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A sensor to perform in-situ thermal conductivity determination of cometary and asteroid material

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Abstract

Measurements of the physical properties of surface and subsurface layers of planetary bodies often provide important information about the structure of the medium and processes that occur there. Thermal properties of the subsurface material of cometary nuclei are crucial in determining the heat and gas transport. Similarly, asteroids' regolith is a buffering zone for the process of heat transfer from the surface to the interior of a body and vice versa. There are space experiments planned to perform temperature and thermal conductivity measurements on a comet (ROSETTA) and one can easily foresee such measurements carried out by future robotic missions on Mars, planetary satellites and asteroids. In this paper we present the results of measurements carried out with a new type of thermal sensors. The elementary cylindrical sensor is made of platinum wire (resistance thermometer) and isotan wire (heating element) that can operate independently. Their advantage is that they use very well known and calibrated materials for temperature sensors (platinum) and for heaters (isotan). By choosing these materials the problems of temperature measurement, calibration and constant heating power are resolved. We interpret the results of measurements made for a number of sensors combined into a long cylinder in teflon, delrin, ice-dust mixture (comet analogue) and regolith-like material in terms of numerical models and show that the obtained values of thermal conductivity are in agreement with what one could expect. Therefore, we can recommend both the sensors and the method of data interpretation for the thermal conductivity determination as very useful tools for future space missions and in laboratory experiments on cometary and asteroid material analogues.

Keywords: Comets; Asteroid's properties; Thermal modeling; Thermal sensor

1. Introduction

Temperature is an important parameter of planetary bodies: it can be used to characterize their surfaces and the process going on the subsurface layers. Exchange of heat between interiors and surfaces of planets and the value of heat flux are important indicators of how these planets have evolved and what is their thermal balance now. For a certain class of planetary bodies, namely the comets, thermal processes determine spectacular features observed from the Earth, such as sublimation of volatile molecules and their expansion into space, followed by dissociation and ionization (Prialnik et al., 2004; Seiferlin et al., 1995).

Heat conduction in subsurface layers of planets, comets and asteroids is closely connected to structural properties of these bodies that can be considered as multiphase, porous media (A'Hearn et al., 2005; Brownlee et al., 2004; Britt et al., 2002; Harris, 1998; Harris et al., 2005; Weissman et al., 2004). Parameters such as porosity, content of volatiles, sublimation temperature of volatile components, cohesion and the size of grains forming the regolith constitute a set of variables that determine the effective thermal conductivity of the porous materials on the surface of asteroids and comets. On one hand, it is of high scientific interest to learn, through laboratory measurements and models, how to describe thermal conductivity as a function

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of structural parameters and composition (Benkhoff and Spohn, 1991; Benkhoff et al., 1995; Benkhoff, 2002; Usowicz et al., 2006). On the other hand, it is important to know how to interpret thermal conductivity measurements performed on planetary objects in terms of subsurface structural properties (Ball et al., 2001; Banaszkiewicz et al., 1997; Hagermann and Spohn, 1999). These two approaches correspond, in terms of mathematical modeling, to direct and inverse problems of data interpretation.

When distant space missions are designed and prepared, it is normal that the number of instruments is limited and only those ones that are robust, reliable and relatively simple are included into the payload. It is therefore not yet feasible that the whole laboratory to study macro- and micro-structure of planetary soils can be sent to the objects in question. Instead one has to rely on measurements of basic physical parameters: temperature, thermal conductivity, compressive strength, etc. The best example is provided by the Rosetta mission with its lander Philae. The latter has on board MUPUS experiment, which is dedicated to investigate physical properties of the Comet 67P/Churyumov-Gerasimenko. It includes accelerometers and thermal sensors (with in-situ thermometers and IR sensors) (Kargl et al., 2001; Kömle, 1997; Kömle et al., 2001; Marczewski et al., 2004; Spohn et al., 2007).

Because thermal measurements are also planned on near future missions, it is important to ensure that the quality of measurements will be the best possible and that their interpretation will provide as much information as it is allowed by the technical and environmental constraints on the set-up of the experiments. This objective gave inspiration to our study. We have started the design a new type of temperature and thermal conductivity sensors that built on our knowledge gained with the ones previously employed e.g. MUPUS (Marczewski et al., 2004), but improve with respect to previous one in several features such as: independent heating and temperature measurement circuits, the usage of four wire method, the accurate calibration of sensors and their modular construction. We also advanced in the interpretation part of the temperature measurements by introducing comprehensive numerical FEM (Finite Element Method) models (Kurpisz, 1991; Seweryn et al., 2005) aimed to deriving the relevant thermophysics parameters of the medium under study. Finally, we carried out a series of experiments with test materials, cometary and asteroid analogues (Gaffey et al., 1993, 2002; Prialnik et al., 2004), in order to check how well the new sensors and models perform. This can be considered as a first step to more detailed and systematic laboratory work.

In Section 2, we describe the sensors. In Section 3, we shortly discuss the thermal conductivity measurement methods used and present the numerical approach we intend to employ. Section 4 is devoted to the description of our experiments and provides their interpretation in terms of thermal conductivity deduced from the measured temperature time dependence.

2. Sensor description and experimental set-up

The temperature sensors used in space for in-situ measurements are mainly of two types: thermocouples and resistance thermometers. Thermal conductivity measurements are usually carried out by heating the medium and observing how its temperature changes with time. A medium with higher conductivity absorbs heat energy faster than a less conductive material, hence its temperature increase is slower. This is the principle of operation of ‘hot rod’-type sensors, in which a long and thin metal cylinder is used as a heat source and temperature sensor. Asymptotically the temperature of such cylinder changes linearly with the logarithm of time ($\log t$) (Healy et al., 1976) and the slope of this linear function is inversely proportional to the thermal conductivity of the surrounding medium. Although this method has been successfully used in uniform media on the Earth it is not too well suited to measure thermal conductivity of layers, the structure and thermal properties of which vary over a scale length that is small compared with the length of the rod. Such a situation can most probably be expected in the first subsurface meter of a cometary nucleus, where, according to the models, properties of the medium may change significantly (Davidsson and Skorov, 2002a,b; Davidsson et al., 2007; Skorov et al., 1999, 2002). This argument was taken into account when MUPUS thermal sensors for the Rosetta-Philae lander were designed. In the MUPUS experiment 16 ring-like sensors of different width were put inside a 37-cm long hollow tube. The sensors at the top of the tube were narrow (about 1 cm), while the ones at the bottom were rather wide (about 4 cm). This design was chosen to guarantee a good spatial resolution in a medium where the temperature can change exponentially from the surface to the depth. The resistive part of the MUPUS sensors is made of less than 1 μm thin titanium film sputtered on kapton foil. Although the sensors were proved to work very effectively, two problems were met during the instrument development. First, the sensors had to be calibrated independently and showed quite different specific resistance than the bulk titanium. Second, due to constraints of the space mission, the front-end electronics controlling the sensor heating does not allow to keep constant supplied power during the experiments. The interpretation of data is therefore much more difficult than for the constant power case. In fact, it is not a problem to provide a stable electric voltage/current source for a spacecraft instrument, using, for instance, typical military COTS electronic elements (e.g. AD584). Much bigger influence on the effective power delivered to the heater has its temperature – resistance characteristics. The temperature-dependent shift of the resistance (and hence the power) can be compensated by an appropriate electronic circuit, on the expense of increasing circuit complexity.

For the reasons above, we have come to the idea of designing a different type of sensors free of the problems presented above. First of all, we looked for well calibrated