproducing our experimental measurements does not include a detailed theoretical description about the thermal conduction of porous material but uses a reduction factor of the thermal conductivity as a free model parameter (see Section 4), which indirectly but not explicitly includes the manifold structural parameters of the bulk material contributing to the heat conduction.

To understand the intricate dependency between the thermal conductivity and the structure of the protoplanetary body, extensive experimental investigations are needed. The results of these measurements will serve as important material parameters for modeling the internal constitution and thermal evolution of planetesimals and cometary nuclei and generally for other thermal processes such as thermophoresis and photophoresis (e.g. Wurm and Haack, 2009).

For investigating the heat conductivity of porous and fragile dust samples, it is very important to choose an appropriate measuring technique. Conventional methods, like the hot wire or the hot plate method (see review by Presley and Christensen (1997a,b)), all need direct contact to the material. By establishing the contact between the measuring apparatus and the material of loose dust assemblies, the frail inner structure of the dust sample will always be changed in terms of compression or disruption. Compressive and tensile strengths of our materials are typically in the range of a few 100–1000 Pa (Blum et al., 2006), and even the slightest contact with a heating wire will cause unknown local changes of the aggregate morphology. Thus, we have developed a non-invasive technique to measure the thermal conductivity by heating the dust aggregate with a laser beam and recording the temporal and spatial propagation of the heat wave by an IR camera, which is comparable to the laser flash technique (e.g. Parker et al., 1961; Fayette et al., 2000). The temperature distribution on the surface and in the interior of the sample is modeled using variable thermal conductivity values until the best fit to the experimental results is achieved.

In this first publication about thermal conductivity measurements in the context of planet-formation research, we will present the measuring technique and the corresponding model calculations for a set of exemplary dust samples with different porosities and different internal structures, consisting of the same dust type. Further measurements with other protoplanetary relevant materials and diverse sintering stages are under way.

2. Experimental setup

As we expect very low values for the thermal conductivity of porous dust aggregates in the order of $\sim 10^{-3}\text{–}10^{-2}\ \mathrm{W\,m^{-1}\,K^{-1}}$, as indicated by the measurements of Comet 9P/Tempel 1 (Groussin et al., 2007, see above), high-vacuum conditions are required for the measurements, as the presence of (even rarefied) air would significantly contribute to the thermal conductivity. Hence, all measurements were performed in a vacuum chamber at pressures around 10^{-5} mbar. From outside the vacuum chamber, an infrared laser beam (wavelength = 813 nm), an overview camera to align the laser, and an IR camera are pointed through respective windows onto the aggregate inside the chamber. To prevent additional sources for heat conduction, the dust sample is positioned onto a block of insulation material with a thermal conductivity of $\sim 0.022\ \mathrm{W\,m^{-1}\,K^{-1}}$. The thickness of the dust samples is so large that we do not expect a considerable heat flow to this substrate (see Section 5 and Fig. 3). The cylindrically shaped dust aggregate (see Section 3) is directly heated by the laser beam mounted vertically to the surface of the dust sample (see Fig. 1).

During the heating and cooling phase, an IR camera monitors the temporal and spatial temperature distribution of the aggregate's surface at an inclination angle of ~30° to the surface normal. The images of the IR camera have a spatial resolution of ~0.3 mm