TESTING TIDAL EVOLUTION OF ENCELADUS WITH N-BODY INTEGRATIONS. Z. Tian[1] and F. Nimmo[1], [1]University of California Santa Cruz (ztian13@ucsc.edu, fnimmo@es.ucsc.edu).

Introduction: The orbital evolution of Enceladus attracts attention because of the enigmatic origin of the satellite's thermal activity [1]. Meyer and Wisdom (MW) [2] investigated possible orbital histories of Saturnian satellites passing through mean-motion resonances (eccentricity type). The model is based on selecting the slow terms (resonance terms) out of the Fourier expansion of the disturbing function (mainly the interactions between the satellites), and adding these low-frequency components of the satellite-satellite interaction effects to unperturbed Kepler motions, together with perturbations from Saturn's oblate shape and the planet-satellite tides.

The model produces a rich variety of orbital behaviors. Starting from the current state, under the influence of the Enceladus-Dione 2:1 resonance, the eccentricity of Enceladus typically grows for some time, but finally goes to zero (exit of resonance) or librates about an equilibrium eccentricity in a limit cycle, or stays at an equilibrium, depending on the tidal parameters (Q and k_2 of Saturn, k_2/Q of Enceladus).

However, this model is limited to a precision of eccentricity squared (e^2). Even though terms up to e^3 are included in the disturbing function, the approximation of e_i with $\sqrt{(2\Sigma_i/L_i)}$ introduces error of e^3, and the tides are of order e^2. Such simplified models and full models may give different (though sometimes qualitatively similar) evolution results for reasons not fully understood (e.g., [3]). It is therefore worthwhile to explore the satellites' resonant evolution with an N-body scheme, in which all physical processes (potentially including inclination as well as eccentricity) are taken into account automatically.

Model: Our model is based on the N-body symplectic mapping method [4,5]. The Hamiltonian is separated into two solvable parts: H_0 includes the free Kepler motion of satellites and free rotation of Saturn and satellites, H_1 includes the perturbation on satellite orbits from other satellites, perturbation from Saturn's oblateness, and tidal perturbations. The integrator alternatively integrates the system state according to H_0 and H_1 for a short time step (1/20 of the shortest satellite orbital period) after one another. Lie-Poisson integrators [6] are used for the rigid body integrations (free rotations, spin-orbit interactions).

We use the full Darwin-Kaula formulation of tides [7] with a constant Q of Saturn. Tides are expanded in frequency, and the sign of phase lag (magnitude $1/Q$) depends on the specific frequencies.

Results: We first rebuld the simple model of MW using the disturbing function. The results agree well. Fig. 1 shows eccentricity e_0 (of Enceladus) *vs.* time, and the evolution on the h_0-k_0 plane for 3 Gyr.

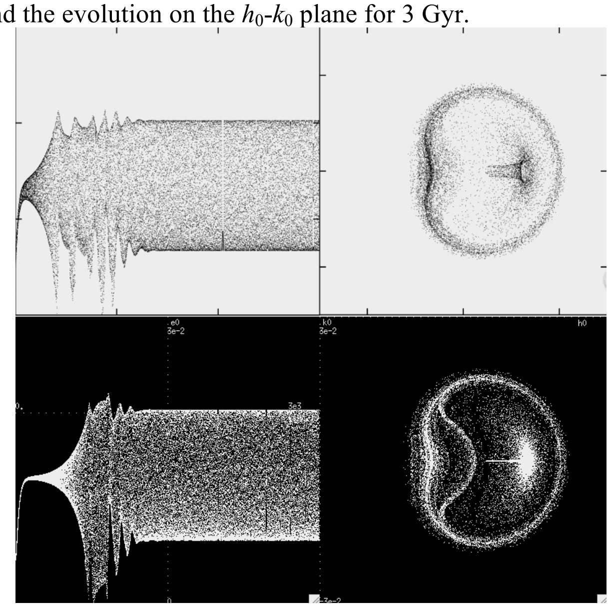

Fig. 1 Comparison of our simple model results (lower) with results from MW (upper). Left: e_0 *vs.* time, vertical range is 0 to 0.03, horizontal range is 0 to 3 Gyr; right: evolution on the h_0-k_0 plane. $(k_2/Q)_{En}=1.0e^{-4}$, and $k_{2S}=0.341$, $Q_S=18000$.

For the N-body model, integration is underway. Based on our limited initial results (Fig. 2 for the same tidal parameters), we expect the N-body integrations will produce qualitatively similar behaviors of Enceladus evolution, but with a different range of tidal parameters corresponding to the occurrence of each of the behaviors.

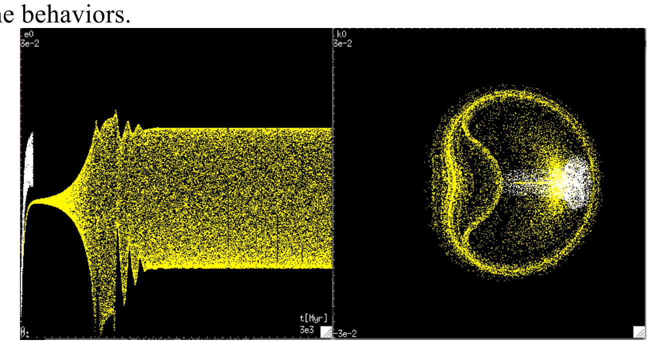

Fig. 2 Comparison of the N-body results (white) with our simple model results (yellow). Parameters are same as those in Fig. 1.

Once we have finished validating the N-body model, we will test whether certain resonances are prohibited (in the sense that they can't be escaped from) as argued by [8]. We will investigate the stability of resonances predicted to have occurred both from outwards satellite migration assuming a constant *Q* of Saturn, and 'resonance locking' outwards migration as advocated by [9]. Different resonances may be encountered in these two scenarios [1].

Ultimately, we will also build a coupled thermal-orbital model as previous authors have done (e.g. [10,11]) to see whether cyclical behavior - one of the possible explanations for the high heat flow of Enceladus - occur.

References: [1] Nimmo F. et al. in *Enceladus and the Icy Moons of Saturn,* U. Arizona Press, 2018. [2] Meyer J. and Wisdom J. (2008) *Icarus, 193,* 213–223. [3] Wisdom J. and Tian Z. (2015) *Icarus, 256,* 138-146. [4] Zhang K. and Nimmo F. (2009) *Icarus, 204,* 597-609. [5] Wisdom J. and Holman M. (1991) *Astro. J., 102,* 1528-1538. [6] Touma J. and Wisdom J. (1994) *Astro. J. 107,* 1189-1202. [7] Kaula W. (1964) *Rev. Geophy. 2,* 661-685. [8] Cuk M. et al. (2016) *Astrophs. J., 820,* 97. [9] Fuller J. et al. (2016) *MNRAS, 458,* 3867-3879. [10] Shoji et al. (2014) *Icarus, 235,* 75-85. [11] Ojakangas G. W. and Stevenson D. J. (1986) *Icarus, 66,* 341-358.