INCLINATION DAMPING ON TITAN AND CALLISTO. B. G. Downey and F. Nimmo, Dept. Earth and Planetary Sciences, University of California Santa Cruz, Santa Cruz, CA 95064, USA

Introduction: Titan and Callisto, despite potentially large energy dissipation in their oceans that takes energy out of their orbits by damping inclination, still have relatively large inclinations of 0.33° and 0.19° respectively. Either they have stiffer shells than expected, lowering the energy dissipation estimate and raising the likelihood of a long-lasting primordial inclination, or a recent (<0.5 Ga) event increased their inclinations.

Short Damping Timescales: Oceans dissipate energy via obliquity tides. The energy is taken out of the orbital energy stored in the inclination at a rate dictated by

$$\dot{E}_{obl} = \frac{108\pi}{25}\frac{\rho h \nu \Omega^8 R_M^{10}\theta_0^2}{\left(\frac{9\Omega^6 R_M^8}{25} + \frac{144\nu^2 g^2 h^2}{\xi^2}\right)}$$

where

$$\nu = \xi\left(\frac{\frac{-9}{25}\Omega^6 R_M^8 + \sqrt{\left(\frac{9}{25}\Omega^6 R_M^8\right)^2 + 4(144)\left(0.40 c_D g \Omega^4 R_M^7 \theta_0\right)^2}}{2(144)g^2h^2}\right)^{1/2}$$

the turbulent viscous diffusivity, is numerically-derived, and $\xi \in [0, 1]$ describes how rigid (0) or weak (1) the lid is [1]. Calculations of the energy dissipation included in an inclination damping timescale [1] $\tau = i/\frac{di}{dt}$ yield expected inclination decay times of ~400 Myr and ~700 Myr for Titan and Callisto respectively. Fig. 1 compares these inclination decay times to other icy satellites to show how unusually short theirs are.

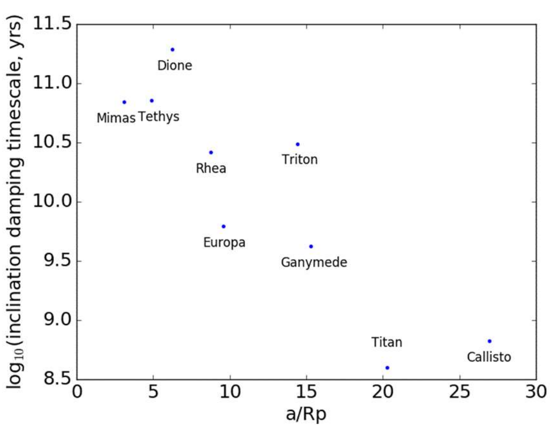

Figure 1: Inclination decay times for various icy satellites suspected to have oceans plotted against semi-major axis in planet radii. Enceladus has zero inclination and so is not included here. Dissipation rates are from [2] and assume obliquity tides in an ocean.

Dissipation Explanation: These rapid decay times are incompatible with primordial inclinations, so either the energy dissipation estimates are too large or Titan's and Callisto's inclinations were recently excited.

Overestimated Dissipation. The two largest unknowns in the obliquity damping equation are the bottom drag coefficient, c_D, and the lid damping factor, ξ. Likely values of c_D are 10^{-4}-10^{-2} in dissipation models for Titan which is compatible with the derived value for Earth of 2×10^{-3} [3]. Varying the drag coefficient by an order of magnitude will have a less than order of magnitude decrease in the estimated ocean energy dissipation as shown in Fig. 2, so uncertainty in the drag coefficient is unlikely to explain the discrepancy. The energy dissipation due to obliquity tides scales linearly with the damping factor, so it would take $\xi < 0.1$ for the energy dissipation to decrease by an order of magnitude, a constraint that would mean a very rigid lid on both moons. We will investigate whether such a damping factor is plausible using the approach of [4].

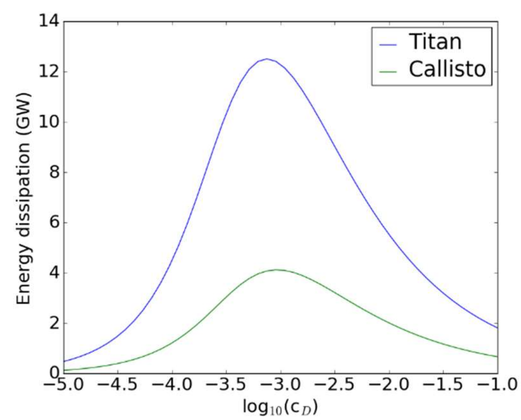

Figure 2: Energy dissipation in Titan's and Callisto's oceans due to obliquity tides as a function of the bottom drag coefficient, c_D, which is set to 2×10^{-3} for the rest of the work.

Time-varying Dissipation. The second explanation that assumes that the energy dissipation calculations are correct would have Titan and Callisto migrating outwards because of varying tidal dissipation induced by resonance locking with Saturn and Jupiter respectively [5]. The mean motion evolution of the satellite due to tidal locking with a resonance in the planet that has an evolution timescale, t_α, is

$$n(t) = \Omega_p + \left(n_{now} - \Omega_p\right)\exp\left(\frac{t - t_{now}}{t_\alpha}\right)$$

[6] where n is the mean motion and Ω_p is the planet rotation frequency. While migrating outwards, Titan and Callisto could have passed through a number of mean

motion resonances (MMRs) with interior moons, potentially exciting their inclinations. Because the orbits are typically diverging, capture into resonance will not occur [7], but transient inclination excitation will still take place. Figures 3 and 4 show the hypothetical semi-major axis evolution in the Saturnian and Jovian systems assuming that the t_α values either predicted in or derived from [5] and [6] have been constant since satellite formation.

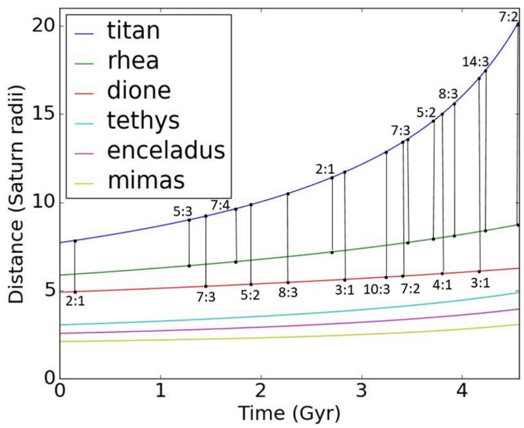

Figure 3: Semi-major axis evolution of the Saturnian inner satellites under the influence of resonance locking with t_α values of 4, 8, 12, 51, 49 [6], and 47 Gyr [5] from inner to outer satellites. Instantaneous MMRs plotted where possible showing Rhea and Dione are the only ones in resonance with Titan.

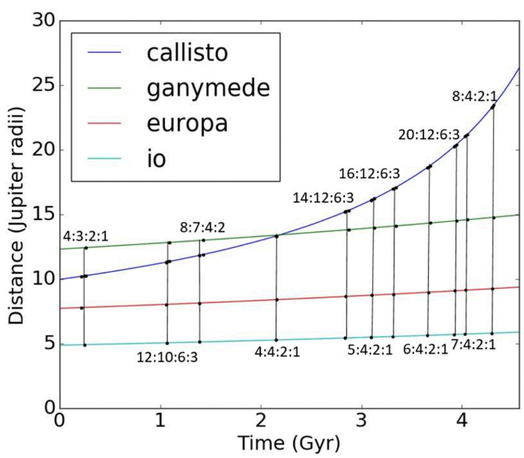

Figure 4: Semi-major axis evolution of the Jovian inner satellites with t_α values of 44, 101, 217, and 52 Gyr from inner to outer satellites. Instantaneous MMRs plotted. Io, Europa, and Ganymede are extrapolated as if formed in resonance.

Conclusion: Figuring out the source of Titan's and Callisto's large inclinations would give more information on either the internal structure of these icy satellites or their dynamical history. The former would be helped by better moment of inertia and/or tidal response data from spacecraft, to narrow in on their physical properties. On the dynamical history side, models coupling tidal dissipation with orbital migration could constrain where satellites were either formed or captured, what the internal modes and evolution of the planet are, and thus times and locations where orbital elements of the satellites could have been excited.

References: [1] Chen and Nimmo (2016), *Icarus*. [2] Chen et al. (2014), *Icarus*. [3] Hay and Matsuyama (2017), *Icarus.* [4] Matsuyama et al. (2018), *Icarus.* [5] Fuller et al. (2016), *Monthly Notices of the Royal Astronomical Society.* [6] Nimmo et al. (2018), *Univ. Ariz. Press.* [7] Dermott et al. (1988), *Icarus.*