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Constraining the parameter space of comet simulation experiments

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ABSTRACT

Our interpretation of the data returned by Rosetta and other cometary missions is based on the predictions of theoretical models and the results of laboratory experiments. For example, Kossacki et al. (2015) showed that 67P's surface hardness reported by Spohn et al. (2015) can be explained by sintering. The present work supports Rosetta's observations by investigating the hardening process of the near-surface layers and the change in surface morphology during insolation. In order to create as simple an analogue as possible our sample consists of pure, porous H_2O ice and carbon black particles. The observations suggest that translucence of the near-surface ice is important for enabling subsurface hardening. As an end product of our experiments we also obtained carbon agglomerates with some residual strength.

1. Introduction

The space missions Giotto, Deep Space I, Stardust, Deep Impact, EPOXI and, most recently, Rosetta have substantially contributed to our understanding of the processes driving the activity of comets. Especially Rosetta and its lander Philae obtained information on 67P/Churyumov–Gerasimenko (hereafter 67P) on unprecedented scales, observing from orbit and on the surface of the nucleus.

The Rosetta mission also marks the first time that a detailed map of a comet nucleus could be generated. Images of comet 67P taken by the OSIRIS imaging system (Keller et al., 2007) show a wide variety of different structures and textures. This includes dust-covered terrains, smooth terrains, 'brittle' materials with pits and circular structures, large-scale depressions, and exposed consolidated surfaces (El-Maarry et al., 2015; Thomas et al., 2015). Higher resolution OSIRIS data also gave evidence of bright icy outcrops on the surface of 67P (Pommerol et al., 2015). These meter-sized bright spots are widespread on the surface within the different areas.

As discussed by Barucci et al. (2016) the detection of the spectral signatures of H_2O ice in these bright spots confirms that they are icy. In their studies they compared 13 of the bright spots identified by OSIRIS with data obtained by the VIRTIS instrument (Coradini et al., 2007). Eight of them show clear evidence of H_2O ice in their spectra, with a surface water content reported to range from 0.1% to 7.2%. Bright spots could also be observed at other periodic comets. For example Comet 9P/Tempel 1 (Sunshine et al., 2006) and 103P/Hartley 2 (Li et al., 2013) also revealed the presence of intriguing bright spots on their surfaces.

Some data collected by the various Rosetta instruments warrants further investigation by laboratory experiments: The evidence of surface water ice in active regions whilst large parts of the nucleus surface remain covered in dark dust has puzzled researchers since the Giotto days. Moreover, the morphology of the nucleus surface raises questions which physical processes might lead to the shaping of, e.g., the layer-like surface features or smooth-floored pits (Birch, 2017).

A number of comet simulation experiments have helped improve our understanding of the physics that drives cometary activity and thereby shapes cometary nuclei. The KOSI campaign (KOmeten SImulation, i.e. comet simulation) of the late 1980 s to early 1990 s was one of the largest and possibly most ambitious campaigns. KOSI was prompted by the appearance of comet 1P/Halley and the Giotto mission in 1986 and supported the design of the Rosetta mission. A review of the main results and their critical analysis can be found, for example in Lämmerzahl et al. (1995), Kochan et al. (1998) and Sears et al. (1999). KOSI included 11 large scale experiments and several small scale experiments (e.g. Kömle et al., 1996). Although those experiments provided crucial new insights into the physics and morphology of cometary analogue materials, the set-up was very complex. Moreover, several experimental parameters were changed at any given time, which makes it difficult to analyse all results in a quantitative manner.

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In order to minimize these difficulties and to create a solid experimental foundation for further theoretical investigations, a change in experimental scale took place, with small-scale experiments performed under conditions approximating those in the environment of cometary nuclei, focusing on phenomena that had not been directly or fully addressed in previous experiment campaigns. Gundlach et al. (2011) investigated the temperature dependent sublimation properties of hexagonal water ice and the gas diffusion through a dry dust layer covering the ice surface. Brown et al. (2012) investigated the characteristics of ice sublimation. The influence of a small amount of dissolved minerals on the temperature dependence of the sublimation coefficient of ice was investigated by Kossacki and Leliwa-Kopystynski (2014). Pommerol et al. (2011, 2015) and Poch et al. (2016) focus on the characterisation of the visible spectrophotometric properties of analogues of solar system icy surfaces with comets as a key aspect.

Small-scale experiments involving less complexity than the simulations of the KOSI era allow us to isolate the key parameters and processes involved in cometary activity. In order to investigate solar light absorption by a porous dust-ice mixture, a series of experiments was carried out in the Open University's Planetary Ices Laboratory. Our model comet consisted of only two ingredients: H_2O ice and carbon particles (carbon black). These samples were irradiated for several hours, temperature and hardness profile were measured and the change of the surface structure recorded. The dependence of sample evolution on subsurface solar light absorption by dark admixtures to the ice was studied by varying quantities of carbon particles added to the porous H_2O ice. Against the backdrop of the Rosetta's observations, showing a comet that, in terms of composition, appears to be more of a slightly icy rubble pile than a dirty snowball, our samples may seem like a poor analogue because they consist almost entirely of water ice. However, the purpose of our experiments is not to simulate as accurate a comet analogue as possible; this is what the KOSI experiments did, informed (and constrained) by the state of knowledge at the time. Instead, our aim is to understand the origin and mechanisms cometary activity: where energy is absorbed, how dust ejection is achieved and how the physical properties of the icy component of a comet changes. This is best investigated using a simple setup like ours. Our setup ensures efficient absorption of solar radiation at depth by the carbon particles whilst maintaining translucence of the ice.

2. Laboratory experiments

The set-up for our experiment was as follows: a cylindrical container consisting of two Perspex half shells (inner diameter of the container $d = 12.4\,\mathrm{cm}$) was installed on a nitrogen-cooled base plate inside an environmental chamber. The base plate was pre-cooled to an initial temperature T_0 while the chamber was depressurised. After the base plate had reached T_0, the chamber was opened, the container filled with the sample material and the chamber was then closed and depressurised again. The sample was cooled until the temperature gradient inside it had stabilised. Then the sample was irradiated using a Solar Simulator with an AM0 filter for several hours. During the irradiation phase T_0 was kept constant and the temperature profile inside the sample was measured using a vertical array of RTD sensors (PT100) with a spacing of 1 cm, starting 1 cm from the base plate. Additionally, a time-lapse record of the morphology of the sample during the irradiation phase was obtained using a set of commercial off-the-shelf webcams.

The ice for the samples was produced by spraying deionized water into LN_2 using a commercial spray gun. In doing so the droplets froze out immediately and settled at the bottom of the Dewar to form a loose aggregate of small spherical particles. These ice particles were subsequently sieved which led to samples including grain sizes of $d_{ice} \leq 1.0\,\mathrm{mm}$, with a random size distribution within that range. A small amount of carbon particles (carbon black CAS# 1333-86-4, $d_c \leq 300\,\mathrm{nm}$) by weight was added to the ice grains and mixed by stirring. Carbon black was chosen to obtain a darker material whilst trying to keep the composition of the mixture as simple and chemically inert as possible and therefore a low albedo like observed at comets. The hardness of this basic granular mix is about 4–6 kPa. For comparison, the surface hardness of freshly fallen snow can range from 2.5 kPa to 10 kPa (Pomeroy and Brun, 2001).

Hardness was measured using the method described by Poirier et al. (2011). In their method, a ball is dropped from a known height onto the sample. Hardness is then calculated from the kinetic energy of the impactor and the volume of the impact crater formed. Poirier et al.'s method effectively measures dynamic hardness which, according to Epifanov (2004) translates into ultimate tensile strength divided by 0.383. In order to obtain the best results, we gradually varied the size of the balls (16.5–32.7 mm), their density (we used wood, glass, metal), and the drop height (300–426 mm), depending on sample hardness. Although this method is more accurate than using a handheld field penetrometer, a measurement error of up to 20% remains (Grabowski, O. private communication).

The samples in our experiments were $h_0 = 15\,\mathrm{cm}$ high, with a density of $\rho = 461 \pm 66\,\mathrm{kg/m^3}$. Using $\rho = 917\,\mathrm{kg/m^3}$ for the density of water ice (e.g. Steiner et al., 1991), this translates directly into a corresponding porosity of $\varphi = 0.5 \pm 0.07$. This value is comparable to the density of $470 \pm 45\,\mathrm{kg/m^3}$ of 67P reported e.g. by Sierks et al. (2015).

The temperature of the base plate was set to $T_0 = 173\,\mathrm{K}$. Whilst the initial conditions were left unchanged for the entire series of experiments, the percentage of carbon added was varied between 0.02% and 0.5%. The samples were irradiated for 18 hours with an insolation intensity of approximately $650\,\mathrm{W/m^2}$.

Strictly speaking, insolation intensity does not remain constant during the experiments as shadowing effects occur for two reasons. Firstly, water condensate on the view port results in reduction of insolation over a small area (usually the centre) of the view port for the first 15 to 20 minutes. Secondly, the view port loses some transparency as the carbon particles ejected from the sample start to adhere to its inner surface. Over the entire irradiation phase this leads to a reduction of the insolation provided to the sample surface. For our initial experiments up to 0.2% carbon black, we monitored the loss of intensity with a photodiode placed next to the sample and found an intensity loss between 10.6% and 12%, so we do not expect the decrease of intensity to have a large influence on our results. The particles are evenly distributed across the viewport, therefore the reduction of incoming irradiation is constant over the sample surface (Fig. 1) .

3. Results

A summary of the experiments is given in Table 1. As expected, the height of the samples decreases as surface ice is lost by sublimation. In terms of sample height, ice loss is largely constant although there is a small increase in ice loss between 0.1% and 0.5% (which might be expected, as higher carbon content implies more effective absorption of solar radiation).

3.1. Hardness

The results of the hardness measurements are given in Fig. 2, where the initial observation of an activity peak around 0.2% carbon is mirrored: Samples with 0.2% and 0.3% carbon show the greatest increase in hardness, in particular at a depth of approx.