Wavy Lineaments on Europa: Fracture Propagation into Combined Nonsynchronous and Diurnal Stress Fields. Zane Crawford[1], Robert T. Pappalardo[1], Amy C. Barr[1,2], Damhnait Gleeson[1], McCall Mullen[1], Francis Nimmo[3], Michelle M. Stempel[1,4], and John Wahr[5]; [1]Laboratory for Atmospheric and Space Physics and Center for Astrobiology, University of Colorado, Boulder, CO 80309-0392; [2]now at: Dept. of Earth and Planetary Sciences, Washington University, Saint Louis, MO 63130; [3]Dept. Earth Sciences, University of California Santa Cruz, CA 95064; [4]now at: Division of Geological and Planetary Sciences, Caltech 150-21, Pasadena, CA 91125; [5]Dept. of Physics, University of Colorado, Boulder, CO 80309-0390.

Summary: Understanding the processes that have operated on Europa and the manner in which they may have changed through time is fundamental to understanding the satellite's geology and present-day habitability. Previous studies have shown that lineament patterns on Europa can be explained by accumulation of tensile stress from slow nonsynchronous rotation (NSR) [1-7], while the cycloidal planforms of other Europan lineaments can be explained if fractures propagate through a diurnally changing tensile stress field [8-10]. We find that fractures propagated into combined diurnal and NSR stress fields can be "wavy" in planform for NSR stress accumulated over ~2 to 8° of ice shell rotation and average propagation speeds of ~1 to 3 m s^{-1}. The variety of Europa's observed lineament planforms from cycloidal, to wavy, to arcuate can be produced by accumulation of NSR stress relative to the diurnal stress field. Varying proportions of these stress mechanisms plausibly may be related to a time-variable (slowing) NSR rate.

NSR and Diurnal Stress Mechanisms: Europa's ice shell may rotate slightly faster than the tidally locked interior on a very long time scale (>10^4 yr period [11]). This NSR sets up a stress pattern that sweeps eastward across the surface over time, leaving a distinctive structural pattern in its wake [1-5]. NSR stress patterns may have swept across the surface of Europa by an uncertain amount [2-7,9].

Diurnal stress results from the raising and lowering of tides and libration as Europa orbits Jupiter each 3.55 days [7]. It has been suggested that diurnal stresses are responsible for Europa's unique cycloidal shaped lineaments and perhaps other cracks [8-10].

Candidate stress mechanisms can combine [5], but stress combinations and the effects on lineaments have not been much explored. Diurnal and NSR stresses are of similar ~100 kPa magnitude for ~1° of ice shell rotation. NSR stresses build near-linearly with the amount of ice shell rotation, swamping diurnal effects after ~10° of NSR.

Stress Modelling: To model stresses on Europa, we first determine Love numbers h_2 and l_2 (nominally 0.916 and 0.207, respectively) assuming a nominal internal structure [12] and any desired thickness of the ice shell (nominally ~20 km). The vector components of surface displacement are functions of the gravitational potential and the Love numbers. From these the strain tensor can be determined, when multiplied by the shear modulus (nominally 3.5 x 10^9 Pa) to produce the components of the stress tensor. This in turn diagonalized to obtain the eigenvectors and eigenvalues, which are the directions and magnitudes of the principal surface stresses.

There are two major differences between the "change in flattening" method used by others and our gravitational potential method. (1) The flattening method assumes a thin ice-shell which cannot support stresses, while we assume a finite thickness shell, which can support stresses and resist the hydrostatic deformation of the underlying ocean. (2) The flattening method assumes a homogeneous body, while we assume a realistic internal structure, which makes a non-trivial difference in the way that the potential is re-distributed when Europa deforms.

Combined NSR and Diurnal Stresses: It has been shown that slow propagation of fractures into a time-varying diurnal stress field can form fractures with a cycloidal planform, potentially explaining the origin of such structures on Europa [8-10]. We explore the implications of fracture propagation into a stress field that combines time-varying diurnal stress with greater magnitude static stress field from NSR. The NSR stress has the effect of swamping the time-varying diurnal stresses, effectively reducing the total stress trajectory variation during Europa's orbit.

When fractures are propagated into the diurnal plus nonsynchronous stress field at speeds of ~1 to 3 m s^{-1}, the resultant fractures transition from cycloidal (with ≤~2° NSR), to "wavy" (for ~2 to 8° NSR), to arcuate (>10° NSR) as nonsynchronous rotation stress builds and ultimately swamps diurnal stresses. The planform of wavy lineaments has a remarkable resemblance to specific lineaments on Europa, including Agenor Linea [13].

Combining diurnal and NSR stress has important implications for the formation of cycloidal structures [13]. Adding NSR alters the longitude of cycloid formation, affecting conclusions regarding their longitude of formation. Moreover, a component of NSR stress allows cycloids to terminate naturally, when they encounter equatorial compressive zones. Finally, addition of NSR stress allows Europa's ice strength to be greater than the very small 40 kPa value assumed in previous work [8-10].

Europa's Lineament Variety: It is curious how a single satellite can display features that combine different proportions of diurnal and nonsynchronous stress. It has been noted that cycloidal structures are generally observed higher in the stratigraphic column (more recently in Europa's preserved geological history), while older lineaments are more straight [14]. If this effect is real, it may imply a lessening of NSR stress, thus a predominance of diurnal stress, later in Europa's preserved history. It is plausible that this could be due to a slowing of NSR, as might result from thickening of Europa's ice shell [15].

Acknowledgements: This work is supported by the NASA Planetary Geology and Geophysics Program and the NASA Astrobiology Institute.

References: [1] Helfenstein and Parmentier, *Icarus*, 61, 175-184 (1985). [2] McEwen, *Nature*, 321, 49-51 (1986). [3] Leith and McKinnon, *Icarus*, 120, 387-398 (1996). [4] Geissler et al., *Nature*, 391, 368-370 (1998). [5] Figueredo and Greeley, *JGR*, 105, 22,629-22,646 (2000). [6] Kattenhorn, *Icarus*, 157, 490-506 (2002). [7] Greenberg et al., *Icarus*, 135, 6 4-78 (1998). [8] Hoppa et al., *Science*, 285, 5435 (1999). [9] Hoppa et al., *Icarus*, 153, 208–213 (2001). [10] Greenberg et al., *Celestial Mech. Dynam. Astronom.*, 87, 171-188 (2003). [11] Hoppa et al., *Icarus*, 137, 341-347 (1999). [12] Anderson et al., *Science*, 281, 2019-2022 (1998). [13] Gleeson et al., *this conference*. [14] Figueredo and Greeley, *Icarus*, 167, 287-312 (2004). [15] Ojakangas and Stevenson, Icarus, 81, 220-241 (1989).

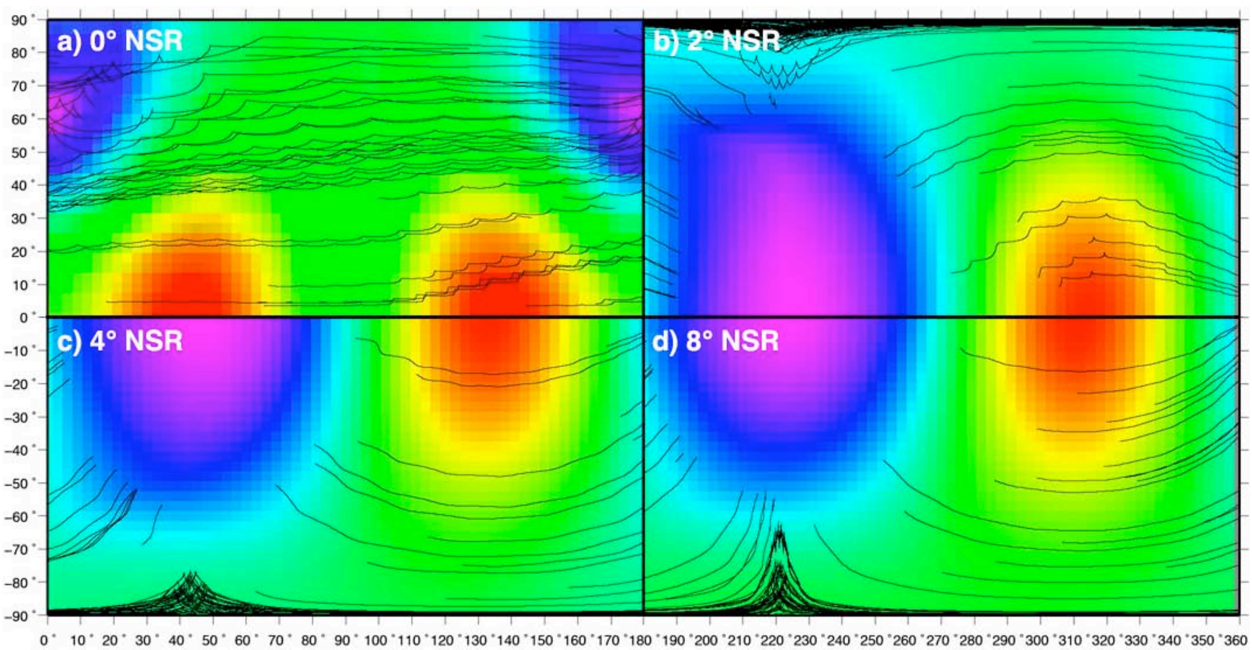

Figure 1. Quadrants of Europa's surface showing lineaments propagated at 1 m s^{1} into time-varying stress fields, generated from random starting points. In each case, crack initiation strength is 75 kPa and crack propagation strength is 25 kPa. Colored backgrounds indicate the maximum principal tensile stress achieved in each case throughout Europa's orbit (tension positive), with violet indicating least tensile and red indicating greatest tensile principal stress (scaled differently for each case). a) Diurnal-only stresses (0° NSR) generate structures with cycloidal planforms (maximum tensile stress varies from approx. 45 to 165 kPa). b) 2° NSR stress added to the diurnal stress field generates lineaments that resemble cycloids, but with rounded cusps (approx. –30 to 370 kPa). c) 4° NSR stress added to the diurnal stress field generates lineaments that are wavy in planform (approx. –160 to 550 kPa). d) 8° NSR stress added to the diurnal stress field generates arcuate lineaments that show little effect of the time-varying diurnal stress field (approx. –420 to 960 kPa).