The Influence of Obliquity on Europan Cycloid Formation

T.A. Hurford [a,*], A.R. Sarid [b], R. Greenberg [c], B.G. Bills [d,e]

[a] *Planetary Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771*

[b] *Department of Earth and Planetary Science, University of California: Berkeley, Berkeley, CA 94720*

[c] *Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721*

[d] *Jet Propulsion Laboratory, Pasadena, CA 90119*

[e] *Institute for Geophysics and Planetary Physics, Scripps Institution of Oceanography, La Jolla, CA 92093*

Abstract

Tectonic patterns on Europa are influenced by tidal stress. An important well-recognized component is associated with the orbital eccentricity, which produces a diurnally varying stress as Jupiter's apparent position in Europa's sky oscillates in longitude. Cycloidal lineaments seem to have formed as cracks propagated in this diurnally varying stress field. Maps of theoretical cycloid patterns capture many of the characteristics of the observed distribution on Europa. However, a few details of the observed cycloid distribution have not been reproduced by previous models. Recently, it has been shown that Europa has a finite forced obliquity, so Jupiter's apparent position in Europa's sky will also oscillate in latitude. We explore this new type of diurnal effect on cycloid formation. We find that stress from obliquity may be the key to explaining several characteristics of observed cycloids such as the shape of equator-crossing cycloids and the shift in the crack patterns in the Argadnel Regio region. All of these improvements of the fit between observation and theory seem to require Jupiter crossing Europa's equatorial plane 45° to 180° after perijove passage, suggestive of complex orbital dynamics that lock the direction of Europa's pericenter with the direction of the ascending node at the time these cracks were formed.

Key words: Europa, Cycloids, Tectonics, Obliquity

1 Introduction

After the Voyager spacecraft revealed cycloids in the limited area it imaged, the formation of cycloids remained unexplained until Hoppa and Tufts (1999) proposed that cycloidal cracks form as a result of tensile cracking in response to diurnally varying tidal stresses produced by Europa's orbital eccentricity. In their model, cycloid-shaped cracks form in the following way: When the tensile strength of ice is reached, a crack forms perpendicular to the local direction of the tensile stress and begins to propagate across the surface. Because diurnal tidal stress changes in both magnitude and orientation, cracks propagate across an ever-changing stress field. Thus, propagation can follow a curving path until it reaches a place and time where the tensile stress is insufficient to continue the propagation. The propagation remains dormant until later in the orbit, when the stress at the end of the crack once again exceeds the ice strength. At that time, propagation continues in a direction perpendicular to the new orientation of tensile stress. The shape of the crack

* terry.a.hurford@nasa.gov (Terry A. Hurford)

2 The Global Picture of Cycloid Formation

2.1 Comparison of theoretical models with observation: zero obliquity

Fig. 1 shows maps of idealized cycloids that would form at locations across Europa's surface, assuming only diurnal stress variations caused by the eccentricity. The crack shapes shown are those that propagate from initial crack sites at various locations, selected at intervals of 15° in longitude and at 10° intervals in latitude between 10° and 70° in the north and south. We also model cycloids that form at 5° latitude both north and south of the equator. Fig. 1a shows crack patterns assuming a net westward component of propagation, while Fig. 1b assumes the net sense of propagation is towards the east. The cracking patterns depend on the rate of crack propagation and the assumed ice strength values (the tension required to start and maintain crack propagation). Here we use parameters similar to those inferred from fitting cycloids in the southern hemisphere (Hurford *et al.*, 2007). Specifically, the initiation stress is 68 kPa, the propagation strength is 38 kPa and the effective propagation speed is 4.8 km/hr. The crack maps in Fig. 1 are idealized, of course, because details of the local parameters controlling crack propagation may influence a specific cycloid's development.

For comparison, Fig. 2 shows mapped cycloids actually observed on Europa. Bart *et al.* (2003) and Greenberg *et al.* (2003) noted that hypothetical modeled cycloids reproduce many of the characteristics of observed cycloids: (1) The long east-west trending cycloids observed in the southern, mid-latitudes near longitude 180° (Fig. 2) are similar to hypothetical cycloids at the same latitudes, albeit not the same longitudes (Fig. 1a&b). In fact, these include the

cycloids modeled by Hoppa *et al.* (2001) and Hurford *et al.* (2007). (2) Long east-west trending cycloid chains run just north and south of the equator in Fig. 1, as observed near 0° and 180° in Fig. 2. Such cycloids are prominent near 0° and 180° in Fig. 2 and are not seen at other longitudes because image resolution or coverage is inadequate or cycloid features have been disrupted by chaotic terrain. (3) Near 90° longitude in the far north (Fig. 2) are cycloids with north-south orientations. Like the ones in the hypothetical map (Fig. 1), they tend to be relatively short and are located far from the equator. (4) The formation of angular or "boxy" crack patterns observed near the equator (Fig. 2) is similar to the model cracks in Fig. 1 in this region. These observed "boxy" cycloids lie in Argadnel Regio (often called the "Wedges" region), which is located just south of the equator and west of 180° longitude. The cracks in this region, besides demonstrating the boxy cycloid shapes, are often dilated into wedge shapes. Similar crack patterns diametrically opposite (in the northern hemisphere near 0° in longitude) have been noted (Greenberg *et al.*, 2003; Greenberg, 2005), but there they have not been modified by dilation.

Besides matching the general characteristics of observed cycloids, maps of idealized cycloids might match patterns observed in cycloid distributions. (A) In Fig. 1 small zones in which no cycloids form are predicted near 0° and 180° longitude. In these zones the maximum tensile stress never reaches a level high enough to initiate crack formation, thus no cycloids originate from these regions. (B) Cycloid patterns in the northern and southern hemisphere are symmetric. In fact, the pattern in each hemisphere is a mirror image of the other, reflected about the equator.

eling cycloids with the inclusion of non-synchronous rotation still produces zones in which no cycloids form near 0° and 180° longitude but the size of these zone increase and their centers shift eastward from 180°. However, with the reorientation of the surface through non-synchronous rotation, these zones where cycloids fail to form may not be preserved in the observed cycloid distribution. Most importantly, the distribution of idealized cycloids maintains the symmetry between the northern and southern hemisphere. Since idealized cycloids that formed with the stress from non-synchronous rotation included reproduce the overall characteristics of the observed cycloids, which were also reproduced by the diurnal stresses alone and fail to reconcile the detailed mismatch between the idealized and observed distribution, we will exclude the effect of stress from non-synchronous rotation on cycloid growth patterns in this paper.

Similarly, a small amount of reorientation by polar wander may account for the mismatch between the model and the observations of cracks. Sarid *et al.* (2002) found a mismatch between the model of strike-slip displacement and observations strike-slip displacement, which they attributed to polar wander of Europa's ice shell. However, polar wander of the type they describe would have shifted the Argadnel Regio region north after its formation, implying that it formed even further south of its current location, enhancing the asymmetry across the equator.

In summary, the main disagreement is that the observations do not fit the predicted symmetry across the equator: Cycloids that cross the equator are not symmetrical, and the "boxy" cracks just west of 180° are south of the equator, while those just west of 0° are north of the equator.

3 Obliquity and Cycloid Modeling

The key to modeling the observed characteristics that do not fit the previous model (Fig. 1) may be the satellite's obliquity, ε. If Europa's orbital plane were fixed in orientation, then tidal damping would have rapidly removed any initial obliquity (Peale, 1974; Gladman *et al.*, 1996). However, the orbit plane is not fixed, but precesses about an axis very close to Jupiter's spin axis. This precession is mainly caused by torques from Jupiter's oblate figure, but also has contributions from interactions with Io, Ganymede, and Callisto (Lieske, 1998).

As a result of the orbital precession, the configuration to which the spin pole is driven by tidal damping is not one of zero obliquity. Instead, as for the Moon, the obliquity adjusts to a value such that the spin pole, orbit pole, and local invariable pole all remain coplanar. Such configurations have been called generalized Cassini states (Colombo, 1966; Peale, 1969; Ward, 1975), because they are similar to behavior of the Moon, as first enunciated by G.D. Cassini in 1693.

If the orbit precession is steady, as assumed by Bills and Ray (2000) in their analysis of obliquity for the Galilean satellites, then obliquities would be tidally damped to constant, non-zero values. If the orbit-plane precession rate is periodically modulated by interactions among the neighboring satellites, then the tidally damped obliquities will correspondingly fluctuate (Ward and de Campli, 1979; Bills, 2005). Given that effect, Europa's mean obliquity is close to 0.1°, and oscillates by roughly 10%, with dominant periods of decades to centuries. On still longer time scales ($> 10^4$ years) the eccentricity and inclichanges in a and θ while the obliquity causes changes only in θ. Jupiter's angular position with respect to a fixed location above Europa's surface oscillates with an amplitude of $2e$ east and west and ε north and south, changing slightly the angular distance to the tidal bulge θ. The change in θ plus daily changes in a combine, yielding the diurnally varying part of the tide, producing elastic stress on the surface (See Appendix A).

For a water-ice crust, following Hoppa *et al.* (1999b, 2001) we use the conventional values of the elastic parameters $\mu = 3.52\text{x}10^9$ Pa and $\nu = 0.33$ (Gammon *et al.*, 1983), and assume a tidal response given by $h_2 = 1.275$, which corresponds to a diurnal tidal amplitude of changes in the radius of ~ 30 m. The coefficient $3M/8\pi\rho_{av}a^3$ is approximately $2.5\text{x}10^{-4}$.

To simulate the formation of a cycloidal crack at a given location, our model also requires values for: the effective rate of crack propagation, which largely governs length and curvature of the arcs; the sense (eastward or westward) of the propagation, which determines the direction of curvature of each arc; the crack initiation strength (the tension required to initiate cracking); and the crack propagation strength (the tension below which the crack propagation halts). For the various cases described below, we specify the values adopted for each of these parameters.

4 Effects of Obliquity on Cycloids

4.1 Fitting Global Cycloid Patterns

Figs. 8 and 9 show hypothetical cycloids formed when 0.1° of obliquity is added to the model using an initiation stress of 68 kPa, a propagation strength of 38 kPa and an effective propagation speed of 4.8 km/hr (all typical parameter choices that give generally resonable agreement with observed cycloid shapes). Figs. 8 and 9 assume westward and eastward propagation, respectively. As shown in the separate parts of Figs. 8 and 9, the pattern depends on where in the orbit, relative to perijove, Jupiter crosses Europa's equator (or equivalently, the angle from the ascending node to the position of pericenter, known in celestial mechanics as argument of pericenter, ω). For example, Fig. 8b shows the hypothetical cycloid pattern when Jupiter crosses Europa's equator 1/8 of an orbit after perijove (i.e. when $\omega = 315°$), and so forth.

An obliquity of 0.1° is enough to break the equatorial symmetry seen in Fig 1. For example, in Fig. 8a and Fig. 9a, when the argument of pericenter is zero, "boxy" cycloids just west of 0° longitude are shifted southward while 180° away they are shifted northward. Moreover, some cycloids propagate across the equator.

Depending on the argument of pericenter, ω, the shift in the hypothetical cycloid pattern changes. With $\omega = 0°$ (Fig. 8a), cycloid patterns near the equator around 30° longitude are shifted south $\sim 6°$, but with $\omega = 315°$ (Fig. 8b) cycloids in at this same region are shifted north by $\sim 4°$ in latitude. With $\omega = 270°$ and 225° (Fig. 8c & d), these cycloids are shifted even farther modeling the formation of cycloids can still uniquely constrain formation longitudes. As long as the location of cycloids have been moved in longitude only since their formation, preserving their formation orientations, fits are unique as statistically significant.

5 Discussion

We have shown the effects of obliquity on the formation of hypothetical cycloids on Europa. Obliquity introduces a component of stress due to the daily migration of the tidal bulge in latitude, breaking the symmetry in idealized crack patterns about the equator. These effects may account for many of the previously unexplained characteristics of the observed cycloid pattern on Europa's surface: Cycloids that cross the equator are not symmetrical, and the "boxy" cracks just west of 180° are south of the equator, while those just west of 0° are north of the equator.

Adding obliquity results in cycloids propagating across the equator without changing their eastward or westward sense of propagation, now explaining how such observed cycloids can form. The model now predicts long chains of equator-crossing cycloids near the same longitudes as the "boxy" patterns. It is, in fact, the north-south shifting of these regions that give rise to the cycloids that cross the equator. Observations of equator-crossing cycloids match such concentrations, near the Argadnel Regio region and 180° in longitude away.

"Boxy" or angular cycloids resemble the observed crack pattern in the Argadnel Regio region, west of the subjovian point (near 210° longitude) (Bart *et al.*, 2003). Without obliquity, models produce such shapes at this longitude.

but they predict a symmetry about the equator. However, observed features are concentrated south of the equator and centered around a latitude of 5°S. Maybe the conditions needed to form angular cycloids north of the equator did not exist when cycloids in this region formed, naturally producing the observed asymmetry, but the addition of the stress from the obliquity into the model of cycloid formation leads to an asymmetry about the equator which can explain the observed asymmetry. A tenth of a degree of obliquity, the amount estimated by Bills (2005), is adequate to shift the center of the stair-shaped cycloids south by at least 5° in the Argadnel Regio region, if these cracks formed when the argument of pericenter, ω was between 180° and 315°. Larger amounts of obliquity would produce larger shifts in latitude.

Moreover, angular cycloids in the Argadnel Regio region have prominent segments with orientations that are north-east/south-west or north-west/south-east. However, cycloid formation models without obliquity would produce angular cycloid with north-west/south-east orientation south of the equator. The asymmetry introduced by the inclusion of stress from obliquity in the model of cycloid formation also allows angular cracks with north-east/south-west orientations to be produced south of the equator. Thus, more completely reproducing the angular cycloids observed in the Argadnel Regio region.

As we have shown, the shift in the cycloid pattern can be to the north or the south depending on when in the orbit Jupiter crosses Europa's equator. Formation of the crack pattern in the Argadnel Regio region, being south of the equator, would require the argument of pericenter to be between 180° and 315°. Similarly, the "boxy" cycloids in the northern hemisphere near 0° longitude would also require the argument of pericenter to be between 180° and 315°. Moreover, equator-crossing cycloids between 0° and 30° longitude specific cycloids may be able to place a more precise upper limit to the size of Europa's obliquity (Sarid *et al.*, 2006).

Hoppa *et al.* (1999a) generated predictions of the sense of strike-slip motion on Europa's surface (i.e. left-lateral versus right-lateral), using the surface stress due to diurnal variations in stress produced by Europa's eccentricity. In order to compare Hoppa's model to observations, Sarid *et al.* (2002) produced maps of the observed strike-slip motion seen along Europan ridges, and attributed mismatch between the model and observations to polar wander. That work should now be revisited, taking into account the effects of obliquity, which may be an alternative way to match the model and observations.

Recent additions to cycloid formation models focus on cycloid cusps (Groenleer and Kattenhorn, 2008). In these models normal and shear stresses are resolved onto the tip of the cycloidal crack while it remains dormant. Shear motion at a critical point in the orbit leads to the formation of a tailcrack which propagates away from the cusp to become the next arc in the cycloid chain. Cusp angles will be affected by the ratio of shear to normal stress needed to produce the next arcuate segment and will subtly affect characteristics of the cycloid. However, these additions can not explain the formation of equator crossing cycloids (Fig. 5).

6 Conclusions

Europa's obliquity may have played a substantial role in defining crack patterns. The observed north-south asymmetry of cycloids may be evidence for the small but finite obliquity of Europa predicted by Bills (2005). Obliquity

may be the key to producing aspects of the observed cycloid distribution such as equator-crossing cycloids and an asymmetry in the "boxy" patterns. All of these improvements of the fit between observation and theory seem to require that the argument of pericenter was between 180° and 345° at the time of crack formation, suggestive of complex dynamics, such as a linkage between the ascending node and the orbital resonance. Future modeling of cracks should not assume that the obliquity is zero or has no effect on tectonic formation: While much more work is needed to understand the role of obliquity in the tectonics, we have shown that it was probably strong enough to be included in cycloid and stress models.

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$$\sigma_{xx}(t) = \frac{1}{2}(\sigma_{\phi\phi}(t) + \sigma_{\theta\theta}(t)) - \frac{1}{2}(\sigma_{\phi\phi}(t) - \sigma_{\theta\theta}(t)) \cos 2\beta(t), \text{ and} \tag{12}$$

$$\sigma_{yy}(t) = \frac{1}{2}(\sigma_{\phi\phi}(t) + \sigma_{\theta\theta}(t)) + \frac{1}{2}(\sigma_{\phi\phi}(t) - \sigma_{\theta\theta}(t)) \cos 2\beta(t), \tag{13}$$

$$\sigma_{xy}(t) = \sigma_{yx}(t) = -\frac{1}{2}(\sigma_{\phi\phi}(t) - \sigma_{\theta\theta}(t)) \sin 2\beta(t) \tag{14}$$

where the angle $\beta(t)$ between north and the $\sigma_{\theta\theta}(t)$ direction, which describe the orientation of the principal stresses and is given by

$$\beta(t) = \cos^{-1}\left[\frac{\sin(\varepsilon \sin(nt - \omega)) - \sin\delta\cos\theta(t)}{\cos\delta\sin\theta(t)}\right]. \tag{15}$$

With the formulation of σ and $\sigma(t)$ in similar reference frames, the diurnal stress, σ^D, can now be evaluated. It is often convenient to express the diurnal stress tensor in terms of the principal stresses, such that shear stresses are zero.

$$\sigma^D = \begin{vmatrix} \sigma_1^D & 0 \\ 0 & \sigma_2^D \end{vmatrix}. \tag{16}$$

The principal stresses are

$$\sigma_1^D = \sigma_{xx}^D \cos^2\gamma_D + \sigma_{yy}^D \sin^2\gamma_D + \sigma_{xy}^D \sin 2\gamma_D \tag{17}$$

and

$$\sigma_2^D = \sigma_{xx}^D \sin^2\gamma_D + \sigma_{yy}^D \cos^2\gamma_D - \sigma_{xy}^D \sin 2\gamma_D \tag{18}$$

where γ describes the orientation of the principal stress axis and is given by

$$\gamma_D = \frac{1}{2}\tan^{-1}\left[\frac{2\sigma_{xy}^D}{\sigma_{xx}^D - \sigma_{yy}^D}\right]. \tag{19}$$

The angle, γ_D is measured from the σ_{xx}^D direction to the σ_1^D direction.

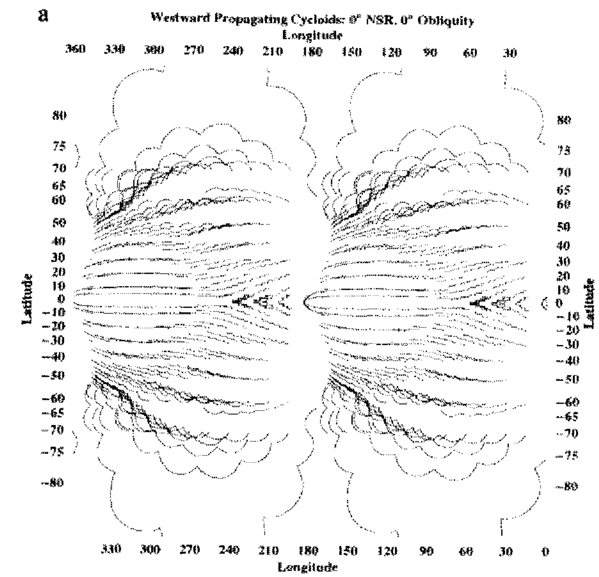


Fig. 1. Maps of hypothetical cycloids formed using typical parameters found from modeling cycloids near the south pole: The initiation stress is 68 kPa, the propagation strength is 38 kPa and the propagation velocity is 4.8 km/hr (Hurford *et al.* 2007). Only diurnal stress caused by Europa's eccentricity contributes to the stress field in which these hypothetical cycloids form. (a) shows westward propagating cycloids while (b) shows cycloids which propagate towards the east.

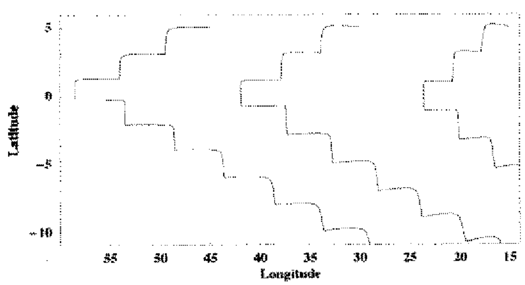


Fig. 3. Maps of westward propagating hypothetical cycloids formed at 5°N using typical parameters found from modeling cycloids near the south pole: The initiation stress is 68 kPa, the propagation strength is 38 kPa and the propagation velocity is 4.8 km/hr (Hurford *et al.*, 2007). Only diurnal stress caused by Europa's eccentricity contributes to the stress field in which these hypothetical cycloids form.

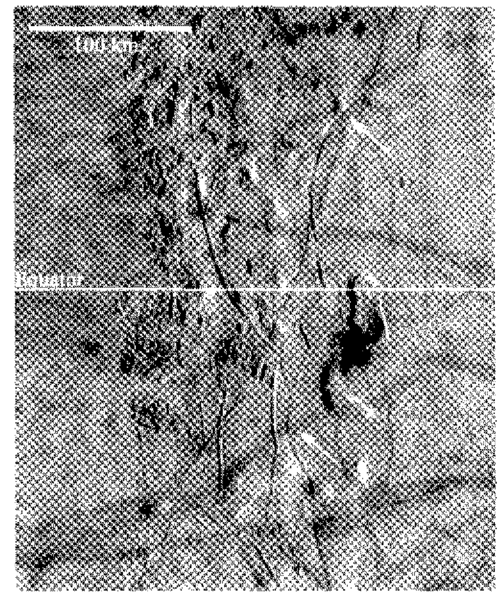


Fig. 4. An example of a cycloid which trends mostly north-south as it crosses the equator. Most equatorial crossing cycloids do not share this characteristic.

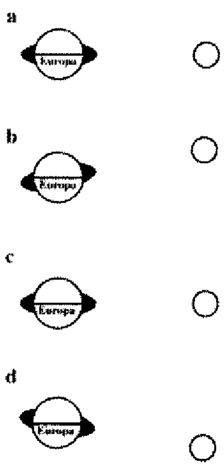


Fig. 7. Obliquity causes a diurnal migration of the tidal bulge in latitude. At some point during Europa's orbit, Jupiter is aligned with the equatorial plane of Europa (a) but obliquity causes Jupiter to move north of the equatorial plane until it reaches its farthest northern point 1/4 an orbit later (b). Then Jupiter moves south until it once again is aligned with the equatorial plane (c) before moving to is farthest southern point 3/4 of an orbit later (d).

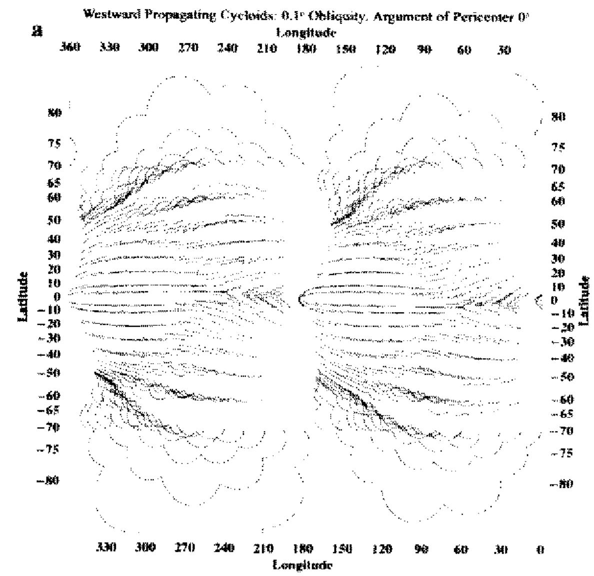


Fig. 8. Maps of cycloids that propagate westward, using typical parameters found from modeling cycloids near the south pole (Hurford *et al.*, 2007). Only diurnal stresses caused by Europa's eccentricity and 0.1° of obliquity contribute to the stress field in which these hypothetical cycloids form. Each panel (a-h) shows a different pericenter position measured relative to the ascending node, i.e. the argument of pericenter, in increments of 45°.

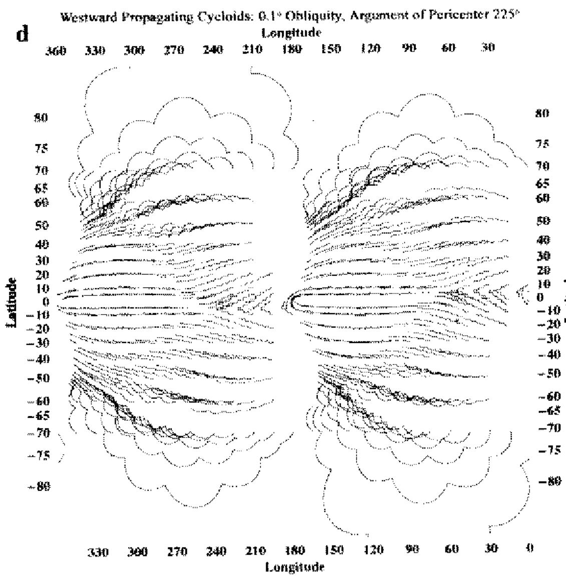
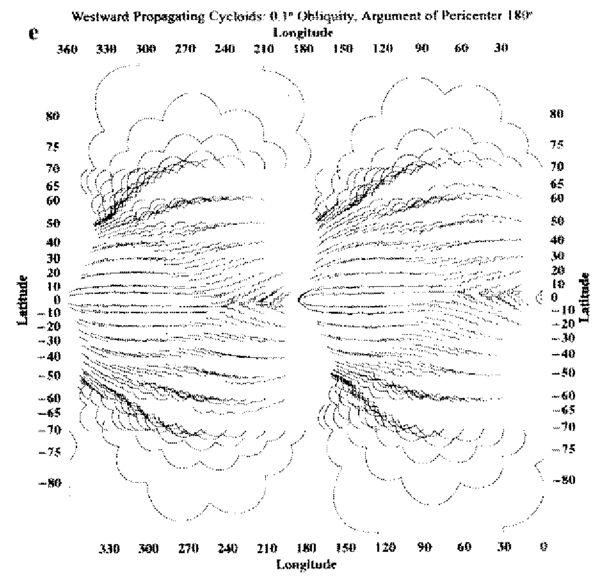


Fig. 8. (*Continued*)



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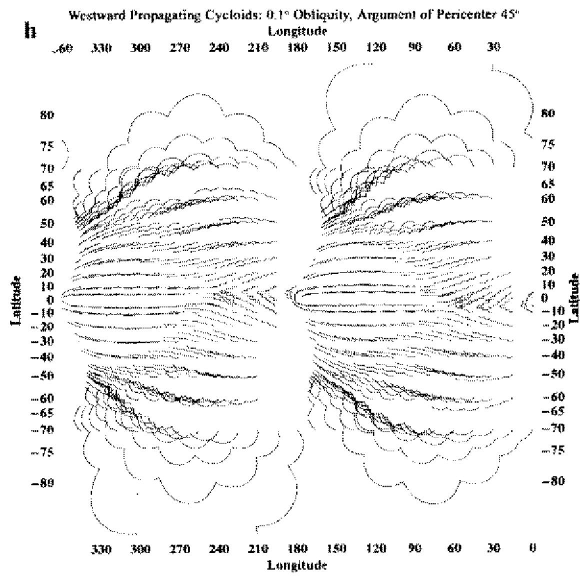

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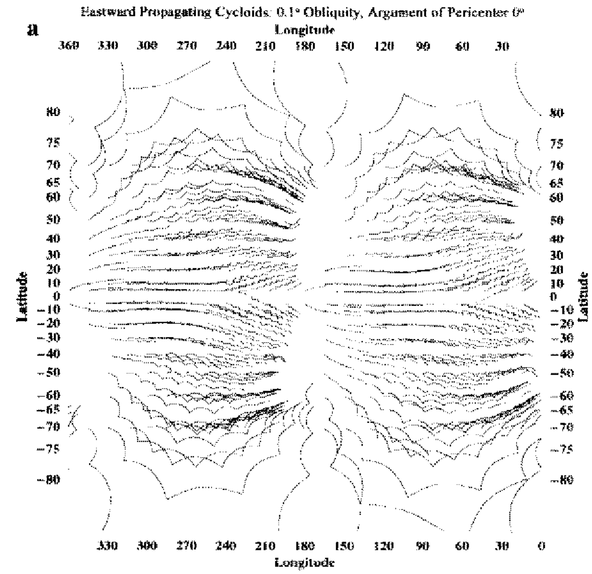


Fig. 9. Maps of cycloids that propagate eastward, using typical parameters found from modeling cycloids near the south pole (Hurford *et al.*, 2007). Only diurnal stresses caused by Europa's eccentricity and 0.1° of obliquity contribute to the stress field in which these hypothetical cycloids form. Each panel (a-h) shows a different pericenter position measured relative to the ascending node, i.e. the argument of pericenter, in increments of 45°.

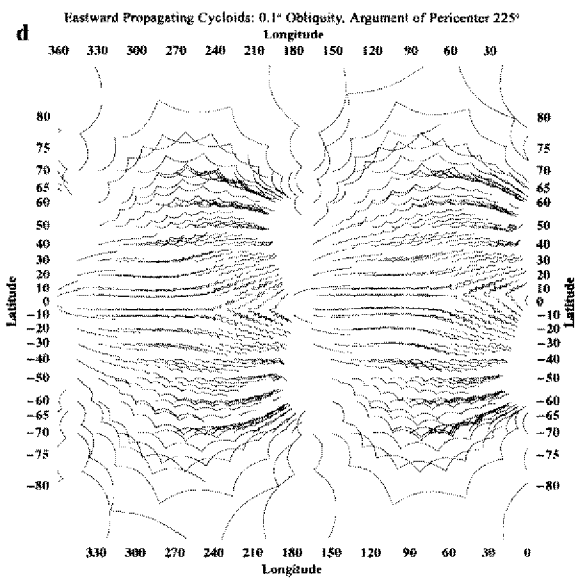
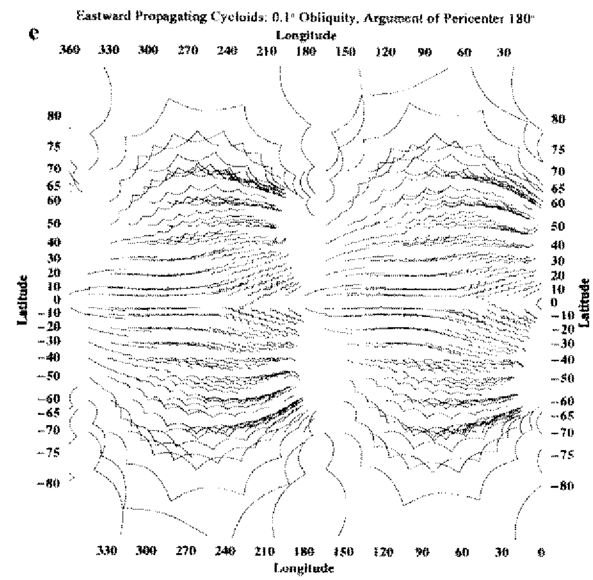


Fig. 9. (*Continued*)



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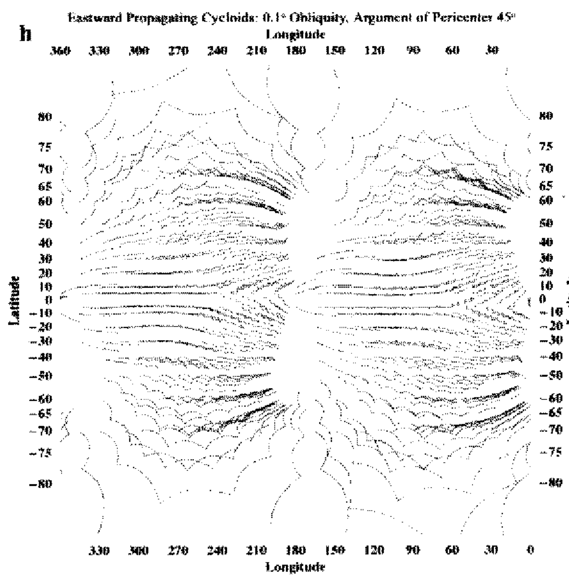

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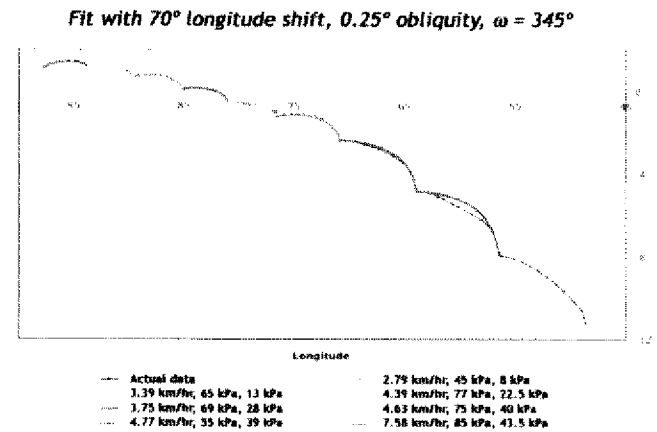

Fig. 10. A preliminary fit of an equator-crossing cycloid, which is shown in Fig. 5. The cycloid is fit using the method outlined in Hurford *et al.* (2007) and the values of the various parameters (crack speed, initiation strength and propagation strength) are listed below the figure.