HOW LIBRATION AFFECTS STRIKE-SLIP DISPLACEMENT ON ENCELADUS. T. A. Hurford[1], B. Bills[1,2], R. Greenberg[3], G.V. Hoppa[4] and P. Helfenstein[5], [1]Planetary Geodynamics Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA. [2]Institute for Geophysics and Planetary Physics, Scripps Institution of Oceanography, La Jolla, CA 92093, USA. [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. [4]Raytheon, Woburn, MA 01801, USA. [5]CRSR, Cornell University, Ithaca, NY 14853, USA.

Introduction: Enceladus is a small (radius ~250 km) moon, which orbits Saturn with a period of 1.37 days and an orbital eccentricity of 0.0047. The varying tidal influence from Saturn in this non-circular orbit constantly reshapes Enceladus, producing stress on its surface. It has been proposed that these diurnal stresses control the timing and location of jets from fractures near the south pole [1], and generate heat along these fractures [2].

Tidal stress resolved onto a fault can produce strike-slip displacement in a process informally called "walking" [3]. In tidal "walking" faults open and close out of phase with left- and right-lateral shear, producing small offsets along the faults. When the stress normal to a fault is tensile, the fault opens allowing shear stress to produce an offset. About half an orbit later, the stress normal to the fault changes from tension to compression, closing the fault. Once closed, friction along the fault limits the ability of shear stress to completely relieve the entire offset. After one cycle, the fault displays a small net sense of strike-slip displacement along its length. Over many successive cycles of opening and closing the small strike-slip offsets build, producing a greater amount of strike-slip displacement.

The sense (left- or right-lateral) of strike-slip displacement along a fault depends on the orientation and location of the fault, according to the tidal walking theory [3]. Latitudes poleward of 45^o exhibit left-lateral displacement in the northern hemisphere or right-lateral displacement in the southern hemisphere for all fault orientations while the mid-latitudes show a mixture of both left- and right-lateral displacement. In a survey of strike-slip displacement along faults on Europa left-lateral faults were observed in the high northern latitudes while right-lateral faults were observed in the high southern latitudes, matching the theory of tidal walking [4].

One might expect to observe a similar pattern in a survey of strike-slip displacement on Enceladus. However, if Enceladus physically librates, this would affect the diurnal stresses produced by tides on its surface.

Libration and Tidal Stress: Saturn distorts Enceladus raising a tide on its surface. The exact height of the tide raised on the surface is dependent on the internal structure and properties of Enceladus. However, even if resistant to deformation, Enceladus' low surface gravity would still result in a sizable tide. A conservative estimate places the height of the primary tide at 500m. Enceladus' finite eccentricity causes the primary tide to oscillate in magnitude by 1% or 5m as it completes an orbit, providing one component of the diurnal tidal stress.

The other component of diurnal stress is produced by the daily oscillation of the tidal bulge in longitude. Enceladus' orbital eccentricity also causes the longitude of the tidal bulge to oscillate as it tracks the position of Saturn throughout the orbit. This oscillation is called the "apparent libration" in longitude. However, on a moon experiencing a forced libration, the longitude of the tidal bulge will naturally oscillate, even if the orbital eccentricity were zero. This motion is commonly referred to as the "physical libration" in longitude. Although the free libration period of Enceladus, considered as a solid body, is estimated to be near 4 times the orbital period [5,6], the period of a decoupled shell would be shorter. To the extent that tidal heating influences the mean thickness and lateral variation in local thickness of the ice shell, the amplitude and phase of the forced libration will likely change over time. The orbital eccentricity (apparent libration) and rotational (physical libration) effects combine, jointly controlling the periodic longitudinal oscillation of the tide. The longitude of the tide at any point throughout the orbit is the difference between the apparent and physical libration or $-2e\ \mathrm{Sin}(nt) + F\ \mathrm{Sin}(nt + \phi)$ where $2e$ is the amplitude of the apparent libration, n is the mean motion, and t the time since pericenter passage and F is the amplitude of the physical libration, which has a phase ϕ relative to the apparent libration.

Affect on Tidal Walking: When we add the effect of physical libration, the prediction of the sense of displace by tidal walking along strike-slip faults can be affected (Fig. 1).

When the amplitude of the physical libration is less than the apparent libration (i.e. $< 2e$) the sense of strike-slip displacement cannot be changed. In this case, left-lateral faults should dominate the north polar region while right-lateral dominates the south polar region. Even though Enceladus is allowed to librate, the amplitude of the libration is not large enough to significantly change how the orientation of the principle stress axes rotate during the orbit, leading to identical offset patterns (although the amount of offset may be affected).

When the amplitude of the physical libration is comparable to the apparent libration (i.e. ≥ 2*e*), active faults can produce the opposite sense of strike-slip motion if the physical libration has the proper phase. In these cases, the stress field throughout the orbit rotates in the opposite direction, causing offset in the opposite sense. Hence physical libration can explain the presence of left-lateral strike-slip displacement near the south pole if observed.

Indirect Evidence for Libration: A survey of strike-slip faults near Enceladus' south pole has found tentative examples of both right- and left-lateral strike-slip displacements. This result indicates that the physical libration may have an amplitude at least as large as the amplitude of the apparent libration (i.e F ≥ 2*e* radians or 0.54°). The relative phase between the physical and apparent libration probably changes with time, allowing both right-lateral offsets to form along strike-slip faults when the two are relatively out of phase with each other, until a later time when the two are in phase with each other, a condition in which left-lateral offsets occur (Fig. 1).

If we interpret observed left-lateral faults in the South Polar region to be caused by libration, then a lower amplitude limit of 0.54° is required to explain their observed distribution. This value compliments Cassini's upper limit of 1.5° [6]. Other methods can be explored to indirectly constrain the libration state. Studies of heat generated by tidal shear stress along rifts in this region predicted locations of hotspots [2], which have been observed by Cassini's Composite Infrared Spectrometer (CIRS) [7]. In general, there is a good correlation between hotspot locations and predictions of tidal heat generation along Damascus, but CIRS detected the hottest region along Baghdad near the south pole in an area that wasn't predicted to have the highest temperature [2,7]. The mismatch may be due to the fact that the model in [2] overestimates the amount of shearing along the faults [8] but may not match even with a better estimate of the amount of shear. However, the mismatch between theory and observation may be reconcilable by including physical libration in the theory of tidal shear heating along these rifts.

Conclusions: Enceladus' physical libration allows another source of tidal heating that may be pivotal to explaining the heat flux observed near its south polar region. Moreover, this heating may be cyclic. When the physical libration is out of phase with the apparent libration more heat will be generated. However, when the two are in phase, the tidal bulge just changes magnitude during the orbit, and less heat is produced. This will have a significant impact on the evolution of Enceladus.

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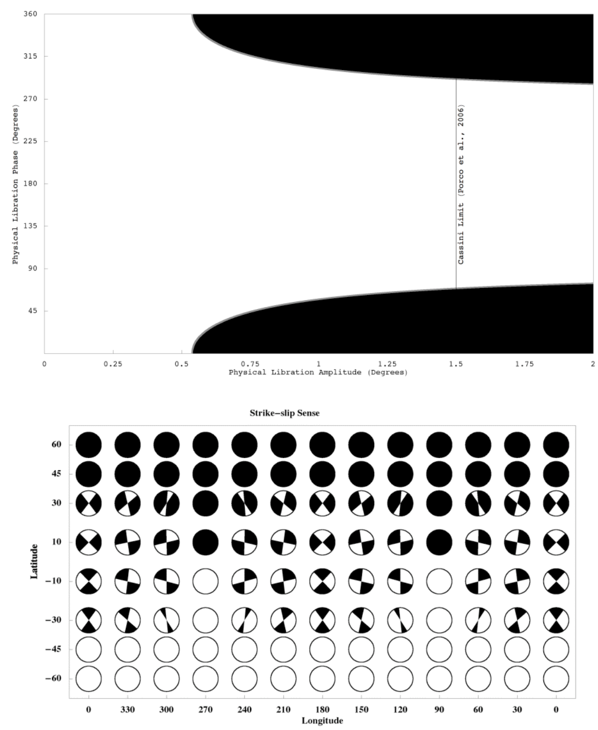

Fig. 1. The sense of strike-slip displacement on Enceladus. These plots, used together, show the effect of libration on strike-slip displacement. For values of physical libration amplitude and physical libration phase, which define the white region in (a), right-lateral displacement is shown as white in (b) while left-lateral displacement is black. For values of physical libration amplitude and physical libration phase, which define the black region in (a), right-lateral displacement is shown as black in (b) while left-lateral displacement is white. Along the grey margin between white and black regions in (a) no strike-slip displacement occurs along any faults of any orientation.