CAN THERE BE DISSIPATION WITHOUT HEAT? CONSTRAINTS ON TIDAL DISSIPATION IN THE MEDIUM-SIZED SATURNIAN SATELLITES. J. C. Castillo¹, D. L. Matson¹, and T. V. Johnson. ¹Jet Propulsion Laboratory/California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA (email: Julie.C.Castillo@jpl.nasa.gov).

Introduction: Much can be learned about tidal dissipation in icy bodies by studying the medium-sized Saturnian satellites. They have densities that range between 960 kg/m³ (Tethys) and ~1460 kg/m³ (Dione) [1]. They accreted very cold (e.g., [2]). Thermal models governed by the decay of long-lived radionuclides yield freezing of the smallest satellites, in a few hundred million years. A Maxwell-rheology model used to simulate body tides indicates that little dissipation, if any, is expected in these bodies. Even on the long term, tidal dissipation cannot build up a significant amount of heat. In the largest and densest ones (Rhea and Dione), the core temperatures reach the ice melting point while the lithosphere is thick (see also [3]).

However these satellites show evidence that they underwent some tidal dissipation resulting in dynamical evolution (e.g., eccentricity damping) and endogenic activity which created geological features. Understanding the mechanisms of tidal dissipation in the cold Saturnian satellites has become especially urgent since the discovery of a geyser associated with a strong thermal anomaly at Enceladus’ South Pole [4].

We focus on some discrepancies between the observations and the state of our knowledge of the dissipation factor and the existing rheological models used to describe the tidal response of the satellites. In the present work, we especially want to address the following question: can tidal dissipation, (significant enough to drive dynamical changes and endogenic activity), start without being triggered by a thermal event which significantly raises the temperatures of at least part of the satellite? We argue that such triggering must indeed be the case. First, however, we provide a few examples that frequency-dependent rheological models that are mainly temperature-dependent, such as a Maxwell model, cannot realistically describe tidal dissipation in cold icy satellites, and that parameters describing the internal structure should also be taken into account. Frequency dependence modeling requires the understanding of material response at different scales: microscale, but also mesoscale, such as fractures, porosity, bubbles in fresh ice, grain size variations, relation between the rock and ice components. This problem concerns not only the dissipation factor, chiefly a function of viscosity and the frequency-dependent model, but also the tidal Love number k₂, chiefly a function of the elastic properties of the model. It has been proposed [5] that faults significantly decrease the global rigidity of the Moon and increase k₂ and tidal dissipation. Bodies as cold as the Saturnian medium-sized satellites are likely to be highly fractured and maintain such defects deep in their interiors [6] for at least part of their history, before some warming facilitates ice creeping and compaction [7].

Different rheological models include structural parameters in their description of the frequency dependence of material behavior [e.g., 8, 9]. However the actual structure of the cold icy satellites remains inaccessible, at least for now. The lack of data also applies to the rheological properties (viscosity and elastic parameters) for the range of temperatures encountered in the Saturnian satellites, i.e., 70 to 230K. A major difficulty of laboratory measurements is that the mechanisms taking place in the tidal friction should be reproduced at the same range of frequencies that occur in nature. For example, studies often refer to the measurement of ice dissipation factor at 100 K and frequencies of 1-10 Hz, which is ~300 [10]. However this measurement has been obtained at seismic frequency and using such a number can lead to substantial error. At least, if this number is used in coupled thermal-dynamical models of the Saturnian satellites, we show that it rapidly leads to full melting of the bodies and potential endogenic activity in the long run, which is discrepant with the observations.

The lack of rheological data and understanding of the tidal response is a potential roadblock to future study. Assessing this problem is of special interest with regard to our recent study of Iapetus’ dynamical evolution, which Castillo et al. [11] propose to be triggered by heat from short-lived radiogenic species. But, this problem also applies to other puzzles in the Saturnian satellite systems, some of them outlined below.

Approach: In the calculations described below we use coupled thermal-dynamical models that include modeling of the mechanical lithosphere thickness and tidal stress and strain profiles. We deal with tidal dissipation by calculating the tidal Love number and dissipation for a viscoelastic model by numerical integration [12, 13]. Thermal models include radionuclides for a chondritic composition. At this stage of the demonstration, they do not include short-lived radiogenic species. Parameters that are a function of temperature, pressure, or frequency must be updated with each computational cycle. We also consider the in the calculation the presence of ammonia but the results are not discussed in the present document. For the examples discussed below we derive constraints from recent history but also from the integrated history from formation to present.

Mimas, Saturn’s Closest Medium-Sized Satellite: This satellite is subject to the most important tidal stresses, among the medium-sized Saturnian satellites. It also exhibits one of the oldest surface in the Saturnian system, with little evidence for endogenic activity throughout its history. While its eccentricity is anomalously high (e = 0.202), it is very probable that the satellite underwent some tidal evolution to damp his eccentricity from initial higher value [14, 15]. Besides, with little pressure increase with depth and little temperature variation with time, this body is a good reference for testing the effect of structure on tidal dissipation. The dissipation factor computed for a Maxwell rheology is about 10⁷ today, and never gets smaller than 10⁵ over the satellite’s history.
Mimas is often pointed out as a reference for validating models proposed for the origin of Enceladus’ geological activity [16]. The fact that Mimas shows no signs of intense geological activity is a strong indicator that little heat is produced in the interior. Also high eccentricity and linear evolution requires a dissipation factor averaged over 4.55 By of $\Omega \sim 1250$ for an initial eccentricity of $e_0$ of 0.12. If we assume that the dynamical evolution is linear then it is actually possible to derive a constraint on $e_0$. Starting with $e_0 \sim 0.12$ requires smaller values of $\Omega$ for eccentricity to be damped to present value. However, the associated heat production results in rapid melting of the interior: e.g., for $\Omega = 1000$ and $e_0 \sim 0.15$, ice melting point is reached in less than 100 My and can be maintained for a while, after full eccentricity damping, before the body freezes.

**Enceladus, the Outer Solar System’ Hottest Icy Satellite:**
In a conventional model of Enceladus, based on long-lived radiogenic decay, Enceladus should present a thermal evolution and tidal dissipation similar to what is computed for Mimas. Enceladus’ present eccentricity is six times smaller than that of Mimas and the tidal dissipation for a given $Q$ and $k_2$ is 40 times less at Enceladus. The maximum temperature reached in Enceladus is $\sim 220$K, versus $\sim 195$K in Mimas. Thus, the value of dissipation factor used in the studies ($Q \sim 10^9$, e.g., [17]) is not consistent with the thermal evolution outcome. However the fact that intense endogenic activity is observed at Enceladus, which contains twice as much rock as Mimas might indicate that the difference in evolution is the result of a thermal event in the history of Enceladus that created the conditions suitable for significant tidal dissipation to start and be sustained. Enceladus is very interesting because of the difference between the N and the S pole which expresses variations in viscoelastic properties and resulting dissipation as a function of latitude and longitude, that probably started early in the history.

**Tethys, The Lightest, Biggest Satellite Known:**
Tethys provides a good example of the limits of the Maxwell model. For Tethys to reach synchronous rotation in 4.55 By, its average dissipation factor must be less than $10^{10}$. Coupled thermal-dynamical evolution of Tethys modeled as a Maxwell body, indicates that the present dissipation factor should be at least greater than $10^{10}$. This questions the validity of the Maxwell model for describing Tethys’ interior. This satellite might be the most mysterious of all. With a density of $\sim 960$ kg/m$^3$ [1], its internal temperature is not expected to reach the ammonia melting point. Following [6], this body could even retain some porosity with depth. Models that consider the presence of an ocean during the history of the satellite to explain the extensional geological features observed at the surface are likely to be unrealistic. However, Tethys has an eccentricity close to zero that would indicate tidal evolution. An additional mystery includes a discrepancy between the shape, which corresponds to a differentiated body, and the density [18].

**Some Keys to the Problem:**
While there is evidence that frequency-dependent behavior of an icy satellite is function of both its structural properties and temperature, it seems crucial that minimum temperature conditions should be present in the satellite for significant tidal dissipation to start and be preserved on the long run, as a function of orbital evolution. We will present the comparison between different rheological models: Maxwell, Andrade, Caputo, Voigt-type Cole-Cole relaxation model, Cole porous model, etc. We will also discuss the importance of considering the different scales of the heterogeneities (composition and structure) present in planetary interiors.

We will also present the result of applying different rheological models as a function of depth (for example in satellites larger than 500 km in radius in which compaction and temperature gradient can modify the structural properties of the interior) and of time (e.g., compaction of the satellite during thermal evolution). We stress out the importance of developing models with radial- latitude- longitude- structure-frequency- dependent dissipation factors, and integration over the long run of the history. We will emphasize the case of Enceladus in order to understand the dichotomy between the North Pole and the South Pole in terms of dissipative properties.

The presentation will focus on Mimas, which appears as the best example to assess dissipation in a cold body. Forming Mimas at the same time as Iapetus [11] permits one to model a non-linear evolution with rapid eccentricity damping in the early history, followed by a rapid freezing of the interior with the end of orbital evolution. It has been proposed that we examine dissipation as the result of friction on faults [19]. We argue that Mimas provides a good example that significant heat is not produced this way. Also, while ice rheological properties, e.g., as a function of stress, are not well established between 70 and 220K, they are certainly not favorable to significant tidal dissipation.

A major conclusion of these different observations is that lapetus, which undergoes $\sim 10^8$ of the tidal dissipation undergone by Mimas, is not likely to evolve much by any dissipation mechanism. This observation is further evidence that a source of heat, such as short-lived radionuclides decay, is needed in the Saturnian system.

**References:**
[18] Stevenson, personal communication.  
**Acknowledgements:** This work was carried out at the Jet Propulsion Laboratory-California Institute of Technology, under contract to NASA.