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SIMULATION EXPERIMENTS WITH COMETARY ANALOGOUS MATERIAL

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Abstract

Comet simulation experiments are discussed, in the context of physical models and the results in cometary physics, gathered especially from the GIOTTO space mission to comet P`Halley. The "status of the today knowledge" about comets, the experiments could start from, is briefly reviewed. The setup of the KOSI (German = Kometen Simulation) - experiments and the techniques to produce cometary analogous material, on the basis of that knowledge are described in general, as for the different KOSI experiments. The limitations of the simulation of physical processes at the surface of real comets in an earth-bound laboratory are discussed, and the possibilities to receive common insights in cometary physics are shown. Methods and procedures are described, and the major results reviewed. As with attempting to reproduce any natural phenomenon in the laboratory, there are short-comings to these experiments, but there are possibly major new insights to be gained. Physical laws only have the same consequences under same experimental or environmental conditions. A number of small-scale comet simulation experiments have been performed, since the early 60ties in many laboratories, but the largest and most ambitious series of comet simulation experiments

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to date were performed between 1987 and 1993 using the German space agency's (DLR) space hardware testing facilities in Cologne. These experiments were triggered by the scientific community after the comet P´Halley´s recurrence in 1986 and the many data gathered by the space missions in this year. Simulation experiments have proved valuable in developing methods for making cometary analogues, and for exploring specific properties of such materials in detail. These experiments provided new insights into the morphology and physical behavior of aggregates formed out of silicate- /water-ice -grains likely to exist in comets. The formation of a dust mantle on the surface, and a system of ice layers below the mantle from the different admixed materials, have been detected after the insolation of the artificial comet. The mechanisms for heat transfer between the comet's surface and its interior, compositional, structural, and isotopic changes that occur near the comet's surface, were described by modeling in accordance with the experimental results. The mechanisms of the ejection of dust and ice grains from the surface, and the importance of gas-drag in propelling grains were investigated by close-up video cameras.

1. INTRODUCTION

The study of comets has played a crucial role in establishing the nature of the solar system and gravitational theory (Hoskins, 1997). Comets may have played a part in determining the Earth's inventory of volatiles (Prinn and Fegley, 1989) and perhaps even in the origin of life on Earth (Ponnamperuma, 1981). Some short-period comets may evolve into asteroids (Degewij and Tedesco, 1979; Weismann et al., 1989; Wetherill 1991), linking interstellar space to the inner solar system, and thus some may be the parent bodies of meteorites (Campins, 1998). Three events have resulted in an enormous growth in our understanding of comets over the last two decades.

(1) The armada of spacecraft that encountered Comet P/Halley in 1986, two from Russia (Vega 1 and Vega 2), two from Japan (Sagigake and Suisei), one from Europe (Giotto) and the International Comet Explorer (ICE). Details of past and planned cometary missions appear in Table 1.

(2) The European Space Agency's decision to make a cometary probe one of its "corner-stone" missions.

(3) A spectacular series of comets (Halley, Kohoutek, Hyakutake, Shoemaker-Levy 9 and Hale-Bopp).

These two decades of activity have resulted in numerous books on comet research (Wilkening, 1982; Ponnamperuma, 1981; Newburn et al., 1981; Lagerkvist et al., 1986; Battrick et al., 1986; ESA-SP 249, 1986; Rolfe and Battrick, 1987; Delsemme, 1977; Grewing et al., 1988; Hunt and Guyenne, 1989), much of which was summarized in Huebner (1990). It is almost certain that the upcoming decade will be equally important, with the scheduled Rosetta (Atzei et al., 1992), Stardust, Deep Space 1, Champollion/Deep Space 4, and Contour spacecraft missions.

Stardust and Champollion/DS4 involving sample return. Stöffler (1991) has discussed the requirements and operation of a curatorial facility for returned comet samples. Rosetta was originally planned as a sample return mission, but that role has now been transferred to the Champollion/Deep Space4-mission. The Rosetta-mission will conduct extended observations from the orbit and also "in situ" investigations of samples by a small lander station (RoLand). The last two decades of cometary research have also been characterized by an increasingly important role for ground-based studies, like theoretical modeling, thermodynamic and structural studies of ices, and studies of cometary analogues under conditions approximating those of the comets. Of course, these three areas are closely related, the last two especially. Theoretical modeling has been reviewed many times (Keller, 1990; Donn, 1991; Colangeli et al., 1992a; Rickman, 1991) and an entire book has been dedicated to the properties of ices of relevance to comets and solar system science in general (Klinger et al., 1985). In this chapter, we review laboratory comet simulation experiments. These experiments have been extremely successful, notwithstanding several limitations, and are of particular interest to the community that will eventually examine returned samples. We review the procedures and the results, and try to place some of the results in the context of astronomical observations of comets. But first we briefly review current views on the formation and evolution of comets and discuss the role and limitations of simulation experiments.

2. WHAT ARE COMETS - A BRIEF REVIEW

Comets are thought to have either formed in interstellar space by the agglomeration of interstellar grains (Greenberg, 1982) or in the Jupiter-Saturn region of the solar system by condensation and accretion processes. Subsequent interaction with the major planets caused them to be ejected to a spherical symmetric cloud, the Oort cloud, 10^4 to 10^5 AU from the Sun, (Oort, 1950; Rickman and Huebner, 1990; Bailey et al., 1986). About 60 comets have also been detected in the plane of the solar system (the Kuiper Belt) 40 to 50 AU from the Sun but in view of the small area that has been searched it is probably that there are 35000 in the belt (Jewitt and Luu, 1992; 1995). "The Centaurs" are a recently recognized group of comets in the outer solar system which are transitional between Kuiper Belt and short-period comets (Stern and Campins, 1996). The short-period comets (with a /P prefix to the comet name) have been placed on elliptical orbits by interactions with stars, passing the sun, that bring them into the inner solar system. The dust being evolved from the nucleus of Halley's comet has solar abundances of oxygen and carbon and the non-volatile elements, and closer to solar abundances than CI chondrites of nitrogen and hydrogen and may thus be considered more primitive than chondritic meteorites.

3. RESULTS FROM SPACE MISSIONS TO COMET P'HALLEY IN 1986

Much of our present observational data for the nucleus of comets resulted from spacecraft observations of comet P/Halley. Only 20% of surface of the nucleus was observed to be active, the remainder being dark, like black velvet with an albedo of around 4% (Keller et al., 1988). It is agreed, that this low albedo results in an optical and additionally in a geometrical albedo, in "light-traps" within the irregular shaped dark dust cover of the surface. Gas and dust are ejected from the surface until the emission is somewhat quenched by the covering dust mantle, formed out of the cometary the emitted and back-fallen material ice-/mineral-matrix during the insolation. Craters, avalanches, one of the KOSI results and fissures in the dust mantle can additionally contribute to the emission activity. The dust to gas ratio is as high as 2.0. The dust grains were either silicate grains similar to carbonaceous chondrites, carbonaceous grains rich in C, H, O and N, and particles that were probably a mixture of silicates and CHON particles (Jessberger et al., 1988; Maas et al., 1990; Krueger et al., 1991). Thus Whipple's (1950) view that cometary nuclei are essentially icy conglomerates, has been supplanted by a number of models involving fairly large amounts of dust (Donn, 1991; Colangeli et al., 1989; 1992a). Weissman (1986) suggested a rubble-pile structure, while Gombosi and Houpis (1986) suggested a structure consisting of silicate grains cemented by ices, an "icy-glue model". Donn and Hughes (1986) have suggested that the nucleus is a random assemblage of ice-coated silicate grains with fractal structure. Details of surface processes gleamed from spacecraft observations and laboratory measurements might ultimately help chose between or further refine these proposed models for the cometary nucleus. The main and spectacular results, gathered by the GIOTTO space mission to comet P´Halley: Its low albedo of 4%, the low gravity of 1/20.000g (g=Earth´s gravity) and the low density of $0.3 \div 0.5$ g cm^{-3}, H_2O being the main volatile component, delivered the basic inputs for a recipe, for the production of cometary analogous material. The ratio of the ice- / mineral-mixture is still under discussion.

4. COMETARY MODELS

Cometary models based on telescopic observations and in recent times on the Space Mission results, deliver input parameters for the comet-simulation experiments.

It was probably Whipple (1951) who first proposed that sublimation of volatile compounds would result in the formation of a refractory crust on the comet as it entered the inner solar system. The general vision of a comet, consisting of a solid nucleus, being a mixture of water-ice and minerals ("dirty snowball") was convincingly demonstrated by the GIOTTO Space Mission to comet P`Halley in 1986. Many authors have pursued this idea (Brin and Mendis, 1979; Shulman, 1972; Dobrovolsky and Kajmakow, 1977; Horanyi et al., 1984; Dobrovolsky et al., 1986; Prialnik and Bar-Nun, 1988). Fanale and Savail (1984, 1986) produced a quantitative model, based on heat balance, gas transport, dust transport and mantle development and they also allowed for the effects of latitude, rotation and spin axis orientation. They found that comets with a perihelion less than 1.5 AU will develop a mantle, especially after repeated passes through the inner solar system, but the high activity often observed requires that some exposed water-ice be present, or that other components, already volatile at lower temperatures, like CO_2, CO or other frozen gases should be aggregated in the nucleus.

Crust formation of 1-3 cm resulted in irreversible changes to the comet and the H_2O flux to drop below 3×10^{-12} cm^{-2} s^{-1} (compared to a maximum of about 10-18 cm^{-2} s^{-1}). Fanale and Savail (1986) also pointed out that if Apollo asteroids are extinct comets they have ice within about 10 cm of their surfaces. The ratio of volatile-/refractory-components is even today under discussion. In contradiction to Fred Whipple´s "dirty iceball" (1951), Keller (1989) introduced the "icy dirtball" - model of a cometary nucleus with a predominant refractory component. By comparison of the so far existing cometary models with the observed cometary activity, Möhlmann (1995) concluded a cometary nucleus consisting of a cohesively bound matrix of refractory and porous matter with water ice in the pores. Cometary activity is explained by so-called "debris-zones" between the originally building blocks. The debris-zones were formed at the interfaces of colliding building blocks, during the first growth phase of the comets. In this zones the original ice-/ mineral-matrix was destroyed by the impact and was changed to an ice-dust mixture without any internal bond. In another model, to describe the phenomenon of comet splitting with an average frequency of about one splitting per 100 years and comet, and the confinement of cometary activity to small areas of the almost passive surface, covered with a dust mantle, Möhlmann (1996) discusses the possibility that the sublimation zones are located at places, differing from the active areas. These active areas are the very confined "source sites", where the subsurface flows from distant regions reach the surface. The pressure driven subsurface flows of volatiles may also reach internal regions of the nucleus via cracks, originating new cracks, finally causing cometary splittings.

5. COMETARY SURFACES

After the agglomeration of grains to form the comet nucleus, there were three distinguished stages during which alteration probably occurred. These were first, the short-lived initial formation stage. Secondly, the stage that lasted most of the life of the solar system when the nucleus resided in the Oort cloud. Third, the relatively short stage when the nucleus was deflected into the inner solar system.

During the initial phase there was the possibility of internal heating by ^{26}Al, although isotopic evidence for this, in the form of the decay product, ^{26}Mg, was not found in the GIOTTO data for Halley's comet. It has also been argued that internal heating was minimal because most comets must be composed mainly of amorphous ice in order to be able to produce the large volumes of gases observed. Associated with the formation of the comet from the primordial material, was probably some impact-compaction, and there will have been the formation of highly porous filamentary silicate structures by the aggregation of small grains in the low gravitational field of the accreting comet and due to sublimation of volatiles. Solar corpuscular radiation during the Sun's Ó-Tauri phase may have resulted in the loss of volatile compounds by sputtering.

During the long phase of storage in the Oort cloud there was little alteration by solar heating, because of distance from the Sun, but exposure to cosmic rays will probably have produced an altered zone many meters thick. This is sometimes referred to as the "irradiation driven mantle". The laboratory experiments suggest that this process will involve the release of gases and re absorption, and the formation of organic compounds. There may also have been some weak heating from nearby stars. Thomas et al. (1994) calculated that even at an environmental temperature of 30K the sinter necks of ice particles with radii of 0.1 and 1 mm grow by surface diffusion. The growth rate of the relevant. neck radius x/r is 1.5 to 2 orders of magnitude in 1 million years.

However, the most complex surface activity will occur during the passage of the comet nucleus through the inner solar system, when solar heating produces sublimation of volatiles, loss and re-crystallization of gases, redistribution of heat in the subsurface layers of the nucleus and the formation of complex strata of re crystallized volatiles.

The amorphous ice of the interior will be crystallized near the surface and a "sublimation driven mantle" (= the refractory dust mantle) will be produced on the surface. This will insulate the original surface, increasing the surface temperatures and the internal pressures, eventually stopping the sublimation and the emission activity (quenching). Thus there is an aging process, so that comets new to the inner solar system will be very active whereas others will have their activity greatly attenuated. One of the major unknowns at the moment is whether the insolation driven mantle will be disrupted early in the comet's period in the inner solar system, by the accumulated gas pressure beneath, like under a lid. Kührt et al. (1994) found, that over a wide range of parameters the cohesion of the matrix material is stronger than the vapor pressure building up underneath the mantle. These conditions lead to stable mantles, but do not explain per se the activity of cometary nuclei. In KOSI 9 (Grün et al., 1993) it was observed, that the dust mantle can be removed partially by an avalanche, and the bare ice- / mineral-matrix will be exposed to solar radiation. Möhlmann (1994) describes the formation of a regolith layer, consisting of particles in the cm and dm range, that can fall down after lift-off and can be deposited at inactive parts of the cometary surface. The heating effects associated with passage through the inner solar system will be superimposed on the earlier irradiation produced mantle.

In any event, the surface of a short period comet in the inner solar system has a complex layered structure. On the surface is the dust mantle. Below this, there are hard re crystallized layers corresponding to each of the major volatile components, as may be seen later, observed already in the first KOSI experiments.

Skorov et al. (1995) developed a kinetic model of gas flow in a porous cometary mantle, described as a bundle of cylindrical inclined channels not crossing each other. The emergent gas flow rate is found to vary with pore length/radius ratio in excellent agreement with Clausing`s (1932) empirical formula. On this basis Markiewicz et al. (1998) investigate the influence of small scale structures of a cometary surface layer on the way in which cometary activity develops. It is found that the erosion of an ice filled channel embedded in a matrix composed of non-volatile material is effectively limited by the gas re-condensating at the bottom due to the back flux of molecules reflected from the side walls. There are also probably gas-filled voids and regions of disrupted mantle where vents may release gas and dust to space or where ice may be exposed. The ability of the gases to eject dust, or even lift-off larger silicate- or ice-boulders, depends on the cometary activity related to the distance from the sun. Dependent on size (gas drag coefficient) and mass there are boulders fallen back to the surface. This is the reason that comets are highly irregular in shape, and might show considerable surface relief.

6. COMET SIMULATION EXPERIMENTS - GENERAL IDEAS AND SCIENTIFIC OBJECTIVES

In general it is a remarkable, pioneering step from the observation of a comet as a cosmic phenomenon with tail sizes of hundreds of millions kilometers, daring to simulate that in an Earth-bound small laboratory. May be that at the beginning there was the confidence, that common physical laws are valid independently from the location, but definitely dependent on the accompanying environmental conditions. In case, not all conditions around, on and in a real comet can be secured in an Earth-bound lab, the influence of these limitations on the degree of validity of the results has to be shown (as far as possible).

Fundamental differences between real and simulated comets are the mass, size and unknown composition, all possibly important constituents and the physical state and of the real cometary material. Besides that, the real physical processes taking place around, on and in a kilometer sized object, are compressed in the laboratory experiments to a scale of a few centimeter. In the protoplanetary disc, dust grains agglomerated to larger aggregates and volatile material like water vapor condensed on these grains. It is nearly impossible to produce larger samples under microgravity conditions and by condensation and crystallization out of the gas-phase. Microgravity cannot be simulated easily on Earth for a longer experiment time. The production by spraying a watery suspension of micron sized minerals into liquid nitrogen (LN_2) replaces the condensation and crystallization out of the gas phase. The scientific objectives of laboratory investigations lie in the possibility to investigate "in situ" physical phenomena in and on cometary analogous material within a short distance above the surface within the surface and beneath. The transferability of the laboratory insights to real comets depends on the quality or the degree of realization of real cometary conditions.

The important physical parameters in the simulation experiments are: composition and physical status of cometary analogous material, and the environmental conditions as insolation, temperature and vacuum, both during the sample production phase as well as during the experiment.

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7. EXPERIMENTS WITH ARTIFICIAL COMETS IN THE LABORATORY

7.1 Historical Review

The earliest comet simulation experiments were performed already in 1967 by Russian groups in Dushanbe, in the former Tadjik Socialist Soviet Republic and in St. Petersburg, the former Leningrad (Kajmakov and Sharkov, 1967a; 1967b; Ibadinov K.I. and Kajmakov E.A., 1970). Small samples of water ice and sand, deposited on a cold finger in a small vacuum cell were exposed to a strong light source.

7.2 Production Of Cometary Analogous Materials

Thin films, a technique that is well known from certain other measurements, was used by Greenberg, (1977, 1982, 1986) and Strazzulla et al. (1983). Greenberg streamed gaseous mixtures on the basis of water vapor on to a cold finger. Roessler et al. (1990) studied the condensation of water vapor on a LN2-cooled, rotating cylinder for the production of larger samples. The sample material approved to be even fluffy but technical problems came up with the removal of the material, to make that a permanent process. This method was also by far less effective to deliver in a reasonable time enough material to fill the KOSI sample containers (≈ 10 dm^3). To overcome this problems, and even to control the admixture of the dust component in a better way, the team discussed another production method (see Roessler et al. 1990, Fig.13). The general idea was derived from the technique, used by the heating power stations, with pulverized-coal firing. Here the coal dust is injected by the transporting air into a burning chamber. It seemed to be very attractive, to inject the liquid components, water-vapor with e.g. organic admixtures into a LN_2 cooled reaction chamber, where it could condense on LN_2-cooled mineral dust grains, also injected by a nozzle. Identified as very complex, this method was not investigated in greater detail.

For larger samples, spraying methods have to be used, following an idea of Saunders et al. (1986). They injected a watery suspension of clay minerals into liquid nitrogen at 500 psi. Several Russian groups have used the same procedure (see Dobrovolsky et al., 1986, for references). Kochan et al. (1989a,b), Roessler et al. (1990), Grün et al. (1991a, 1992), Kochan and Junglus (1993) and Seidensticker and Kochan (1992) used a large-scale automated version of the method to produce 30-cm diameter comet analogues by a depth of 14 cm. Later a larger sample container was used, 60 cm in diameter and 30cm in height. The samples were prepared by spraying kilogram quantities of a watery suspension of phyllo (kaolinite / montmorillonite)- and / or neso (olivine / dunite)-silicates (4-8 mm), and in a liquid dispersed carbon (0.85 nm)
into liquid nitrogen, sometimes with an admixture of other components as CO_2 or methanol. In Fig. 3 a schematic view of the „sample production machinery“ is given. The various mixtures processed in the different KOSI experiments are listed in Table 1, see before "References“.

Figure 1. The "sample production machinery", at left the LN_2 dewar and the spray-gun above.

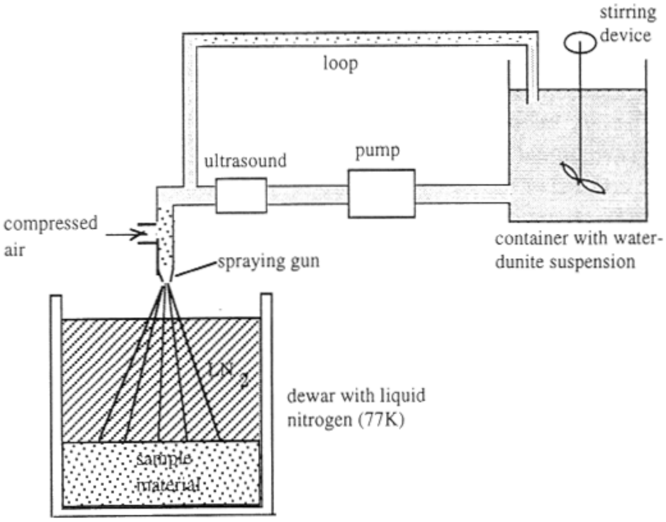

Figure 2.Schematic view of the spraying machinery.

The spraying machinery is the result of a technology development done at the Institute for Planetology, University Münster. This equipment is nowadays used in DLR.

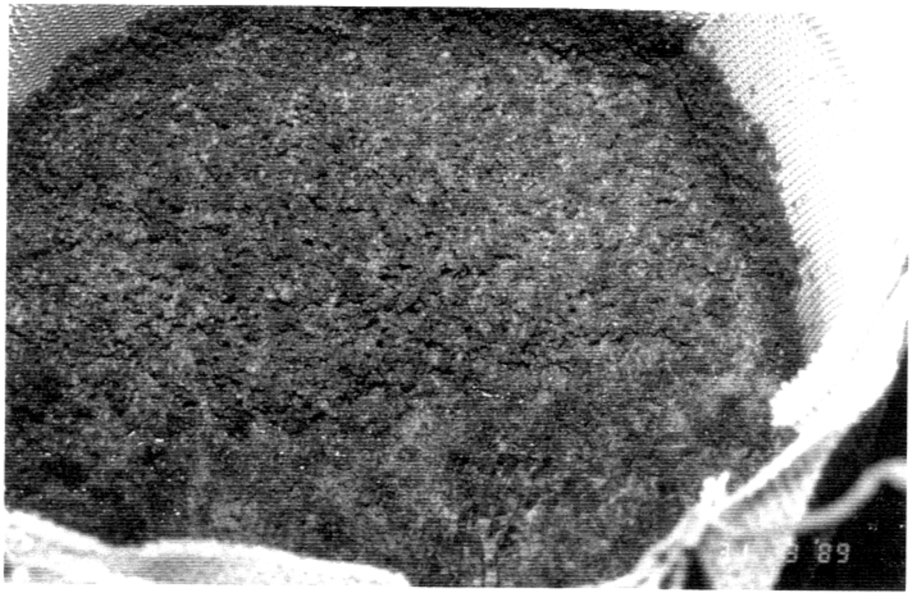

Figure 3. Typical fluffy, dark cometary analogous material, produced by the spraying method, described above.

The larger scale production for cometary analogous samples for comet simulation experiments is not based on the condensation of volatile components on mineral grains, like in the early state of the solar system. In addition it is performed in the terrestrial gravitational field. In the early phase of the KOSI experiments very often the influence of the Earth´s gravitational field was discussed, irrespective of the circumstance, that even in the protoplanetary nebula, the agglomeration- and condensation processes were not separated from gravitational fields. The influence of the Earth gravitational field was also discussed in the context of the emission of ice-/dust-particles.
The observation of this phenomenon was one task of the Colonian team. It came out, that the particles are by far not "loosely deposited" on the surface of the insolated sample. With high resolution optics it was observed, that the particles are bonded to the ice-/mineral-matrix. Before they are free and coupling into the gas jet, the bonds have to be eroded by sublimation of the gluing ice during the insolation. Calculations based on these observation have shown, that the binding force is orders of magnitude stronger than the force resulting from the Earth gravitational field (Ratke and Kochan, 1989).
More general comments should be made regarding the sample preparation by spraying. The upper limit in admixing minerals in the sample material by spraying was in between 20 to 25 %. The general discussion, whether Fred Whipple´s definition, the comets to be "dirty snowballs" is valid was reopened by H.U. Keller (1989) by his view of "icy dirtballs". The admixture of higher amounts of the mineral components by stirring, resulted in very inhomogeneous samples. These samples were not used in the KOSI experiments. Starting from the idea of a very inhomogeneous surface of a real comet, processed and modified by several solar passages, this decision was probably

wrong. Perhaps a sample with a higher amount of the refractory components (minerals) could better represent the surface of an elder, modified (= processed) comet. The emitted ice-/dust-particles have been collected during the insolation by means of around 200 small (film-) boxes arranged in an array of heated trails, to prohibit any moisture deposition during the chamber warm-up phase. To monitor the time variation of the particle emission, dynamic collectors were built, with rotating carousels carrying collecting shells, stepwise exposed by an opening (Thiel et al., 1995). The stepwise sampling, delivered a time profile of the cometary dust emission. Figure 4 shows the array with the trails and the small collector boxes during the experiment integration

The dust particles, sampled by the different collectors where inspected by means of an optical as well as by a scanning electron microscope (Thiel, et al. 1995). In the first 6 from in total 11 KOSI experiments, performed in the big chamber , a mixture from 90% olivine and 10% montmorillonite, all by weight, was used in the sample preparation. Different from that, in KOSI-1 99% kaolinite was used. As reported by Grün et. al. (1993), and based on the inspection of the dust residuals, regularly done by K. Thiel, the emitted particles, in this case from olivine (KOSI-9), showed grain sizes up to a bit more than 100 µm. This agglomerates were formed of olivine powder mostly around 0.2 µm and 3 µm (Fig.1 in Grün et al., 1993). It seems, that the larger agglomerates, were already formed during the injecion of the watery suspension of minerals into liquid nitrogen. This clearly can be seen in Fig. 5 (courtesy K. Thiel), where a solidification front was running through this droplet, producing a structure, not so far from the dendritic branching. The sample was made by admixing of 10% montmorillonite with 90% water. To summarize this excursion, the dust particle latterly collected in the different samplers, resemble possibly not agglomerates composed during the insolation and during the emission process. These ice-/dust-particles were preformed during the sample production process.

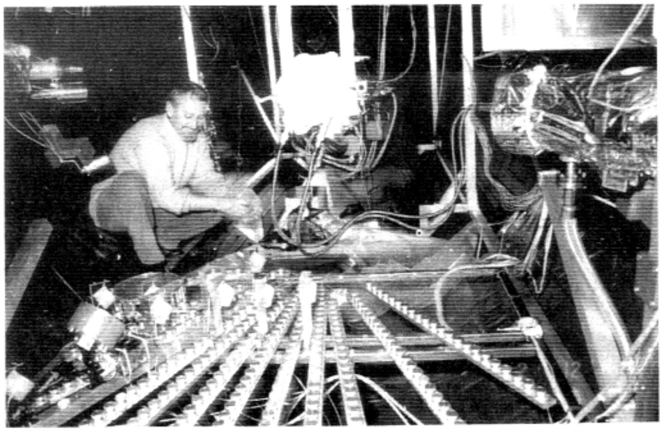

Figure 4. Integration of the nearly 200 dust-collectors into the dust collectors frame (KOSI-3).

Figure 5 demonstrates, following the interpretation of Thiel et al. (1995), that the montmorillonite platelets got this specific orientation during the freezing by the solidification front. In contrast to this, Figure 6 shows the structure of a particle emitted from a sample with 90% water-ice and 10% olivine. In the case of a mineral admixture of merely olivine, the texture of the collected dust particle is highly irregular with low internal cohesion. So the physical status of an emitted and collected dust particle is predefined basically by its composition and the sample production by spraying. In 5 of 11 KOSI experiments in the space simulator a mixture, mostly 9 :1, of olivine : montmorillonite was inserted. The low internal cohesion, and the smaller size of the dust grains favored the dust emission during the insolation.

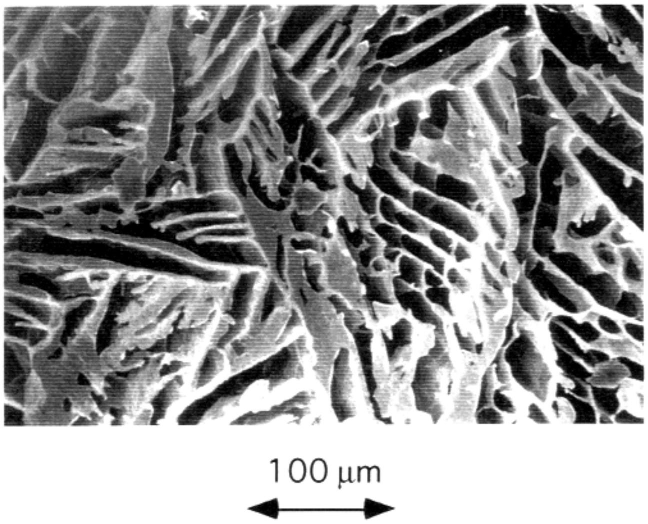

Figure 5 SEM micrograph of an emitted and collected particle containing 100% montmorillonite by weight (Courtesy: K.Thiel).

Coming back to the problem of the sample production at very low temperatures out of the gas phase, resulting in amorphous ice: This task was claimed by the colleagues of the Tel Aviv University (Bar-Nun, 1991). On a cold plate of 48K they deposited e.g. a mixture of 1:1 $CO:H_2O$, and at 70K a 1:10 mixture CO_2 : H_2O. In the same paper A. Bar-Nun announced the construction of an even larger machine to produce gas-laden amorphous ice, but in addition with an admixture of mineral dust. With a lot of technical effort, it is possible to produce amorphous ice-/gas-mixtures. To add the minerals and to transfer the material into the experimental container where it is e.g. insolated, leads to much more complicate technical problems. Either a lock has to be installed between the production machine and the experimental sample container, or the production of the sample has to take place directly in the experiment container. In any case this needs environmental temperatures at around 40K. Until now, no KOSI-like experiment with amorphous ice was reported.

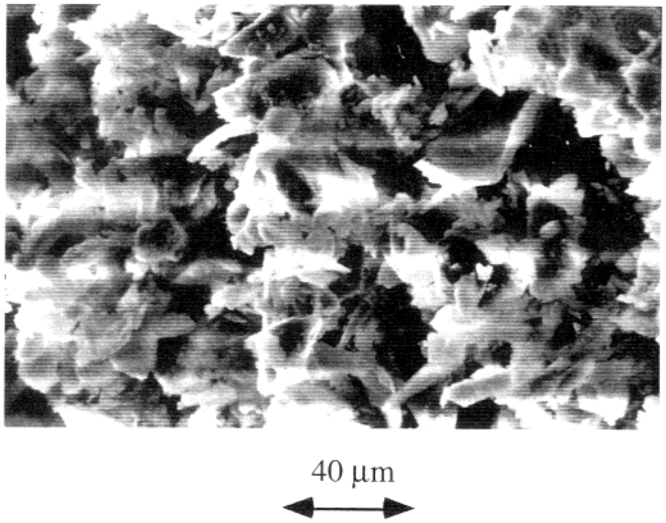

Figure 6. SEM micrograph of an emitted and collected particle containing 100% olivine by weight (Courtesy: K.Thiel).

7.3 Small-Scale Comet Simulation Experiments

Greenberg's measurements were made in the apparatus in which the analogues were produced (Greenberg, 1977; 1982; 1986). A series of experiments has been performed by the Russian group at Dushanbe, much of which was summarized by Dobrovolsky et al. (1986) and by Ibadinov, et al. (1991). Comet analogues, e.g. composed H_2O-ice with admixtures of graphite-, quartz- or nickel-particles, 1 - 30 μm were irradiated with Xe lamps at 10^{-4} Pa and 80 K (Fig. 6a). Seidensticker and Kochan (1992) describe a small chamber at the DLR. Table 2 shows the relevant parameters of this chamber.

Cold Shroud	Form: vertical cylinder
Diameter	0.60 m
Hight	0.64 m
Volume	0.2 m^3
Temperature	≤ 80 K (LN_2-Cooling)
Samples	
Diameter	≤ 0.10 m
Hight	≤ 0.10 m
Vacuum system	prepump+oil diffusion pump
Pressure	≤ 10^{-3} Pa
Light Source (bulb)	1x 6.5KW Xenon high pressure
Insolation-Intensity	≤ 2 SC (1Solar Constant = 1.37 kW m^{-2})

Table 2 :System Parameters of the Small Camber

In Fig. 7 a photographic view of the small simulation chamber is presented. At the left side the upright standing chamber can be seen with the oil-diffusion pump below and the video camera and the LN_2-inlets on top. To the right are the Xenon high pressure lamp and a video screen with recorder positioned.

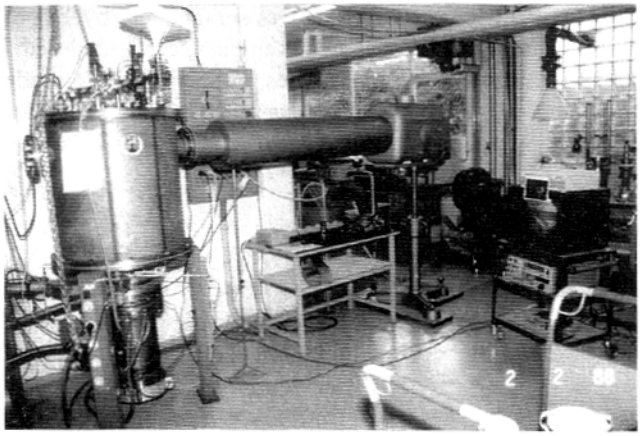

Figure 7. Photographic view of the small simulation chamber at DLR Köln.

Fig. 8 shows the internal instrumentation mounted below the cover of the small chamber. This instrumentation mainly consists of the cold shroud, the small sample container in the middle and a hardness tester above this container. The hardness tester is operated via a vacuum feed through. So it is possible, to monitor the hardness of the sample even during the experiment, when the chamber is closed. The sample container, standing on a LN_2 cooled copper prism is tilted 45 degrees against the horizontal. The sample container and the area in front of it can be seen through a window by a video camera. So, during the experiment, the modification of the sample surface and the dust emission easily can be monitored.

Two other facilities should also be mentioned in this context, the first is built by Kömle et al. (1996). Before this team constructed its own facility, they performed series of experiments in DLR, specifically directed to

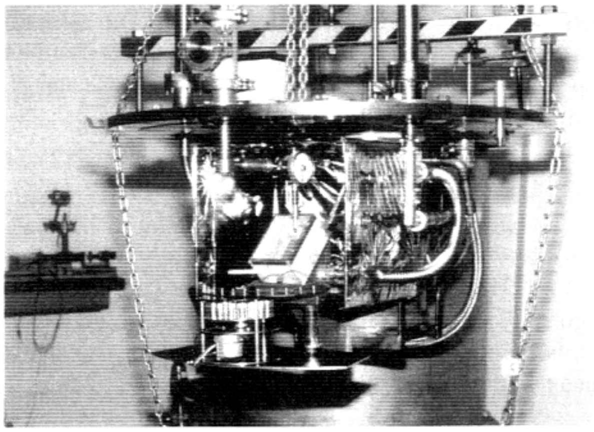

Figure 8. Internal instrumentation of the small simulation chamber at DLR Köln.

simulations of cometary crusts. These experiments originated from investigations of the role of crusts of different albedo and porosity in the thermal behavior of comets. Starting with perforated metal plates with different hole-widths, and with quartz grains of different size, at least the influence of the admixture of organic material on the cometary thermodynamics was investigated. To report the results in brief, the organic admixtures led to cohesive residuals with a thermal conductivity of at lest one order of magnitude higher, than that of a loosely agglomerated dust layer. The second facility, to be mentioned in addition, which is dealing with the simulation of planetary atmospheres Ferri et al. (1997) describe this facility and its application to Titan environment simulation.

More specialized equipment was used by Roessler et al. (1992a) to explore the effect of vacuum UV on comet analogues. Strazulla et al. (1983) have used small-scale simulation experiments to investigate the modification to the surfaces of thin films of condensed gases by ionizing radiation. Ions of H, He and heavier nuclei were generated in the 10-100 keV energy range by a van de Graff generator. The operating pressure and temperature range were $<2 \times 10^{-7}$ torr and 4-200 K, respective Bar-Nun et al. (1985) investigated the trapping and release of H_2, CO, CO_2, CH_4, Ar, Ne and N by amorphous water ice at 16K and 5×10^{-8} to 10^{-6} torr in special facilities.

7.4 Large - Scale Comet Simulation Experiments

The largest and most ambitious experiments to date are those of the so-called "KOSI" (= Kometen-Simulation) experiments that have been described in detail by Kochan et al. (1989a,b), Grün et al. (1991a, 1992), Kochan and Junglus (1993), and Seidensticker and Kochan (1992) (Figures 9 a,b). The large DLR Space Simulator, designed initially to test space hardware, is, within the cold shroud, a 4.9 m long 2.5 m diameter cylinder that can be evacuated to a pressure of $\leq 10^{-6}$ Pa (10^{-8} Torr), see Tab.3.

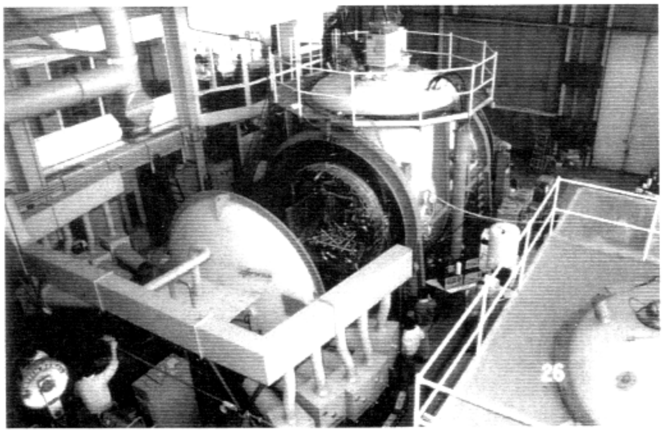

Figure 9 a. DLR Space Simulator during integration of KOSI experiments

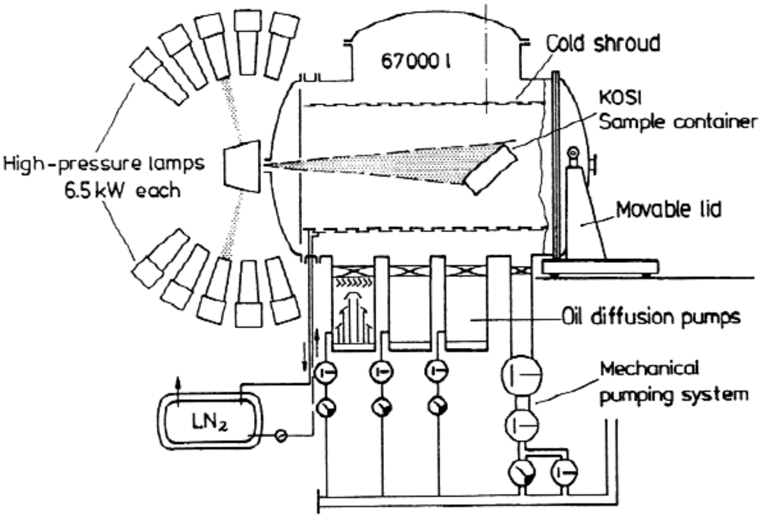

Figure 9 b. Schematic view of the subsystems of the DLR Space Simulator. The position of the sample container is indicated.

For the experiments, a sample container, 30cm in diameter and 15cm in depth is used. This container, made out of copper, is cooled with its own LN_2 cooling system from the backplate. This cooling system is separately operated by a LN_2-pump, to guarantee, that the sample is always kept cold, even during the warm-up phase of the chamber, and when at least the chamber will be opened. By this means the sample is preserved in the last status of insolation. This is important for the subsequent inspection of the processed sample, after a transfer into a glove box. Figure 10 shows the small sample container, 30cm in diameter and 14cm in depth within its mounting support. In this glove box, the sample is kept in an open LN2-bath. The disintegration from the mounting support in the chamber and the transfer in the glove box has quickly to be performed. So it was made sure, that the pipe connections from the separate external cooling system could be opened very fast. After the experiment, performed in the simulation chamber, where a lot of phenomena were observed "in situ" other investigations of the processed cometary analogous material are done after the disintegration from the mounting support. These are an overall optical inspection of the surface by viewing, and photographic camera, the measurement of the surface topography, the hardness in longitude and latitude, the formation of an internal structure (layering) Ten xenon lamps, whose spectrum approximates that of the Sun, provide a flux of around 1.4 SC (solar constant) over an area of 0.7 m diameter.

Chamber	
• Form	horizontal cylinder
• Cold Shroud: diameter * length	2.5 m * 5.1 m
• volume	25 m^3
• absorptivity / emissivity	0.90 / 0.92
• Experiment Support Structure: width * height * length	1.7 m x 1.7 m x5.0 m
Vacuum System	
• Effective Pumping Capacity :	3 * 15.000 l / s
• Final Pressure	$\leq 10^{-6}$ Pa
Cooling System	
• Cooling Liquid	liquid nitrogen (LN$_2$)
• Cooling time	≈30 min
• Time for warming up	≥ 4 h
Solar simulator:	
• System	divergent beam (half angle 4°)
• Radiation Source	10 Xenon, high pressure bulbs of 6.5 kW each
• Beam Diameter at Sample Position	0.7 m
• Irradiance	≈ 1.4 solar constants (1SC=1.37 kW / m^2)

Table 3: Data of the DLR Space Simulator

The chamber also contains ionization gauges, a quadruple mass spectrometer, several hundred dust detectors, ten piezo electric detectors, television cameras and an infrared photometer. Eleven experiments were performed between 1986 and 1993 (Table 1).

The Space Simulator, constructed in the seventies, was dismounted and replaced by a smaller chamber, following the principle of a dewar vessel, with two outer walls and a vacuum in between. With this equipment it is even possible to simulate conditions on planetary surfaces with an atmosphere (Kochan et al., 1997). A new large-scale simulator is being constructed at Tel Aviv (Bar-Nun, 1991)

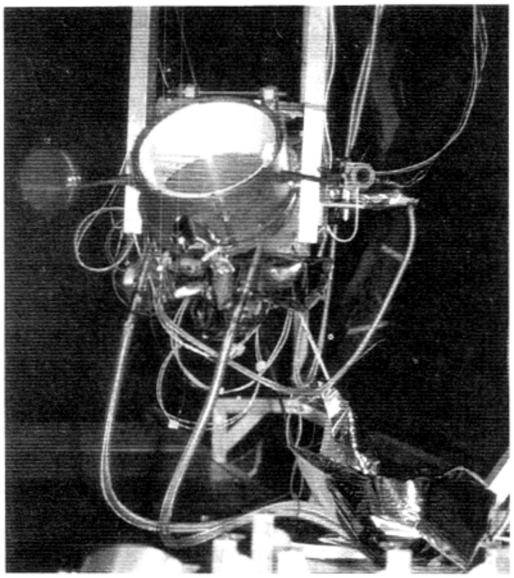

Figure 10. The small sample container, 30cm in diameter and 14cm in depth with integrated thermoresistors Pt 100 within its mounting support.

7.5 The Simulation Experiments - Performance And "In Situ" Results

The main topics we will discuss in the following are the physical phenomena to be observed "in situ" by different sensors, grouped around the artificial comet in the Space Simulator. Later the structural and compositional changes at the surface and within the bulk sample will be reported, investigated after de-integration of the sample. The inspection is performed under LN_2-conditions in a separate glove box.

Every experiment is preceded by a longer preparation phase: In a democratic procedure every scientist in or connected with the KOSI team was free, to make a proposal regarding the topic of the next big experiment. One proposal was selected, and everyone was free to join this experiment. In KOSI-workshops the contribution of other colleagues was accepted or in case of a key function also requested by the PI. The sample material was defined and the experimental timeline was agreed. Insolation-intensity and -time profile and the composition and grain size of the sample material, the main experimental parameters, were defined at the beginning. The performance of preparatory tests of the sample material in the small simulation chamber was discussed. The position of the different experimental sensors or cameras within the mounting structure were individually allocated in definite coordinates. Lengthy discussions finally guaranteed, that everyone got the requested view on the target. A nice statement was made, that the small "comet" should become anxious, seeing so many instruments.

The observed physical phenomena, e.g. the particle emission, the thermal history but also the modification of the bulk-sample by the experimental procedure in the Space Simulator will be reported in the following. But first we will review experiments on radiation effects, as these were the major surface alteration prior to the comet entering the inner solar system.

8. RADIATION EFFECTS ON COMETARY MATERIAL

Beyond about 5 or 6 AU, irradiation by charged-particles is more important than sublimation in determining the nature of cometary surfaces. In fact, individual interstellar grains could have undergone irradiation prior to accretion onto the comets, as could grains ejected from the comet. The effects of charged-particle irradiation on comet analogues has been investigated by Strazzulla and Johnson (1991) and Strazzulla et al. (1983; 1991). Sputtering by energetic solar wind particles results in the release of a number of neutral species and the build-up of a refractory crust. Strazzulla et al. (1991) argue that even water-rich comets would acquire a carbonaceous mantle several meters thick that would survive several passages through the inner solar system. Thus spacecraft attempting to sample primordial cometary material could have many meters of crust to penetrate. Astronomically observed emission features around 3.2 to 3.4 mm and 6.8 mm have been attributed to organic compounds in comets that could have been derived from this radiation-produced mantle.

9. INSOLATION EFFECTS ON COMETARY ANALOGOUS MATERIAL

9.1 Physical Phenomena Above, On, And Beneath The Surface Of An Artificial Comet Observed During The Experiment

Here the physical phenomena will be reported, which are observed and recorded during the insolation phase via sensors mounted above, e.g. video cameras or within the cometary analogous sample, e.g. thermoresistors (Pt-100). The most impressive phenomenon during the insolation phase is the emission of ice-/dust-grains, more or less permanently escaping from the surface, sometimes freshening up to eruptions and bursts. Figure 11 shows (in false colors) such a particle burst emitted from the tilted surface of the sample container. In Figure 12 two observed trajectories (with numbers) are shown and in addition the relevant ballistic parabolas, calculated from the relevant initial conditions, angle of elevation and velocity. The big difference between the observed and the calculated trajectories result from the strong interaction of the particles with the emanating gas jet. The shape of the trajectory depends on the amount of momentum transfer and on the time of interaction. This can be seen, that particles starting near the upper rim of the sample container, having a long passage crossing the sample container, show a very much longer trajectory, than particles emitted near the lower rim (see Fig 18 from above). At the beginning as could be seen with high resolution cameras, the particles are not loosely deposited at the cometary surface. They are, and this seems to be one important result, connected to the ice-/mineral-matrix by sinter necks. The upstreaming gas originating from the sublimation of the volatiles, inside the sample, first erodes the sinter necks and then the particles can entrain into the gas jet and are lifted-off.

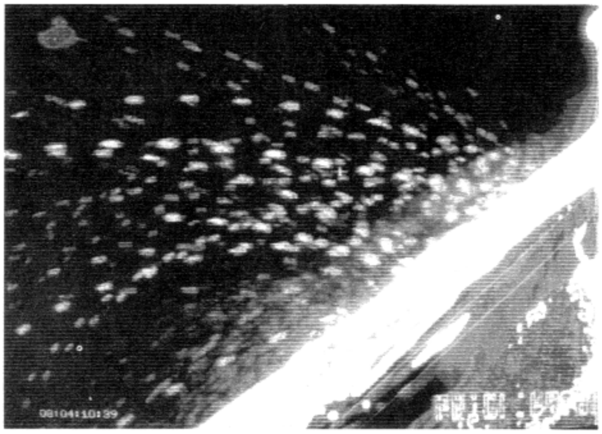

Figure 11. A particle burst emitted from the tilted surface of the sample container (in false colors).

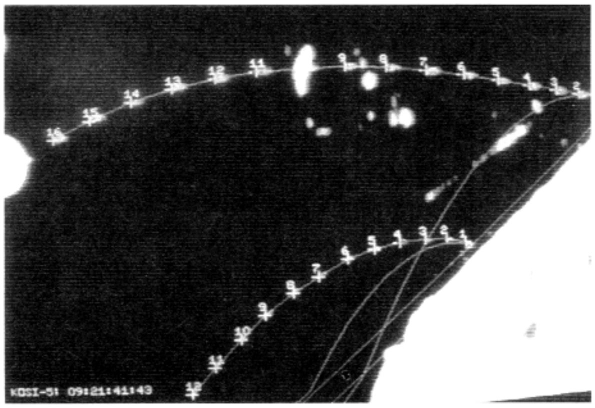

Figure 12. Two observed trajectories (with numbers) together with the calculated ballistic parabolas.

9.2 Emission Of Particles

Different observation methods used in the KOSI experiments, especially one, using a particle sampling- and investigation- instrument, developed and constructed by the Heidelberg group (see Mauersberger et al., 1991), allowed to determine the ice-content of the emitted particles. In case of a sample made out of a mixture of e.g. minerals and H_2O the emission of ice-/dust-grains will be reported, with a changing ratio of both components, depending on dust mantle development. This is the reason to use here the word particles as contrasting to gas.

Thiel et al. (1991), using particle collectors in the KOSI experiments, found that the flux of emitted particles decreased rapidly with increasing size. Measurements with a rotating dust collector reveal that the number of particles rapidly decreases with time. The explanation for this phenomenon lies probably in the formation of a cohesive dust mantle, gradually quenching the gas emission. Kochan and Koerver (1991) and Kochan et al. (1991) placed CCD-video cameras equipped with macro lenses over comet analogues in the small DLR chamber.

The observed particles were some 100 µm in size and the final velocities a few m/s. The enlarged images show ice-dust agglomerates covered with much smaller ice grains. So this much smaller grains could act as gluing material between the larger agglomerates. Grains do not instantly erupt from surface. But the gas flow erodes the connections with the original matrix or within larger agglomerates until drag exceeds gravity and particles lift off slowly (few cm/s). The failure stress estimated from the angle at which avalanches occur on the surface, is very low, ~10 Pa (Grün et al., 1993). High speed shutter video and computerized image processing indicate that the trajectories of the particles are not ballistic, but reflect the transfer of momentum from gas to the dust and thus acceleration by gas-drag(see Fig.14). Length of the trajectory and velocity of the particles depend on the emission angle and the location on the sample surface, where the particle starts. Particles, starting near the antisolar rim of the sample container cross nearly the complete the sample surface. In case, the trajectory has small deviations from the solar direction, these particles interact the longest time with the emanating gas jet. The resulting trajectories are long and the final velocities high, caused by the long lasting acceleration. Already in the very first experiments (Kochan et al. 1989b) it was detected, that the dust emission showed a pronounced peak in the sunward direction. The velocity of most particles ranged from 1 - 2 m/s. Kölzer et al. (1995) reported temporal variation in emission events of KOSI 5. Mass, size, density, trajectories, and drag equations for transfer of momentum from gas to dust were determined and source locations measured. They concluded that surface development has two steps, formation of dry particles and then build-up of mantle.

The simulated trajectories calculated by Markiewicz et al. (1990) and Gebhard (see Grün et al. 1993) for emitted particles assuming gas-drag are in good accordance with the observations.

9.3 Gas Emission

As expected, the gas flux produced in the during the KOSI experiments in which phase transformations in the ices are limited generally correlates with the intensity of irradiation (Grün et al., 1993). The H_2O and CO_2 released during KOSI irradiation of samples and measured by mass spectroscopy had release rates of 1018 cm^{-2} s^{-1} which is very similar to Halley data assuming 10% activity (Grün et al., 1991c).

Hesselbarth et al. (1991) measured gas fluxes and compositions using pressure gauges and a quadruple mass spectrometer about 1 m from surface KOSI 4 experiments. Fluxes were ~1017 to 1016 cm^{-2} s^{-1} with CO_2 fluxes being about a factor of two below H_2O fluxes. When insolation reaches one solar constant, H_2O and CO_2 production increased rapidly and then more slowly, H_2O production slowing down faster than CO_2 production. The H_2O and CO_2 are released separately, CO_2 subliming at lower temperatures (125 K) from deeper sample layers than H_2O (250 K). Thus there is fractionation in the composition of the gas and a H_2O / CO_2 profile in the sample whereby the surface layers are CO_2-depleted by the ratio increases abruptly below the sublimation layer, due to recondensation, and then decreases slowly with depth.

Ibadinov and Aliev (1987) found that the concentration of CO_2 in the surface layers of comets due to sublimation of H_2O and found that it could not be more than a few percent.

Bar-Nun et al. (1985) measured the release of H_2, CO, CO_2, CH_4, Ar, Ne and N_2 from water ice. The CO, CH_4, Ar, and N_2 were released in four temperature intervals corresponding to release mechanism and phases changes in ice. Between 30 and 59 K, straight evaporation occurred, over the temperature ranges 135-155 K, 165-190 K and 160-175 K gas release associated with conversion of amorphous to cubic ice, clathrate breakdown, and conversion of cubic to hexagonal ice, respectively. Ne was not trapped by the ices.

9.4 Compositional Changes

9.4.1 The Dust-To-Ice Ratio

Mauersberger et al. (1991) examined 1200 particles in the mass interval from $2x10^{-10}$ to 10^{-5} g ice by measuring pressure changes caused by their evaporation upon landing on a heated shell within a closed compartment, having a chimney as entrance opening, 0.5 m apart from the surface of the KOSI samples. Brief signals were produced by pure ice particles while ice/dust mixtures produced longer pulses. The ratio of silicate dust to ice dust rose to about 200 in an hour where it remained for many hours. As mentioned above, silicate, ice and mixed silicate-ice particles being ejected by comet P/Halley were detected by the GIOTTO spacecraft.

Thiel et al. (1991), using the particle collectors and piezo-impact detectors in the KOSI experiments, showed that the ratio of ice-free to ice-containing particles decreases from about 13 to 0.77 as particle size increases from ~200 μm to ~500 μm. This ratio would be higher for particles smaller than the 200 μm detection limit of the Piezo detectors.

9.4.2 Dust-To-Gas Ratio

The DIDSY experiment on GIOTTO found a mass dust-to-gas ratio of 1:7 -1:1, the range depending on what mass range was integrated to determine the total mass of ejected particles (McDonnell et al., 1987). In fact, because the largest mass detected was below that expected to be ejected, Grün and Jessberger (1990) suggest that these estimates should be increased by a factor of three. Cosmic abundances suggest that the dust-to-gas ratio should be 1:1 - 2:1. The KOSI-3 experiment produced a maximum gas flux density of 140 x 1016 cm^{-2} s^{-1} and particle count rate of 60 s^{-1} (Kölzer et al., 1995). For the

KOSI-9 experiment these values were typically and 4 x 1017 cm^{-2} s^{-1} and 30 particles per 15 minute period (Grün et al., 1993). Kölzer et al. (1995) and Grün et al. (1993) did not report dust-to-gas ratios, but it is clear that during the KOSI experiments these ratios would have been many orders of magnitude below those observed for Halley's comet or expected on the basis of cosmic abundances.

9.4.3 Gas Composition

Figure 13 shows the H_2O and CO_2 release for a typical KOSI experiment (KOSI 4, see Hesselbarth et al., 1991, Lämmerzahl et al., 1995). Water release rates decrease from ~1018 cm^{-2} s^{-1} to ~1016 cm^{-2} s^{-1} while CO_2 release rates decrease from ~1017 cm^{-2} s^{-1} to ~1016 cm^{-2} s^{-1} during the 50 h duration of the experiment. The H_2O/CO_2 ratio was usually found to be 6-3, compared with typical values of 14 for the starting material, reflecting the greater volatility of CO_2 than H_2O (Grün et al., 1991c).

Once released into the coma UV photolysis triggers a complex series of kinetically controlled reactions. Roessler et al (1992a) made a detailed study of the UV photolysis products of the KOSI comet analogues using mass spectroscopy. Through a number of reaction pathways reactive intermediates, polyoxymethylene which has been reported by Huebner, (1987), to be present in comets) breaks down to H_2CO, CO_2 and CO. The kinetics leading to C_2, C_3, H_2O, NH_3, NH, SH and HCN have been reviewed by Jackson (1991).

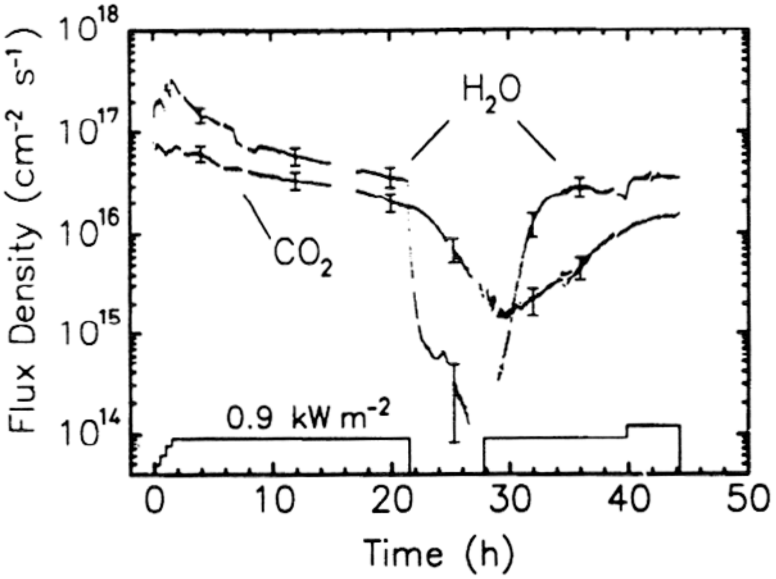

Figure 13. Surface gas flux densities inferred from mass spectrometric measurements for an ice/dust mixture (KOSI 4) at an interrupted insolation. (Courtesy Hesselbarth et al., 1991)

9.4.4 Isotopic Fractionations

Isotopic fractionation during the KOSI experiments was measured by Klinger et al., (1989b) and Roessler et al.(1992b). They found δD values for the interior and crust of -47.7 and -35.7 permil, respectively, and for $\delta^{18}O$ the found values of -6.40 and -4.27 permil. (For the Orguiel CI chondrite, δD and $\delta^{18}O$ values are -50.5 and -7.05 per mil, respectively). Thus, as expected, mass fractionation causes the surface of the KOSI samples to be enriched in the heavy isotopes while the interior was essentially unchanged.

9.4.5 Impact-Induced Effects

The effects of bombardment of a simulated cometary surface were explored by Thiel et al. (1995) who impacted "Terraperl" particles of various sizes into the surface of the KOSI 10 sample. The first idea behind was the re-activation of sample surface the by breaking the dust mantle. The second aim was the demonstration and quantizising of coupling of the well defined injected particles into the emanating gas jet. To cite the second result first, the momentum (mass) of the injected particles was too big, that the particles directly coupled into the jet. They fell till to the sample surface, from where they were „emitted". By the impact the dust mantle was partly broken. In a process similar to wind-sifting, particles from the sample, bond into the dust mantle, became free to entrain the gas jet as was done by the injected and impacting particles. Figure 16 demonstrates the particle injection from above the tilted sample surface at the left hand side. The particles hit the surface and are "emitted" to the right hand side. The impacts caused 1-7 K drop in temperature, depending on impactor size, and increased the gas flux and thereby gas drag on escaping particles. Particle accelerations of <10 to 17 m s^{-2} were observed, depending on particle size. All these processes are expected to occur on comets.

Figure 14. Particle injection during KOSI 10 from above on the tilted sample surface at left.

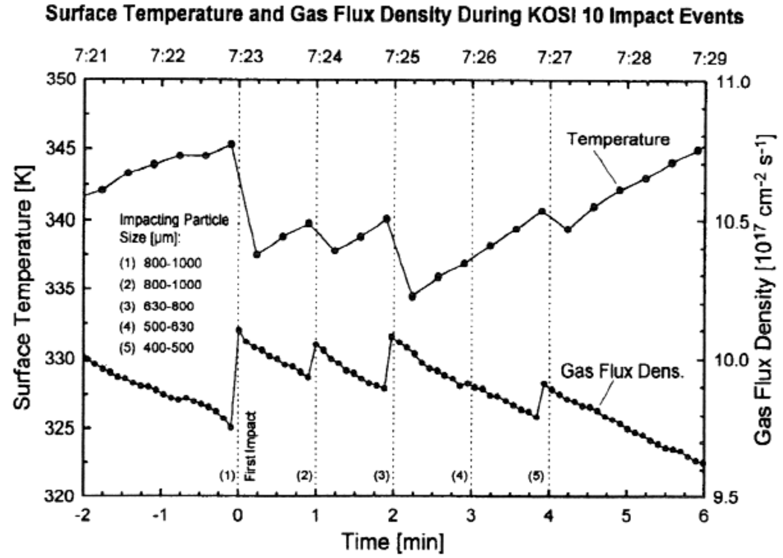

Figure 15. Local surface temperature and gas flux density during the KOSI 10 impact events (Thiel et al. 1995)

10. THERMAL BEHAVIOR

10.1 Thermal Conductivity

Thermal conductivity data are required for thermal modeling of the comet nucleus, but equally important is a quantitative understanding of the physical processes that occur in the surface layer of the comet nucleus. The theoretical models can be compared with the results of the large-scale simulations. Values for the thermal conductivity of snow, snow-ice and snow-dust mixtures with porosities similar to those of the KOSI samples were measured by Spohn et al. (1989a,b). They used a 70 mm diameter 125 mm long cylindrical sample heated at one end, and cooled at the other, with thermocouples located throughout.

Thermal conductivity values ranged from 0.15 to 0.65 W m^{-1} K^{-1} with little or no dependence on temperature over the range 80 to 170 K or mineral grain content. Benkhoff and Spohn (1991) reported matrix thermal diffusivity values ($j = K/\rho C$, C is the specific heat, 1 M J m^{-3} K^{-1} except for the KOSI 5 sample for which the value was 0.4 M J m^{-3} K^{-1}) of 2-13 x 10^{-8} m^2 s^{-1} at 125 K. In contrast, crystalline ice has a thermal conductivity of 3.5 to 8 W m^{-1} K^{-1}, about a factor of 10 larger than the values observed for the comet analogues and much larger than can be accounted for by porosity alone.

Kossacki et al. (1994) discuss the influence of grain sintering on the thermoconductivity of porous ice. The sintering of ice grains, which leads to a continuous growth of the grain to grain contact area (Hertz factor) is incorporated in the thermal evolution model. The sintering process may lead to significant changes of the matrix conductivity on time scales of hours to days. In simulation experiments with paraffins in addition to a water- / mineral-mixture, Kömle et al. (1996) found that a cohesive residuum was formed, having a heat conductivity, one order of magnitude higher than the typical loose dust mantle.

10.2 Temperature Profiles

Typical temperature profiles through the KOSI samples are shown in Fig. 18. There is a steep temperature gradient through the dust mantle, when present (see KOSI 5 data), and a shallower gradient below the crust with discontinuities at 210 K due to the crystallization front of H_2O and 125 K due to the crystallization front of CO_2. Most remarkable are the convex profiles sometimes shown. These cannot be explained by conduction alone and require redistribution of heat by vapor transport.

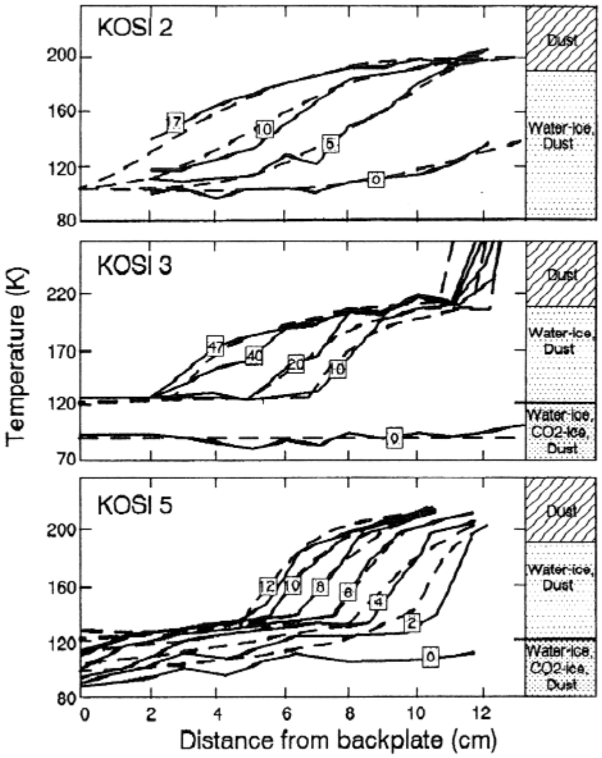

Figure 16. Typical temperature profiles through the KOSI samples 2, 3, 5.(Courtesy Spohn et al. 1989 a,b)

Theoretical studies of thermal profiles in cometary materials by Mekler et al. (1990), Spohn and Benkhoff (1990) and Espinasse et al. (1989, 1991) have been conveniently summarized by Rickman (1992). Huebner and Boice (1992) have performed three-dimensional time-dependent theoretical modeling of surface layers, energy balance at surface, thermal properties of ice and dust-ice mixtures, recondensation at surface. They found that 50% of heat loss from the surface of the KOSI samples was by H_2O evaporation and 5% was by heat conduction from new surface.

Since heat conduction alone produces concave profiles, heat transfer by both solid state conduction and gas transport must be modeled.

The thermal profiles of Spohn et al. (1989a,b) are shown in Fig. 18, superimposed on the experimental data. They provide a very good match to the experimental data.

11. PHYSICAL PROPERTIES OF THE COMETARY ANALOGOUS MATERIAL - INVESTIGATED LATER OUTSIDE THE SIMULATION FACILITY

11.1 The Dust Mantle

In the KOSI experiments, the final dry dust layer was a usually few millimeters thick (Grün et al., 1993). It took about an hour to fully form a mantle over the laboratory samples, but the process is strongly temperature-dependent. Kömle et al. (1991) also simulated the non-volatile or sintered crust on Halley in the laboratory. They covered the ice sample by inert corundum grains of different diameters, simulating so a different porosity of the model mantle. In other experiments the sample container was covered with darkened metal plates with bore holes. They found that the crust resulted in higher temperatures and pressures (several Pa) than expected from thermodynamic equilibrium. Ibadinov et al. (1991) derived quantitative empirical relationships between sublimation rate, crust thickness, time, and depth using comet analogue experiments.

11.2 Surface Topography

The surface topography of the KOSI samples was determined by dust removal by gas drag and, on inclined surfaces, by avalanches and slippage. Valleys and ridges were formed on the surface. Grün et al. (1993) described a situation in which there was surface movement during the KOSI 9 experiment (200-1900 W/m^2, 10 wt % olivine in ice). During the first period, gas and particle flow decreased and temperature increased after a crust had formed. When gas flow reached 1021 H_2O molecules $m^{-2}s^{-1}$ during second period, up to eight avalanches per minute occurred on the surface that damaged the mantle and exposed fresh ice and enhanced gas and dust production. Many of the dust grains were fluffy aggregates. No avalanches and resulting damage to the crust occurred during the third period and gas and dust flow was not enhanced.

11.3 Stratigraphy Of The Outer Nucleus

The high sublimation rate at the beginning of the experiment results in the rapid formation of a dust mantle and internal re-crystallization layers which becomes an obstacle to further heat flow and quenches the further gas flow away from the nucleus (Grün et al., 1991c). The presence of the dust mantle also means that redistribution of heat throughout the comet by gas transport is important and the build-up of pressure can cause disruption of the crust and erratic and systematic variations in comet activity (Grün et al., 1993). Figures 17, 18 and 19 demonstrate an avalanche on the sample surface,

followed by an emission of dust, resulted by an exposition of fresh ice-/mineral-matrix.The thermal wave into the sample results in a complex stratigraphy in the icy layers under the crust. Evaporation of water and other volatiles leads to the production of a refractory dust mantle on the surface, and the heat wave penetrating into the interior, results in a crystallization front and an evaporation front. The loss of volatiles causes erosion of the surface, while crystallization results in the liberation of heat. Evaporation results in transport of gases, especially the more volatile CO_2. The CO_2 redistributes heat as it diffuses throughout the pore-space in the comet. There is an outward flow of CO_2 to the surface and an inward flow to deeper cooler regions where it re-crystallizes.
Most of these expectations are borne out by the KOSI experiments. There are dust-rich surface regions, crystallization fronts, causing H_2O-rich inner crusts and regions of solidification with large crystals e.g. CO_2.

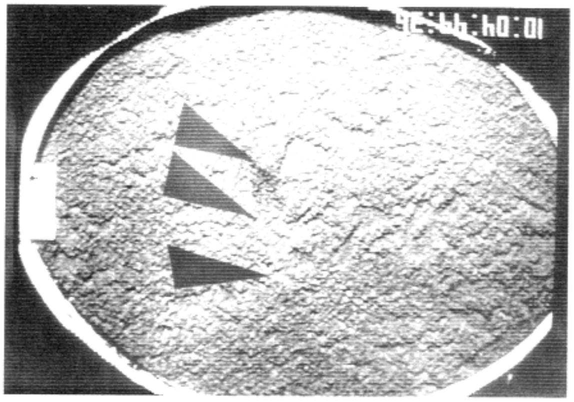

Figure 17. Avalanche at the sample surface during KOSI 9 between the two lower marks.

Figure 18. Particle burst from the tilted sample surface resulting from the above avalanche.

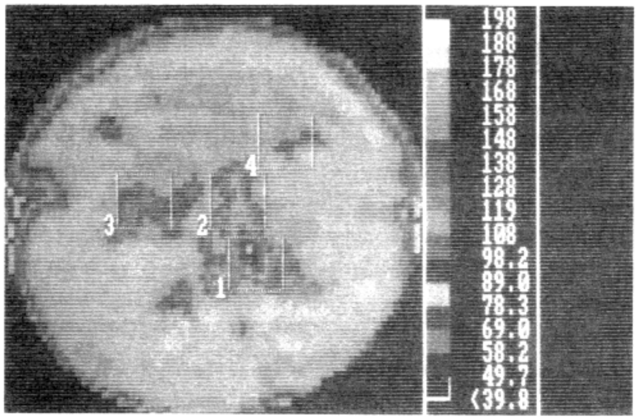

Figure 19. Infrared picture of the sample surface during the above avalanche. The temperatures are originally color-coded. In here the areas strongly deviating from the overall sample surface temperature are marked by squares 1-4. In 1 the temperature difference is maximum around 100 degrees, in 2: 70 degrees, in 3: 50 and in 4: 30 degrees. The low- temperature areas coincide with the avalanche region. (courtesy Lorenz et al. 1995)

11.4 Strength Parameters

Penetration strength is important to sample return missions since it will determine the design of landing-, anchoring-, and drilling-equipment. On the basis of the experiences gathered from the KOSI experiments, Kömle et al. (1997) hope to investigate the surface properties of a cometary surface "in situ" by an anchoring device for RoLand, the ROSETTA mission lander.

Kochan et al. (1989c) have reported penetration measurements, the force required to push a 0.5 mm diameter steel rod with a hemispherical tip into the samples at 0.2 mm/s, on KOSI comet analogues after irradiation (Fig. 12). Fig. 22 shows the KOSI 5 sample in the glove-box during the hardness test with the penetrometer. All KOSI experiments showed a hard layer beneath the dust mantle resulting from the sublimed and after inward diffusion re-crystallized volatile components. The strength, thickness and depths, where the layers were found inside the bulk sample varied. A sample material made up from three volatile components, water, methanol and CO_2, showed icy layers of these species in different depths. In the LN_2 cooled sample container the temperatures decrease with increasing depth. So the formation of internal layers follows the crystallization temperature of the different components. In conclusion, the real comet possibly made up from a lot of volatile components, should be built up of different shells like an onion. This effect was named "thermochromatography" (Hsiung and Roessler, 1989).

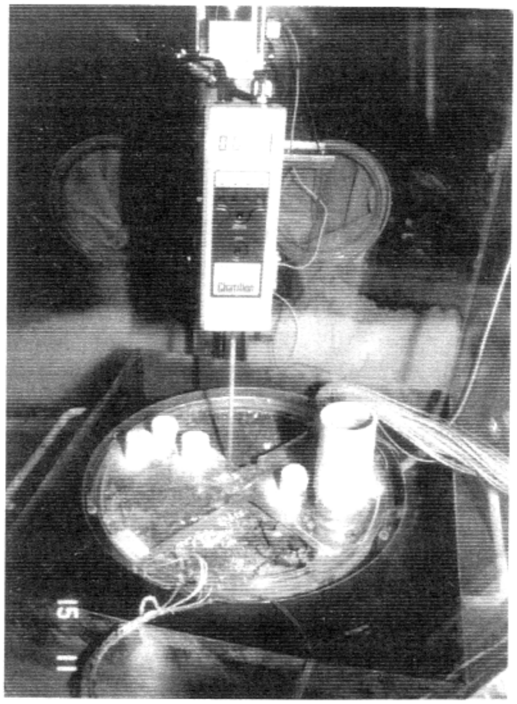

Fig. 20. Hardness test of the insolated sample using a penetrometer.

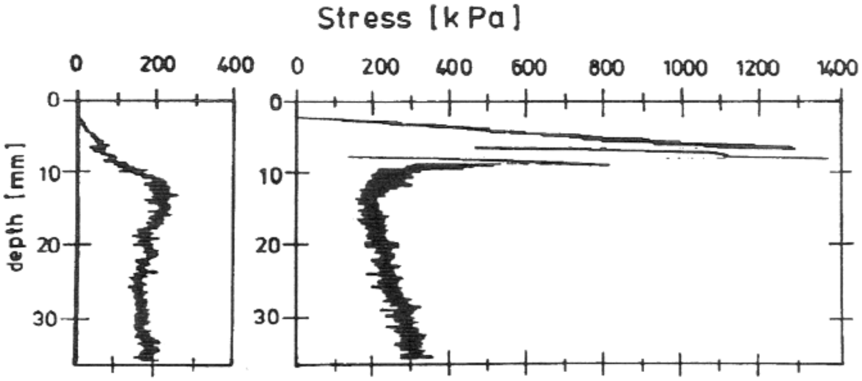

Fig. 21. Stress-depth profiles of a cometary analgous sample before (left) and after insolation (right). Small chamber experiment.

Where recrystallization of water vapor was extensive, stress values of 0.2 to 5 MPa were observed but in areas where it was less extensive, values were only 0.05 to 2 MPa. Below 200 K, pure crystallized ice has strengths of about 5 MPa. Thus, as might be expected, the penetration strength of the material depends very strongly on porosity, with pure amorphous ice having values one-hundredth those of crystallized ice, or less.

The compressive strength of the comet analogues was measured as a function of temperature, density and composition by Jessberger and Kotthaus (1989). Standard triaxial and uniaxial cells were used at 123, 233 and 253 K with a 10 MPa force and 1 mm/min displacement. Compressive strength decreases from 0.8 to 1 MN m^{-2} with increasing temperature, decreasing density (from 0.8 to 0.5 g cm^{-3} and increasing proportion of dust and tuff fragments (0 to 50 %).

11.5 Density, Porosity And Albedo

Comet analogue sample materials are usually of low density (0.4 to 0.60 g cm^{-3}), high porosity (29% to 50%), and low albedo (0.07 to 0.20). Variations in the density and albedo appear to be dependent on the relative proportions of CO_2 and H_2O and the proportion of silicates, carbon and ice. Samples with the lowest porosities generally also contain the largest proportions of particulates (carbon and dust) to ices (CO_2 and H_2O). The values seem to be consistent with those of Comet P/Halley. Thiel et al. (1995) showed that the porosity and density of the sublimation residues depends on particle size and they proposed exponential relationships with decreasing density and increasing porosity as particle size increases.

11.6 Spectral Reflectivity And Albedo

Oehler and Neukum (1991) have reported the reflectivity spectral data for the visible and near IR region (0.36-2.5 μm) for the KOSI 3,4,6 experiments and Grün et al. (1991c) mention data for the KOSI 3 experiment. The measured albedo were 10 to 20 % with an errors of less than 10%. Some experiments resulted in small decreases in albedo, but others showed a surprising increase attributed to frost that formed after the experiment. The 1-5 mm dust mantle produced on these samples caused a decrease in the absorption of H_2O and CO_2 at 1.5 and 2.0 mm, but again a water-ice absorption band that appeared after the irradiation was thought to be due to frost

11.7 Textural Changes

11.7.1 Petrographic Studies

Stöffler et al. (1991, 1992) have developed methods for preparing thin sections of cometary analogue material adopting methods used for snow research. They impregnate the samples with diethyl phthalate at 268 K and then freeze, cut and section the material. At 253 K, a special sledge microtome being used to make the thin sections. The sections can then be examined under optical microscopes in a cold laboratory at 258 K.

Pure water-snow crystals increased in grain size and the samples increased in porosity after exposure in the KOSI apparatus. Snow-ice and dust mixtures had a loosely consolidated dust formed on the surface after exposure in the KOSI apparatus due to sublimation of ices from the surface.

12. ROLE AND LIMITATIONS OF LABORATORY SIMULATION EXPERIMENTS

All scientific investigations of Nature make some use of laboratory studies, whether it is examining a mountain through a microscope or applying petrologic and thermodynamic techniques to mineral and rock structures in the hope of understanding the formation of continents. Comet simulation experiments have been used to address some of the engineering questions associated with comet mission, such as whether an experiment destined for a spacecraft has been adequately designed, whether it will pose and address the right questions, and whether the equipment will survive conditions likely to be encountered. The simulations also help with the interpretation of spacecraft data, and can even help identify and design corrections for problems that are encountered during a mission. For example, Lafontaine et al.(1992) and Eiden and Coste (1992) discuss the need for immediate anchoring of the spacecraft and Oehler et al. (1992) used IR spectroscopy calibration data from comet simulations to determine surface temperatures of comets. The drill bit designs, and acoustic sounding techniques used to derive internal structure, were also dependent on the comet simulation experiments (Kochan and Junglus, 1993).

But of course the major impetus for laboratory simulation experiments is to understand the physical and chemical processes likely to be occurring in or on a comet. Klinger et al. (1989) and Keller and Markiewicz (1991) present different perspectives on this topic. The former authors point to a number of early results of the comet simulation experiments that have or should cause a revision to current ideas about cometary processes. First, they point out that vapor phase transport of heat is important in determining the history of the comet nucleus. Secondly, they argue that more realistic estimates of thermal conductivity of comet solids are now available. Third, they suggest that the dust mantle that forms on the surface of the nucleus does not prevent heat from penetrating the nucleus; to the contrary, the dust mantle causes higher internal temperatures and pressures than would otherwise apply. Keller and Markiewicz (1991) stress the difficulties of simulating cometary processes. They argue that since the starting material used in the large-scale simulations is not produced by condensation, so that large refractory grains might not be fluffy enough to be emitted from the nucleus by gas-drag. Secondly, Keller and Markiewicz (1991) point out that that the gravitational fields in the laboratory are three orders of magnitude stronger than cometary fields. Third, so sizes are 10^{-4} to 10^{-5} times those of the comet nuclei, so that temperature gradients inside the analogues are about 100 times greater than in the comets. Finally, they argue that the time scales for laboratory experiments are necessarily quite different from those of the cosmos. Thus gas flow from sublimating ice, interactions of gas and dust and heat transport properties cannot be accurately modeled. These are obviously reasonable criticisms and clearly the comet simulations are only applicable to conditions in the vicinity of the nucleus and then only on the centimeter to meter scale. The experiments and the data should be viewed with these cautions in mind. However, probably the major uncertainty concerns the refractory irradiation driven mantle, which could be meters thick.

Thus while uniquely valuable insights into comet evolution have been observed, in many respects these experiments are incomplete. Could the silicate mantle even reach meter dimensions, so that certain meteorites might be cometary? To what extent do comets grade into asteroids?

In reviewing the KOSI experiment program it is worthwhile to state that it have been six scientifically exciting years of fruitful cooperation in an interdisciplinary team. Young colleagues full of enthusiasm, made their first own experience with planning and realizing experiments under simulated space conditions. The team was organized top down by an advisory committee, a panel with representatives from all institutes, a scientific coordinator and a speaker of the MSc- and PhD-students. In eight cometary workshops the results of the last experiment were discussed and the objects to be investigated in the next experiment were agreed. A denominated P.I. became responsible for the timeline of experimental preparation and performance when the date was finally allocated.

The KOSI experiments resulted in 20 PhD- and Msc-theses, and around 100 publications. Looking through the relevant literature of today, the impetus of KOSI can be found in many experiments and papers.

Parameters of KOSI experiments

Experiment	**KOSI-1**	**KOSI-2**	**KOSI-3**	**KOSI-4**	**KOSI-5**	**KOSI-6**	**KOSI-7**	**KOSI-8**	**KOSI-9**	**KOSI-10**	**KOSI-11**
Date	**May 87**	**April 88**	**Nov. 88**	**May 89**	**Nov. 89**	**May 90**	**Jan. 91**	**Oct. 91**	**Dec. 91**	**Dec.92**	**May 93**
Sample size (height / diameter in cm)	12 /29	15 / 29	14 / 29	13 / 29	13 / 29	13 / 29	29 / 60	30 / 60	13 / 30	13 / 30	13 / 30
Sample composition (weight %)											
H_2O-ice	90	90	77.8	77.6	70.2*	41.6*	83*	100*	90	90	45.1
CO_2-ice	-	-	13.8	13.8	16.8*	15.0*	15*	-	-	-	5.8
other ices	-	-	-	-	methanol 4.2	-	-	-	-	-	9.1+
total dust content	10	10	8.4	8.6	8.8	43.4	2.1	-	10	10	40
Dust composition (weight %)											
olivine	-	89	89.1	89.2	89.3	71.3	88.9	-	99.9	99.9	50
montmorillonite	-	10	9.9	9.9	9.9	17.0	-	-	-	-	50
carbon	1	1.0	1.0	0.9	0.8	11.7	3.1	-	0.1	0.1	-
other	kaolinite 99	-	-	-	-	-	kerogene 8.0	-	-	-	-
Initial sample properties											
albedo	0.2	0.06	0.17	0.09	0.08	0.12	0.07	0.90	0.06	n.d.	0.56
density (g cm^{-3})	0.4	0.55	0.48	0.51	0.56	0.59	0.46	0.40	0.44	0.50	0.54
porosity	60%	50%	55%	55%	40%	29%:	45%	56%	53%	49%	49%
Irradiance											
flux range (SC)	0.15 - 1.15	0.9	1.4	0.65 - 0.85	1.2 - 1.0	1.2 - 1.4	1.0:	1.0	1.4 - 0.15	1.0-0.6	1.3-0.5
duration (h) (including dark phases)	38.4	39.4	47.2	44.5	12.9	30.3	34.0	40.0	59.0	4.75	15.25

*: Isotopically marked layers of HDO and $^{13}CO_2$

SC: Solar constant = 1.37 kW m^{-2}

":" indicates uncertain data

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