LABORATORY SIMULATION OF COMETARY PROCESSES: RESULTS FROM FIRST KOSI EXPERIMENTS

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ABSTRACT. In situ observations of comet Halley provided the first photographs of a cometary nucleus and yielded information about its environment, including the emitted gas and dust. The relation between these measurements and properties of and processes on the nucleus is established by theoretical modelling, while laboratory experiments may provide some of the physical parameters needed. In addition, laboratory tests can stimulate new ideas for processes that may be relevant to cometary physics. Processes to be studied in detail by large-scale laboratory experiments may include: (1) heat transport phenomena during sublimation of porous ice-dust mixtures, (2) material modification and chemical fractionation caused by the sublimation processes, (3) buildup and destruction of dust mantles, (4) detailed studies of gas release from mixtures of volatile ices, and (5) the investigation of ice and dust particle release mechanisms. The KOSI-team (Kometensimulation) carried out sublimation experiments with ice-mineral mixtures in a large Space Simulator. During initial experiments, cylindrical samples of 30-cm diameter and 15-cm thickness were irradiated with up to 2700-W/m^2 light energy. The samples consisted of water-ice or water- and CO_2-ice mineral mixtures. The experiments showed the importance of advection for heat transport into the interior. It was found that the sublimation of CO_2 advances into the sample at a higher speed than that of water vapor release. Therefore, emission of volatile gases responded to insolation changes with a time lag of several hours. The ratio of the emitted gas species, as well as the dust-to-gas mass ratio, differs significantly from the values within the sample. A partly permeable refractory mantle of minerals and carbonaceous material developed with time. Dust and ice particle emission has been observed to occur from irradiated dirty ices as well as from dust mantles.

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1. Introduction

In 1986 human perception of a cometary nucleus changed from that of an astronomical point source to that of an extended physical body that hosts a diversity of surface structures and processes. The Halley missions photographed the nucleus and yielded information about the cometary environment, of both gas and dust. Images of the nucleus (Keller et al., 1986; Sagdeev et al., 1986) indicated active areas which emit gas and dust and inactive areas which showed no emission. In situ measurements in the coma (Krankowsky et al., 1986) proved that water ice is the main constituent contributing to the gas emission, although even more volatile species such as CO, CH_4, NH_3, CO_2 and others have been identified (cf. Krankowsky and Eberhardt, 1989). Measurements of the chemical composition of cometary grains indicate that these grains are composed of silicates of approximately chondritic composition (Jessberger et al., 1988) and of refractory carbonaceous material (Kissel and Krüger, 1987) at a mass ratio of about 2:1. The dust-to-gas mass ratio has been estimated to be on the order of two (McDonnell et al., 1989). The questions that remain are "what do these measurements tell us about the composition of the nucleus?" and "what are the detailed processes that relate the composition of near-surface layers to that of the coma?"

Several authors (e.g., Klinger, 1981; Smoluchowski, 1981; Weissman and Kieffer, 1981; Kührt, 1984; Prialnik and Bar-Nun, 1988) have published theoretical studies of the temperature profiles deep within the nucleus, which are the key to understanding the thermal history of comets. Theoretical models of comet nuclei have been developed, describing the processes occurring due to heating by solar radiation: the penetration of a heat wave inward, accompanied by the transformation of initially amorphous ice into crystalline ice, gas release during this process, and the buildup of gas pressure in deep layers, resulting in explosions and crater formation (cf. Prialnik, 1989). The effect of dust mantles on heat transport and sublimation of cometary ices, first mentioned by Whipple (1950) has been extensively modelled by Brin and Mendis (1979), Shulman (1972), Horanyi et al., (1984), Fanale and Salvail (1984), Prialnik and Bar-Nun (1988) and others. These models are rather advanced. The results, however, rely heavily on physical parameters and on assumptions about the complexity of the composition and structure of comets.

In order to survey the relationship between composition and physical processes that could occur in a cometary environment, several attempts have been made to study experimentally the sublimation process of mixtures of ices, minerals and carbonaceous compounds (cf. Ibadinov, 1989). Most previous laboratory simulation experiments were done using thin ice samples, ranging between a few microns to a few millimeters, thus excluding those phenomena whose results cannot be extrapolated to much greater sample thickness. It is in the centimeter- to meter-range in which the important near-surface heat transport phenomena dominate. Several authors, including Delsemme and Wenger (1970) and Bar-Nun et al. (1985), studied the trapping and release of gases by water ice and found significantly different behavior of these multicomponent ices from that of individual species. They also observed the emission of ice grains that were dragged away by the release of more volatile gases. Extensive experimental work was carried out by Soviet groups, who heated up ice samples electrically or irradiated them with light sources inside a cold chamber (e.g., Kajmakov and Sharkov, 1972; Ibadinov, 1989). Among the interesting results was the formation and ablation of dust mantles during the sublimation process. In another approach (Saunders et al., 1986; Storrs et al., 1988), silicate minerals and organic compounds covered with water ice were placed into a vacuum chamber. After sublimation of the water ice, highly porous, filamentary sublimate residues were found for some classes of phyllosilicate minerals or in cases when organic compounds (tar) were present. These experiments showed strong modifications of the refractory compounds by the sublimation process.

Investigations performed by the KOSI-team (Kometensimulation) (Grün et al., 1987; Kochan et al., 1989a; Klinger et al., 1989a) focused on certain processes that occur on scales relevant to some cometary phenomena. The scale for the heat transport into the interior is given by the thermal skin depth. This is the depth d at which a sinusoidal temperature variation of period P induced at the surface is reduced by a factor 1/e : $d \sim P^{1/2}$ (see, e.g., McKay et al., 1986). For an icy nucleus and a period of 6 years (an orbital period of short-period comets), the skin depth is about 5 m, whereas for a typical spin period of 2 days, the thermal skin depth is on the order of 10 cm (see also Spohn and Benkhoff, 1989). A scale for gas interactions is the mean free path (for a recent discussion, see Crifo, 1989). This scale is on the order of a few centimeters for sublimating water ice at the condition of 1 AU. However, the scale for the hydrodynamic outflow is determined by the dimension of the comet nucleus which is about four orders of magnitude bigger than any laboratory experiment. Therefore, details of the emission processes can be studied in laboratory simulations, but not the processes that dominate the cometary coma. During KOSI experiments, phenomena are studied that occur within centimeter to meter distances from the nucleus surface. The scale of the simulation experiments matches the scale for the diurnal heat transport into the interior as well as the scale of gas interactions.

KOSI experiments are performed twice a year in the Space Simulator of Deutsche Forschungsanstalt für Luft- und Raumfahrt (DLR) in Köln. Supporting experiments for the investigation of some specific processes are conducted in a small chamber that is suited for sample sizes of up to 10 cm. At the present time, KOSI experiments are still in the orientation and development phase. Within about one year, dedicated experiments will be performed whose aim is to achieve a detailed understanding of specific processes. Results from the initial experiments show already that laboratory studies can help to develop an understanding of the diversity of effects observed, and thus these studies demonstrate the potential for obtaining relevant information on cometary processes. As a by-product of these experiments, techniques to handle and analyse low-temperature ice samples are being developed.

2. Experimental Setup

The Space Simulator is a vacuum chamber with dimensions of 2.5-m diameter and 4.8-m length, surrounded by a liquid-nitrogen-cooled shroud and with an external light source to simulate solar radiation. Ten xenon lamps can

Table 1 : KOSI experiments: Initial sample compositions and properties ("albedo" stands for mean bidirectional reflectance) and insolation sequences

	KOSI-1 May 87	KOSI-2 April 88	KOSI-3 Nov. 88	KOSI-4 May 89
composition (weight %)				
H_2O ice	90	90	78	77
CO_2 ice	-	-	14	15
total dust content	10	10	8	8
relative mineral composition				
olivine	-	90	90	90
montmorillonite	-	10	10	10
kaolinite	100	-	-	-
carbon	1*	0.1	0.1	0.1
albedo	~ 0.2	0.06	0.18	0.09
density (g/cm^3)	0.4	0.6	0.5	0.5
porosity	n.d.	40%	50%	50%
penetration strength (MPa)	n.d.	0.2	0.2	0.1
insolation sequences				
duration (h) / intensity (SC)	13 / 1.1 -	17 / 1.0 4 / 0 4 / 1.0 4 / 0 4 / 1.0 4 / 0 2 / 2.0 -	10.3 / 1.3 6 / 0 30.8 / 1.3 -	20 / 0.6 6.3 / 0 12 / 0.6 4.5 / 0.8 -

* formed large aggregates
n.d.: not determined

insolate samples of less than 1.3-m diameter with up to 2.3-kW light power; the actual maximum insolation intensity is determined by the position of the sample in the divergent beam (Kochan et al., 1989b). The spectrum of the lamps roughly matches the solar spectrum in the visible wavelength region. The background pressure in the chamber is $\lesssim 10^{-4}$ Pa (or $\lesssim 10^{-6}$ mbar). The shroud keeps the background temperature at ~77 K and thereby acts as an effective pump for gases released from the sample - such as H_2O and CO_2.

A summary of the four KOSI experiments performed so far is shown in Table 1. The cylindrical sample container for the ice-dust mixtures has a diameter of 30 cm and a height of about 15 cm (see Fig. 1). Initially the container is mounted horizontally for transfer of the ice-dust mixture, while during the experiment, it is tilted up to 45° in order to be effectively insolated. The bottom of the sample container is a liquid-nitrogen-cooled copper plate. The inner wall of the container is made of Teflon to shield the

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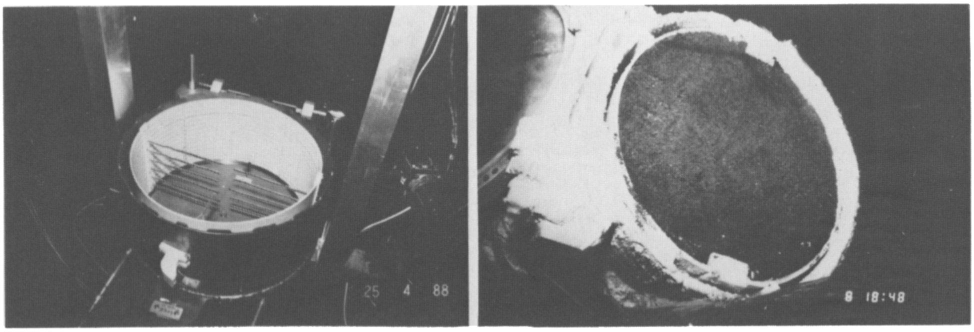

Fig. 1. Sample container used for the KOSI experiments, both empty (left) and charged with sample material (right), respectively. The container's dimensions were 30-cm diameter and 15-cm depth. A Teflon cylinder insulated the sample from the liquid-nitrogen-cooled outer copper shell. The dark material was used in the KOSI-4 experiment.

sample material from the outer cooled copper wall. A motor-driven cover protects the sample during transition phases from detrimental temperature effects and from contaminants. Inside the container, several temperature sensors are installed to measure sample temperatures at various depths and over radial distances.

Instruments are mounted to a rectangular support structure at about 1-m distance from the sample container to analyse the emitted gas and dust and to observe in situ the modifications of the sample during insolation (Fig. 2). Instrumentation includes several ionization gauges at various positions in front of the sample and a quadrupole mass spectrometer to measure the flux, the composition and the speed of the released gases. Several hundred dust collectors, up to ten piezo-electric impact detectors (both mainly mounted to the bottom of the frame), and television cameras (mounted both inside and outside the vacuum chamber) determine the rate, the size and the speed of the emitted dust particles. Two instruments were installed during the KOSI-4 experiment that could detect ice particle emission by the gas released upon the particles' collection. The sample surface itself is also monitored by the TV cameras.

The sample material consisted of ices (H_2O, CO_2) and minerals simulating cometary dust. Although CO_2 is less abundant in the cometary gas than CO, it was selected as a second volatile constituent besides water, since preparation and storage of the sample is possible at liquid-nitrogen temperature. The dust materials were selected on the basis of the observed mineralogical composition of solar system materials and the availability of analogue material in large quantities. The mineralogy of carbonaceous chondrites (Kerridge and Matthews, 1988), the mineralogy of interplanetary dust particles (Mackinnon and Rietmeijer, 1987; Sandford and Walker, 1985), and the data of comet Halley obtained by the GIOTTO mission (Jessberger et al., 1988) justify the selection of Mg-rich silicates of olivine and pyroxene composition, of phyllosilicates and of carbonaceous material. Carbon (soot)

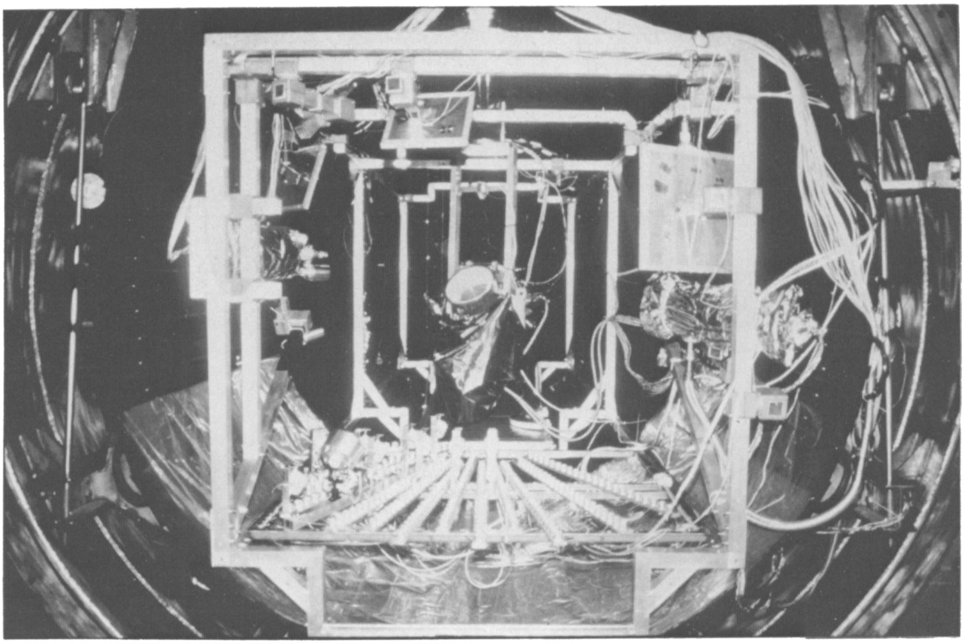

Fig. 2. View into the opened Space Simulator. In the center, the sample container is visible. The rectangular structure supports mirrors (top and right), gas diagnostics (upper left) and dust detectors and collectors (bottom). Around the edges, the cylindrical cold shroud can be recognized.

was chosen as a simple substitute for carbonaceous matter, and montmorillonite and kaolinite are representatives of the phyllosilicates. Olivine and pyroxene are the main constituents of powdered dunite. Carbon with a grain size of only 23 nm was suspended in water. The median grain sizes of the other mineral powders were below ~ 5 µm (Bischoff and Stöffler, 1988).

All samples were prepared from dust mixtures suspended in water. Noncoherent fluffy ice-dust mixtures were produced by spraying these suspensions into liquid nitrogen (cf. Saunders et al., 1986). This method is both simple and efficient to produce approximately 10 kg of material needed for an experiment. Because of the high content of minerals in the water (approximately 10% by weight), the individual grains were not completely separated from each other in the suspension. Therefore dust aggregates found after sublimation of the ice may have been formed during the freezing of the suspension. Alternative sample preparation techniques that avoid the mutual contact of dust particles in the presence of liquid water are under development. All KOSI ice samples were made mostly, if not completely, of crystalline ice. It is planned for the near future also to use amorphous gas-laden ice samples.

The propellant gas used for the spraying was nitrogen or carbondioxide. Spraying with CO_2 already provided a mixture of H_2O and CO_2 ices, and in

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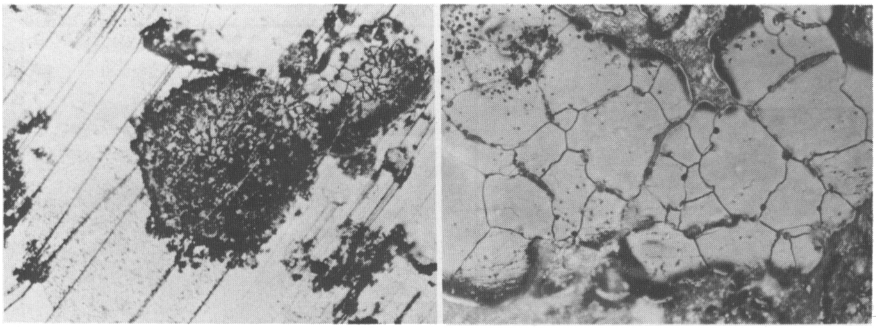

Fig. 3. Micrographs of a polished section of a KOSI-2 sample obtained by the polarizing microscope in reflected light; the horizontal width of microphotographs is 1.4 mm. In the center of the left micrograph is a spherical dust-ice aggregate; in the upper right corner of the left micrograph is polycrystalline ice with interstitial dust; the white matrix with diagonal lines is pore space filled with crystallized diethylphthalate. The right micrograph shows polycrystalline ice; the dark lines are grain boundaries between ice crystals where some dust aggregates are located (the worm-like features).

two cases, CO_2-ice was added to the sample material. The content of the CO_2-ice in the mixture was then measured by gas chromatography (Roessler et al., 1989). The initial compositions of the samples of the first four KOSI experiments are given in Table 1.

Analyses performed with the samples in a glove box (Roessler et al., 1989) before and after insolation include the measurement of reflectance spectra (albedo), both at visual and near-infrared wavelengths, determination of the penetration strength (Thiel et al. 1989) and determination of the density and porosity (cf. Table 1). Polished sections of aliquots of KOSI samples were made (Stöffler et al., 1989) based on techniques used in snow research (e.g., Good, 1982, 1987). The porous samples were impregnated with liquid diethylphthalate at ~268 K and then cooled to ~255 K. Polished sections are prepared by a sledge microtome. Preliminary studies of these sections with a polarized microscope indicate that the dust grains are contained either in spherical aggregates of dust and ice or in irregular polycrystalline sections of ice, where they preferably occupy the grain boundaries of the ice crystals (Fig. 3). The spherical aggregates ranging in size from some 10 μm to more than 2 mm (Bischoff and Stöffler, 1988) are obviously formed when the dust-water suspensions are sprayed into liquid nitrogen.

Besides using different sample materials, the KOSI experiments were carried out applying different insolation sequences. As shown in Table 1, during the KOSI-1 experiment, the sample was insolated for 13 hours with 1.1 SC (1 solar constant = 1370 W/m^2) light power density onto the sample surface. The insolation sequences of the other KOSI experiments were more complex (cf. Table 1). Before, between and after insolation, there were dark

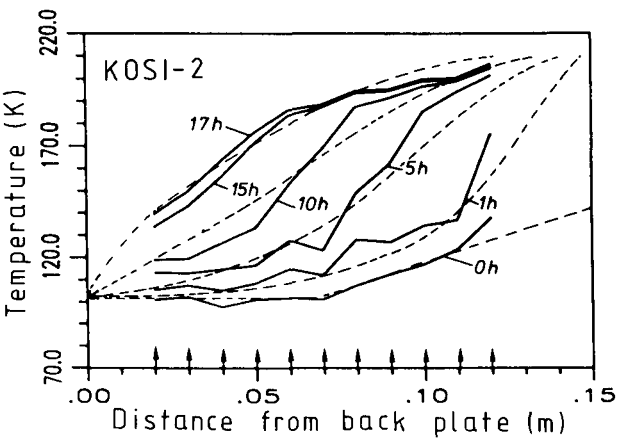

Fig. 4. Temperature profiles (solid lines) measured at different times after the start of insolation during the KOSI-2 experiment. The bottom ice temperatures did not reach the back plate temperature of approximately 80 K because of insufficient coupling between the ice and the back plate. The measurements are compared with the thermal model (dashed lines) of Spohn and Benkhoff (1989).

phases of several hours' duration to produce stable initial conditions. Small deviations from the indicated sequences occurred because of occasional lamp failures and because of intended stepwise switch-on (KOSI-4) and -off (KOSI-2) of the lamps. Due to the different insolation sequences and due to the different sample compositions, data shown in the next sections strictly apply only to a specific KOSI experiment. However, the conclusions drawn are based on results that were confirmed by several experiments.

3. Heat Transport

Detailed temperature profiles within the ices-mineral sample are obtained during each experiment. Temperature profiles taken at six different times during the KOSI-2 experiment are shown in Fig. 4. The energy input rate to the sample was kept constant at 1370 W/m^2. The temperature near the upper surface of the ice reached 205 K. With time, the temperature profile became flat near the surface and then decreased convexly towards the temperature of the back plate. A layer that displayed a small temperature gradient near 200 K was observed to grow in thickness during the course of the experiment. About 15 hours after the start of the experiment, the temperature difference between thermocouples at 6 and 12 cm from the back plate was only ~ 20 K. In later experiments (KOSI-3 and -4), when CO_2-ice was added to the sample, a similar temperature plateau developed at about 120 K. The two temperatures are probably associated with discrete levels of sublimation of H_2O and CO_2, respectively (cf. Spohn and Benkhoff, 1989).

The KOSI sample materials had a density of about 0.5 g/cm^3. Such low-density material necessarily contains a great number of pores that are interconnected. As long as such a system is confined in a closed volume and kept at a constant temperature, the pressure in the pores is equal to the vapor pressure of the ice at the given temperature. When a thermal gradient is maintained within the sample material, a pressure gradient develops as a result of the variation of the temperature with depth. This pressure gradient produces a driving force for the flow of vapor through the pore system. In this way, supersaturation can occur locally and leads to a rise of temperature. This effect will occur in deeper layers of the sample material, even when the vapor can leave the sample through a permeable layer at the top surface. Net sublimation occurs at the surface of the ice layer. The vapor that circulates through the pore system contributes to the heat exchange between the surface and the deeper layers of the sample (Klinger et al., 1989a, Spohn et al., 1989). The heat transfer to colder ice layers has three components (Spohn and Benkhoff, 1989): heat conduction by gas (about 90%), heat conduction by solids (10%) and heat transport by a very small amount of deposition of latent heat due to the net mass transport. About 60% of the power arriving at the upper ice surface is transported by vapor to the interior of the sample. This mass and heat transport occurred both for water and CO_2; for the latter, however, they occured at greater depth within the sample and at a lower temperature level.

The surface temperature of the dust mantle is determined by the balance between absorbed light energy, emitted thermal radiation and heat conducted into the interior. During the insolation period of the KOSI-3 experiment, the uppermost thermocouple (at 13 cm from the back plate) penetrated the surface of the sample, became exposed to direct irradiation and reached temperatures above 400 K. The temperature sensor at 12 cm never became exposed to direct light, but measured temperatures as high as 300 K in the upper layers of the dust mantle. Preliminary IR-temperature measurements of the sample surface tend to support these very high temperature readings.

The temperature at the interface between the dust mantle and the ice-dust mixture was found to rise during insolation above the temperature of an ice surface that freely sublimates into vacuum. This rise occurred even though the energy flux through the interface was reduced because of the dust mantle. A flat temperature profile characterized the heat transport by water vapor down to some distance from the water sublimation surface (Spohn et al., 1989, Spohn and Benkhoff, 1989). A similar behavior of the temperature profile has been found below the CO_2 sublimation surface. Only during the initial phases of the insolation did the temperature profile have the steep gradient expected for solid-state heat conduction.

Heat transport by vapor, found to be of great importance in the simulation experiments, will also occur in comets. Future modelling of cometary temperature profiles has to take this effect into account. As a consequence, a better understanding of the thermal evolution of comets will result.

4. Sample Characterization after Insolation

After the transfer of the irradiated KOSI samples to a glove box (Roessler et al., 1989), the samples were inspected and a number of small specimens, including drill cores, were taken from different positions within the samples.

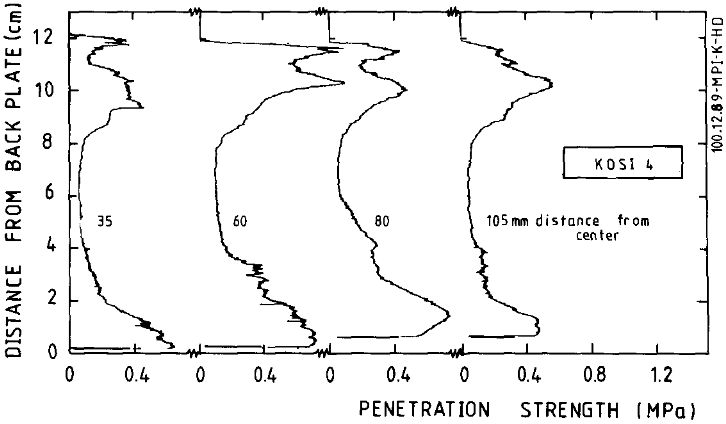

Fig. 5. Profiles of the penetration strength measured at different positions on the KOSI-4 sample after insolation. The penetration strength was measured with a motor-driven force-meter which pushes a cylindrical piston of 5-mm diameter into the sample.

These specimens were used for chemical, isotopic and petrographic characterization of the different phases of the sample and they were compared with the initial properties of the sample material. Visual inspection of the specimen showed, beneath a millimeter- to centimeter-thick dust mantle, a several-centimeter-thick, hard and coherent, but porous ice crust. This material was somewhat brighter than the noncoherent material underneath this crust which closely resembled the original sample material. For the KOSI-3 and -4 experiments, the bottom layer of several-millimeter (KOSI-3) or several-centimeter (KOSI-4) thickness, respectively, was brighter and contained some large ice platelets. The CO_2-content at various depths was determined by gas chromatography (Roessler et al., 1989). Except for the bottom 2 cm (KOSI-3) or 6 cm (KOSI-4), respectively, no significant CO_2 abundance was found within the sample after irradiation. At the bottom, however, it was close to its original value of ~15% (by weight) or had even slightly increased.

The isotopic ratios $^{18}O/^{16}O$ and D/H have been measured at various depths of the KOSI-2 sample (Klinger et al., 1989b). It was found that in near-surface layers (≤ 4 cm) an enrichment of heavy isotopes occurred, whereas in the deeper layers the corresponding depletion was smaller or even negligible. These results need further confirmation. The results from the first attempts of a petrographic characterization of the ice-mineral mixtures have been discussed above (cf. Fig. 3).

Both before and after the KOSI experiments, the "penetration strength" of the samples was measured. The measuring device is a motor-driven force-meter which pushes a cylindrical piston of 0.2-cm^2 cross sectional area into the sample (Thiel et al., 1989). The "penetration strength" is defined by the ratio of the measured force and the cross section of the piston and is recorded as a function of depth (Fig. 5). For all KOSI experiments it was

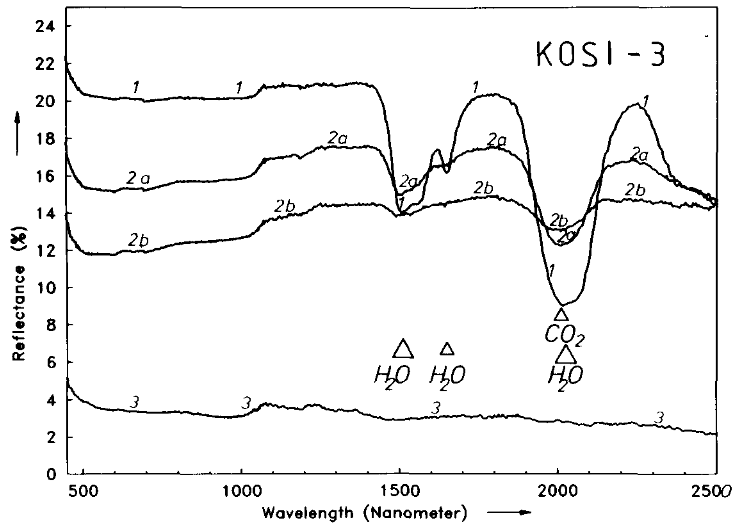

Fig. 6. Reflectance spectra of the KOSI-3 sample. Trace 1: original sample; trace 2: irradiation-processed sample (2a is the upper part of the inclined sample surface, and 2b the lower part); trace 3: pure carbon. The sample temperature was approximately 130 K, the measurement is in sample normal, and the illumination is at a 30° phase angle.

found that right below the dust mantle, a hard crust had formed. The penetration strength had risen from originally 0.1-0.2 MPa to 0.4-5.0 MPa over thicknesses of 30 to 70 mm, depending on the insolation intensity and duration. In addition, in a single experiment the actual values varied over a wide range depending on the location of the measurement spot on the sample surface. Below this hard layer the penetration strength showed the original value. Fig. 5 also shows an increased penetration strength in the lowest 4 cm of the sample after the KOSI-4 experiment. This observation indicates that a major transformation of the sample material in the near-surface and bottom (if CO_2 was present in the sample material) layers occurred during the sublimation experiments (Grün et al., 1989a). The hardening of the initially less-coherent material is a consequence of the redeposition of vapor within the sample.

Before and after insolation, the samples are characterized by reflectance spectroscopy. The radiance coefficient (Hapke, 1981) is measured in the wavelengths range from 500 nm to 2500 nm. The spot size on the sample is about 10-cm diameter. The sample is contained in a glove box and is cooled by liquid nitrogen. The sample is illuminated and viewed through four quartz windows that allow the measurement of reflectance spectra at phase angles of 30°, 50° and 70°. Fig. 6 shows the reflectance spectra of the sample before and after insolation at a 30° phase angle. The bidirectional reflectance averaged over the wavelength range is 18% ± 4% for the original KOSI-3 sample and 16% and 14% on different parts of the irradiation-processed

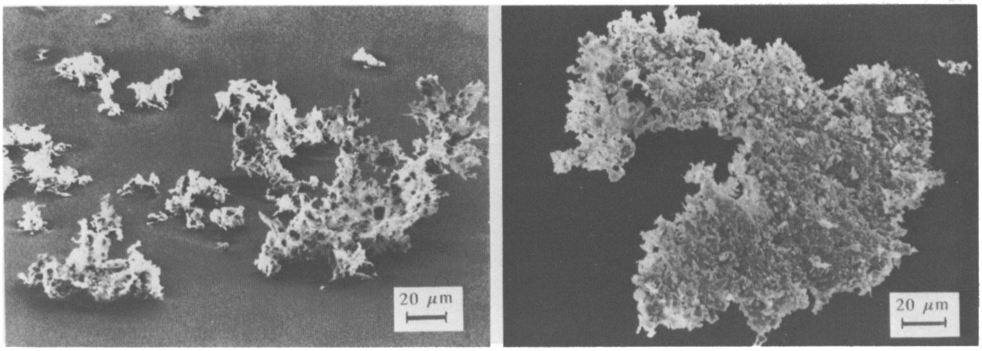

Fig. 7. SEM micrographs of dust grains emitted during the KOSI-3 experiment. The dust composition was 90% (by weight) olivine and 10% montmorillonite. Left: Fluffy grain. Right: Compact grain.

sample. For comparison, pure carbon powder has an average reflectance of 3%. These values correspond roughly to the albedo of the sample. The reflectance spectra show characteristic absorption bands for H_2O ice. The abundances of the minerals olivine and montmorillonite are too low for their absorption bands to be noticeable in the presence of the dark carbon. Narrow absorption bands of CO_2-ice near 2000 nm cannot be identified in the original sample on top of the heavy absorption band of water ice at this wavelength. A comparison of the spectra of the KOSI-4 sample before and after insolation shows that insolation leads to a reduction of the water absorption bands as well as to a differentiated surface with respect to the total reflectance level. The differences in the spectra from different parts of the surface are explained by the formation of a dust mantle of variable thickness and texture on top of the ices.

There is evidence that cometary nuclei in general and their near-surface layers in particular are of high porosity (≥ 0.5). Estimates of the mean density of Halley's and other cometary nuclei indicate that their densities are low (< 1 g/cm^3), lower than expected of solid nonporous ice-dust mixtures. Therefore, the fractionation effects found to take place during the sublimation of porous ice-dust mixtures in the laboratory should also occur under cometary conditions, leading to stratification in the surface layers of cometary nuclei.

5. The Dust Mantle

Inspection of all samples after insolation showed that a layer of dry dust a few millimeters to ~1 cm thick had formed over the ice mixtures. Due to the inclination of the sample (45°), this layer was generally thicker at the lower parts of the sample surface than on the top parts. Secondary Electron Microscope (SEM) analysis of the mantle material (Thiel et al., 1989) and residues of emitted dust particles (Fig. 7) showed that both were of very similar structure. The density of the mantle material was on the order of

0.1 g/cm. The fluffy texture of the mantle indicated an almost complete lack of volatiles in it. This structure was mainly controlled by the mineralogical composition of the dust component in the ice-mineral mixture and by the preparation method. SEM investigations of different ice-dust mixtures that were sublimation-processed in supporting experiments revealed that the fraction of phyllosilicates in the suspension was the main parameter that determined the final structure of the residual material (cf. Storrs et al., 1988). Higher fractions of phyllosilicates yielded spongy particles of regular pore shape. The pores were separated by straight partition walls made of silicate platelets. Olivines, on the other hand, led to irregular fluffy material made up of roundish constituents glued delicately together, forming completely irregular pore spaces.

Most of the following experiments were performed in the small chamber mentioned above. High-resolution video records (Kochan et al., 1989c) taken of the sample during insolation showed a highly structured, rough surface. The observations demonstrated that the surface was not motionless within the field-of-view of the camera (2 cm × 2 cm). Many small particles vibrated with various amplitudes and frequencies. The observed amplitudes were in the range of the particle dimensions, and the frequencies varied from approximately 1 Hz to 100 Hz. It was noted, that after varying times, particles flew off. This suggests a type of fatigue fracture well known in the field of material sciences for metals and ceramics. The fatigue fracture lifetimes observed were less than 15 minutes, which corresponds to about 10^5 cycles. Another type of dust emission process started with particles obviously bonded to the surface. These particles were not vibrating in the gas stream. After a certain time, they partially lost their bonds to neighbouring particles and turned about remaining bonds until these also broke. Then the particles were totally detached and were accelerated by the gas stream. These observations suggested that the particles were bonded to their neighbours only at some points (small areas). The bond-bridges were eroded in the gas stream until the lifting force exerted by the gas drag equaled the bonding forces. A third type of dust ejection mechanism was observed when a thicker (several-millimeter-thick) dust mantle had developed during insolation. Violent local dust eruptions occurred either spontaneously or triggered by large particles falling back onto the sample surface or stimulated by a mechanical device. Many particles were emitted within a short time interval from a narrow region of the sample. This type of dust eruption was quenched by raising the ambient pressure in the chamber to a value on the order of the vapor pressure of the ice at the observed surface temperature.

The observtions described above showed that the common view of the dust emission process by the balance of gas drag and gravity (Gombosi et al., 1986) or by micro-eruptions (Grün et al., 1989b) has to be reconsidered. Also, the supposition of loosely deposited particles on fresh surfaces without any bonding has to be revised. Close-up views of the sample during the KOSI experiments revealed significant forces between the mineral grains and the ice or among the mineral grains of the dust mantle. Of course, gravity, being 10^4 times larger in the simulation experiments than in the cometary environment, plays an important role in retaining the dust mantle during the simulation experiments. However, preliminary model calculations of bond strength based on reasonable assumptions for the material parameters indicate that these cohesive forces can be orders of magnitude higher than

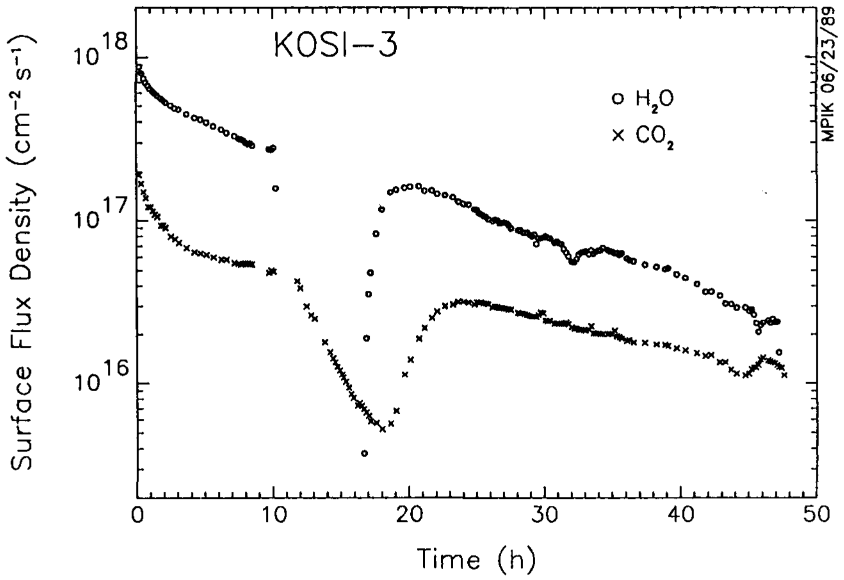

Fig. 8. H_2O and CO_2 gas flux densities at the sample surface, inferred from measurements at a distance of 90 cm and at an angle of 38° from the surface normal (KOSI-3). The sample had been insolated with 1.3 SC from 0 h to 10.3 h and from 16.3 h to 47.1 h; for the last two hours, the irradiation intensity was increased by approximately 0.1 SC.

the gravity force. The mechanisms observed for single particles may also be relevant to the mechanical behavior of larger crustal areas. Laboratory experiments and corresponding modelling are planned to measure the bond strengths and to investigate the kinematics of the erosion mechanism.

Buildup of centimeter-thick dust mantles and subsequent decreases of the gas and dust emission have been observed in all KOSI experiments. This behavior resembles that of inactive areas on the sunlit side of Halley's nucleus. Constant or decreasing insolation favors a continuous growth of a dust mantle. Dust mantle disruption and subsequent blowoff may be caused by an increasing insolation rate or external influences, such as the fall-back of large cometary particles or meteoroid impacts. Both effects will be studied in future laboratory experiments in order to investigate how inactive areas may be activated again.

6. Gas Emission

Surface flux densities of H_2O and CO_2 determined from mass spectrometer measurements during the KOSI-3 experiment are shown in Fig. 8. Immediately after the initial switch-on of the irradiation, both the CO_2 and H_2O emission rates jumped to maximum values. The value of about 10^{18} water molecules per cm^2 and second released from the fresh surface compares well with the gas production rates observed at comet Halley when it was assumed that only 10% of the total surface of its nucleus was active. Emission rates decreased during exposure to the irradiation, reaching values of a few 10^{16} $cm^{-2}s^{-1}$, which is typical for cometary gas production averaged over the entire surface area. The ratio of H_2O/CO_2 flux decreased from about 6 at the beginning of the experiment to 3 at the end, although the mole concentration of both constituents had a ratio of ~14 in the original sample material and CO_2 was emitted from deeper layers.

During the off-period of irradiation and shortly thereafter, the emission ratio of H_2O/CO_2 varied over a large range. When the lamps were switched off, the water emission ceased rapidly, while the CO_2-emission decreased much more slowly, at a time constant of about 3 to 4 hours. During the lamp-off period, only CO_2-emission from the sample was observed. When insolation was continued, water emission started immediately, reaching its maximum value about 3 hours later. CO_2-emission continued to decrease for 2 more hours before it started to increase again, reaching its maximum value about 6 to 7 hours after switch-on. This is an indication that CO_2-sublimation took place in deeper layers of the sample. Later, the CO_2-emission declined roughly in proportion with the water emission. Evaluation of the gas flux data shows that approximately 300 g of carbon dioxide (i.e., 60% of the total content) left the sample during the experiment, while a total of 500 g of water (i.e. only about 15% of the total contents) was released during the KOSI-3 experiment. The angular distribution of the emitted gas was measured to be slightly narrower than a cosine-distribution about the surface normal. The full width at half maximum (FWHM) of the distribution was about 90°.

In the KOSI experiments, significant differences have been observed between the concentration of different volatile species in the solid phase compared with those measured in the gas phase. Of course, no steady state was reached during the experiments. Similarly, in the cometary scenario, a hierarchy of internal and external modifications prevent a perfect steady state from ever being reached. Sublimation changes the surface systematically, meteoroid bombardment affects the surface stochastically, rotation and nutation periodically vary the aspect angle of insolation for each point on the surface, precession due to nongravitaional forces as well as orbital motion introduces other time variations, and nongravitational forces and planetary perturbations change the orbit on a longer time scale. Each time scale is related to a depth inside the nucleus where the variation is still recognizable. Since gases of different volatility may originate from different depths within the nucleus, it is quite conceivable that the composition of the emitted gases never reflects the average composition of the ices in the comet.

During the KOSI experiments, we observed, for already processed samples, a considerable time lag between insolation and the release of the more volatile species (CO_2). In comet Halley about 15 vol% of the released gas was CO (Krankowsky and Eberhardt, 1989), about half of which appeared to have originated from an extended source out to a distance of 10^4 km from the nucleus (Eberhardt et al., 1987). If we apply the observation of a time lag of volatile gases due to their release from greater depth to Halley's situation, some of the CO could have originated from a layer deep within the nucleus.

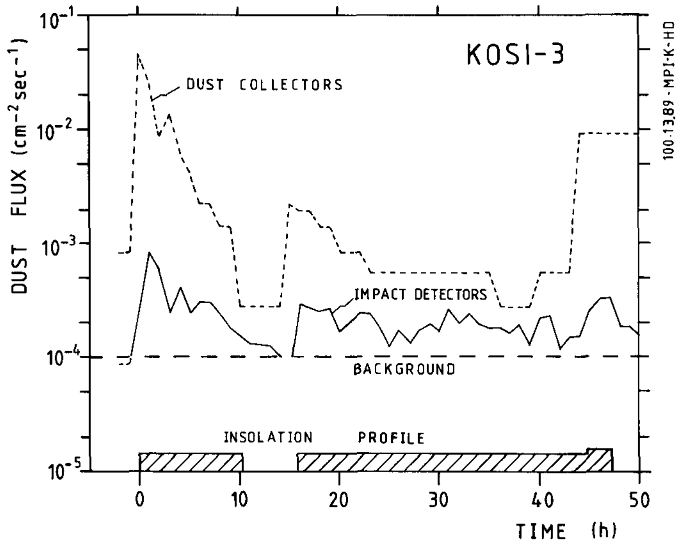

Fig. 9. Dust flux densities determined with the help of remotely activated dust collectors (100 cm from the sample, upper trace) and with piezoelectric impact detectors (about 90 cm from the sample, lower trace) during the KOSI-3 experiment. Hourly averages are given where possible. For comparison, the background count rate of the impact detectors is shown. The dust collectors collected all particles larger than 1 μm in diameter, whereas the impact detectors recorded only mineral grains that were larger than 150 μm in diameter and that still contained some ice.

This layer could be located a few diurnal skin depths below the surface and, therefore, there would be only a little difference between the CO-emission on the day or night sides - whereas most water is still emitted only on the day side. Quantitative hydrodynamical modelling of chemically heterogeneous gas emission from the nucleus could show effects on the coma that could be tested by the observations.

7. Dust Release

During the KOSI-3 experiment, records of the dust emission activity were obtained by two methods. Dust collectors (Thiel et al., 1989) activated for time intervals of about 1 hour collected dust particles released from the sample (Fig. 9). Immediately after switch-on of the irradiation, the dust emission rate jumped to high values and decreased thereafter at a time constant of a few hours. At the beginning of the second insolation period, the increase of the dust emission rate was less than 1/10 of the initial rise. Only at the end of the insolation period did the emission rate increase again, because of a slight increase of the insolation level. The difference in the time histories of the dust and gas release rates can be explained if one assumes that the size distribution of dust particles on the sample surface is time variable as well. This assumption has to be verified in future experiments. The diameters of the collected particles ranged from about 1 to 400 μm, and the densities of the collected residues were on the order of 0.1 g/cm^3. About 90% of the mass was represented by particles of 100 μm and larger size. A total of about 700 mg of mineral grains (cf. Fig. 7) was emitted during the KOSI-3 experiment. This value compares with 500 g of H_2O, which were emitted during the same experiment. The rest of the almost 50 g of minerals in the original mixture that sublimated during the experiment remained as a dust mantle on the surface of the sample.

The angular distribution of the emitted dust was much narrower than that of the gas. The width of the dust distribution was only about 25° (FWHM). This difference in the angular distributions indicated that the main dust acceleration occurred close to the sample surface, where the gas flow was still dominated by the pressure gradient within the sample.

Indications of the nature of the emitted particles were obtained from other measurements by piezoelectric impact detectors (Fig. 9). Kohl et al. (1989) showed that these detectors record only particles that were bigger than about 150 μm in diameter. An additional requirement for particle detection was that they must contain ice. Therefore, the count rates of these detectors (Fig. 9) refer to emitted icy particles, whereas the dust collectors recorded all particles emitted. The fraction of icy particles is about 20% of all emitted big dust particles, but large variations with the insolation phase are possible. Direct detection of emitted ice particles during the KOSI-4 experiment confirmed the importance of volatile material in contributing to solid particle emission. This aspect of dust emission will receive increased attention in future KOSI experiments.

During the KOSI experiments, the dust-to-gas mass ratio of the emitted species was about 10^{-3} compared with about 0.1 in the original sample. This ratio is strongly affected by gravitation and the cohesive force between particles. However, this finding from the KOSI experiments cautions us against taking the value of 2 for the emitted species of comet Halley (McDonnell et al., 1989) to be representative of the nucleus composition.

The observation of ice-grain emission at an insolation of 1 SC suggests that comets may emit significant numbers of icy grains that sublimate only after some time has elapsed. Hanner (1981) finds that, e.g., 10-μm-sized dirty ice grains have lifetimes on the order of several 100 s. Ice grains may provide an extended source for water molecules and perhaps other volatiles that have to be taken into account in hydrodynamic coma models (e.g., Gombosi and Körösmezey, 1989). Under cometary gravity, even centimeter- and decimeter-sized ice chunks can be emitted. Subsequent sublimation can release dust grains at significant distances from the nucleus. Observations of bursts of small particles at large distances from the nucleus by the DUCMA instrument on board the Halley missions (Simpson et al., 1987) may be explained by the delayed sublimation of these secondary icy bodies.

In summary, laboratory experiments can provide new dimensions in the study of cometary processes. Experiments such as KOSI will help to develop new ideas about small-scale processes that could occur near the surface of comets and to support comet modelling by providing needed parameters. Only by means of future space missions can we obtain close-up views of the surface of a comet nucleus or receive cometary material for detailed laboratory investigation. Until then, laboratory experiments will be an important tool for cometary science.

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