CYCLOIDAL AND WAVY LINEAMENTS ON EUROPA FROM DIURNAL, OBLIQUITY, AND NONSYNCHRONOUS ROTATION STRESSES IN A VISCO-ELASTIC ICE SHELL. R. T. Pappalardo[1], D. A. Patthoff[1], J. B. Li[1,2], B. J. Ayton[1,3], and D. Dubois[1,4]. [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA (Patthoff@jpl.nasa.gov), [2]Departments of Applied + Computational Mathematics and Computer Science, California Institute of Technology, Pasadena, CA, [3]Computer Science and Artificial Intelligence Laboratory, Massachusetts Institute of Technology, Cambridge, MA, [4]LATMOS, University of Versailles St. Quentin, Guyancourt, France.

Introduction: Jupiter's icy moon Europa displays a variety of lineament types ranging from arcuate to "wavy" to cycloidal. While some have suggested that cycloidal fractures form as a result of tail crack propagation in a rotating diurnal stress field [1-3], most previous studies have attributed the cycloidal shapes to the eccentricity (diurnal) tidal stresses that Europa experiences as it orbits Jupiter [4-6]. More recently, obliquity stresses have been explored as a mechanism for creating cyloids [7]. The stress resulting from eccentricity or obliquity tides is relatively small (10s kPa) and could combine with other stressing mechanisms, such as nonsynchronous rotation (NSR) [8-10].

Previous work has invoked simulations of diurnal and added obliquity stress to explain Europa's observed cycloidal lineaments. However, these models assumed an elastic ice shell, and neither of these two stress mechanisms alone can simulate Europa's wavy lineaments. Preliminary elastic-shell modeling [8,9] of diurnal stress and added NSR stress suggested that combining diurnal and NSR stress might be key to explaining "wavy" lineaments, as the NSR reduce the diurnal fluctuation of stress that results in cycloid cusps. Subsequently, it was found that small amounts of NSR stress might have contributed to the formation of cycloids but that significant NSR was not necessary to account for their planform shape [10].

Here we expand on previous elastic-shell modeling [8, 9] to demonstrate that NSR can combine with diurnal and obliquity stresses to create cycloidal lineaments or lineaments with a "wavy" planform, as simulated with the viscoelastic model SatStress [11]. These stress mechansims could combine to produce the observed range in planform morphology of Europa's lineaments, from cycloidal to wavy to arcuate.

Model: We employ an updated version of SatStressGUI [12] that assumes a four-layer visco elastic satellite. We assume an ice density of 920 kg/m^3 and an NSR period of either 3 Myr or 20 Myr. The remaining parameters are shown in Table 1. The resultant h_2 and k_2 Love numbers on the diurnal (for eccentricity or obliquity) and adopted NSR time scales are shown in Table 2.

The magnitude of diurnal and obliquity tidal stresses is controlled primarily by the thickness and viscosity of the lower ice layer, with a thicker and more viscous lower ice resulting in a smaller stress magnitude. For NSR, the magnitude of the simulated stress is chiefly dependent on the period of NSR and thickness and viscosity of the upper ice layer, such that a longer NSR period or a thicker ice shell with a low viscosity results in a smaller stress magnitude.

Cycloidal to wavy to arcuate lineaments: If only diurnal tidal stress, or obliquity plus diurnal tidal stresses, are considered, then cycloidal lineaments are formed in response the changing magnitude and direction of the resultant principal stresses, for an appropriate range of parameters (notably propagation speed, ~1–5 m/s). When NSR stress is added and is similar in magnitude to the diurnal or obliquity stress, the simulated propagating lineaments can be wavy in planform shape. As the magnitude of the NSR stress is increased such that NSR stress dominates over diurnal and obliquity stress, the simulated lineaments are generally arcuate, consistent with the findings of [8, 9].

The length of each cycloidal or arcuate segment is determined by the propagation speed. For the range of speeds that creates successful cycloidal lineaments (~1–5 m/s), a slower speed means that a shorter arcuate segment created each orbit.

This work is the first to consider the formation of cycloidal or wavy lineaments using a visco-elastic stress model. Future work will consider the quantitative fit of model cycloidal and wavy lineaments to Europa's actual lineaments, to better constrain the stress environment in which Europa's lineaments formed.

References: [1] Marshall & Kattenhorn (2005) *Icarus, 177*, 341-366. [2] Kattenhorn & Marshall (2006) *JSG 28*, 2204-2221. [3] Groenleer & Kattenhorn (2008) *Icarus, 193*, 158-181. [4] Hoppa et al. (1999) *Science*, *285*, 1899-1902. [5] Hoppa et al. (2001), *Icarus*, *153*, 208–213. [6] Greenberg et al. (2003), *Celestial Mech. Dynam. Astron., 87*, 171-188. [7] Rhoden et al. (2010) *Icarus, 210*, 770-784. [8] Crawford et al. (2005) *LPSC XXXVI*, abstract 2042. [9] Gleeson et al. (2005) LPSC XXXVI, abstract 2364. [10] Hurford et al. (2007) *Icarus, 186*, 218-233. [11] Wahr et al. (2009) *Icarus 200*, 188-206. [11] Patthoff et al. (2016) *LPSC XLVII*, this meeting.

Acknowledgements: We are grateful to the Europa Project (RTP), NASA's Postdoctoral Program (DAP), JPL's Student Undergraduate Research Fellowship

(JBL and BJA), and the French Ministry of National Education, Higher Education, and Research (DD). This work was was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

Table 1: Europa model parameters

Layer	Young's Modulus (Pa)	Poisson's Ratio	Thickness (km)	Viscosity (Pa s)
Upper ice	9.11E9	0.33	4	1E21
Lower ice	9.11E9	0.33	16	1E14
Ocean	0	0.0	80	0
Core	1E11	0.25	1460	1E25

Table 2: Calculated Love numbers for Europa's diurnal and adopted NSR periods

h_2 diurnal	k_2 diurnal	h_2 NSR 3 Myr	k_2 NSR 3 Myr	h_2 NSR 20 Myr	k_2 NSR 20 Myr
1.230	0.256	1.987	0.987	1.987	0.987

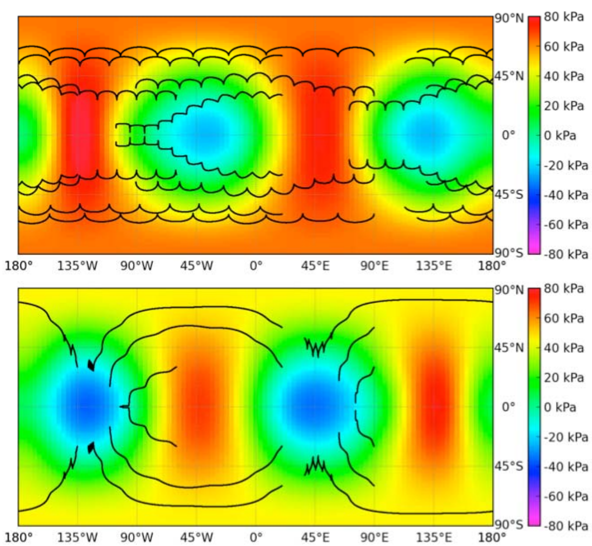

Fig. 1: *Top:* Diurnal (eccentricity) stresses can produce cycloidal lineaments when fractures propagate across Europa's surface, modeled using the viscoelastic model SatStressGUI. *Bottom:* When NSR stress of similar magnitude is added (here resulting from a 3 Myr NSR period), resultant lineaments are wavy in planform. For this and the other plots, fracture propagation is westward at 2 m/s from a variety of starting locations. The background color scale illustrate stress magnitudes for 90° past perijove with tension as positive, for these and the other plots.

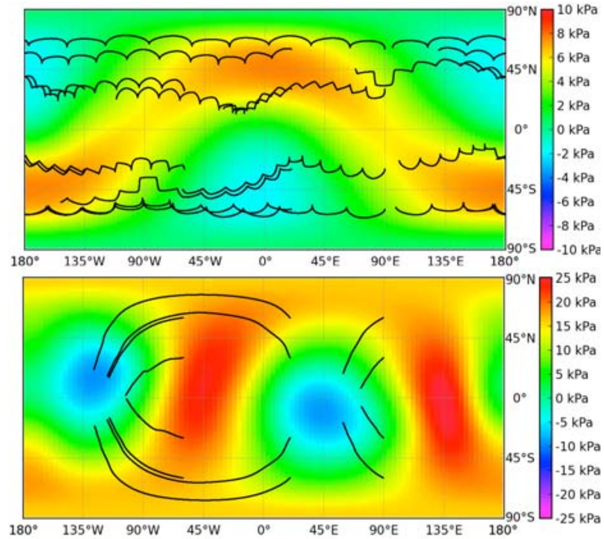

Fig. 2: *Top:* Representation of hypothetical Europa cycloidal lineaments generated by obliquity stresses only (with orbital eccentricity set to 0.001, to minimize diurnal stress), for an obliquity of 0.1° and an argument of pericenter of 0°. *Bottom:* Addition of NSR (here as resulting from a 20 Myr NSR period) can produce lineaments that are wavy in planform. Note the background color scales are different in magnitude from each other and from those of Figs. 1 and 3.

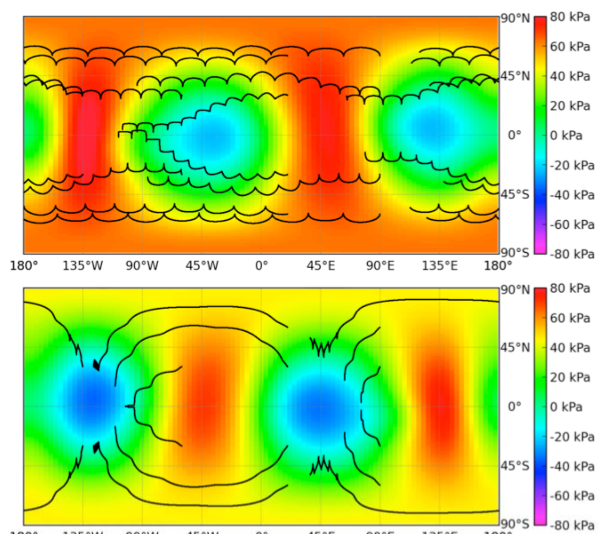

Fig. 3: *Top:* Diurnal stresses combined with obliquity stresses can produce cycloidal lineaments, with obliquity stress breaking the north-south symmetry of the other stress mechanisms (as recognized by [7,10]), and only subtley different from the diurnal-only case of Fig. 1. *Bottom:* When NSR stress of similar magnitude is added (here assuming a 3 Myr NSR period), wavy lineaments can be generated. For calculating the contribution from obliquity stress, we assume an obliquity of 0.1° and argument of pericenter of 0°.