# OPENING THE BLACK BOX: A LABORATORY-BASED DISSIPATION MODEL FOR WATER ICE – DESCRIPTION AND IMPLICATIONS.

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**Introduction:** We will present the latest developments of our testing of water ice response to cyclic loading performed in conditions approaching those expected in outer planet icy moons. Since 2008 we have been running the *Planetary Tides Simulation Facility (PTSF)* integrated in JPL's Ice Physics Lab [1, 2]. At this time the PTSF is fully calibrated and its performance and errors are quantified [3]. After 400 data points covering a broad parametric space, we have identified behavior trends that lend themselves to the definition of a new dissipation model. We will introduce the main characteristics of this model, adress its utilization into geophysical models, and discuss the impact of this new approach for tidal response modeling.

**Experimental Procedure:** The *PTSF* facility is unique in that it can hold tests over periods of several months without disruption. We measured the compliance of pure, compact water ice samples over a frequency range of 3x$10^{-6}$ to $10^{-2}$ Hz and stress amplitudes from 0.05 to 0.6 MPa, covering the conditions relevant to, e.g., Europa, Enceladus, and Mimas. For grain sizes ranging from 50 to 200 microns, we observed attenuation driven by dislocation motion and grain-boundary sliding. While the setup can achieve temperatures as low as 150 K, the strain measurements are practically limited when the viscosity becomes greater than ~5x$10^{16}$ Pa s.

For that past two years we have elected to focus our measurements on water ice, because the frequency-dependence of the mechanical properties of this ubiquitous material is mostly unknown. Samples are supplied from the JPL *Ice Factory* [2]. Deionized water is frozen, ground, and sieved in a cold room at 253 K. The ice seeds are then compacted to 120 MPa within a custom-built press for several hours, at dry ice temperature, in order to moreve all porosity from the sample. Sample their quality is evaluated through cryo-microscopy (homogeneous grain size and geometry, absence of porosity, see [4]) and, for the smallest grain sizes, cryogenic Scanning Electron Microscopy.

Independent measurements of the Young's modulus and steady-state viscosity as well as the effective modulus and phase lag between stress and strain are generally obtained at 12 different frequencies spanning 3.5 decades.

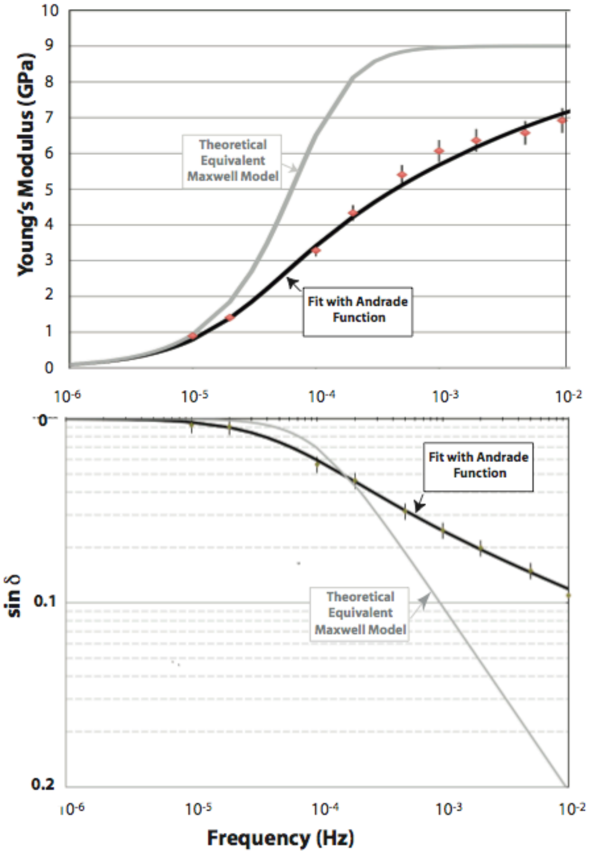

*Figure 1. Typical results of ice attenuation properties sampled over a wide frequency range. Top: effective modulus spectrum; Bottom: is the friction coefficient spectrum. The sample whose response is shown had a 50±15 μm grain size, and was deformed in the grain-boundary-sliding regime at a temperature of 243 K, under a mean stress of 0.2 MPa and cyclic stress of 0.1 MPa. Red points are data points with their error bars. The dark curves are the best fits to these data. The grey curve corresponds to the theoretical form of the Maxwell model for the same viscosity and unrelaxed Young's modulus as measured for that sample. The departure of the data from the theoretical Maxwell model is striking, especially at high frequencies.*

**Key Results:** Data so far confirm the long-suspected idea that the Maxwell model is not applicable over the range of forcing frequencies encompassing planetary tides when the forcing frequency is greater than the inverse of the Maxwell time (viscosity to elastic modulus ratio) characterizing the material. While the Maxwell model predicts a rapid drop of the attenuation with increasing viscosity (e.g., decreasing temperature) and frequency, the observed attenuation remains relatively high and shows little dependence on frequency (negative slope of 0.15 to 0.3). Our results invalidate the Burgers element model as well and question the recent introduction of that model into satellite tidal response modeling. That model does attempt to account for anelasticity but its simplistic form cannot reproduce the complexity of default interaction occurring in natural materials [5, 6]. The extended Burgers element is far better in that regard in that it can include as many elements as necessary to capture that complexity.

Our results are consistent with similar experimental measurements obtained on various silicates materials and oxides [e.g., 7, see 8 for a review]. Hence, we derive the mechanical compliance of the samples using the inversion approach used in these studies. Two models are generally considered for fitting those data: the Andrade model and the extended Burgers element. These two agree in their description of anelasticity (i.e., over the same frequency band), but diverge at lower and higher frequencies. Our observations so far suggest that the Andrade model yields the best fit (Figure 1) at frequencies approaching $3\times10^{-6}$ Hz. The same function systematically fits both the friction coefficient and effective modulus spectra, which demonstrates the robustness of the results (Figure 1).

In this model, the compliance is described by

$$J(\chi) = \frac{1}{\mu} - \frac{i}{\eta\chi} + \beta(i\chi)^{-\alpha}\Gamma(1+\alpha) \qquad [1]$$

where the first two terms represent a Maxwell body, with $\mu$ the unrelaxed elastic modulus, $\eta$ the steady-state viscosity, and $\chi$ the pulsation. The parameters $\alpha$ and $\beta$ describe the anelastic response of the material. Specifically, $\beta$ determines the amplitude of the anelastic response and is a function of the density of defects in the material, while $\alpha$ represents the complexity of the material [9], i.e., heterogeneity of the grain size and geometry, presence of second-phase impurities, etc. A Maxwell body is equivalent to assuming that defects are uniformly distributed within the material and do not interact with each other.

Based on the silicate dissipation literature, Castillo-Rogez et al. [10] suggested that the parameter $\beta$ can be expressed, in first approximation, as

$$\beta \sim \eta^{-\alpha}\mu^{-(1=\alpha)} \qquad [2]$$

Our survey of a broad range of experimental conditions, for viscosities ranging from $5\times10^{12}$ to $5\times 0^{16}$ Pa s and in the dislocation creep and grain-boundary sliding regimes, appear to match this empirical relationship.

**Implications and Applications:** The perceived impact of this result on the tidal response depends on the type of application and the degree of fidelity that one wants for models that are otherwise poorly constrained in many regards. The impact is most significant in the case of processes resulting from forcing in a frequency range where anelasticity dominates, for example in the case of despinning evolution [10] or for bodies whose tidal Love numbers could potentially be derived from spacecraft observations [11]. These new constraints on ice dissipation are also likely to affect the orbital evolution of satellites like Mimas, subject to strong tidal stressing (up to 1 MPa amplitude) at high frequency, but otherwise cold.

We will present the latest developments of this model and elaborate on some of the major implications resulting from strong anelastic-driven dissipation.

**References:**

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