LONG TERM AND "DIURNAL" TIDAL STRESSES ON EUROPA. by Richard Greenberg[1], Paul Geissler[1], Robert Pappalardo[2], and the Galileo Imaging Team, [1]Lunar and Planetary Lab, University of Arizona, and [2]Brown University

The complex, superimposed patterns of tectonic features on Europa, first revealed by Voyager and now at higher resolution by Galileo, may be due to global stress patterns generated by tidal flexing. The tidal potential due to Jupiter has several fourier components, whose time variations relative to the body induce stress. The dissipative response lags of these components allow torque to be imposed on Europa's rotation, possibly keeping it non-synchronous, which in turn can grossly affect tidal strain. Interpretation of geological patterns observed on Europa's surface requires understanding of possible tidal stress patterns.

The dominant component of the tidal potential is what would be imposed by Jupiter if Europa were in a circular orbit. If Europa's figure were perfectly responsive to this potential (i.e. effectively fluid and instantaneously responsive), it would conform to the shape of an equipotential contour: It would be elongated along a Jupiter-pointing axis, with an amplitude of ~0.5km, proportional to the mass of Jupiter and inversely proportional to a^3 (a is the distance to Jupiter).

If this tide were raised from a zero amplitude, the induced stress field on an elastic surface would have tension in all directions near the sub- and anti-Jupiter points; there would also be compression along the meridian 90^o from those points. We call this stress field the primary field. The maximum magnitude of the strain (expected at those locations) would be about $0.5km/R_E$ ~ 3e-4. For changes in the amplitude (e.g. due to changes in the distance of Jupiter from Europa), the induced stress field is simply the difference between the starting and the final stress; it has the same functional form as, and varies only in magnitude from, the primary field. The stress field has been plotted by [1] and [2] for such a case.

Because Europa is actually on an eccentric orbit, both the distance and the direction of Jupiter oscillate relative to circular motion. Thus the amplitude of the tide increases and decreases with a period of 3.6 days, and its direction relative to Jupiter oscillates back and forth with the same period, but shifted by 1/4 phase (e.g. the tidal bulge is oriented toward Jupiter just as reaches its maximum amplitude). The direction change (in radians) is comparable to the fractional oscillation in amplitude, which in turn is about three times the orbital eccentricity (e=0.01).

Therefore, the crust of Europa undergoes periodic ("diurnal") stress changes with a period of 3.6 days (approximately one Europan day), and their amplitude is roughly a factor e smaller than the primary field. Because the change involves direction as well as amplitude, the periodic stress changes are more difficult to visualize. However, the tide can described in terms of separate physical components: (a) the dominant constant component locked to the mean direction of Jupiter, which rotates in an inertial frame at rate n, where n is the orbital mean motion; (b) a standing wave composed of two waves, each with amplitude 2e times (a), that travel in opposite directions at a rate n/2 relative to the mean direction of Jupiter, such that they line up at perijove and apojove so as to add to and subtract from the amplitude; (c) a standing wave that alternately raises a tide 45^o on one side of (a) and then 45^o on the other side. Component (c) is also composed of two traveling waves like (b), except one has 4/3 the amplitude and the other has -4/3 the amplitude.

Determination of the stress field is simply a matter of summing at any time the various components, which have the same pattern as the primary field, but a much smaller amplitude and different direction.

Note that components (a) (b) and (c) above break down into fourier components [3]: (1) the primary component rotating at a rate n in inertial space (matching the mean angular velocity n of Jupiter around Europa); (2) a wave component 14e/3 as large as (1), rotating at rate 3n/2 in inertial space, aligned with (1) at perijove; and (3) a component 1/7 as large as (2), rotating at rate n/2 in inertial space, aligned with (1) at apojove.

These tidal components of the (assumed) instantaneously responsive Europa generate an external potential field. A passing body would feel a different gravitational pull from Europa than if Europa were spherical. The force may not be radial to Europa. Such a body can thus exert a rotational torque on Europa. However, Jupiter itself cannot exert a net torque, because averaged over an orbital period, symmetry considerations show the torque to be zero.

However, Jupiter could exert a torque on a more realistic Europa. Consider the effect on the tidal figure if there is a time lag in Europa's response to Jupiter's tidal potential. This can be treated as a phase lag in each of the fourier components (1, 2 and 3) of the tide. If there is a lag in the response, the tidal bulge orientation of each component is shifted in the forward (or backward) direction if Europa's spin is faster (or slower) than that component. For synchronous rotation, component (1) has no shift, (2) is shifted backward, and (3) is shifted forward. The shift in each component is approximated by addition of another tidal component with magnitude proportional to the phase lag [3]: One is oriented 45^o backward from (2) and the other is oriented 45^o forward from (3).

These two components are the only ones that can contribute to a net torque exchange with Jupiter. At perijove, both of these lag components are oriented 45^o backward from the direction of Jupiter. Since the pull of Jupiter on this elongation tends to spin up Europa, and because Jupiter's effect is greatest at perijove, it seems reasonable to expect that the net effect will be to increase Europa's rotation rate faster than synchronous. In fact, careful averaging of the net torque over an orbit confirms this result (as pointed out by [4]).

If Europa's rotation is non-synchronous, the primary stress would continually be reoriented relative to the surface of Europa, which may well be the source of global tectonic patterns. The stress field that develops between one orientation and another is the difference between the primary stress fields for each orientation [5], and can be much larger (~1/e) than the diurnal component, but operate over time scales at least 10,000 yr. [6] and probably much longer [4].

Note that the tidal torque exerted on Europa by Io may be comparable to that of Jupiter. For example, consider the torque by Io on the tide raised by Jupiter. Io is in conjunction with Europa only at Europa's apojove. Thus symmetry prevents any net torque due to the non-lag portion of the tide, but definitely allows a torque on the two lag components, in the sense of slowing Europa's rotation. While Jupiter's mass is greater than Io's by a factor ~30000, this is largely offset by the fact that its net torque depends on Europa's orbital eccentricity (0.01), and Io gets much closer to Europa. Moreover, tides raised by Io also may have significant effects. Therefore it is well worth considering these other factors that may have determined the current rotation rate of Europa.

The various kinds of tidal stresses discussed here operate over widely different time scales on Europa. Secular variation in the magnitude of the primary component, due for example to long-term orbital evolution, has been considered by [2], but there is no clear evidence yet of correlation of observed global fracture patterns with this source of stress. Non-synchronous rotation, if it exists, would also operate over very long time-scales. Effects of stresses due to this source were considered by [5] and [7].

Tectonic effects of the rapidly varying diurnal stresses have not yet been studied. Tidal flexing (component b) should produce alternating extensional and compressional stresses centered on the sub- and anti-Jupiter points. Longitudinal oscillation of the orientation of the tidal bulges (component c) will produce stress fields similar to those predicted for non-synchronous rotation, alternating in sign each Europan "day". These diurnal stresses could be related to the fine-scale linear features found by Galileo imaging to be widely present and seemingly continually forming on Europa. Perhaps the short-term stresses initiate such features, or they may simply open and close existing cracks, pumping fluid up to the surface, and creating the symmetrical ridges that characterize much of the geology. Mapping of the theoretical diurnal stress patterns and comparison with observed features will be a test of such models.

References: [1] Melosh, H.J., Icarus 43, 334, 1980; [2] Helfenstein, P., and E.M. Parmentier, Icarus 53, 415, 1983; [3] Jeffreys, H., MNRAS 122, 339, 1961; [4] Greenberg, R., and S.J. Weidenschilling, Icarus 58, 186, 1984; [5] Helfenstein, P., and E.M. Parmentier, Icarus 61, 175, 1985; [6] Hoppa, G., et al., this volume; [7] McEwen, A., Nature 321, 49, 1986.