Using Geological Implications of a Physical Libration to Constrain Enceladus' Libration State. T.A. Hurford[1], B.G. Bills[2,3], P. Helfenstein[4], R. Greenberg[5], G.V. Hoppa[6] and D.P. Hamilton[7], [1]Planetary Systems 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]Jet Propulsion Laboratory, Pasadena, CA 91109, USA. [4]CRSR, Cornell University, Ithaca, NY 14853, USA. [5]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ 85721, USA. [6]Raytheon, Woburn, MA 01801, USA. [7]Department of Astronomy, University of Maryland, College Park, MD 20742, USA.

Introduction: Observations of Enceladus' south pole revealed large rifts in the crust, called "tiger stripes", which exhibit higher temperatures than the surrounding terrain and are likely sources of observed eruptions [1,2]. Tidal stress may periodically open the tiger stripe rifts, controlling the timing and location of eruptions [3]. Moreover, shear motion along rifts may produce the heat to drive eruptions [4].

Implications of Libration: Enceladus' finite orbital eccentricity causes small daily changes in the distance between Enceladus and Saturn, affecting the height of the tide. Orbital eccentricity also causes the longitude of the Saturn-side tidal bulge to oscillate as it tracks the position of Saturn throughout the orbit. By the analogy with lunar terminology, this oscillation in longitude is called the "optical libration." However, on a moon experiencing a physical libration, which involves oscillations in its spin rate, the longitude of the tidal bulge will naturally oscillate with respect to a fixed location, even if the orbital eccentricity were zero. The orbital eccentricity and rotational effects combine, yielding the diurnal oscillation of the tide, producing daily changes in the shape of Enceladus and elastic stress on the surface [5]. The diurnal tidal stress will be influenced on the type of physical libration (i.e. its amplitude and phase) experienced by Enceladus (e.g. Fig. 1).

Constraints on Libration from Cassini Data:

1. UVIS Data. On July 14, 2005 and October 24, 2007, Cassini's UVIS instrument observed the occultation of a star by Enceladus. These observations yield an absorption spectrum at far ultraviolet wavelengths, allowing molecular components of the plume to be identified. Moreover, column densities for the plume can be calculated using the spectrum. The column density calculated from the 2005 occultation is $1.6\text{x}10^{16}$ cm^{-2} [6], while a column density of $2.6\text{x}10^{16}$ cm^{-2} was calculated in 2007 [7], implying a higher eruption rate.

These occultations occurred when Enceladus was at two different points in its orbit, 0.27 and 0.71 of an orbital period past pericenter respectively. In a simple model the column density is proportional to the fraction of the tiger stripe segments that are in tension. Fig. 2 illustrates how the fraction of the tiger stripes in tension changes throughout the orbit for the case of Enceladus with no physical libration and a physical libration of 1.5° that is out of and in phase with the optical libration. In the case of no libration, column density might be high during the first half of the orbit and low during the second half, which does not match the UVIS data. However, some combination of physical libration amplitude and phase will match UVIS data, constraining the libration state.

2. CIRS Data. Periodic shear stress along the rifts may generate heat along their lengths [8,9,4]. Studies of heat generated by tidal shear stress along rifts in the south polar region of Enceladus predict locations of hotspots [4]. In general, there is a good correlation between hotspot locations and predictions of tidal heat generation, but CIRS detected the hottest region near the south pole in an area that was not predicted to have the highest temperature [1,4]. The mismatch between the theory of tidal shear heating and the observations of heat may be due to the fact that the model in [4] overestimates the amount of shearing along the faults [10] but may not match even with a better estimate of the amount of shear. Or the mismatch may be reconcilable by including physical libration in the theory of tidal shear heating.

Fig. 3 illustrates how a physical libration can affect tidal shearing along the tiger stripes. In Fig. 3a the amount of shearing is calculated in a similar method as was described by Nimmo et al. [4], except we use a thin shell approximation for the diurnal tidal stresses, the results are in good agreement previous studies [4]. When a physical libration is added the pattern of tidal shear is affected. Since the amount of heat generated depends on the amount of tidal shear, the location of hot spots would also be affected. In the case of the libration shown in Fig. 3b, areas of high shearing seen in Fig. 3a are still present, but new areas of high shearing have emerged. Thus, CIRS observations may constrain Enceladus' libration state.

3. ISS Data. The cycloidal shape of at least one of the tiger stripe rift, Cairo Sulcus, suggests that its formation may have been controlled by diurnal tidal stresses [11].

Preliminary work to model the formation of the cycloid-like rift were unable reproduce it at its current location. However, models of the formation of the feature may provide evidence of the longitude (relative to a Saturn centered reference frame) at which this feature might have formed [12]. A systematic search for possible formation locations found that arcuate segments, which resemble the entire rift, could be created at longitudes between 30° and 60° (modulo 180°) [11]. This feature is one of the stratigraphically youngest [13] active tiger stripe and it may have formed at its current location. Previous work [11] neglected the effect of libration in diurnal tidal stress in modeling this feature, thus models of its formation may be incorrect. Thus, modeling the formation of this feature may also constrain Enceladus' libration state.

Implications for Heating: The heat emanating from the south polar region has been estimated to be at least 6 GW [1,14]. This small moon of Saturn (Radius = 250 km) was expected to have cooled long ago, based on estimates of heating within the satellite, which place radiogenic and tidal heating at about 0.4 GW, less than a tenth of the observed heat emanating from the south pole [15,16,2].

However, the estimates of tidal heating rely on the tidal response of Enceladus that may be too conservative, so tidal heating may be greater than expected. In fact, recent studies require a larger tidal deformation of Enceladus in order to produce sufficient tidal stress to open cracks on the surface and generate heat through tidal shearing [3,4], implying at least 8GW of tidal heating. This amount of heating might be sufficient to explain heat observed at the south pole, but it is a global budget and therefore it is unlikely that most of this tidal heating would be focused near the south pole.

Even more heat could be dissipated by a physical libration of Enceladus [17]. If we neglect possible secondary librations and assume zero obliquity, then the factor by which tidal dissipation is modified can be expressed as, $f_H = (3e^2 + L^2) / 7e^2$ where $L = \mathrm{Sqrt}[4e^2 + F^2 - 4eF\cos(\psi)]$ is the amplitude of the oscillation in the longitude of the tidal bulge described by orbital eccentricity, e and physical libration F with a phase ψ. The physical libration can enhance or retard tidal dissipation, depending on the value of L. The greatest enhancement to tidal heating is ~8.6 times greater. Thus, constraining the libration state of Enceladus has important implications for heating.

References:

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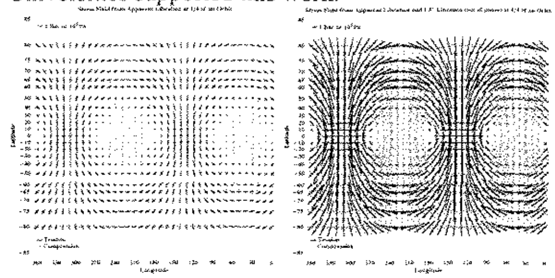

Fig. 1. The tidal stress at ¼ of an orbit past pericenter is illustrated. On the left the stress is produced just by the optical libration while a physical libration has been included in the case on the right.

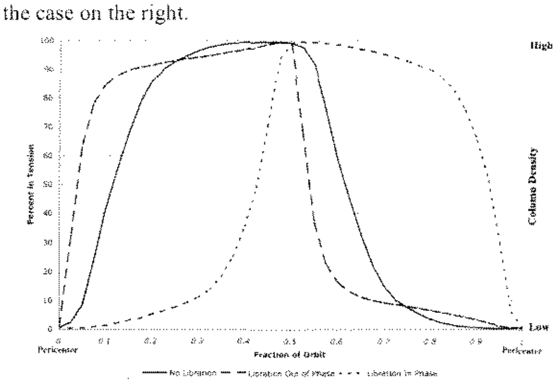

Fig. 2. The fraction of the tiger stripes in tension is plotted over the course of one orbit for three different libration states.

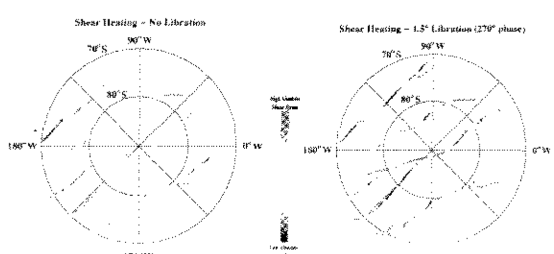

Fig. 3. Absolute tidal shear has been calculated along the tiger stripes in the south polar region for the case of only an optical libration and a physical libration of amplitude 1.5° that is out of phase with the apparent libration by 270°.