Implications for Europa's Obliquity from Cycloid Modeling. A. R. Sarid-Rhoden[1], B. Militzer[1], E.M. Huff[2], T.A. Hurford[3], M. Manga[1], and M. Richards[1]; [1]University of California at Berkeley, Department of Earth & Planetary Science, Berkeley, CA 94720; Lawrence Berkeley National Lab, 1 Cyclotron Rd, Berkeley, CA 94720; [3] NASA Goddard Space Flight Center, Code 693, Greenbelt, MD 20771.

Introduction: It has been proposed that cycloids are cracks that form in response to tidal stress on Europa, which varies throughout each orbit due to Europa's eccentricity [1][2]. A substantial obliquity would alter this pattern of tidal stress [3] and could thus be constrained through cycloid modeling. Considerations of tidal dissipation indicated that Europa's obliquity should be insignificant [4], but interactions among Jupiter's largest satellites may force Europa's obliquity to be larger than expected [5]. If Europa acts as a solid body, its obliquity should be ~0.1°; a mechanically decoupled ice shell could result in an obliquity that is several times larger. In addition, the obliquity will change on geologically relevant timescales: 10-1000yr, and the spin pole direction can change by as much as 2°/day [6].

Using an eccentricity-only model, several authors have obtained fits to cycloids in Europa's southern hemisphere. The fits by Hoppa et al. [1] captured the general trend of each cycloid, but the fits worsened with each additional arc and did not fit the cusp locations well. Hurford et al. [2] used a different set of mechanical parameters for each arc of a cycloid, improving fits but requiring many more free parameters. In addition, they found that stress due to non-synchronous rotation (NSR) improved fits. In both studies, the formation longitude of the cycloid was used as a fit parameter because observed cycloids could not be fit at their current locations; the misfit in longitude is likely the result of NSR, which would move features eastward over time.

Despite the successes of cycloid modeling in the southern hemisphere, the eccentricity-only model fails to reproduce observed equator-crossing cycloids because the stress field is symmetric across the equator. In addition, the eccentricity-only model produces cycloids in the equatorial region that are much more angular than observed cycloids. Obliquity causes the tidal bulge to librate in latitude, perhaps enabling the formation of equator-crossing cycloids [3]. In this work, we include obliquity in calculations of the tidal stress field and apply this tidal model to the formation of cycloids.

Methods: We used the thin shell equations, altered to account for obliquity, to calculate tidal stress [e.g. 2]. We assumed that cycloids form in response to the changing stress field in the following way. First, the tensile stress increases beyond the failure threshold of the ice, creating a crack perpendicular to the direction of maximum tension. As the stress field changes in magnitude and direction, the crack propagates along an arcuate path, following the maximum tensile stress direction. When the stress falls below the propagation threshold, the crack becomes dormant. The stress field continues to change such that, when cracking reinitiates, the crack propagates in a different direction, creating a cusp. This is the physical model used in previous cycloid modeling studies [1][2].

Our combined physical and tidal model contains six free parameters: obliquity, spin pole direction, starting longitude, time since pericenter passage (a proxy for starting stress), stopping stress, and speed. The parameters are constant for all arcs of a cycloid. Since we are most concerned with identifying the signal of obliquity, we did not include stress from non-synchronous rotation. However, allowing the starting longitude to vary does account for possible eastward rotation. It is plausible that non-synchronous rotation occurs, but it is so slow that the stress is viscously relaxed and does not contribute to surface stress [1].

In order to identify good fits to observed cycloids, we have combined several numerical techniques, which we use to search the parameter space. These techniques rely on a quantitative measure of goodness-of-fit when evaluating model cycloids. In the past, the parameter space was searched "by hand" and fits were subjectively evaluated.

Results: Our fits are much improved over those of Hoppa et al. [1]. They are almost as good as the fits of Hurford et al. [2] and with far fewer free parameters, since we held the parameters constant for all arcs of a cycloid. We have also obtained fits to equatorial cycloids. Our work has shown that good fits require obliquity but not stress from NSR. However, as we could not fit cycloids at their current longitudes, eastward rotation of the ice shell is still implied. Our fits indicate a variable obliquity, which is consistent with a mechanically decoupled ice shell [6].

References: [1] Hoppa, G.V. et al. (2001) *Icarus, 153*, 208-213. [2] Hurford, T.A. et al. (2007) *Icarus, 186*, 218-233. [3] Hurford, T.A. et al. (2006) *LPSC XXXVII*, Abstract #1303. [4] Peale, S.J. (1999) *Ann. Rev. of Astro. & Astrophy. 37*, 533-602. [5] Bills, B.G. (2005) *Icarus, 175*, 233-247. [6] Bills, B.G. et al. (2009) In: *Europa*, W. McKinnon (ed.), in press.