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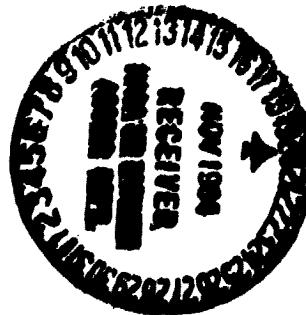
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THE RHEOLOGY OF ICY SATELLITES

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NASA FINAL REPORT

During the past year we completed our high-temperature creep studies in orthoenstatite under conditions of controlled oxygen fugacity. The results were presented at the Fall annual American Geophysical Union meeting in December and are given in the Ph.D. thesis by A. Dehghan which is appended to this report.

The most significant result was that creep was controlled by the extremely thin layer of SiO_2 which wetted the grain boundaries. Slight reduction of the $(\text{Mg}, \text{Fe})\text{SiO}_3$ enstatite during hot-pressing produced microscopic particles of Fe and the thin film of intergranular SiO_2 . This result highlights another complication in determining the flow properties of iron-bearing silicates which constitute the bulk of terrestrial planets and moons. The phenomenon which we have documented may be important in the ductile formation of any extra-terrestrial body which formed in a reducing environment.

During the past year we also began theoretical work on the rheology of "dirty" ice. This work involves micro-mechanical modeling of hardening phenomena due to contamination by a cosmic distribution of silicate particles. The larger particles are being modeled using suspension theory. In order to handle the distribution of particles sizes, we are treating the hardening as a critical phenomenon, and using real-space renormalization group techniques. Smaller particles interact directly with the dislocations. Known as "particulate hardening", this effect has been extensively studied in metals. We are using the results of these studies to assess the magnitude of such hardening in ice. We are similarly studying the defect chemistry of ice in order to assess the effects of chemical contamination by methane, ammonia, or other likely contaminants. Preliminary work on the ice problem is given in Appendix B.

APPENDIX B

Preliminary Work on the Rheology of "Dirty" Ice

A. The Rheology of a Suspension of Silicate Particles in an Ice Matrix

Silicate particles having diameters between 100 μ and about .1 cm will be carried in suspension in the flowing ice. Their effect on the effective viscosity can be evaluated using a marbles in molasses model. Larger particles will settle out of suspension; smaller particles (smaller than the grain size) can be expected to make larger contributions to the effective viscosity through their interactions with the dislocations and grain boundaries as will be discussed in the following section.

The change in viscosity due to a distribution of spherical particles all the same size has been extensively studied. After correcting for non-Newtonian, inertial, and nonhomogeneous suspension effects, Thomas (1965) shows that a wide variety of data for uniform suspensions can be fit by

$$\eta_r = 1 + 2.5\phi + 10.5\phi^2 + 0.00273 \exp(16.6\phi) \quad (1)$$

where ϕ is the concentration of spherical particles by volume. Equation (1) describes the data up to a concentration of $\phi = 0.6$, and is plotted in Figure 1. In a more recent study using very uniform glass beads, Chong et al. (1971) obtained slightly stiffer results which they fit using the equation

$$\eta_r = \left[1 + \frac{1.25\phi}{1 - \phi/.605} \right]^2 \quad (2)$$

which is also plotted in Figure 1. Note that this expression is asymptotic to $\phi = 0.605$. The solids concentration at which the relative viscosity tends to become infinite is often denoted ϕ_{∞} and has been the subject of much study. Chong et al., argue that $\phi = .605$ for a truly monodispersed system (which approaches orthorhombic packing) and that the larger ϕ_{∞} found by Thomas (1965) is the result of particle-size variations in those systems.

At very high concentrations, as the spheres approach close packing, Frankel and Acrivos (1967) have shown that an asymptotic expression can be derived by only considering the fluid in the gap between points of closest approach:

$$\eta_r = \frac{9}{8} \frac{(\phi/\phi_\infty)^{1/3}}{1 - (\phi/\phi_\infty)^{1/3}} \quad \text{as } \phi/\phi_\infty \rightarrow 1 \quad (3)$$

In this expression, ϕ_∞ is the maximum attainable concentration (which depends upon packing). In Figure 1, (3) has been fit to the Chong et al. data (assuming $\phi_m = .605$) and the Thomas data (assuming $\phi_m = .625$).

Much less work has been done on suspensions in which the particles are not the same size. Based on their experimental observations for bidispersed systems, Chong et al. (1971) suggest the following empirical relation

$$\eta_r = \left[1 + .075 \frac{\phi/\phi_\infty}{1 - \phi/\phi_\infty} \right]^2 \quad (4)$$

Moshe (1979) suggested that (4) might be used for any particle size distribution. He then discussed how ϕ_∞ might be estimated for a given particle distribution. However, the only theoretical justification for assuming that ϕ_∞ is the only additional variable comes from the asymptotic expression (3), which was derived with no empirical assumptions.

Note that the relative viscosity of a mixed distribution is always less than that for equal-sized spheres. Intuitively, this is because the smaller particles can flow more easily around the larger particles; based on (4), it is because ϕ_∞ is larger for a mixed distribution because it can be more efficiently packed. Friedson and Stevenson (1983) make the important observation that the viscosity of a suspension of mixed particle sizes can be bounded. The upper bound is given by the uniform sphere case (2) while the

lower bound is given by the simple expression (Roscoe, 1952)

$$\eta_r = (1-\phi)^{-2.5} \quad (5)$$

This expression may be derived by using Einstein's (1906) formula for dilute suspensions (of arbitrary particle sizes)

$$\eta_r = 1 + 2.5\phi \quad (6)$$

to calculate the effect of adding a small amount of larger and larger particles in successive steps. At each step the fluid viscosity is taken to be the viscosity resulting from all the previous steps. The reason this gives a lower bound is that it ignores the interactions between particles, and these interactions tend to increase the effective viscosity.

The theoretical challenge is to develop a model which can predict the relative viscosity for a suspension at intermediate to high concentration having a prescribed particle size distribution (corresponding to the expected cosmic distribution). There is some empirical and theoretical guidance as to how such a model might be formulated. At small concentrations the expression must approach the Einstein equation (6) while at large concentrations it should reflect the packing in some form such as the asymptotic result (3). At intermediate concentration, an additional complication is the formation of temporary aggregates which effectively "freeze" the liquid within them (Vand, 1948). The result is a higher apparent concentration. Roscoe (1952) shows that, in the simplest case of uniform spheres, the lower boundary (5) becomes

$$\eta_r = (1-1.35\phi)^{-2.5} \quad (7)$$

which is also plotted in Figure 1.

The curves in Fig. 1 suggest that the stiffening of ice by suspended particles may be successfully modeled as a critical phenomena where $\phi \rightarrow \phi_{\infty}$

corresponds to the critical volume fraction. Indeed, the stiffening problem is very similar to the freezing problem in which large patches of the liquid become ordered and stiffen as the critical temperature is approached from above. In the suspension problem at hand, large patches become locked into clusters as the critical volume fraction is approached. We plan to exploit this similarity by formulating the suspension problem as "lattice gas" (Runnels, 1972) and using real space renormalization group theory to investigate the critical volume fraction and behavior near this critical point for an arbitrary particle distribution (Burkhard and VanLeeuwen, 1982; Domb and Green, 1976). We shall seek guidance in this approach from our colleague in the Mathematics Department at USC, Professor Marc Kac, who has contributed basic mathematical research on critical phenomena.

B. Effects of Fine-Grain Particles on Dislocation Motion

When the particles are smaller than the grain size they effect the creep by directly influencing the microscopic flow mechanism. Baker (1978) and Baker and Gerberich (1979) studied the creep properties of polycrystalline ice containing sand particles having diameters approximately 1/10 that of the grain-size. They found two major effects: a) the particles suppressed grain-growth normally associated with dynamic recrystallization and b) the particles increased the effective activation energy (by a factor of three for a 1% sand concentration). Baker and Gerberich (1979) tentatively ascribe this increase to an internal stress mechanism. We would like to explore this and other mechanisms associated with dispersion hardening (Brown and Ham, 1971). Friedson and Stevenson (1983) point out that the magnitude of such effects in icy satellites ultimately depends upon the small particle cut-off of the assumed cosmic particle distribution, and that this is poorly

constrained. Nevertheless, it should be informative to estimate the effect for various assumed distributions in anticipation of such constraints. Conversely, the prediction of unacceptably large viscosity increases might be used to constrain the particle distribution.

C. Effects of Chemical Doping

Chemical doping usually effects the creep properties of a solid by altering its defect structures. For ice, these are Bjerrum defects which are related to the proton arrangement. In reviewing the current state of knowledge regarding dislocation creep in ice, Poirier (1982) points out that a dislocation moving through the ice lattice with immobile disordered protons cannot move without creating Bjerrum defects which violate the Bernal-Fowler rules of hydrogen bonding (Glen, 1968). The dislocation moves by nucleating a kink pair where a Bjerrum defect makes the local proton configuration more favorable. We propose to study the defect chemistry of ice, and how it might be altered by the presence of ammonia, methane, and other likely contaminants. We are fortunate to have Professor Kroger as a colleague at USC whose collaboration in the defect chemistry should prove invaluable. Although numerous experiments have been carried out, including doping with HF and NH_3 (Jones and Glen, 1969), HCl (Nakamura and Jones, 1970), HCl, HBr, NH_4OH , NH_4F , NaF, KF, NaOH, H_2O_2 , and He (Nakamura and Jones, 1973), HF (Mai, Perez, Ta'ibouet, and Vassoille, 1978) and NaCl (Riley, Noll, and Glen, 1978), with the exception only of the latter work where there was a pronounced work hardening, the results are generally inconclusive. Of particular significance to the icy satellites is the observation that NH_3 hardens ice, although no convincing reason has yet been found for this effect (Poirier, 1982). A detailed analysis of these data should be undertaken.

D. Flow Mechanisms Near the Brittle-Ductile Transition

Because the temperatures in the icy satellites are at most on the order of $.5T_m$ (Ellsworth and Schubert, 1983), it is possible that tectonic deformation (particularly near the surface) is not a fully ductile process. This is certainly true of short-time processes such as cratering. Mike Ashby has recently completed experimental studies on the brittle/ductile behavior of ice at low loading rates and Lange and Ahrens (1983) have looked into the brittle behavior of ice and ice-silicate mixtures at high loading rates. We would also like to assess the importance of brittle and pseudo-ductile flow processes in the evolution of these bodies. One of us (CGS) spent the past year on Sabbatical in Cambridge working with Professor Ashby, and will continue this collaboration by spending one month in Cambridge, summer 1985.

APPENDIX A

**High Temperature Deformation of Hot-Pressed
Polycrystalline Orthoenstatite**

by

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University of Southern California
February, 1983**