AN OBSERVATIONAL CONSTRAINT ON TITAN'S TIDAL DISSIPATION. Brynna G. Downey[1], Francis Nimmo[1], and Bruce Bills[2], [1]Dept. Earth and Planetary Sciences, University of California Santa Cruz, CA 95064, USA (bgdowney@ucsc.edu, fnimmo@ucsc.edu), [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (bruce.bills@jpl.nasa.gov)

Introduction: A satellite's spin state holds clues to its interior properties. Tidal dissipation within a body drives it to synchronous rotation and to a Cassini state, which is an equilibrium steady state in which the precessional periods of the spin axis and the orbit normal are the same [1, 2, 3]. Therefore, observations of the spin states of satellites in our solar system can shed light on their tidal dissipation properties. Using the equations of motion of a body's spin axis under the influence of tidal and precessional torques, we derive a relation between the tidal dissipation factor, k_2/Q, and the spin vector. The observed spin orientations of the Moon and Titan can be used to estimate their values for k_2/Q.

Spin Equilibrium: A satellite's spin axis precesses about its orbit normal due to torques on its permanent triaxial figure. At the same time, the orbit normal precesses about the Laplace plane normal (defined as the average precessional plane) due to torques from the planet's oblateness, the Sun, and when applicable other satellites. Tidal torques drive the system to equilibrium, which for a circular orbit corresponds to synchronous rotation and an equilibrium spin vector, called a Cassini state. In a Cassini state, the precessional periods of the spin axis and orbit normal are the same, and the spin vector lies approximately in the plane defined by the orbit normal and Laplace plane normal, which we call the Cassini plane. The spin vector is separated from the orbit normal by the obliquity, θ, and the longitude of the node of the equator plane on the orbit plane is ϕ. In spherical coordinates, the obliquity and equator node are equivalent to colatitude and longitude respectively. The angular offset of the spin vector from the Cassini plane, γ, is defined as $\sin\gamma = \sin\theta\sin\phi$. The equator node and Cassini plane offset depend on the degree of dissipation in the body.

Using the spin equations of motion in [4] due to precessional and tidal torques we solve for the steady-state obliquity, θ, and equator node, ϕ. In the absence of tidal dissipation, $\phi = 0$, but when dissipation is included, ϕ will be non-zero (e.g., [5]):

$$\tan\phi = \frac{3\dfrac{n}{c}\left(\dfrac{M_p}{M}\right)\left(\dfrac{R}{a}\right)^3\dfrac{k_2}{Q}\cos\theta\left(1-\dfrac{1}{2}\cos\theta\right)}{\dfrac{3}{2}\dfrac{n}{c}\left[(J_2+C_{22})\cos\theta + C_{22}\right]+\eta\cos i},$$

where $n, c, M, R, a, k_2/Q, J_2, C_{22}, \eta, i$ are the satellite's mean motion, normalized polar moment of inertia, mass, radius, semi-major axis, tidal dissipation factor, degree-2 gravity coefficients, orbital node precession frequency, and orbital inclination, and M_p is the planet's mass.

Application to the Moon: Lunar laser ranging data have found that for the Moon, $\gamma = -0.27"$ [5, 6]. From our calculations, $\phi = -2.3"$, which corresponds to an effective total body k_2/Q of 1.3×10^{-3}. The solid-body k_2/Q has been determined from lunar laser ranging to be 6×10^{-4} [7], so about half of the tidal dissipation in the Moon can be attributed to solid-body deformation.

The remainder of the dissipation could arise from the effect of torques other than those from solid-body tides within the Moon. For example, [8] explore the effects of solid-body tides, viscous core-mantle coupling, and viscoelastic deformation of the solid inner core on the Cassini plane offset. Our functional form for the offset caused by solid-body tides is different from theirs though. In addition, [9] explore the role that viscous dissipation at the core-mantle boundary and the inner core boundary plays on the offset. Given the number of potential sources of deformation and torque on the interior of the Moon, further analysis is needed to disentangle the effects on the Cassini plane offset.

Application to Titan: Having benchmarked the theoretical equilibrium spin state for a satellite under the influence of solid-body tides against the lunar k_2/Q and Cassini plane offset, we can apply the theory to Titan. Using the observed Cassini plane offset of $\gamma = -0.091°$ [10] and an equator node of $\phi = -17°$, we deduce a theoretical k_2/Q upper bound of 0.2 for Titan. Titan's degree-2 potential Love number from Cassini data is $k_2 = 0.6$ [11], meaning that the tidal quality factor, Q, has a lower bound of 3. A caveat is that we assume that all of the offset is from internal processes and we neglect atmospheric effects (c.f., [12]).

Implications for tides on Titan: Using the standard rate of solid-body eccentricity tidal heating in a synchronous satellite (e.g., [13]) and the rate of eccentricity decay due to satellite tides (e.g., [14]), we calculate an eccentricity damping timescale, τ_e. For $k_2/Q = 0.2$, $\tau_e \sim 4.7\,Myr$. The deduced dissipative properties for Titan imply that its orbital eccentricity should damp on a timescale much less than the age of the solar system, requiring a recent excitation. Such an excitation mechanism, involving close encounters with a now-destroyed satellite, has recently been proposed as an explanation for Saturn's young rings [15].

References:

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