IMPLICATIONS OF SECOND ORDER RESONANCE FOR THE THERMAL AND ORBITAL EVOLUTION OF MIMAS.

Z. Tian[1] and F. Nimmo[1], [1]University of California Santa Cruz (ztian13@ucsc.edu, fnimmo@ucsc.edu).

Introduction: Mimas, the innermost Saturnian moon, presents several puzzles. It appears geologically inert, despite its high eccentricity and proximity to Saturn, both of which normally drive tidal heating [1,2]. Libration observations could be indicative of a subsurface ocean [3], which would be surprising in view of its small size and inability to retain heat [2]. Last, its age is uncertain – it could be as old as the solar system, or several Gyr younger [4]. In this work we explore how the dynamical evolution of Mimas might be able to solve some of these puzzles.

Mimas's eccentricity of 0.02 is surprisingly high, given that it is not currently in an eccentricity-type resonance. This requires that the damping timescale is long compared to the time since Mimas's eccentricity was last excited. A damping timescale comparable to the age of the solar system is not compatible with the hypothesized subsurface ocean.

The most recent resonance capable of exciting Mimas's eccentricity is the 3:2 resonance with Enceladus [5]. The equilibrium heating rate achieved in this resonance depends on the dissipation factor (Q) of Saturn. Astrometric measurements suggest Q~2000 is likely for Mimas [6,7], implying an equilibrium heating rate of ~9 GW or 18 mWm^{-2} [8]. Such a high heat flux is incompatible with the existence of the deep, unrelaxed Herschel basin [9]. A further problem with the 3:2 resonance is that it is hard to exit this resonance once it was encountered [5].

An alternative that we explore below is that a second-order 6:4 $e_{Mi}e_{En}$ mixed-term resonance can excite Mimas's eccentricity without violating the heat flux constraints, while also permitting it to subsequently evolve to its present-day resonance with Tethys.

Model: We study the system of Saturn, Mimas (Mi) and Enceladus (En). We use the same model as in [5]. It includes the slow terms (resonance terms) up to second order in eccentricitiy from satellite-to-satellite interaction, and perturbations from Saturn's oblate shape and the planet-satellite tides.

Results: We start the system before it gets near the group of 3:2 Mi-En mean motion resonances. An example of a successful scenario is shown in Figs 1 and 2. Fig 1 shows the system passing through the 3:2 e_{En} resonance but avoiding capture, contrary to [5]. The system then encounters the second-order 6:4 $e_{Mi}e_{En}$ resonance, which causes the eccentricities of both bodies to grow. Fig 2 shows the longer-term evolution of this system: the eccentricities grow to the equilibrium value determined by the Q and k_2 (second order Love number) of Saturn and satellites, but the libration angle continues to grow and eventually the resonance breaks. Dissipation in the satellites then damps the eccentricities, and the semi-major axis evolution continues allowing the present-day resonances to be established subsequently.

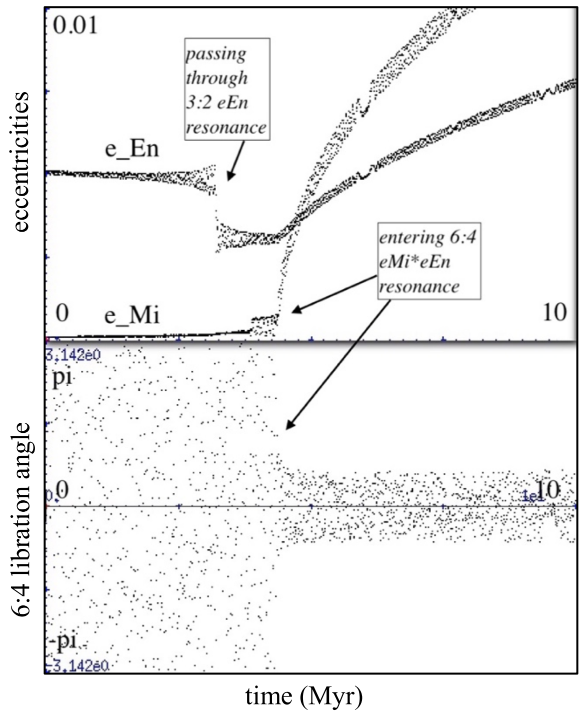

Fig.1 The system's passage through the 3:2 e_{En} resonance, and capture into the 6:4 $e_{Mi}e_{En}$ resonance. It is part of Fig.2. Q_{Saturn}=2000, $k_{2Saturn}$=0.341, k_2/Q_{Mi}=5.4x10^{-5}, k_2/Q_{En}=9x10^{-5}.

Interpretation: It was believed that the 3:2 e_{En} resonance either could not be avoided [5] or can be avoided with perturbation from Dione [10]. Instead, we find that Enceladus has some probability of naturally passing through the resonance if e_{En} is larger than 2.5x10^{-3} prior to encounter with this resonance. A reduced probability of capture into resonance at higher eccentricities is a common feature of such systems [11].

Implications/Future work: The equilibrium tidal heating for Mimas in Fig 2 is ~3 GW, or 6 mWm^{-2}. This rate of heating is consistent with the non-relaxation of Herschel. In this model, escape from the resonance has to have happened recently, since the eccentricity would rapidly damp to its present-day value. However, assuming a lower k_2/Q for Mimas would both increase the equilibrium eccentricity (without changing the heating rate) and slow the eccentricity damping.

Constraints on k_2/Q for these bodies provide information on their internal structures [12]. Since k_2/Q also determines the rate of eccentricity damping, these constraints also place limits on how recently the resonance could have been excited, and thus a lower bound on the age of Mimas.

We plan to vary k_2/Q and initial eccentricities for both Mimas and Enceladus, to map out the area of parameter space which is compatible with 1) passage through, or eventual escape from, the 3:2 and 6:4 resonance; 2) the present-day eccentricity of Mimas; and 3) the absence of relaxation of Herschel. Figs 1 and 2 provide an example of a scenario that satisfies these constraints; what remains is to determine how wide the acceptable parameter space is.

References: [1] Squyres et al. *Icarus* 1983 [2] Neveu and Rhoden, *Icarus* 2017 [3] Tajeddine et al. *Science* 2014 [4] Charnoz et al. *Icarus* 2011 [5] Meyer and Wisdom Icarus 2008 [6] Lainey et al. *Icarus* 2017 [7] Fuller et al. *MNRAS* 2016 [8] Nimmo et al. in Enceladus and the Icy Moons of Saturn, U. Az. Press, 2018 [9] White et al. *Icarus* 2017 [10] Cuk, El Moutamid, Tiscareno, Cassini science meeting, 2018 [11] Borderies & Goldreich, *Celest. Mech.* 1984 [12] Zhang & Nimmo, *Icarus* 2009.

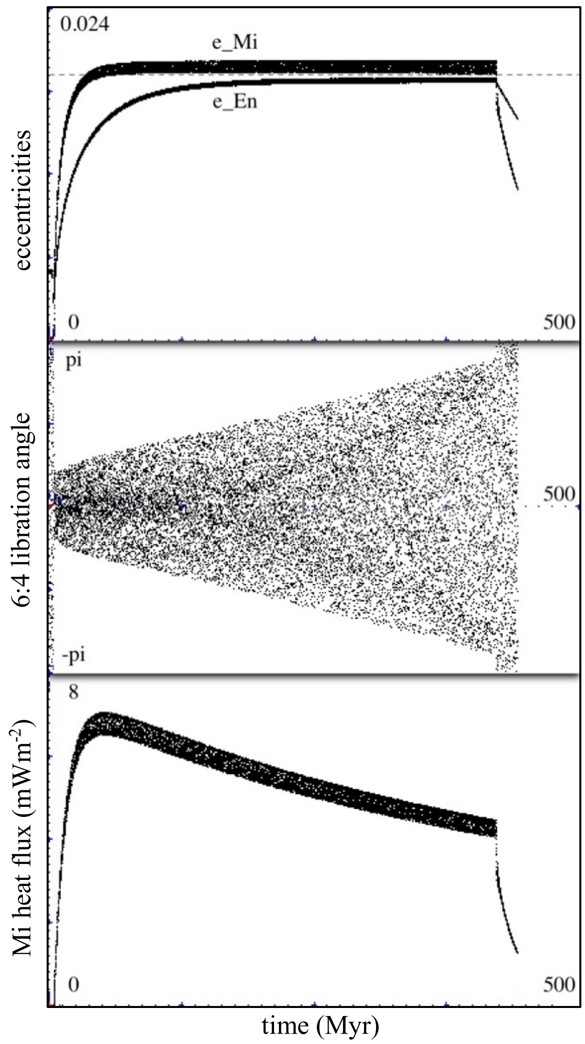

Fig. 2. The system's passage through the 6:4 $e_{Mi}e_{En}$ resonance. It is the same case as in Fig. 1. When the resonance angle reaches π, the system exits the resonance. It takes 20 Myr for e_{Mi} to decrease by 0.01 after the resonance. Dashed line: current e_{Mi} value. The heat flux in the bottom panel decreases with time because the semimajor axis of Mimas is increasing due to dissipation in Saturn.