Using CIRS Data to Constrain Enceladus' Libration State. T. A. Hurford[1], P. Helfenstein[2], J.R. Spencer[3] and F. Nimmo[4], [1]Planetary Systems Laboratory, NASA Goddard Space Flight Center, Greenbelt, MD 20771, USA, [2]CRSR, Cornell University, Ithaca, NY 14853, USA, [3]Department of Space Studies, Southwest Research Institute, Boulder, CO 80302, [4]Department of Earth and Planetary Sciences, University of California, Santa Cruz, CA 95064.

Introduction: Diurnal tidal stress produces shearing along the Enceladus' tiger stripes, which can drive strike-slip displacements [1] and in turn may dissipate energy through frictional heating, possibly generating heat along their lengths [2,3,4] Tidal shear heating along the tiger stripes may have the capacity to drive eruptions seen from Enceladus' south polar region [4].

The predicted amount of tidal shearing (a proxy for frictional heating) along the rifts in the south polar region of Enceladus have been compared with the locations of hotspots observed by Cassini's Composite Infrared Spectrometer (CIRS) [4,5]. There is a reasonable correlation between hotspot locations and predictions of tidal shearing along the Damascus fault. However, on the Baghdad fault, CIRS detected the hottest region near the south pole, which does not experience the highest amounts of shear in the tidal shear model [4,5].

The mismatch between the theory of tidal shear heating and the observations of heat on Enceladus may be due to the neglect of physical librations, which affect the diurnal tidal stress and therefore the amount of tidal shear heating along the tiger stripes. Hurford et al. showed how a physical libration can affect diurnal tidal stress and especially tidal shearing along the tiger stripes [6]. Here we fit the observed emitted power along the tiger stripes with a model of tidal shear heating.

Observations of Surface Heat: Fig. 1 shows the CIRS observations of power along the tiger stripe from Rev. 61. This higher resolution observation allows the spatial variations in power along the tiger stripes to be detected. Each tiger stripe has been segmented into thirteen regions and the amount of energy radiated by the surface within those regions measured. The black line in Fig. 2 shows the power emitted per region along the tiger stripes. Each tiger stripe has its own unique power signature and the total power emitted from the region can be measured. The locations of triangulated jets are also indicated in Fig. 1 [7].

Models of Tidal Shear Heating: We predict the power generated along tiger stripes from the amount of shear experienced by each tiger stripe. Using a thin shell model to approximate the diurnal tidal stresses [8], the average absolute shear per orbit is calculated along each tiger stripe. Then, assuming that the amount of heat generated is proportional to the amount of shear experienced, we scale the average shearing in each of the thirteen regions along the tiger stripe to calculate the power predicted to be generated in that region. Our scaling factor is constrained by the total power observed for the region, about 2.9 GW.

We first used this model to predict the power generated along the tiger stripes in the case with no physical libration. Fig. 2 shows this result in blue. This model predicts that Baghdad radiates about the same amount of power all along its length, which does not fit the observations. We now can quantify this mismatch, which was qualitatively noted in earlier work [4]. In general the tidal shear model predicts a heating pattern that approximately matches the shape of the observed heating but it is not a perfect fit to the data.

Incorporating a physical libration into our model of diurnal tidal stress we surveyed the phase-space of libration amplitude and phase with respect to the optical libration to see if our tidal shear heating model could better fit the observations. Fig. 2 also shows the best and worst fit this model produces with the observations. The goodness of fit is determined by summing the square of the residuals between the predictions and observations. Our best fit had a physical libration of amplitude 0.7^{o} and a phase of 170^{o} with respect to the optical libration while our worst fit had a physical libration of amplitude 0.6^{o} and a phase of 30^{o}. In the our best fit, Baghdad no longer is predicted to have a uniform distribution of heat along its length and produces a hotter region near the south pole as observed. However, the total power at this hot spot still does not match the observations. In general, a physical libration allows for the suppression of heat production along the eastern sides of the tiger stripes, driving the better fit.

Fig. 3 shows the physical libration phase-space and the location of the best (green point) and worst (red point) fits. Contours show the difference in the sum of the square of the residuals relative to the best fit's value. We can see that the best fit resides in a shallow well within the phase-space and fits with libration that fall within the 5% contour are probably just as likely. Moreover, there exists a second zone of good fits.

Shaded regions in Fig. 1 were not used in this study. These regions either had no CIRS data associated with the tiger stripe or lat/lon data was lacking in our models of the tiger stripe.

Discussion: Enceladus' physical libration has implications for the amount of heat that can be tidally dissipated internally. The best-fit zones (5% contours in Fig.3) suggest that Enceladus can tidally dissipate up to ~5 times more energy than due to diurnal tides without a physical libration [6]. This may account for some of its observed activity.

Also, a forced physical libration has implications for the distribution of mass within Enceladus. Theoretical work on forced librations show that the phase of these librations should be in-phase or out-of-phase with the optical libration. While we allowed for the possibility that the forcing could have any phase relative to the optical libration, we find that indeed our best-fit zones have phases close to either 0^{o} or 180^{o}, as expected.

Conclusions: The inclusion of a small physical libration into models of tidal shear heating can improve the fit to the observed power emitted along the tiger stripes. This may be the first indirect evidence that a physical libration exists. The observational limit on Enceladus' libration from ISS images [9] falls just short of being able to detect libration in our identified best-fit zones but future observations should make it possible to directly detect a physical libration if it exists with these amplitudes. Other Cassini data sets might also be used to indirectly probe Enceladus' rotation state [6].

References: [1] Hoppa et al. (1999) *Icarus* **141**, 287-298. [2] Nimmo, F. and E. Gaidos (2002) *JGR* **107**. [3] Prockter et al. (2005) *GRL* **32**, 14202. [4] Nimmo et al. (2007) *Nature* **447**, 289-291. [5] Spencer et al. (2006) *Science* **311**, 1401-1405. [6] Hurford et al. (2009). [7] Spitale and Porco (2007) *Nature* **449**, 695-697. [8] Melosh, H.J. (1977) *Icarus* **31**. 221-243. [9] Porco et al. (2006) *Science* **311**, 1393-1401.

Acknowledgement: This work was supported in part by NASA Grants issued to T.H. and P.H. through the Cassini Data Analysis Program.

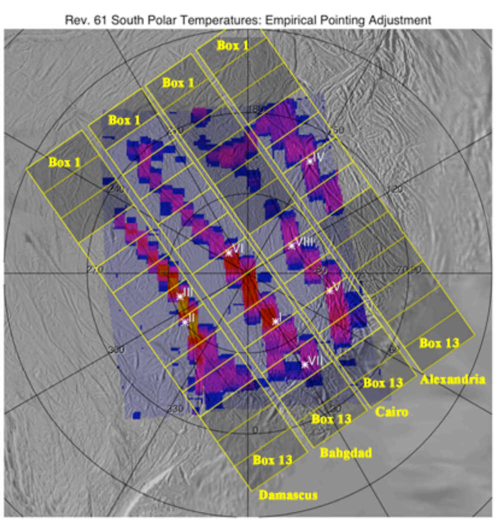

Fig. 1. CIRS observations show spatial variations in temperature along the tiger stripes. Each tiger stripe has been segmented into 13 regions (label as boxes) and the power radiated from each region has been measured (black curve in Fig. 2). The locations of jets triangulated by Spitale and Porco [7] are shown. Shaded regions were not used in this study.

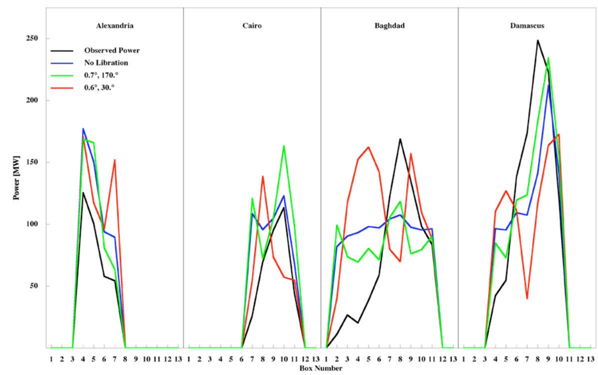

Fig. 2. The power emitted along the tiger stripes is illustrated. The black line shows the observed power measured from each region along the tiger stripes. The prediction of power generated along the tiger stripes from tidal shear heating with no physical libration is shown in blue. A physical libration of Enceladus changes the diurnal tidal stresses along the tiger stripes. The green line shows our best fit to the observations while the red line shows our worst fit with a model of tidal shear heating that includes a physical libration.

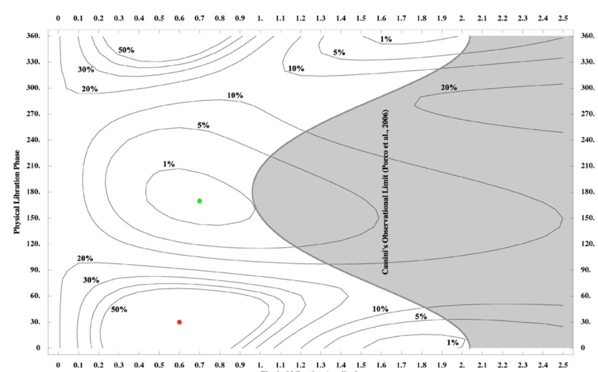

Fig. 3. The phase-space of physical libration amplitude and phase relative to the optical libration is shown along with the locations of the best (green point) and worst (red point) fits of predicted power generation with the observed power emitted. Contours show the difference in the sum of the square of the residuals relative to the best fit's value. The observational limit on Enceladus' libration from ISS images is also shown and any physical libration within the shaded region should have been detected [9].