DYNAMICAL STUDY OF THE TIDAL LOCKING OF EUROPA. E. R. Burnett[1] and P. O. Hayne[1,2], [1]Laboratory for Atmospheric and Space Physics, University of Colorado Boulder (email: ethan.burnett@colorado.edu), [2]Astrophysical and Planetary Sciences Department, University of Colorado Boulder

Introduction: Europa has been a subject of intense interest since the Voyager missions. Pervasive tectonic features observed on its icy surface imply a background stress field that cannot be generated by diurnal tidal-driven stresses alone, so it has been suggested that Europa could undergo non-synchronous rotation (NSR), spinning slightly faster than the synchronous velocity [1]. This would produce the necessary large stress fields in its ice shell. Attempts to directly measure NSR of Europa by imaging have failed [2], and a recent study also found no evidence for NSR from the longitudinal pattern in the exogenic discoloration of the surface ice [3]. A dynamical consideration of Europa tidal locking and NSR could shed new light on this outstanding problem.

Classically, as a planet's rotation slows due to energy loss, dynamic tidal torques on the tidal bulge act to produce a spin state slightly faster than the synchronous angular velocity [4,5]. This effect is countered by static torques on permanent moment of inertia (MoI) asymmetries of the body. Our work explores how the differentiation of Europa into a gravitationally interacting ice shell and solid interior affects classical conclusions on its final spin state.

Approach: We assume Europa's ice shell can move independently of the interior due to the existence of an intervening (inviscid) global ocean. This is depicted in Figure 1.

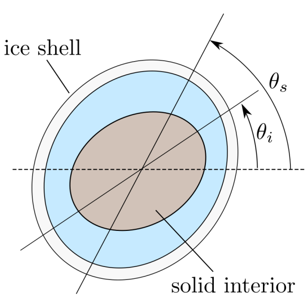

Fig 1. Europa differentiated into an ice shell and solid interior, separated by a global ocean (not to scale)

Neglecting the effects of shell non-rigidity, the spin dynamics of Europa are studied by considering the shell and interior as coupled nonlinear pendulums subject to external forcing torques:

$$C_s\ddot{\theta}_s = L_{\mathrm{grav},s}(\kappa_s,\theta_s) + L_{\mathrm{coupling}}(K_G,\theta_s-\theta_i) + L_{\mathrm{tidal},s}(\theta_s) \quad (1)$$
$$C_i\ddot{\theta}_i = L_{\mathrm{grav,i}}(\kappa_i,\theta_i) - L_{\mathrm{coupling}}(K_G,\theta_s-\theta_i) + L_{\mathrm{tidal},i}(\theta_i)$$

where L_{grav} are the torques of Jupiter's gravity on the permanent MoI asymmetries of the shell and interior, with associated MoI asymmetries $\kappa_i = (B_i - A_i)/C_i$. The term L_{coupling} is the gravity-gradient torque between shell and interior with associated coupling strength constant K_G, and L_{tidal} denotes the dynamic tidal torque on each. In the pendulum analogy, libration about a tidally locked orientation corresponds to the bounded rocking of a pair of coupled pendulums, and non-synchronous rotation corresponds to unbounded revolutions. In our previous work [6], an earlier model for studying libration of Europa [7] was repurposed to explore more general spin states such as NSR. Now we extend that early work to holistically study the dynamical evolution and tidal locking of Europa.

Results: There exists an energy integral for the 2D model of Europa's spin state, neglecting the influences of orbital eccentricity and dissipative tidal torque:

$$E = \frac{C_i}{2}\dot{\eta}_i^2 + \frac{C_s}{2}\dot{\eta}_s^2 - \frac{3}{4}(B_i - A_i)n^2\cos 2\eta_i - \frac{3}{4}(B_s - A_s)n^2\cos 2\eta_s - \frac{1}{2}K_G\cos\big(2(\eta_s-\eta_i)\big) \quad (2)$$

where $\eta_s = \theta_s - nt$ and $\eta_i = \theta_i - nt$ for orbital mean motion n. In a higher fidelity 2D model accounting for dissipative effects, the energy level slowly decays as Europa's spin rate slows. The energy remains quite useful for analysis with the more complex dynamics.

During the tidal locking process, Europa can pass through two critical energy states, $E_{\mathrm{crit},1}$ and $E_{\mathrm{crit},2}$. There is also a critical value of gravitational coupling strength, $K_G^* = 3n^2(B_i - A_i)/2$, which demarcates qualitatively different dynamical evolutions. In the case of weak gravitational coupling ($K_G < K_G^*$), Europa's transition through the higher critical energy state restricts the motion of the solid interior but leaves the ice shell free to potentially undergo full decoupled revolutions, which are actually observed in some simulations. This decoupled behavior is permitted until energy falls below the lowest critical energy state, at which point tidal locking ensues. In the case of strong gravitational coupling ($K_G \geq K_G^*$), this is not possible, and the shell and interior tidally lock in unison by the time the lowest critical energy state is reached.

It is unclear if the gravitational coupling constant K_G of Europa is above or below K_G^*. We execute two parameter studies simulating the long-term dynamical evolution of Europa's spin state – one for each case. For both of these we vary MoI asymmetries κ_i and κ_s above and below a value $\kappa^* = f(e)$ which classically predicts sufficient permanent asymmetry for tidal locking in

Goldreich and Peale's 1D analysis [4,5]. We assume $\frac{C_i}{C_s} = 28$, within the expected range of 7 to 200 [7]. The results are given in Figures 2 and 3.

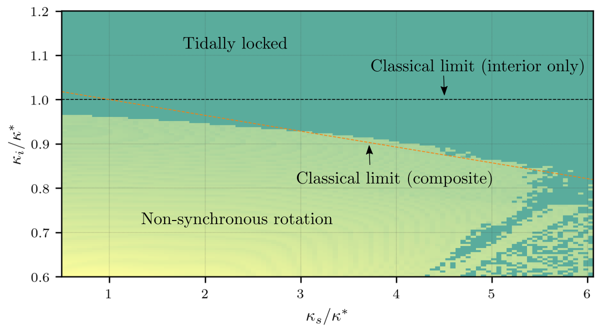

Fig 2. Europa's equilibrium spin state vs. normalized MoI asymmetries of the solid interior and ice shell, weak gravitational coupling case with $K_G < K_G^*$. Each point is simulated for 2500 orbits with amplified dynamic tidal torques to keep simulation times reasonable, similar to the approach of Goldreich and Peale [4,5]. Cells are color-coded by equilibrium energy level, from high values (light shades) to low (dark). The energy delta between NSR and tidal locking divides the two outcomes into light and dark regions, respectively.

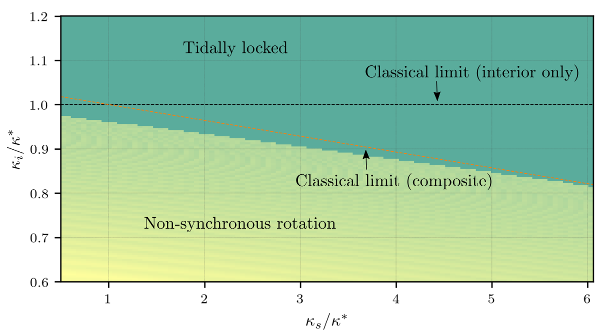

Fig 3. Europa's equilibrium spin state vs. normalized MoI asymmetries of the solid interior and ice shell, strong gravitational coupling case with $K_G > K_G^*$.

Examining Figures 2 and 3, we see that the magnitude of the MoI asymmetry of the solid interior primarily determines whether or not Europa will tidally lock. Universally, if the interior MoI asymmetry is higher than the classical tidal locking limit, $\kappa_i > \kappa^*$ (cases above the horizontal black line), both the shell and interior of Europa will tidally lock. With the simplifying assumption that the shell and interior are rigidly affixed to one another, we can determine a better boundary separating NSR and tidal locking. Noting that the MoI are additive, we modify the classical result of Goldreich and Peale [4,5] to obtain a linear boundary between tidal locking and NSR, which is given by the orange lines. In the case of strong gravitational coupling, this boundary is a useful approximation of the demarcation between NSR and tidal locking cases. However, the effects of independent oscillation and rotation cannot be discounted for the case of weak gravitational coupling.

In the weak gravitational coupling case, for high shell MoI asymmetry $\kappa_s \gg \kappa^*$, tidal locking of Europa can ensue even when the interior does not have anywhere near the expected necessary asymmetry. The result is a complex variation of outcomes depending on the exact relative values of κ_i/κ^* and κ_s/κ^*. We suspect resonances are at play in this region of the parameter space. This study, which neglects the dissipative effects of shell rheology, shows that even a thin ice shell can have an outsize impact on the dynamical evolution of Europa, depending on the strength of internal gravitational coupling.

Discussion: The results presented here were obtained from a model neglecting the influence of other torques on the ice shell and interior. The Poincaré torques and friction torques are expected to be sub-dominant to the gravitational torques [8]. Dissipation in a viscoelastic ice shell is accompanied by a corresponding torque. The shell dissipation and the resulting torque can be quite large depending on the depth and degree of fractures in the ice shell [8]. We are undertaking additional studies to investigate this dissipation, which introduces additional geological considerations to this dynamical study.

The effects of shell rheology are most important for solutions exhibiting large departures of the shell orientation angle from that of the solid interior. We can study the outcome by comparing the shell's Maxwell time τ_m to a reorientation time $\tau_r \sim \pi|\delta\omega|/2$ for differential angular velocity $\delta\omega = \omega_s - \omega_i$. For a primordial thin ice shell, a large τ_m dominates the response. Then assuming a rapid reorientation with $\tau_r \ll \tau_m$, we would expect broad global fracturing in the shell due to the inability for elastic strain to compensate the entire deformation. The decoupled shell rotation solutions observed in our results would actually impart a large amount of energy into the fracturing of the primordial ice shell. By contrast, a modern thick shell's response would be dominated by small τ_m. Then for a reorientation with $\tau_r \gg \tau_m$, there could be a rapid arresting of independent motion due to viscous energy dissipation deep within the ice shell.

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