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Primordial Comet Mantle: Irradiation Production of a Stable, Organic Crust

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Laboratory data and corrected estimates of cosmic ray dose are used to predict the thickness and survivability of the cosmic ray-produced, primordial comet mantle ("crust"). These results support the hypothesis that the refractory mantle produced by cosmic ray irradiation of a new comet may be able to survive a comet's entry into the inner solar system for many revolutions. Because this mantle may extend to several meters in depth, the proposed CRAF and Rosetta probes would have to be extended to reach unprocessed cometary material. © 1991 Academic Press, Inc.

1. INTRODUCTION

The outer layers of a comet, the comet's mantle, will be sampled during the proposed Rosetta comet–sample–return mission and will be (perhaps) penetrated and measured by CRAF. It has been pointed out by a number of authors that this region of the comet is altered by cosmic ray particle processing during the comet's 4.6×10^9 years residence time in the Oort cloud (Donn 1976, Whipple 1977, Strazzulla 1986, Johnson *et al.* 1987). That such an alteration may have occurred would appear to be reenforced by the recent measurement of the difference in the *ortho–para* ratio of water molecules effusing from a new comet and a periodic one (Mumma 1989, Mumma *et al.* 1990). Since a prime goal of each of the proposed missions is to establish the connections between the comet's constituent materials and their precursor materials, any post-formation alterations to the region from which a sample is taken are important. There are, of course, other processes that can affect the structure and state of the comet mantle before the comet is ejected from the Oort cloud into the inner solar system (Stern and Shull 1988, Stern 1988, 1990). Whereas estimates of the effect of these processes are based on considerations involving a number of uncertain physical quantities (e.g., Oort cloud densities, supernova events near our solar system), determination of the cosmic ray particle processing of the mantle is based on spacecraft measurements of cosmic ray particle fluxes and on laboratory measurements of energetic particle alterations of materials. Therefore, the effect of cosmic ray particles on the comet mantle can, in principle, be described with some certainty. Other mantle processing in the Oort cloud would be superimposed on the effects described here.

There has been some confusion generated as to the thickness of the radiation-produced crust due, in part, to incorrect energy deposition estimates. These have been corrected and a review of the effects produced by ion irradiation on materials relevant to comets has been recently presented (Strazzulla and Johnson 1991). Earlier, Johnson *et al.* (1987) discussed how ion irradiation of ices containing organic compounds in the presence of the interface with the interplanetary vacuum leads, in an irreversible way, to the production of a nonvolatile organic residue which forms a mantle. New volatile and reactive species (e.g., Donn 1976, Whipple 1977, Moore *et al.* 1983) will also be formed, but these are easily lost due to other mantle-altering processes or on heating as the comet approaches the Sun. Therefore, a comet exposed to

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background particle radiation in the Oort cloud develops an outer network of nonvolatile material. When a new comet enters the inner solar system the warming can lead to activity due to fissures in the crust and the breakoff of unstable pieces of the crust. If the comet enters a periodic orbit in the inner solar system the remaining mantle will be further altered due to inner solar system processes (Fanale and Salvail 1984, Prialnik and Bar-Nun 1988).

In this paper we present experimental results that support the hypothesis that the cometary organic crust, once developed by ion irradiation in the Oort cloud, can "survive" gas ejection from deeper layers. Parts of the organic cometary surface may, therefore, be as old as the comet itself.

2. LABORATORY EXPERIMENTS

Ion irradiation experiments have been performed on a variety of astrophysically relevant materials including molecular solids (e.g., frozen H_2O, CO_2, NH_3, SO_2, S, and various mixtures) and hydrocarbons (C_6H_6, C_6D_6, CH_4, etc.), as recently reviewed by Strazzulla and Johnson (1991) and Johnson (1990). Whereas the giga-electron volt energies of interest for the primordial mantle formation are not easily obtainable in the laboratory, the effects generally scale with the energy deposition per unit path length (dE/dx) in the material.

With a typical dose of ~100 eV/molecule, ion bombardment of carbon- and sulfur-containing species produces a substantial residue (Moore *et al.* 1983, Foti *et al.* 1984, Johnson *et al.* 1984; Andronico *et al.* 1987, Lanzerotti *et al.* 1987; Strazzulla and Johnson 1990). In some experiments (Lanzerotti et al. 1987, Strazzulla *et al.* 1991) continued bombardment (up to $\sim 10^{17}$ keV–MeV ion/cm^2) without warmup causes the material to evolve toward a refractory solid which we call irradiation-produced hydrogenated amorphous carbon (IPHAC). The "final" state is roughly independent of the initial hydrocarbon: that is, this new material "forgets" its state before irradiation, and the ion type and energy affect only the fluence (irradiation dosage) and the thickness.

We used an apparatus described in Strazzulla *et al.* (1991) to irradiate frozen gases and obtain *in situ* IR transmission spectra with an FTIR (Perkin–Elmer 1710) spectrophotometer. A scattering chamber at a vacuum of 10^{-7} mbar with KBr windows was viewed with the FTIR.Thick layers (approximately micrometers) of frozen C_6H_6 (chosen as an example of hydrocarbons) and H_2O mixtures were accreted onto a silicon substratum in contact with a cold finger (77–300 K) by admitting the gases into the chamber through a needle valve. These targets were then bombarded by 3-keV Ar (chosen because its small penetration range) ions having a 2 × 2-cm^2 spot on the target (greater than the spot of the IR beam). The equivalent thickness of each component was measured by counting interference fringes for 632.8-nm reflected laser light in a calibration experiment. Because the penetration depth in a frozen H_2O + C_6H_6 target is about 0.02 μm for 3-keV Ar ions, only the upper layers ($\sim 10^{-2}$ of the target thickness) are damaged by the incoming ions so that the new refractory material covers a much thicker ice layer. For example, in one experiment the thickness of the deposited layer was 1.25 μm for H_2O and 1.58 μm for C_6H_6. After irradiation with 3-keV Ar ions (77K, 1.5 × 10^{16} ions/cm^2) and warming at 300 K a residue with a thickness of 0.145 μm was obtained. A moving mechanical stylus produced a profile of the surface to obtain the thickness. This is about seven times the range of the irradiating ions. The value 0.145 μm is the maximum thickness as the residue is fluffy with many voids.

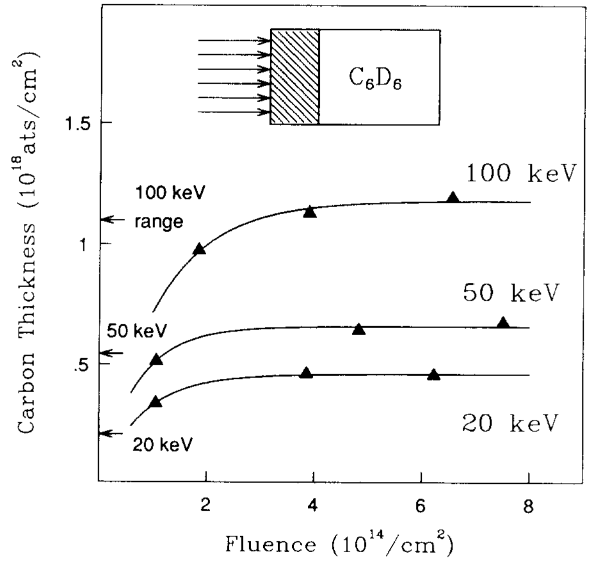

FIG. 1. Thickness of organic residue, obtained after irradiation of frozen deuterated benzene with argon ions at various energies, versus ion fluence. Ion ranges are indicated by arrows.

The above results are confirmed by a set of experiments performed using more energetic (10–100 keV) Ar ions to bombard frozen layers of C_6D_6 whose thickness was always larger than the ion range. In this case the residue thicknesses were measured by ion backscattering techniques (e.g. Brown *et al.* 1980). The results are summarized in Fig. 1 where the thicknesses (in C atoms/cm^2) of the residues are plotted against ion fluence. The results refer to Ar ions with energies of 20, 50, and 100 keV whose penetration depths are indicated by arrows. From Fig. 1 it is seen that the thickness of the residue is greater than the calculated ion range. The unaltered ices are lost, during the warmup, through fissures and voids in the organic crust. As the underlying ices are lost the crust recedes and eventually sticks to the substrate. Experiments with mega-electron volt protons (Lanzerotti *et al.* 1987, Moore *et al.* 1983) also exhibit solid formation. Therefore, these results should be general.

All irradiation experiments performed so far have used thin deposits, a few micrometers at most, at about unit density. It is important eventually to carry out irradiation experiments on centimeter-thick deposits also to determine the efficiency of residue formation and retention. In addition, as comets are probably very porous (Donn 1990, Rickman *et al.* 1987) deposits with a porosity of 0.5 should be used.

3. DISCUSSION

In a closed system long-term irradiation leads to a material which is a stable mixture of species as bonds are broken and re-formed. However, the loss of H is a primary controlling process. In a mixture with atomic composition of C, H, O, N, and S, the removal of H permits the enhanced formation of, for example, C–C, C–N, C–O, C–S, and S–S bonds. This converts the ice mixtures (e.g., H_2O, NH_3, CO, CH_4, H_2S) to refractory "organics" with residual trapped volatiles (e.g., O_2, CO) and some unrecombined radicals (at low temperature).

It is shown here, for a case where the ion range (penetration depth) distribution is well defined, that after sufficient irradiation the thickness of residues produced are larger than expected from the thickness of the irradiated zone. This is due, in part, to the ion straggling (i.e., energy loss is a statistical process) and to the transport of species through the irradiated region to the surface so the crust can "grow." However, it is due primarily to the evolving material porosity as ion penetration is determined by the column thickness (number of atoms/cm^2). This is important because of the probable porous structure of a new comet, <1 g cm^{-3}, as proposed by Donn (1990, and reference given therein) and Rickman *et al.* (1987). For a different point of view see Peale (1989).

The enhancements in thickness measured here cannot be directly converted to use for the comet crust. For instance, unidirectional bombardment is known to produce microscale surface topography, producing large peaks and valleys (Carter *et al.* 1983), as indicated by micrometer-size holes in an ice sample (Johnson *et al.* 1985). More nearly isotropic bombardment may reduce this effect, and the other mantle-altering processes will agitate the outer layers, changing the structure.

What is more important for the behavior of a comet is that the voids and pathways produced (Strazzulla *et al.* 1988) are seen to allow relatively large amounts of underlying condensed gas to diffuse out during warmup while maintaining the structural integrity of the crust. That is, experiments show that the adhesion of the material allows the crust to recede slowly while losing a volatile underlayer many times its thickness. Of course, extremely rapid warming can in principle blow off a crust and "bursts" have been seen at those temperatures for which radical recombination occurs (Greenberg 1982, Moore *et al.* 1983). However, the rate of the temperature rise used here is much faster than that experienced by a comet deflected into the inner solar system from the Oort cloud. Therefore, the increasing temperatures on entering the inner solar system are not likely to cause ejection of the major part of the irradiation-produced crust.

4. CONCLUSION

Laboratory experiments suggest cosmic ray irradiation of comets in the Oort cloud will produce a nonvolatile crust the thickness of which depends on the initial porosity (Strazzulla and Johnson 1991). For a high-porosity comet, porosity $\cong 0.8$, the initial crust may be $\cong 10$ m thick. Based on our laboratory evidence, most of the crust would survive the initial approach to the Sun and subsequent perihelion passages. Observational results, particularly the images of the nucleus obtained during the Halley encounter, show that $\cong 80\%$ of the surface is dark and inert, both of which are consistent with the presence of an organic mantle.

A number of intriguing mantle-altering processes, in addition to cosmic ray irradiation, have been discussed recently (Stern 1988, 1990, Stern and Shull 1988). These processes include transient heating by stars and, possibly, collisions with other comets. The extent in depth of these effects varies from shallow, <1 μm, to rather large (approximately meters). Since it has been shown that competing regolith mixing processes inhibit the formation of a crust on Pluto (Johnson 1989), we briefly comment on these comet-surface alterations. (1) It is seen here, as in other laboratory work, that heating can enhance radical reactions and remove volatiles. Small, transient, temperature enhancements of the type described, however, cannot alter the thickness of the irradiation-produced primordial mantles. (2) Bombardment by ISM grains can eject surface material if it is still volatile (i.e., early in the comet's life in the Oort cloud), but it is likely to add to the thickness once the porous organic material has been established. (3) Finally, a relatively unlikely, but low-velocity, collision between comets can pierce the mantle. This will clearly produce a damaged crust on such comets so that fresh comets may exhibit different surfaces.

The primordial irradiation-produced mantle ("crust"), therefore, is certain to form but will not be uniform due to the initial irregularity of the surface and any large collisions. Therefore, there will be regions of the mantle which may be lost and crevices will exist allowing volatiles to have access to the vacuum, thereby forming active regions (Johnson *et al.* 1987). The subsequent behavior of these regions will be controlled by inner solar system processes (e.g., Prialnik and Bar-nun, 1988; Fanale and Salvail, 1984). The proposed nucleus penetrator for the Rosetta mission is up to 3 m. The results obtained here suggest the thickness of the radiation-processed zone to be several times greater and that this material is fairly stable on the comet's surface. Hence, there is a high probability that the mission will sample cometary matter that has been heavily irradiated and reprocessed in the Oort cloud.

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