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Photometry and bulk physical properties of Solar System surfaces icy analogs: The Planetary Ice Laboratory at University of Bern

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ABSTRACT

We have designed and constructed an original facility to characterize the VIS–NIR Bidirectional Reflectance Distribution Function (BRDF) and some complementary bulk physical properties of planetary analog samples containing water ice. The central part of the facility is a highly accurate gonio-radiometer (PHIRE-2) operating in the VIS–NIR spectral range (400–1100 nm) installed in a large laboratory freezer. Its development was based on the experience gained on the gonio-radiometer PHIRE-1 (Gunderson et al., 2006). The PHIRE-1 design was modified to permit operations at sub-zero temperatures and to optimize the performance of the instrument. The photometric measurements are complemented by a detailed simultaneous characterization of the physical state and possible temporal evolution of the samples using a combination of macro- and micro-imaging, thermal, electrical and sample mass measurements. The modified design will support the interpretation of current and future remote sensing and in-situ datasets on icy planetary objects with a special emphasis on cometary nuclei, Martian polar regions and Jovian satellites.

1. Introduction

Water ice dominates the bulk and surface compositions of solid objects in the Outer Solar System: comets, satellites of giant planets, Kuiper Belt Objects (KBO). A deep understanding of its physical state, reactivity and associations with other molecules is thus of importance for the study of these bodies. In the inner Solar System, the Mars exploration program has largely been focused in the last decades on the inventory of current reservoirs of H_2O and on the role of this molecule in the long-term evolution of the red planet (Hubbard, 2008). The presence of water ice at the poles of our Moon, possibly stored in the permanently shadowed floors of craters, has been a major topic of discussion with potential implications for the human exploration of the moon (Feldman et al., 1998; Colaprete et al., 2010). This same mechanism of water-ice storage has also been hypothesized for the polar regions of Mercury (Paige et al., 1992).

Water can be detected by several techniques with each one providing additional information on the physical state. Visible imaging is efficient, under certain conditions, for the identification of water ice because of its high contrast of albedo and color with mineral surfaces. It also provides valuable information on the geological context of the identified ice deposits (e.g. Byrne et al., 2009). However, the main limitation of visible imaging is the difficulty in distinguishing water ice from other condensed volatiles, for example, CO_2 ice. Near-infrared (1–5 μm) reflectance spectroscopy and imaging is the most appropriate method to identify water ice, because of the strong spectral signatures in this range (Clark, 1981a, 1981b). Other volatiles, mineral and organic components that may be associated with water ice can also be identified but may also lead to possible confusion, for example between water ice and hydrated/hydroxylated minerals (Pommerol et al., 2009; Beck et al., 2011). For both the visible and near-infrared techniques, additional information can be obtained through the use of measurements performed under a series of different geometries (e.g. Hapke, 1993; Shkuratov and Grynko, 2005). The phase function of solid granular materials is sensitive to both their nature and their physical properties. Physical modeling of the reflection process should, in principle, allow retrieval of some of these parameters with more accuracy. For this reason, it is important to be able to test the models in the laboratory where it is possible to vary independently each of the parameters that influence the measurements (Gunderson et al., 2006; Shepard and Helfenstein, 2007; Shkuratov et al., 2007; Pommerol and Schmitt, 2008b).

Thermal infrared and gamma ray/neutrons spectroscopy also provide indirect indications of the presence of water ice (Feldman et al., 2004; Bandfield and Feldman, 2008), from the retrieval of surface temperature and subsurface (< 1 m) hydrogen concentrations, respectively. Determination of surface temperature also permits derivation of the thermal inertia, a physical parameter that provides important information on the nature and density of

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materials in the first centimeters to tens of centimeters below the surface (Putzig et al., 2005). Radar mapping and sounding also allow mapping of water ice both on planetary surfaces and in the first kilometers of the subsurface (Mouginot et al., 2010) because of the contrast in the dielectric constant between water ice and common rocks (Campbell and Ulrichs, 1969).

Together with the design and operation of powerful on-board instruments, laboratory measurements are crucial to retrieve the maximum information from remote-sensing. As the joint use of different methods of observation on the studied object gives more robust and meaningful results, it is also important to perform laboratory studies using multiple complementary techniques, simultaneously. Studies using these techniques have been conducted with many mineral and rock samples and surfaces; however studies are sparser for samples containing water ice, because of a number of experimental challenges imposed. First, as it is necessary to work at sub-zero temperatures, cooling systems and cold-compliant instrumentation have to be used. Second, the production and storage of well-characterized samples is not trivial as samples may evolve during or between measurements, depending on the environmental conditions.

In this paper, we describe a new experimental facility, the Planetary Ice Laboratory, constructed at Physikalisches Institut, Universität Bern, to investigate the photometric and bulk physical properties of materials containing water ice, prepared as plausible analogs of various Solar System surfaces. In the "Background" section, we focus on the description of past experimental studies with water ice samples that are the most relevant for the development of our own facility. We then describe this facility and detail the design of its central piece, the PHIRE-2 gonio-radiometer. In following section, we report on the calibration and performance of the facility and present examples of measurements. Finally, we conclude by describing the future studies that will be performed with the facility.

2. Background

The aim of this section is to present some previous experimental studies of icy analogs in the context of planetary sciences that are particularly relevant for the development of our facility. In general, there are few experimental studies dedicated to the characterization of icy planetary analogs (as opposed to mineral or organic analogs), despite the importance of icy surfaces in the Solar System. This is because, in part, of the necessity of building and operating instrumentation to work at sub-zero temperatures and because of the difficulty in producing well-characterized and stable samples for the measurements.

Stephens and Gustafson (1991) measured the bidirectional reflectance of mixtures between water ice and dark particles for phase angles between 40° and 90° in the visible spectral range. They observed significant temporal variations in the spectral and bidirectional scattering behaviors of the samples as their surface layer evolved by progressive sublimation from the top (appearance of a "surface mantle") and emphasized the importance of this process for the comparison between laboratory experiments and spacecraft observations of planetary bodies.

Roush et al. (1990), completing and enhancing previous studies by Clark (1981a, 1981b) and Clark and Lucey (1984), measured the near-infrared reflectance spectra of intimate mixtures between water ice and minerals over the 0.6–4.5 μm wavelength range. The authors prepared their samples by first mixing size-sorted mineral powder with distilled water in known proportions. Then this mixture was quickly frozen and maintained at liquid nitrogen temperature. Finally, the solid sample was ground and sieved and the resulting powder was placed in the sample holder. These experimental results were used to interpret spectra of the Jovian Moon Callisto, leading to the conclusion that some hydrated minerals must be present on the surface, mixed with water ice.

The KOSI (KOmeten-SImulations) experiments performed at the DLR space simulator in Köln between 1987 and 1993 (i.e. Grün et al., 1991; Seidensticker and Kochan, 1992; Benkhoff et al., 1995; Kossacki et al., 1997) permitted significant progress on the understanding of the behavior of water ice samples placed under simulated space conditions. Specific procedures for the sample preparation and storage were also developed for these experiments. Granular porous water ice was produced by spraying liquid water into liquid nitrogen, generating small aggregates of particles with diameters ranging between 10 and 250 μm. The sublimation rate and thermal state of large samples of porous water ice were studied as a function of simulated solar irradiation with important implications for the thermal structure of the near-surface layer of cometary nuclei during their trajectory around the sun.

More recently, Bryson et al. (2008), Chevrier et al. (2008) and Chittenden et al. (2008) studied the influence of temperature, wind speed and dust coverage on the sublimation of pure compact water ice under Martian conditions of pressure and temperature. Their conclusions, consistent with previous theoretical investigations (Ingersoll, 1970), show that temperature is the most important parameter that controls ice sublimation and that wind has only a minor influence on sublimation rate.

Seiferlin et al. (1996) measured the thermal conductivity of porous H_2O ice, as well as CO_2 ice and mineral powder at low temperature and pressure, representative of the conditions at the surface of Mars and cometary nuclei. Porous water ice was produced according to the procedure already used for the KOSI experiments and described previously. For comparison purposes, pellets of water ice were also produced from direct freezing of liquid water. The authors emphasized the strong influence of the characteristics and temporal evolution of sample's texture on the retrieved thermal parameters.

Heggy et al. (2007) report on laboratory measurements of the dielectric constant of water ice/basaltic dust mixtures in the 1 MHz–3 GHz spectral range. Samples were prepared by mixing mineral powder with liquid water in known amounts and then freezing the resulting liquid directly into the dielectric cell used for measurements. They clearly observe an increase in dielectric constant as the amount of dust in ice increases. Stillman et al. (2010) also measured the dielectric properties of ice/silicates mixtures and detail the strong effects of the presence of brines, adsorbed and unfrozen water on the dielectric constant.

In addition to being sparse and often incomplete, laboratory measurements on samples containing water ice are performed by different teams around the world that use different preparation procedures and different sample physical parameters. Very often, the state of the samples is poorly documented. The possible temporal evolution of the state of the samples during the course of experiments is also a major issue, as emphasized in various studies. Under these conditions, reproducibility of laboratory measurements is far from being guaranteed and inter-comparison between measurements performed with different methods remains highly challenging. These considerations have driven the design of the facility built at University of Bern.

3. Development of the Planetary Ice Laboratory

3.1. The PHIRE-2 gonio-radiometer

The central part of the Planetary Ice Laboratory is the PHIRE-2 gonio-radiometer (Fig. 1) designed to measure the bidirectional