PHYSICAL PROCESSING OF COMETARY NUCLEI; Paul R. Weissman, Jet Propulsion Laboratory, and S. Alan Stern, University of Colorado.

Cometary nuclei were formed far from the Sun in the colder regions of the solar nebula, and have been stored in distant orbits in the Oort cloud over most of the history of the solar system. It had been thought that this benign environment would preserve comets in close to their original pristine state. However, as discussed below, recent studies have identified a number of physical processes that have likely acted to modify cometary nuclei in a variety of significant ways.

Accretion of interstellar material has long been considered as a means of providing comets with a volatile "frosting" that could explain the anomalous brightness of dynamically "new" comets on their first passage through the planetary system (Whipple, 1978). However, the likely erosion rate of cometary surfaces by hyper-velocity impacts of interstellar dust particles exceeds the accretion rate by a factor of 500 to 700 (Stern, 1986). On the other hand, impacts of grains into the fluffy aggregates suspected for cometary nuclei may allow capture with minimal erosion (Ostro et al., 1986).

Collisions of nuclei with cometary debris can have significant effects on cometary regoliths (Stern, 1988), particularly in the inner Oort cloud where they are likely frequent enough to promote global surface development to a depth of meters, and highly localized turnover to 10 to 50 meters.

Heating by short-lived radionuclides is not expected to be relevant to comets because of their long accretion times in the distant regions of the solar nebula and because of their small size. Longer lived heat sources could be significant but only for very large cometary nuclei, > 30 km radius, or for very low values of the thermal conductivity (Lewis, 1971).

Comets in the distant Oort cloud receive little solar heating but are sporadically warmed by nearby supernovae. Stern and Shull (1988) estimate that all cometary surfaces have been heated at least once to 50 K, with a 50% probability that the heating has been > 60 K. Random passing stars also heat comets and simultaneously eject them from the Oort cloud; the effective ejection radius is larger than the effective heating radius for all but the most luminous OB stars and associations, so the net heating effect is much less than for supernovae.

Irradiation of cometary nuclei by galactic cosmic rays during storage in the Oort cloud provides an energy source for chemical reactions in the upper several meters of the nucleus surface, resulting in sputtering of volatiles, creation of free radicals, and polymerization of hydrocarbons (Johnson et al., 1987). Thus, the comet develops a nonvolatile crust on its surface prior to ever entering the planetary region. This crust may be blown off (all or in part) when the comet approaches the Sun, or may form the basis for further crust growth as the nucleus warms and more volatiles sublime away.

When comets are perturbed into the planetary system, they undergo a slow warming from the increasing levels of solar insolation. Typical internal temperatures for any given orbit are given by the fast rotation average:

$$T_i = 280 \ (1 - A)^{1/4} \ a^{-1/2} \ e^{-1/4} \quad K$$

where **A** is the surface albedo, **a** is the orbital semimajor axis, and e is the emissivity, plus or minus 10% depending on the orbital eccentricity and on the thermal properties of the surface materials (Herman and Weissman, 1987). However, it may take very many orbits for the nucleus interior to warm to some equilibrium temperature, during which planetary perturbations may change the orbit repeatedly. Thus, the internal temperature profile of the nucleus will be a complex function of its orbital history.

If comets did indeed form in the colder regions of the solar nebula, then they likely formed as amorphous ices. As the nucleus is heated the amorphous ice undergoes an exothermic phase transition to crystalline ice at about 120 - 140 K. Prialnik and Bar-Nun (1987) find that a new comet undergoes this transition at about 5 AU inbound to the Sun, and a layer about 15 meters thick on the nucleus surface is transformed. On subsequent orbits the transformation does not re-occur until the crystalline layer sublimates away to some minimum thickness that allows solar energy to be conducted to the amorphous layers below. The transition then repeats, but penetrates deeper on each successive transition as the nucleus interior gradually warms. Eventually the entire comet is transformed into crystalline ice.

Continued heating results in loss of volatiles from the nucleus, further contributing to the generation of a non-volatile lag deposit on the surface. Various studies (Brin and Mendis, 1979; Fanale and Salvail, 1984; Horanyi et al., 1984) have attempted to quantify this process but with less than total success. In particular, the question of why crusts form at some sites on the nucleus and not at others, is not understood. Also, it is not known whether active areas manage to perpetuate themselves or whether they sporadically appear, persist for some fraction of an orbit (or orbits), and then die out to be replaced by other sporadic events.

Another poorly understood area is thermo-mechanical stresses on cometary nuclei. The sharp thermal gradients resulting from the expected low thermal conductivity of cometary materials should provide a means for mechanical breakup of crusts, and possibly even the nucleus itself. However, studies to date (Kuhrt, 1984; Green, 1986) have not yet even agreed if the stresses are tensional or compressional, and the poor knowledge of the precise nature of cometary materials makes more exact calculations extremely difficult.

It is important to consider all of these possible processes, both in deciding on a site on the nucleus for collection of cometary samples, and in interpreting the results of analyses of returned cometary samples. Although it can no longer be said that comets are pristine samples of original solar nebula material, they are still the best obtainable samples of that unique period in the formation of the planetary system.

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CONTRIBUTION TO PANEL DISCUSSION ON THE MATERIAL RETURNED FROM A
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As comets are only a few kilometres in diameter, probably none of the high-pressure phases of ice will normally be formed in them. Their principal constituents are likely to be ice I, either cubic or hexagonal, clathrate hydrates of methane, ethane, etc., ammonia hydrates, and other similar compounds of solid solutions. Amorphous forms are probably the more common.

When samples of a comet are returned to earth, they can be studied in numerous ways. If the sample is metastable near liquid-nitrogen temperature, a wide range of measurements can be made, such as x-ray and neutron diffraction, infrared and Raman spectroscopy, neutron inelastic scattering, nuclear magnetic and electron-spin resonance spectroscopy, etc. X-ray diffraction by samples of ice that were recovered at liquid-air temperature, i.e. 87K, were made by McFarlan in 1936, and many have followed him, usually using liquid nitrogen.

In our laboratory, we have studied many crystalline and amorphous phases of ice that have been recovered at low pressure and 77 K, including most of those mentioned in the preceding paragraph, starting in 1963·1 Many of these techniques can be used for studying recovered samples of the ices that occur on comets.

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