DYNAMIC ATTENUATION MEASUREMENTS OF POLYCRYSTALLINE ICE AT PLANETARY CONDITIONS Christine McCarthy, Reid F. Cooper and David L. Goldsby, Brown University, Department of Geological Sciences, Providence, Rhode Island 02912.

Introduction: Heat production on Europa is thought to be driven almost exclusively by periodic forcing produced by the resonance-induced orbital eccentricity. Most of the dissipation of this tidal elastic energy occurs in the outer ice layer[1]. Thus the physical nature of mechanical dissipation in polycrystalline ice is of central importance in addressing the mechanism(s) of energy input required for formation of a sub-shell ocean.

There have been numerous studies on the attenuation (internal friction) of ice. However, many of these studies focused on single ice crystals [e.g., 2-4]. The few studies that examined polycrystalline ice were aimed at terrestrial glaciers and were conducted at either temperatures too warm (>253 K)[5] or at frequencies too high (>.5 Hz)[6] to be applicable to the outer satellites.

We present initial results from our experimental study to measure the attenuation of polycrystalline ice at frequencies and temperatures consistent with planetary conditions.

Method: Samples for this study were fabricated using a technique developed to control grain size [7]. Distilled water was misted into air over a reservoir of liquid nitrogen. The resulting slurry was sifted to collect ice particles of size <25 μm. This ice powder was then hot-pressed under a vacuum in a stainless steel cylindrical die at 196K, employing an axial stress of 100 MPa that was maintained for 2 hours. The process results in a dense cylindrical specimen with a fine grain-size.

Compression-compression dynamic tests were performed using servomechanical-actuator apparatus that was fit with a cryostat. A sinusoidally varying stress was applied in load control and the resulting strain was measured with a gravity-fed extensometer. The mean stress for all tests was ≤1 MPa, about which there was an oscillating stress of 0.1-0.2 MPa (10 to 20% of the mean compressive stress). The oscillating strain magnitude was $\pm$ 1.1 to 2.2×10^{-5}. Frequencies explored ranged from 0.1 to 0.025 Hz. Load, displacement and temperature data were recorded digitally at a rate of 4 Hz. The experiments convoluted attenuation with creep: when the creep was at (nominal) steady-state, extraction of the attenuation response was reasonably straightforward [cf. 8]

Both stress and strain data were fit to periodic curves, seeking parameters consistent with 95% confidence intervals; the steady-state trend associated with creep at the mean stress being first removed. From the data fits, the phase lag (δ) between the applied sinusoidal stress and consequent strain could be calculated. The ratio of the periodic strain to the stress is known as the complex compliance J*, which is a function of frequency; the ratio of the real and the imaginary parts of J* is equal to the tan δ, which is attenuation, Q^{-1}.

Results: Initial results of Q^{-1} as a function of frequency for temperatures 230 and 250K are shown in Fig. 1. The Q^{-1} data at 230K for the frequency range explored are seen to be relatively constant with respect to frequency. The 250K data demonstrate a more complex relationship. The data at frequencies greater than 10^{-2} Hz show a power-law relationship, i.e., $Q^{-1} \propto f^{-m}$ where m ≈ 0.4; at lower frequencies, the relationship steepens, that is, m~1. The attenuation measured is significantly greater (a factor of 10^2 at 10^{-2} Hz) than that predicted by a Maxwell model (discussed below).

Discussion/Planetary Implications: Attenuation in polycrystalline aggregates at high homologous temperature occurs primarily by dissipative processes on grain boundaries. It has been demonstrated that the process is effected by diffusion and produces a power-law response, i.e., $Q^{-1} \propto f^{-m}$, where m is in the range 0.1 to 0.5 [9]. As frequency is lowered, the power law shifts to behavior associated with creep, e.g., a slope of m=1 for a Maxwell solid. This transition is seen in our 250K data, but not in the lower-temperature data.

In Fig. 1 we have contrasted our data with a Maxwell-model calculation for the conditions 250K, 1 MPa and a Young's modulus of 9 GPa; the stress-temperature conditions give rise to a viscosity of 10^{13} Pa s—consistent with creep in ice wrought by the motion of lattice dislocations [7]. One sees that our experimental aggregates are significantly more attenuating than predicted by this model, at least at the frequencies studied. Further, extrapolation of the 250K results to lower frequencies suggest that this difference will persist, even at conditions of interest for tidal forcing on Europa (i.e., $f<10^{-5}$ Hz). (Clearly, though, more experiments are required to make this extrapolation with confidence: this is one thrust of our continuing research.)

Creep of polycrystalline ice under a broad range of planetary conditions sees significant strain accumulated by the relative displacement of grains across grain boundaries—grain boundary sliding (GBS). The diffusion-effected physics of this sliding is identical to that giving rise to the attenuation response. But the attenuation response cannot be understood solely by characterizing the steady-state viscosity: time-variation in applied load creates stress singularities at grain triple junctions that must be relieved as the material approaches steady state. This is the context of transient creep: it results in an effective viscosity far lower than that which characterizes the steady state. These physics give rise to the attenuation plateau at "medium" frequencies[10].

But what of the very low frequencies associated with tidal forcing? Most likely, these conditions could see validity of application of a Maxwell model, but one that must take into account the grain-size-sensitive nature of rheology as affected by GBS. A two order of magnitude decrease in effective viscosity has been demonstrated for experimental aggregates of ice whose grain size is decreased by a factor of 20. Such a viscosity decrease is consistent with shifting the Maxwell "curve" in Fig. 1 horizontally to higher frequencies. Thus grain size is a critical issue in the understanding and modeling of the transient and steady-state rheologies of icy shells.

Another important factor, affecting both grain size and, independently, attenuation is the presence of second phases. We have demonstrated that hydrated salts, of interest in the composition of Europa's shell, effect a factor-of-five increase in attenuation over polycrystalline ice of the same grain size [Ref AGU talk]; further, such second phases are effective in inhibiting grain growth in the ice—keeping its viscosity low and its attenuation high.

References: [1] Tobie, G. et al. (2003) *JGR,108 (E11)CiteID 5124*. [2] Tatibouet, J. et al. (1983) *J. Phys. Chem.*, 87, 4050-4054. [3] Tatibouet et al. (1985) *J. Phys*. 46, C10-339-342. [4] Tatibouet et al. (1986) *J. Phys*. 47, 51-60. [5] Cole, D.M. and Durell, G.D. (2001) *Phil. Mag. A*, 81 (7), 1849-1872. [6] Johari, G.P. et al. (1994) *J. Phys. D: Appl. Phys*. 28, 112-119. [7] Goldsby, D.L. and Kohlstedt, D.L. (2001) *JGR* 106 (B6), 11,017-11,030. [8] Gribb, T.T. et al. (1994) *Magnetic Systems*, ed. M.P. Ryan, Academic Press, 19-36. [9] Gribb, T.T. & Cooper, R.F. (1998) *JGR* 103, 27,267-27,279 [10] Cooper, R.F. (2003) *Plastic Def. in Min. and Rocks*, Min. Soc. Am., WA, 253-290. [11] McCarthy, C.M. et al. (2007) *EOS Trans. AGU 88, Fall Meeting Abstract* #MR11A-07

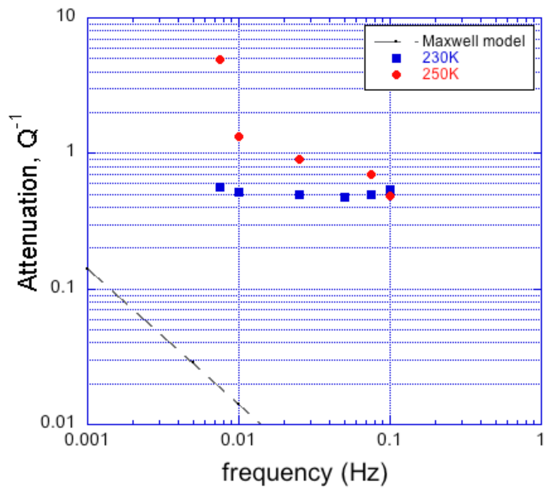

Figure 1: Q^{-1} versus frequency for pure, fine-grained polycrystalline ice at 230K (squares) and 250K (circles). The data are compared to a Maxwell model that employs a 250K, dislocation-creep-effected viscosity of $\eta_0=10^{13}$ Pa s and unrelaxed Young's modulus of 9 GPa. The curvature of the 250K data suggest that the significant increase in attenuation can persist to frequencies consistent with tidal forcing.