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Implications from Ithaca Chasma for the thermal and orbital history of Tethys

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[1] Flexural modeling of Ithaca Chasma on Tethys suggests that the elastic thickness and the surface heat flux were 5–7 km and 18–30 mW/m^2 respectively, when the feature formed (~4 Gyr B.P.). Tidal heating is a plausible heat source, suggesting that Tethys' eccentricity was higher in the past. Depending on Tethys' internal structure, eccentricities in the range 0.001 to 0.02 are sufficient to have generated the inferred heat flux. Because the eccentricity damping timescale is short, < 20 Myr, it is unlikely that this eccentricity was primordial. More likely, Tethys' eccentricity increased during passage through a 3:2 resonance with Dione. In equilibrium, this resonance produces ~2.5 mW/m^2 suggesting that non-equilibrium or periodic heating was important, similar to the case for Enceladus at present.

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1. Introduction

[2] Ithaca Chasma is a large rift valley measuring over 1000 km long and 50 to 100 km wide on the surface of the Saturnian satellite Tethys [*Smith et al.*, 1981; *Moore and Ahern*, 1983]. Based on *Cassini* imagery, flexural profiles across the rift suggest that at time of formation, the elastic thickness of the ice was 5–7 km and the corresponding surface heat flux in the region was ~18–30 mW/m^2 [*Giese et al.*, 2007]. Because of the wide extent of Ithaca Chasma (nearly 5–10% of the surface) [*Moore and Ahern*, 1983] and the minimal amount of extension associated with it (8–10%) [*Giese et al.*, 2007], this localized heat flux is probably characteristic of the global value. A global extrapolation suggests that as Ithaca Chasma formed, Tethys was emitting between 60 to 100 GW of power. We will adopt this range of values below; a smaller global power output would result in correspondingly smaller orbital eccentricities (see equation (1) below).

[3] Because of Tethys' small size (R = 533 km) and a density close to pure ice (ρ = 973 kg/m^3) [*Thomas et al.*, 2007], traditional heat sources such as radiogenic or accretional heating [*Ellsworth and Schubert*, 1983; *Hussmann et al.*, 2006; *Multhaup and Spohn*, 2007] are insufficient to provide the inferred surface heat flux. At present, Tethys' orbital eccentricity is indistinguishable from zero and thus, the satellite at present is likely to be tidally inactive; however, Tethys' eccentricity may have been higher in the past. In this paper, we calculate paleo-eccentricities required for Tethys to have been tidally heated to the extent suggested by topographic profiles of Ithaca Chasma.

2. Methods

2.1. Tidal Dissipation

[4] Models of global tidal dissipation have been applied to various icy satellites [*Ross and Schubert*, 1989; *Segatz et al.*, 1988; *Roberts and Nimmo*, 2008]. For a synchronous satellite in an eccentric orbit, the rate of tidal dissipation, $\dot{E}$, is a function of the orbital eccentricity, e, the mean motion, n, the satellite radius, R_s, the satellite's interior structure as parameterized by k_2, the degree-2 complex tidal Love number, and the gravitational constant, G [*Segatz et al.*, 1988].

$$\dot{E} = \frac{-21}{2} Im(k_2) \frac{(nR_s)^5}{G} e^2 \tag{1}$$

For a given surface heat flux, and thus a rate of energy dissipation, if all other orbital and physical parameters are held constant, the orbital eccentricity of the satellite is simply a function of k_2. The orbital circularization timescale, τ_{circ}, ignoring dissipation in the primary, is also a function of the tidal Love number [*Murray and Dermott*, 1999]

$$\tau_{circ} = \frac{-2}{21} \frac{m_s}{M_p} \left(\frac{a}{R_s}\right)^5 \frac{1}{n} (Im(k_2))^{-1} \tag{2}$$

where m_s is the mass of the satellite, M_p is the mass of the primary, and a is the orbital semimajor axis.

2.2. Interior Structure Models

[5] To calculate the amount of tidal dissipation in Tethys, it is critical to know k_2. Shape data and thermal models suggest that Tethys may be a homogeneous body [*Thomas et al.*, 2007; *Hussmann et al.*, 2006; *Multhaup and Spohn*, 2007]. Assuming a linear viscoelastic Maxwell model, k_2 can be found analytically for a homogeneous body,

$$k_2 = \frac{3/2}{1 + \frac{19\tilde{\mu}}{2\rho g R_s}}, \tag{3}$$

where ρ is the density, g is the gravitational acceleration and $\tilde{\mu}$ the complex rigidity [*Ross and Schubert*, 1989]. The complex rigidity $\tilde{\mu}$ is a function of the mean motion, n, the rigidity, μ, and the viscosity, η,

$$\tilde{\mu} = \frac{n\mu\eta}{\mu^2 + n^2\eta^2} (n\eta + i\mu) \tag{4}$$

[*Ross and Schubert*, 1989].

[6] However, since Tethys shows significant resurfacing and tectonic activity [*Smith et al.*, 1981; *Moore and Ahern*, 1983], it is likely that Tethys is a differentiated body. Therefore, we also considered models of Tethys consisting

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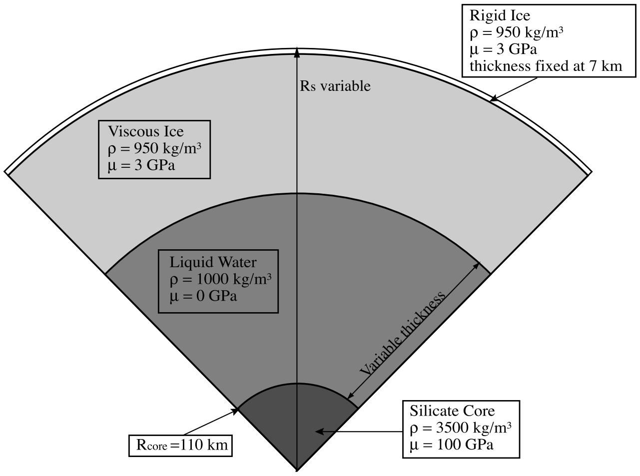

Figure 1. Interior structure model for a differentiated Tethys. For all models, the radius of the core was fixed at 110 km. The outer radius, R_s, was allowed to vary in order to match the observed bulk density of Tethys. For a model without an ocean, R_s = 533 km, the currently observed radius of Tethys. Through all models, the rigid lid and silicate core viscosities were fixed at $\eta = 1 \times 10^{19}$ Pa·s and $\eta = 1 \times 10^{21}$ Pa·s, respectively. The liquid water layer was optional in the models; if included, the thickness of the layer was varied between models.

of three or four layers: a silicate core, an optional liquid water ocean, a viscous icy mantle, and a rigid icy lid (see Figure 1). Based on the observed bulk density, the radius of the silicate core was fixed at 110 km for all models. In addition, a rigid elastic lid of thickness 7 km was assumed for all models based on *Giese et al.* [2007].

[7] The thickness of the viscous ice layer was varied between models; for each model, we calculated the Rayleigh number, *Ra* (see Table 1), based on an assumed basal viscosity, to determine whether convection or conduction was occurring. *Ra* was calculated using the total ice thickness minus the inferred elastic thickness, which we take as a reasonable proxy for the stagnant lid thickness. For *Ra* >1000, we assumed that convection was taking place and that the convecting layer could be adequately modeled as isoviscous [e.g., *Solomatov*, 1995]. The value of k_2 was found for each model by solving the linear tidal boundary value problem using the correspondence principle [*Segatz et al.*, 1988; *Ross and Schubert*, 1989; *Moore and Schubert*, 2000]. For a conductive thermal profile, we determined the equilibrium shell thickness due to tidal heating within the ice shell using the methods given by *Nimmo et al.* [2007] assuming a fixed h_2 Love number of 0.175 and a radiogenic mantle heat flux of 0.1 mW/m^2. The parameters used for all models are summarized in Table 1.

3. Results

[8] For a homogeneous Tethys, we modeled typical values of (Newtonian) ice viscosity ranging from $\eta = 10^{13}$ Pa·s to $\eta = 10^{15}$ Pa·s corresponding to grain sizes of roughly 0.1 mm to 1 mm at 273 K [*Goldsby and Kohlstedt*, 2001]. Tethys' density is close to that of pure ice; therefore, the rheologic properties of Tethys should be dominated by ice and not rock. Rock inclusions may increase the ice viscosity by an order of magnitude [*Friedson and Stevenson*, 1983], but the ice rigidity is unlikely to be significantly affected by the rock inclusions. The eccentricities required for a homogeneous Tethys to produce a surface heat flux of 25 mW/m^2 range from.002 for a low viscosity ($\eta = 10^{13}$ Pa·s) body to 0.071 for a high viscosity ($\eta = 10^{16}$ Pa·s) model, which includes a possible order of magnitude increase in viscosity due to rock inclusions.

[9] Because ice viscosity is highly temperature dependent, the values of η in theory could be greater than $\eta = 10^{16}$ Pa·s. However for a homogeneous Tethys with ice viscosity $\eta = 10^{17}$ Pa, the eccentricities required to produce a surface heat flux 25 mW/m^2 is 0.240, a value not exhibited by satellites of Tethys' size in our Solar System. In addition, the orbital circularization timescale for such a viscosity is approximately 2.0 Ga, making it impossible to simultaneously satisfy the present-day (zero) eccentricity of Tethys and the high eccentricity required to cause the inferred heat flux at Ithaca Chasma.

[10] For a differentiated Tethys, Figure 2 shows the required eccentricities to produce a surface heat flux of 25 mW/m^2 for various structural models. For a low reference viscosity, $\eta = 10^{13}$ Pa·s, there is no equilibrium conductive profile: the layer thickness at which the viscous layer becomes convective is less than the equilibrium conductive thickness (39 km). If the ice shell is thin (<50 km), there are two processes that affect the tidal heat production. As the viscous layer becomes thinner, it is easier to deform and thus exhibits greater heat production per unit volume. However, as the viscous layer thickness decreases, for a fixed heating rate the total heat production will decrease. This results in a critical layer thickness where there is maximal tidal heat production; however, this critical thickness is relatively thin compared to the total thickness of the H_2O layer. When the viscosities are between 10^{14} and 10^{15} Pa·s, this critical thickness is less than the minimum shell thickness required

Table 1. Model Parameters

Parameter	Value
Material Parameters	
ρ	973 kg m^{-3}
ρ_{ice}	950 kg m^{-3}
ρ_{water}	1000 kg m^{-3}
$\rho_{silicate}$	3500 kg m^{-3}
μ_{ice}	3 GPa
$\mu_{silicate}$	100 GPa
Orbital Parameters	
a	294,660 km
n	3.852×10^{-5} rad s^{-1}
$a_{Tethys,res}$	288,010 km
a_{Dione}	377,396 km
M_{Dione}	1.096×10^{21} kg
R_{Saturn}	60,268 km
$k_{2,Saturn}$	0.341
Q_{Saturn}	18,000
Rayleigh Number Parameters, $Ra = \frac{g\alpha F d^4}{k\kappa\eta}$	
F	25. mW m^{-2}
g	0.145 m s^{-2}
α	1.0×10^{-4} K^{-1}
k	3.0 Wm^{-1}K^{-1}
κ	1.0×10^{-6} m^2 s^{-1}
η	10^{13}–10^{15} Pa s

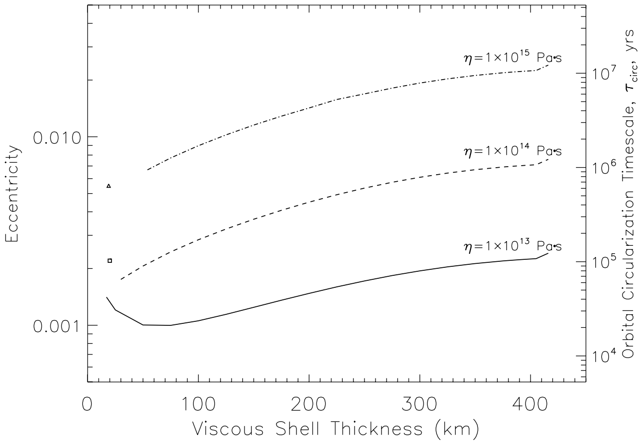

Figure 2. Required eccentricities for a differentiated Tethys to produce a surface heat flux of 25 mW/m^2 and orbital circularization timescales as a function of the viscous layer thickness and basal ice viscosity. The curves were calculated assuming an isoviscous (convective) ice mantle. The square and triangle represent a conductive profile in thermal equilibrium for basal viscosities $\eta = 1 \times 10^{14}$ Pa·s and $\eta = 1 \times 10^{15}$ Pa·s, respectively.

for convection to occur in the layer. Removal of the liquid ocean from the model decreases tidal heat production by a small amount because the rigidity of the thick ice shell above controls the amount of tidal deformation. The resulting eccentricities from these models range from a minimum of 0.001, where the thickness of the ice shell is at its critical thickness, to 0.025, where there is no liquid ocean (Figure 2).

[11] The orbital circularization timescales presented in Figure 2 show identical trends to those of the orbital eccentricity. These results are highly dependent on viscosity. For structures with ice viscosity of $\eta = 10^{13}$ Pa·s, the decay time, τ_{circ}, is less than 10^5 years while for structures with viscosity $\eta = 10^{15}$ Pa·s, the decay time is much longer, $\tau_{circ} \sim 10$ Myrs. In reality, the decay rate is not constant; as the satellite cools, the interior structure will change. However, for the viscosities and structures modeled here, the circularization time is short compared to the lifetime of the Solar System.

4. Discussion

[12] Figure 2 shows that the eccentricities required for Tethys to undergo significant tidal heating are within the range of eccentricities currently exhibited by bodies in our Solar System. While Tethys' near zero eccentricity makes it tidally inactive currently, this state is not necessarily primordial. Therefore, the main question to answer is what could have been the origin of the elevated eccentricity.

[13] One possibility is that this eccentricity is primordial, specifically, that the eccentricity is a remnant of the formation of Tethys itself. Figure 2 shows that the orbital circularization timescales for any assumed structure of Tethys are short, at most 20 million years. If the eccentricity was elevated due to primordial conditions, it would have been damped quite quickly, and thus, surface features related to this primordial eccentricity should date from the beginning of the Solar System. Crater counts suggest that Ithaca Chasma was formed around 4.0 Ga and may even be much younger [*Giese et al.*, 2007]. Therefore, the heat flux recorded by Ithaca Chasma is unlikely to be attributable to tidal heating from a primordial eccentricity.

[14] The eccentricity of Tethys' orbit could have been perturbed by a paleo-resonance. Currrently, Tethys and Mimas are in an inclination-type resonance; this resonance has no effect on Tethys' eccentricity. However, this current orbital configuration of Mimas and Tethys does suggest that Tethys' eccentricity was likely non-zero before Tethys entered its current resonance [*Champenois and Vienne*, 1999a, 1999b]. Tethys may have passed through a 3:2 eccentricity-type resonance with Dione further in the past as a result of outwards migration of these two bodies [*Murray and Dermott*, 1999]. Since Tethys and Dione are currently not in this resonance, they must have been perturbed from it subsequently.

[15] Tidal heating related to an equilibrium resonant configuration where the rate of eccentricity growth due to orbital resonance is balanced by the rate of eccentricity decay due to tidal dissipation has been calculated for Enceladus [*Lissauer et al.*, 1984; *Meyer and Wisdom*, 2007]. Taking the same approach, specifically equations (1)–(16) from *Meyer and Wisdom* [2007], using parameters relevant to a 3:2 resonance between Tethys and Dione (with appropriate adjustment of Tethys' semimajor axis (see Table 1)), the equilibrium tidal heating rate is approximately 9 GW. This equilibrium heating value was calculated using a minimum time-averaged value for the tidal dissipation factor, Q_{Saturn} = 18,000, given Mimas' current position [*Meyer and Wisdom*, 2007]. This heating rate is 6–12 times less than the inferred rates from topographic profiles of Ithaca Chasma. A similar problem has been noted for Enceladus, and non-equilibrium processes may account for the additional heat observed [*Meyer and Wisdom*, 2007]. Q_{Saturn} may also be variable [*Ogilvie and Lin*, 2004], and could have resulted in higher tidal heating rates in the past. Periodic oscillations may also be involved in a manner similar to the predicted behavior for Io [e.g., *Ojakangas and Stevenson*, 1986].

[16] The observations from Ithaca Chasma suggest a more complicated thermal and orbital history for Tethys than previously thought. Ithaca Chasma was likely formed during a period where the eccentricity of Tethys was elevated. Because of the high rate of tidal dissipation and the corresponding short timescale for orbital circularization, our models suggest that it is highly unlikely that this elevated eccentricity was primordial; more likely, it resulted from a resonance passage. Figure 3 shows the expected heat production in Tethys for a hypothetical eccentricity of 0.005 as a function of viscous layer thickness. As eccentricity increases, these curves shift up. However, in equilibrium, assuming a constant value for Q_{Saturn}, a heat flow of ~9 GW would have resulted; periodic or non-equilibrium behavior would be needed to account for the higher heating rates. In the case of Tethys, an ocean is not required to produce the heat flux associated with Ithaca Chasma, provided that the eccentricity was high enough. However, because the amount of heat that can be transported via convection is limited by the rheological properties of ice [e.g., *Solomatov*, 1995], if the eccentricity remained sufficiently high for a prolonged period of time, Tethys' ice layer would have started to melt. As the shell thinned, the tidal heat production would have

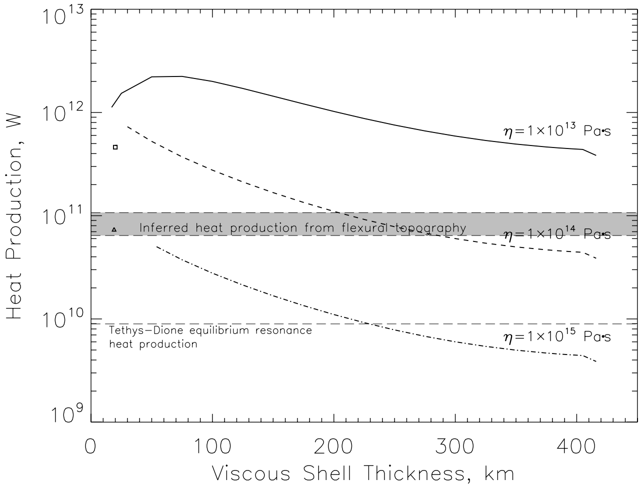

Figure 3. Total heat production with a fixed orbital eccentricity of 0.005 predicted from tidal heating models. Changing the eccentricity will shift these curves up or down. Shaded region shows the total heat production calculated from flexural modeling of Ithaca Chasma. Lower dashed line shows the equilibrium heat production from a 3:2 resonance with Dione where the semimajor axis of Tethys was moved to the resonance location, see Table 1.

increased, which in turn would have thinned the ice shell further. This thermal runaway could have resulted in high heat fluxes that would have continued until the eccentricity-forcing mechanism ceased. Tethys' orbit would have subsequently circularized, reducing the total tidal heat production in the satellite. As a result, the ice shell would have cooled, and if there was a liquid ocean present, this would have solidified. One plausible mechanism for forming Ithaca Chasma is the expansion of water as it froze into ice [*Moore and Ahern*, 1983]. This mechanism easily generates the large (1–2 MPa) stresses that are predicted from the flexural profiles of Ithaca Chasma [*Giese et al.*, 2007; *Nimmo*, 2004]. Because the surface of Tethys is heavily cratered, it is likely that Tethys has not undergone subsequent periods of elevated eccentricity.

5. Conclusion

[17] Although Tethys is currently tidally inactive, tidal heating may have played a significant role in Tethys' evolution. The eccentricities required for Tethys to produce heat on the order of 100 GW are relatively low (∼0.001–0.02). The actual thermal and orbital history of Tethys is likely to be far more complex than the picture presented here. Tidal heating, interior structure and orbital evolution are intimately coupled, and the development of a model that couples these processes is left for future work; the possibility of local heat sources should also be investigated. Equilibrium tidal heating involving a resonance between Tethys and Dione is probably insufficient to produce the amount of heat suggested by the topography of Ithaca Chasma. In addition, while it is plausible that Tethys passed through a paleoresonance with Dione, the conditions for such a resonance occurring have not been modeled in detail. How Tethys and Dione escape from this resonance and evolve to their current configurations (Tethys in resonance with Mimas and Dione in resonance with Enceladus) is not clear. Lastly, ammonia has been detected on the surface of Tethys [*Verbiscer et al.*, 2008], and chemistry may be important in the thermal structure of the satellite [*Multhaup and Spohn*, 2007].

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