Wavy and Cycloidal Lineament Formation on Europa from Combined Diurnal and Nonsynchronous Stresses. Damhnait Gleeson[1], Zane Crawford[1], Amy C. Barr[1,2], McCall Mullen[1], Robert T. Pappalardo[1], Louise M. Prockter[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]Applied Physics Laboratory, MP3-E128, 11100 Johns Hopkins University, Laurel, MD 20723; [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.

Introduction: In a companion abstract, we show that fractures propagated into combined diurnal and nonsynchronous rotation (NSR) stress fields can be cycloidal, "wavy," or arcuate in planform as the relative proportion of NSR stress in increased [1]. These transitions occur as NSR stress accumulates over ~0° to 10° of ice shell rotation, for average fracture propagation speeds of ~ 1 to 3 m s^{-1}. Here we consider the NSR–speed parameter space for these morphological transitions, and explore the effects on cycloids of adding NSR to diurnal stress. Fitting individual Europan lineaments can constrain the combined NSR plus diurnal stress field at the time of formation.

Lineament Transitions: Diurnal and NSR stresses are of similar ~100 kPa magnitude for ~1° of ice shell NSR, with NSR stresses building near-linearly with the amount of ice shell rotation and swamping diurnal effects after ~10° of rotation. When fractures propagate into diurnal plus NSR stress field at speeds of ~ 1 to 3 m s^{-1}, the resultant fractures transition from cycloidal through "wavy" to arcuate planforms as NSR stress builds and ultimately swamps diurnal stresses.

In our generalized lineament synthesis tool, parameters which can be varied to change the resulting lineaments include: the starting location, propagation direction, crack propagation speed, crack initiation strength (i.e. ice tensile strength), stress for crack propagation, and amount of NSR that contributes to the overall stress field. Moreover, we can vary the assumed Love numbers describing Europa's internal structure, from which the stress field is derived.

Here we consider variations in both NSR and propagation speed, the two parameters which most affect lineament morphology. We consider a nominal Europa internal structure (Love numbers h_2 = 0.916 and l_2 = 0.207, and rigidity μ = 3.5 x 10^9 Pa), and we choose a crack initiation strength of 75 kPa and propagation strength of 25 kPa.

Figure 1 illustrates the transitions among cycloidal, wavy, and arcuate lineament morphologies (subjective determinations). Distinctive wavy and cycloidal morphologies can be produced for propagation speeds ~1 to 3 m s^{-1} (depending on the amount of NSR), while lower and higher propagation speeds are not properly in synch with the changing diurnal stress component, which is necessary to permit their formation. The transition from cycloidal to wavy structures (where cycloid cusps become rounded) occurs over a narrow range of NSR ~2°, nearly independent of propagation speed. In contrast, the transition from wavy to arcuate lineaments occurs over about a 3° range of NSR, and at higher NSR for lower propagation speeds (~6 to 9° NSR for 1 m s^{-1}) than at higher speed (~2 to 5° NSR for 3 m s^{-1}).

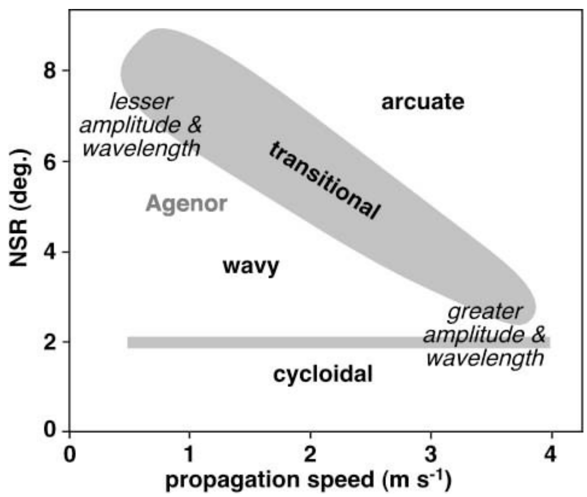

Figure 1. Lineament transitions on Europa as a function of NSR and crack propagation speed.

For cycloidal and wavy lineaments, their wavelength and amplitude (superimposed on overall lineament curvature) increase together as NSR decreases and propagation speed increases (i.e., moving from the upper left to lower right of Figure 1). Thus, there is the prospect that fitting model structures to individual Europan lineaments can constrain the average propagation speed of cracking that initiated the structures, and the stress field in which the lineaments formed.

Agenor Linea, which shows a wavy planform, is a remarkable match to fracture propagation in a combined NSR plus diurnal stress field (Figure 2). Agenor appears to be consistent with formation at ~1 m s^{-1} in a stress field of diurnal plus NSR ~5°. The beginning and ending points of Agenor and its overall curvature suggest it formed close to its current latitude-longitude position on Europa.

Effects on Cycloids: Combining NSR and diurnal stress has important implications for the formation of cycloidal structures. Here we discuss the effects of parameter variation on cycloid planform, some of which have been explored previously for the diurnal-only case [2-4].

We find that adding NSR stress shifts the longitude of cycloid formation compared to diurnal stresses alone. Because a cycloid chain tends to propagate on average in the direction perpendicular to the greatest tensile stress, they will deviate around the large equatorial tensile zones of stress induced by NSR. If the amount of NSR stress is varied, the location of these tensile zones is changed relative to a fixed point of cycloid origin. Similarly, if the cycloid longitude of formation is varied, then its different location relative to these equatorial tensile zones changes, changing the cycloid's overall trajectory.

In the presence of only diurnal stresses, if initiation and propagation strengths are set appropriately to reproduce the curvature of individual cycloidal arcs, the crack generally will be active for too wide a range of stresses to terminate on its own, and cycloids will propagate infinitely around Europa. Adding NSR stress allows cycloids to terminate naturally, by creating large equatorial compressional stress zones that shut down cycloid propagation.

For a given starting location, changing the direction of propagation (east vs. west) changes the cusp direction of a cycloid. East creates cusps pointing poleward, west creates equatorward cusps.

The directions of stresses in the high latitudes vary much more significantly than those near the equatorial regions. Thus, cycloids which form in high latitudes are usually more "bulbous" with an arc representing a variety of different stress directions. Cycloids near the equator tend to be stair-stepped, because the most significant variation in the stresses there are that the E-W stress and the N-S stress alternate in having the greater magnitude. Cycloids observed near Europa’s subjovian point could not have formed there, suggesting polar wander.

The crack propagation speed determines the overall scale of a cycloid. The faster it propagates, the larger the cycloid. Propagation speed also affects overall shape, because with a larger footprint, the cycloid can be deflected by stresses that it would not have otherwise encountered.

Crack initiation strength (here 75 kPa) and propagation strength (here 25 kPa) determine when in the course of a day the cycloid will initiate and terminate. If a cycloid propagates for a relatively large portion of the day, it will experience a larger variation in stress direction, and so each arc will be more curved. If the cycloid propagates only when the stress nears its maximum, it traces a nearly straight line, as the variation in stress direction is very small.

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

References: [1] Crawford et al., *this conference*. [2] Hoppa et al., *Science*, 285, 5435 (1999). [3] Hoppa et al., *Icarus*, 153, 208–213 (2001). [4] Greenberg et al., *Celestial Mech. Dynam. Astronom.*, 87, 171-188 (2003).

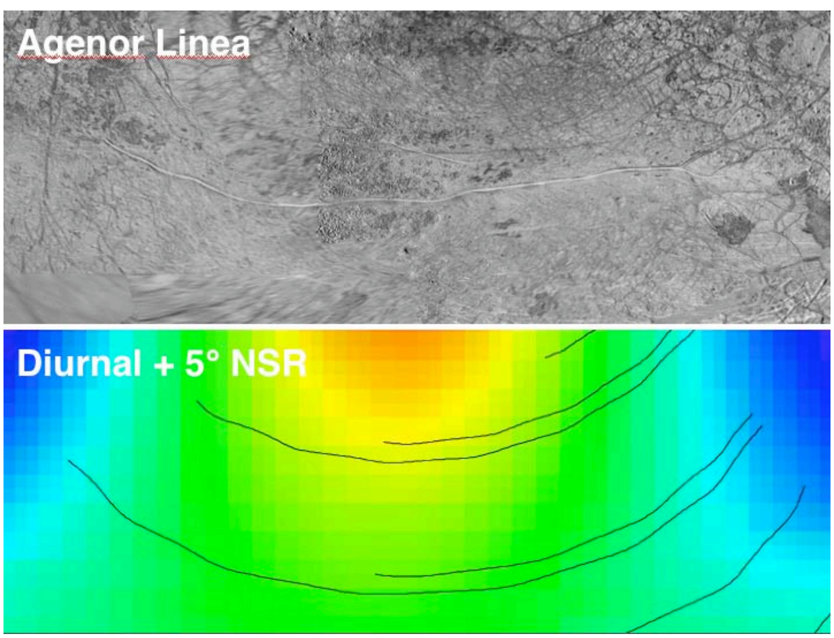

Figure 2. The bright arcuate lineament Agenor Linea, compared to the planform produced by propagation of a fracture at 1 m s^{-1} into a combined stress field of 5° NSR of Europa's ice shell as modulated by diurnal stresses. Colored background indicates the maximum principal tensile stress achieved throughout Europa's orbit, with orange indicating ~540 kPa of tensile stress, and deep blue indicating ~0 kPa of tensile stress (i.e., tensile stress from diurnal stressing is counteracted here by NSR compressive stress). Simple cylindrical projections.