Internal Structure of Enceladus and Dione from Orbital Constraints

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Introduction Enceladus is emitting measurable heat (3-7 GW) from a region centered on its South Pole [1]. Radioactive and accretional heating are expected to be minimal for such a small, low-density body, implying that the observed heat flow is due to past or present tidal dissipation [2]. The tidal heat production for which Enceladus' eccentricity is in steady state, however, cannot exceed 1.1 GW [3]. This estimate depends on Saturn's tidal properties and is independent of Enceladus' present-day eccentricity and internal structure. It therefore seems likely that either Enceladus' eccentricity is not in steady-state at the current time, or that heat was generated at an earlier time and is now being released.

Enceladus' current eccentric orbit is forced by Dione through a 2:1 mean-motion resonance trapping. Orbital resonances, either current or ancient, have the potential to increase a satellite's eccentricity, and thus generate heating and deformation via tidal dissipation [4]. Prior to the current e-Enceladus resonance, the two satellites have passed through a few other resonances near the 2:1 commensurability [5]. These resonances, although not able to generate enough heat in Enceladus to account for the current outflow, provide clue to the amount of dissipation inside each satellites. Here, we constrain the internal structure of Enceladus and Dione by modeling their orbital evolution through the 2:1 resonance numerically. We use a N-body code in our modeling. The connection between orbital evolution and internal structure is established by including perturbations from tidal deformation in the N-body integration.

Orbital constraints Tidal dissipation in a satellite is parameterized by the quantity k_2/Q, where k_2 is the satellite's Love number, and Q is its tidal quality factor. For now, we assume that this quantity is constant throughout the resonance passage for both Enceladus and Dione. Fig. 1 shows a typical simulation through the 2:1 resonant region. Before the two satellites reach the current R_{e_E} (e-Enceladus) resonance, they have passed through two other strong resonances – R_{e_D} (e-Dione) and $R_{e_E e_D}$ (second-order) – and a few weaker resonances (e.g. the third-order $R_{e_E e_D^2}$ and the secondary S2:1). In order for the current trapping at R_{e_E} to occur, the two satellites must have avoided permanent capture at any of these resonances [5].

The first-order R_{e_D} resonance is so strong that once established, it is almost impossible to break. Thus, the two satellites must avoid trapping in order to get through this resonance, which requires the pre-encounter eccentricity of Dione to be greater than some critical value [6]. We have determined this critical e_D to be ≈ 0.003, in close agreement with previous analytical and numerical determinations [7, 8]. The pre-encounter e_D is likely to be a residue of an earlier resonant encounter [5]. Following the R_{e_D} resonance, the satellites will then encounter the second-order $R_{e_E e_D}$ resonance. Despite the weak nature of the second-order resonance, capture into this resonance is assured because of the tidally-damped small free eccentricity of Enceladus. However, escape is also assured due to nearby secondary resonances [5]. Trapping into third- and higher-order, or secondary resonances are also possible, but they are only temporary and do not affect the overall evolution.

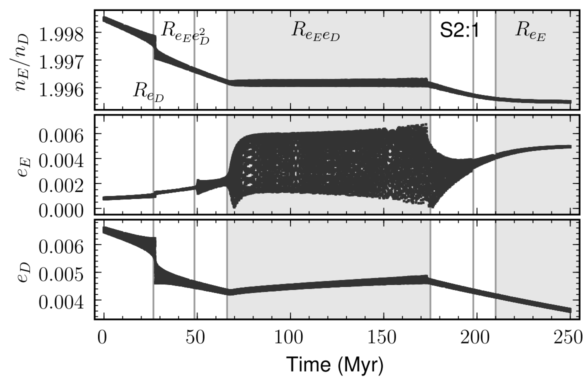

Figure 1: Orbital evolution of Enceladus and Dione during their 2:1 mean-motion resonance passage, assuming $(k_2/Q)_E = 0.0007$, and $(k_2/Q)_D = 0.0001$. Saturn's $Q_S = 1.8 \times 10^4$, and $k_{2S} = 0.341$. Mean motion ratio of the two satellites and their eccentricities are shown.

With the above evolution scenario, we can constrain k_2/Q of the satellites in terms of Saturn's. A satellite's k_2/Q determines the eccentricity damping rate, while Saturn's determines the evolution timescale of the resonance. For Enceladus, an upper bound on its k_2/Q is obtained by requiring the tidal equilibrium eccentricity (toward the end in Fig. 1) to be greater than or equal to the current observed value (0.0047), which gives $(k_2/Q)_E < 8 \times 10^{-4}$ for $Q_S > 1.8 \times 10^4$ [4], assuming $k_{2S} = 0.341$ [9]. For any larger value of $(k_2/Q)_E$, the equilibrium e_E would be too small and the satellite can never obtain its current eccentricity. The current libration amplitude of Enceladus' orbit ($1.5°$ [10]) places a lower bound on the satellite's k_2/Q. As e_E evolves toward equilibrium, the amplitude of orbital libration must decrease to its observed value when e_E reaches 0.0047. This requires $(k_2/Q)_E > 1.2\times10^{-4}$ for $Q_S < 10^5$ [5]. For Dione, its current eccentricity places an upper limit for the k_2/Q of the satellite: $(k_2/Q)_D < 3 \times 10^{-4}$ for $Q_S > 1.8 \times 10^4$. Stronger dissipation would result in a more circular orbit for Dione than is currently observed.

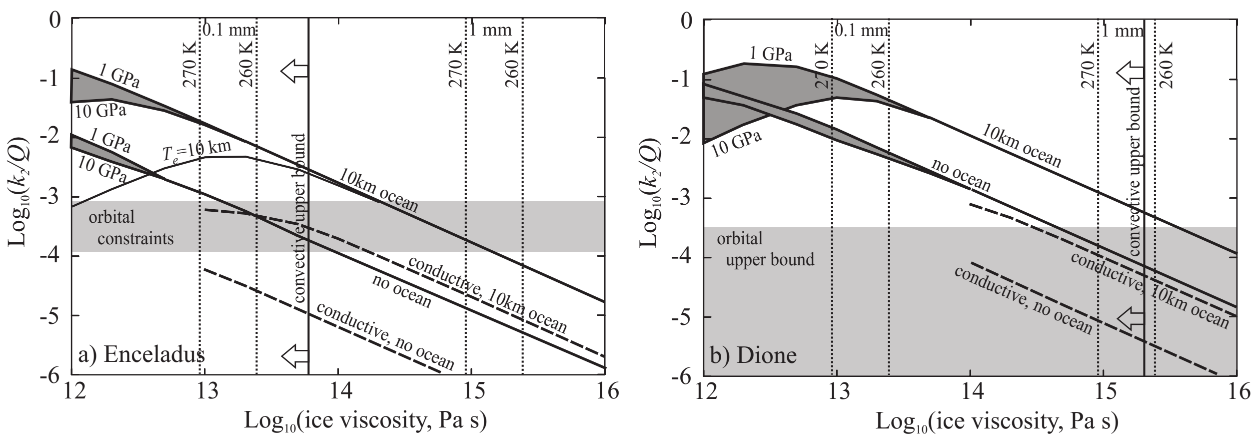

Figure 2: $\mathrm{Log}_{10}(k_2/Q)$ of Enceladus (a) and Dione (b) as functions of ice shell viscosity, with and without an ocean. For convective cases, the dark gray shading gives the variation in k_2/Q when the ice shell rigidity is varied from 1-10 GPa. For conductive cases, the rigidity is set to 3 GPa. Vertical solid line gives upper bound on basal viscosity to allow convection to take place. Vertical dotted lines give ice effective viscosity for different grain sizes (in mm) and temperatures, assuming diffusion creep [13]. Horizontal shaded region denotes orbital constraints on k_2/Q.

Internal structures The two most important structural characteristics of an icy satellite are whether it possesses a subsurface ocean, and whether the ice shell is convecting. Subsurface oceans decouple the ice shell from the underlying interior and thus permits much larger tidal deformation and dissipation [11]. Satellites possessing convective ice shells tend to be much more dissipative than those with conductive shells. Whether or not convection occurs depends mainly on ice grain size, the temperature at the base of the ice shell and its thickness. We now consider the structural implications from the above constraints on k_2/Q. We will assume that Enceladus and Dione are Maxwell viscoelastic bodies and will use the approach of Moore and Schubert [12] to determine their k_2/Q values given a particular density, rigidity and viscosity structure (Fig. 2).

Fig. 2 plots the k_2/Q of the two satellites as a function of basal ice shell viscosity for conductive and convective ice shells. For Enceladus, the orbital constraints require either a convective ice shell sitting directly on the silicate mantle, or a conductive ice shell above an ocean. A conductive ice shell without an ocean yields k_2/Q values that are too small, while a convective one on top of an ocean yields values that are at least a factor of three too large. An ocean beneath a conductive ice shell is the more likely case because i) the inferred viscosity at the base of the ice shell is too high to be convective for ~ 1 mm grain size [15], and ii) an ocean beneath a convective shell freezes quickly and is hard to remelt [14]. For Dione, we also conclude that the ice shell is more likely to be in a conductive than a convective state at present, though this conclusion is less robust than that for Enceladus. Whether or not an ocean is present beneath the shell is unknown, but such an ocean cannot be ruled out from orbital considerations.

Coupled evolution In reality, k_2/Q changes as the ocean freezes or melts. We are currently investigating the effects of a k_2/Q which varies as the ice shell's thermal structure and thickness evolve with time. Our preliminary results show that even for a conductive shell, a subsurface ocean may freeze completely during the course of the simulation shown in Fig. 1, in agreement with [14]. Ocean freezing leads to a drop of $(k_2/Q)_E$ by as much as a factor of 10, and a corresponding reduction in tidal dissipation. Thus, once frozen, an ocean is unlikely to subsequently re-melt. Sustaining a long-lived ocean may require the presence of an antifreeze like ammonia or significant heat production in the silicate core or the ocean itself [16].

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