ENHANCED DISSIPATION IN CREEPING WATER ICE: NEW RESULTS AND IMPLICATIONS FOR ICY WORLDS Tess E. Caswell[1] and Reid F. Cooper[2], [1]Lamont-Doherty Earth Observatory, Columbia University, Palisades, NY, USA (tec2131@columbia.edu) [2]Brown University, Providence, RI, USA

Introduction: Attenuation (Q^{-1}) is the physical process that transforms cyclic, mechanical energy (e.g., strain associated with tidal loading or seismic waves) into heat [1]. Attenuation in ice specifically is integral to the thermal evolution of tidally-forced icy worlds such as Europa [2], Enceladus [3], and others [e.g., 4,5]; it is the fundamental process of tidal dissipation, which provides heat to sustain icy satellite geophysical processes [6]. In these settings the ice may also convect, undergoing steady-state deformation by grain boundary sliding [7]. We provide new measurements of attenuation in water ice from experiments employing a high-resolution measurement system and servo-mechanical actuator with a cryogenic chamber. We show that creeping ice is more dissipative than anticipated by standard models of attenuation, regardless of whether steady-state deformation is by dislocation creep or grain boundary sliding.

Increased attenuation in water ice directly affects models of the thermal evolution of icy worlds and can be applied to future interpretation of seismic data from seismometers landed on an icy satellite [e.g., 8] or from orbital measurements [9].

Methodology: Specimens of polycrystalline water ice (grain size, d = 15 μm – 1 mm) were subjected to simultaneous steady-state creep and cyclic loading. Applied stress during the experiments is described by $\sigma_m \pm \sigma_o \exp(i\omega t)$, where σ_m = 0.4–2 MPa, σ_o = 0.05–0.17 MPa, and $\omega = 2\pi f$ where $10^{-4} \le f$ (Hz) $\le$ 1. Specimens were prepared via three methods: "standard ice" [10] (d = 1 mm), hot pressing sieved powders [11] (d = 40, 70 μm), and the pressure-release treatment of *Stern et al*. (1997) [10] (d = 15 μm).

Experiments were conducted in a 1-atm, servo-mechanical testing apparatus outfitted with a liquid nitrogen-cooled, ethanol bath cryostat with 0.5 °C temperature stability [12]. Strain resolution in the apparatus, after analog-to-digital conversion and noise removal, is 10^{-7}. Attenuation was computed from the phase lag between input stress and resulting strain using nonlinear least squares regression in Matlab [13].

Results and Discussion: The steady-state strain rates and microstructures of the deformed specimens are consistent with dislocation creep (for d = 1 mm) and grain boundary sliding (GBS) rate-limited by the grain boundary viscosity (for all other grain sizes) [14]. The attenuation spectra from each creep regime will be addressed separately. In both creep regimes, measured attenuation is linear in stress, indicating a diffusional mechanism of attenuation [1].

Attenuation in the grain boundary sliding regime. For ice deforming in the regime of grain boundary sliding (GBS) rate-limited by the grain boundary viscosity [14], the attenuation spectra display a broad, shallow slope in Q^{-1} vs f. This is consistent with the

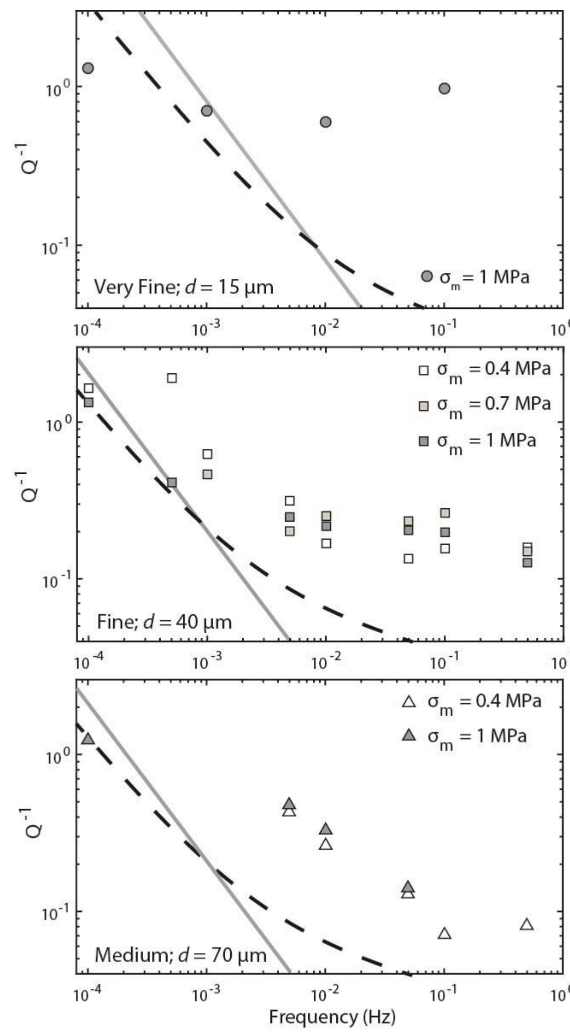

Figure 1: Attenuation spectra for ice specimens simultaneously creeping at steady-state in the regime of grain boundary sliding rate-limited by the grain boundary viscosity [14]. For comparison, solid, gray lines indicate Maxwell model predictions based on the measured steady-state creep viscosity of the specimen. Dashed lines represent Andrade model predictions based on transient creep data.

"high-temperature background," for which $Q^{-1} \propto f^{-\varphi}$ where $0 < \varphi < 0.5$ [1]. The physical mechanism of the high-temperature background is chemical diffusion [15], and spectra are well-represented by inversion of the semi-empirical Andrade model [16]. In these data, however, the spectra shallow at high values of Q^{-1} relative to Andrade model predictions. The magnitude of Q^{-1} at which this plateau occurs increases with decreasing grain size, suggesting a grain size effect. The spectra do not appear to be affected by changing mean stress.

Attenuation in the dislocation creep regime. Attenuation data for ice creeping via steady-state dislocation creep are shown in Figure 2. The specimen is more absorptive than predicted by the Andrade model inversion. Increased attenuation takes the form of a broad peak, centered around a relaxation time corresponding to elastically-accommodated grain boundary sliding at the scale of subgrains in the specimen.

The data are well-matched by the composite model of *Sundberg & Cooper* (2010), which linearly superposes a peak onto the high-temperature background [17]. The observed peak is broader than that modeled, however, because subgrains have a stress-sensitive, statistical distribution of spacing [18] and thus the actual peak is broadened by a distribution of length scales of dissipation. This spacing depends upon the steady-state creep stress [19], which manifests as a shift in the observed peak toward higher frequencies with increasing mean stress.

Implications: Historically, tidal dissipation has been modeled using a Maxwell solid rheology, with few exceptions (e.g., [5]). However, a Maxwell solid model does not account for anelasticity, which is the primary agent of attenuation. The result is that the Maxwell model fails to accurately represent attenuation in real materials, as is demonstrated by the poor fit of the model to our spectra in Fig.'s 1 and 2. The Andrade model provides a better fit to the high-temperature background [15]. However, the data presented here demonstrate increased attenuation relative to either model.

Increased attenuation relative to the Maxwell and Andrade models influences any planetary process affected by dissipation. This includes short-period despinning models, such as that for Iapetus [5, 20]), in which despinning would be accelerated by increased dissipation; tidal heating of a convecting ice shell (e.g., [21]), which will be greater than previously modeled; and inferences into ice shell structure from seismic waves [8, 9] which, without considering the data presented here, would overestimate temperature within an ice shell. Each of these processes require accurate knowledge of attenuation in water ice at planetary conditions.

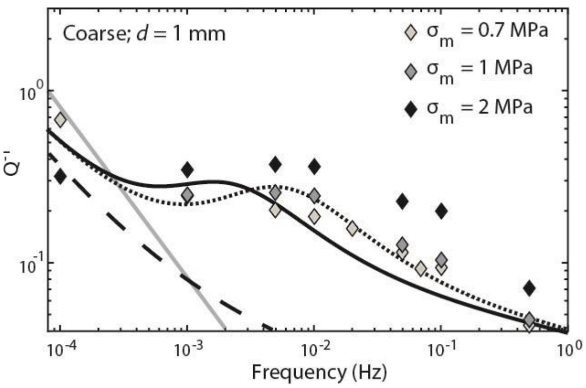

Figure 2: Attenuation spectra for ice simultaneously deforming by steady-state dislocation creep. The spectra are more absorptive than predicted by the Andrade (dashed line) or Maxwell (solid, gray line) models. Instead, they are matched by a composite model [17] that superposes the Andrade model with an absorption peak. The composite model is shown including the contribution of a peak due to elastically-accommodated grain boundary sliding at the scale of the subgrain size observed in the specimen (solid black line) and that predicted by a subgrain size piezometer (dotted black line).

References: [1] Cooper, R. F. (2002) *Rev. in Min. and Geochem.* [2] Barr, A. C. and Showman, A. P. (2009) *Heat transfer in Europa's icy shell* [3] Meyer, J. and Wisdom, J. (2007) *Icarus* [4] Hammond, N. P. and Barr, A. C. (2014) *Geology* [5] Castillo-Rogez, J. C. et al. (2011) *JGR: Planets* [6] Ojakangas, G. W. and Stevenson, D. J. (1989) *Icarus* [7] Barr, A. C. and Pappalardo, R. T. (2005) *JGR* [8] Kovach, R. L. and Chyba C. F. (2001) *Icarus* [9] Panning, M. et al. (2006) *JGR* [10] Caswell, T. E. et al. (2015) *GRL* [10] Stern, L. A. (1997) *JGR* [11] Goldsby, D. L. and Kohlstedt, D. L. (1997) [12] Caswell, T. E. and Cooper, R. F. (2017) *LPSC XLVIII*, Abstract #2000 [13] Nowick, A. and Berry, D. (1972) *Anelastic relaxation in crystalline solids.* [14] Goldsby, D. L. and Kohlstedt, D. L. (2001) *JGR* [15] Gribb, T. T. and Cooper, R. F. (1998) *JGR* [16] McCarthy, C. et al. (2011) *JGR* [17] Sundberg, M. and Cooper, R. F. (2010) *Phil. Mag.* [18] Stone, D. S. et al. (2004) *JGR* [19] Shimizu, I. (1998) *GRL* [20] Levison, H. F. et al. (2011) *Icarus* [21] Tobie, G. et al. (2003) *JGR*