KINETICS OF ICE GRAIN GROWTH: IMPLICATIONS FOR REMOTE SENSING OF PLANETARY SURFACES. R.N. Clark, F.P. Fanale and A.P. Zent, Planetary Geosciences Div., Hawaii Institute of Geophysics, University of Hawaii, Honolulu, Hawaii 96822.

The kinetics of ice grain growth have been treated by considering the thermodynamic properties of abundant planetary volatiles and differences in binding energies between curved and plane crystal surfaces. Ice metamorphism is a process which occurs because molecules are more stable on crystal faces than edges; thus there is a long term trend toward migration of molecules from edges to faces. This process favors the growth of large grains at the expense of small grains. Numerous spectroscopic studies have shown that the spectral signatures of minerals are related to the grain size of the minerals. Therefore it is important to gain an understanding of the expected grain size distributions on planetary surfaces in order to expedite the interpretation of planetary spectral data for condensate-covered surfaces throughout the solar system.

The methods employed in this study are based on the work of Feltham (1957). Feltham related the rate of grain growth in isothermal metals to the activation energies of the metals and their temperatures to yield the following expression for the rate of grain growth:

$$D^2 - D_0^2 = Ate^{-B/T} \qquad \text{(eqn 1)}$$

where D_o is the original grain size, D is the grain size at time t, A is a constant related to the lattice spacing and volume per atom, B is a constant related to the activation energy of the material, and T is the temperature at which the material exists.

Calculations of planetary bond albedos were carried out for the determination of planetary surface temperatures. These results, along with activation energies found by solving the Clausius-Clapeyron equation, were used to solve for the expected growth rates of surface volatile grains on several solar system bodies. If there exists only a small amount of volatile material, then a uniform sheet of the material will tend to form instead of individual grains (Feltham, 1957). If two ices exist on a planetary surface, then the more volatile species will tend to grow the larger grains, or if insufficient material exists, to coat the less volatile grains. Since water is the least volatile of the ices thought to be abundant on planetary surfaces, water-ice grains would tend to be covered by any other volatile species which might be present.

Methane has been shown to exist on Pluto (Cruikshank and Silvaggio, 1980). However, it is unclear whether the CH_4 exists as a surface frost or in the gaseous phase. If CH_4 is present predominantly as a vapor, then vapor pressures on the order of 23 m-atm are required to explain the depth of the 0.9- μm absorbtion band observed on Pluto. At the extremely low surface temperatures present on Pluto (53K, Brown, 1982, private communication) such a high pressure seems very unlikely. However, if the methane exists as surface condensate, then a 10 cm optical path length is required to explain the observed band depth. Our calculations indicate that, even at 53K, methane frost will metamorphose to 1 cm grains in only 10^5 years. Such a grain size is adequate to explain a 10 cm mean path length in a surface where multiple scattering is important.

Water ice is the only volatile yet known to exist on the surfaces of the Uranian satellites (Cruikshank, 1980; Cruikshank and Brown, 1981).

Additionally, these bodies exhibit the largest opposition surges in the solar system, a property indicating an unusual microstructure. Thermodynamic considerations indicate that water ice grains of 1.0μm are stable on these bodies over the age of the solar system.

Water ice is also the only volatile discovered on the observed solid surfaces of the Saturnian satellites. At 100K, the average surface temperature of the Saturnian satellites, water ice grains of 1.0 μm are stable over the age of the solar system. Therefore it is conceivable that grain size distribution is controlled by a steady state between thermal grain growth and processes which act to reduce average grain sizes, such as micrometeorite gardening.

The Galilean satellites show absorption due to SO_2 on Io and H_2O on Europa, Ganymede and Callisto. At the temperature ranges of the Galilean satellites, only a few years are required for the grain metamorphism of SO_2, whereas H_2O ice requires thousands of years for significant metamorphism on Callisto. SO_2 band depths on Io are roughly 30-50%, indicating a mean path length of only 2.0-3.5 μm assuming the ice is evenly distributed over the planet. At 130K, only 30 years are required for SO_2 grains to grow to 3.5 μm. Over most of Io's surface, sublimation and subsequent metamorphism dominate surface processes at any given time, because volcanic activity appears to be resurfacing the planet only in localized areas, at least over the timescale of several months (Johnson et al., 1979). Sputtering may be less important in controlling grain size on Io, despite the greater sputtering rate, due to the high vapor pressure of SO_2. The relatively poor expression of SO_2 frost on Io's visible spectrum is due to the thermodynamic properties of SO_2 which allow it to reconfigure itself as a glaze over less volatile materials once adsorption sites are satisfied.

On Europa, the 1.04-μm water ice band has a depth of 4.5% on the trailing side and 3.6% on the leading side. At the average temperature of 124K, the sputtering rate is roughly equal to the sublimation rate. This fact could conceivably explain the small asymmetry in grain size from leading to trailing side, consistent with observed band depths.

On Ganymede, with a mean temperature of 138K, water ice grains would grow to 10 μm in less than 10^5 years, and to 150 μm in roughly 1 billion years. Spectra of Ganymede show the 1.04-μm water ice band has a depth of 4.4% on the trailing side and 2.4% of the leading side. Again, this asymmetry is indicative of a sputtering effect.

At an average temperature of 149K on Callisto, ice grains would grow to 10 μm in 10^5 years, and to 1 mm in a billion years. The grain size asymmetry observed on Europa and Ganymede is absent on Callisto, consistent with the lower sputtering flux.

The hemisphericaly averaged infrared ice absorption band depths for the Galilean satellites are $J_2(T) = J_3(T) > J_2(L) > J_3(L) = J_4(T) = J_4(L)$. This observation is fully consistent with sputtering destruction of small grains. This sequence cannot be explained without thermal grain growth hypothesis. In view of the strong suggestion of sputtering importance, we adopt the conclusion that, in the case of the Galilean satellites, the role of thermally exchanged vapor flux is dominated by sputtering processes, which favor the destruction of small grains.

References: (1) Cruikshank, D.P. (1980) Icarus **41**, 246-258. (2) Cruikshank and Silvaggio (1980) Icarus **41**, 96-102. (3) Cruikshank, D.P. and R.H. Brown (1981) Icarus **45**, 607-611. (4) Feltham, P. (1957) Acta Metallurgica **5**, 97-105. (5) Johnson, T.V., A.F. Cook, C. Sagan, L.A. Soderblom (1979) Nature, 280, 706-750.