TIGER STRIPE INITIATION: ENABLED BY NONSYNCHRONOUS ROTATION. D.A. Patthoff[1], S.A. Kattenhorn[2], C.M Cooper[3] [1]Planetary Science Institute (apatthoff@psi.edu), [2]Univeristy of Alaska, Anchorage, [3]Washington State University.

Introduction: A vast ocean of liquid water likely lies below Enceladus's icy crust [1-3] helping to amplify tidal stresses experienced by the satellite as it orbits Saturn. On the surface, numerous fractures, ridges, and relaxed craters point to a complex geological history. Some of the most complex geology is located near the south pole where a plume of water has been observed to be emanating from 4 large fissures, the "tiger stripes". The origin of the fissures remains a mystery. Some have related them to the diurnal tidal stresses [4], others have suggested they are a product of gravitational sliding and bookshelf faulting [5], while others suggest they could be related to an impact event [6]. Here we explore how potential tidal effects, diurnal and nonsynchronous (NSR), could initiate the fracturing of the south pole and what it means for the thickness, viscosity, and strength of the ice shell.

Stressing mechanisms: Diurnal tidal stresses act on a short time scale, over the ~33 hours it takes to complete an orbit, and are driven by the elliptical motion of Enceladus around Saturn. The elliptical orbit causes a change in the height of the tidal bulge, up to ~53 m [7], generated by the changing gravitational pull of the parent planet resulting from the variable distance between the planet and moon. The resultant stresses change in magnitude and orientation throughout the orbit. Thus, fractures on Enceladus's surface will experience periods of compression, tension, and resolved shear (both left- and right-lateral) over the course of an orbit. Previous models have shown the magnitudes of diurnal stresses on Enceladus to be on the order of 10-100s kPa [8-11] where the range is dependent on the configuration and viscosity of the ice shell (Fig. 1).

Enceladus is tidally locked to Saturn [12,13]. However, if the interior and exterior icy shell are decoupled from one another, by a global liquid ocean [1-3], Enceladus could experience NSR. In such a scenario, the outer ice shell rotates slightly faster than synchronous [14] caused by the long-term effects of an eccentric orbit and gravitational interaction between Enceladus and the rest of the Saturnian system. As the ice shell rotates faster than synchronous rotation, the tidal bulges remain fixed, oriented toward and away from Saturn. The changing longitudinal position of the bulge relative to the surface generates stresses throughout the ice shell [14-16]. The magnitudes of the NSR principal stresses are controlled mainly by the period of ice shell rotation and the thickness and viscosity of the ice shell [16] (Fig. 2). The viscosity of the ice is controlled by its constitutive properties and temperature. A relatively longer NSR period combined with a low viscosity and thicker ice shell will cause the ice to behave more viscously and relax away the NSR stress, resulting in reduced stresses at any point in time [16]. A comparatively shorter NSR period with a thinner and more rigid ice shell will result in larger NSR stresses. Unlike the diurnal stresses, the orientations of NSR stresses remain fixed relative to the Saturn-Enceladus system during the period of NSR. The time scale on which NSR stresses act is much longer than that of the diurnal stress because a single rotation of the outer layer for icy satellites could take >10,000 yrs to complete [14, 15]. However, the generated stresses can be an order of magnitude larger than diurnal stresses.

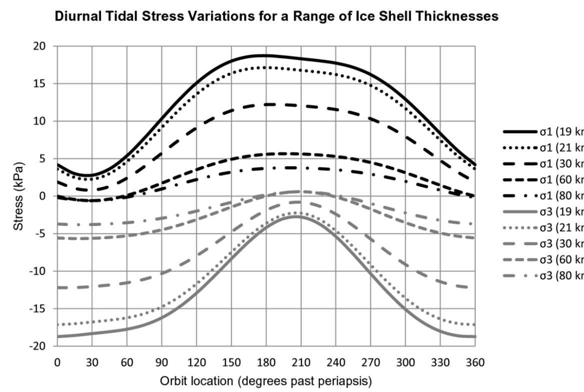

Fig. 1: Changes in the principal stress magnitudes over the course of a single orbit for 5 different thicknesses of the lower portion of the ice shell. Principal stress components shown are σ1 (max tension) and σ_3 (max compression). The thickness (3 km) and viscosity (10^{22} Pa s) of the upper portion of the ice shell are constant, as is the viscosity (10^{14} Pa s) of the lower portion of the ice shell. Stress results represent a point located at 82°S, 120°W.

Discussion: Diurnal tidal stresses are likely too small, possibly by an order of magnitude, to overcome the likely strength of the ice shell on Enceladus and initiate fracturing. Additionally, fracturing as produced from diurnal tides may only be able to penetrate to depths of <500 m where overburden stresses exceed the tidal stresses. However, the magnitudes of NSR stresses modeled here are large enough for most probable ice shell configurations to initiate fracturing in the ice shell. Fractures resulting from NSR could reach to depths of >10 km, possibly reaching a subsurface ocean.

The orientation of the principal stresses for NSR periods less than 1 Myr suggests that fractures should initiate with a strike parallel to the 90°E-90°W lines of longitude as viewed in a south polar projection, aligned with the maximum compressive stress. Hence, relative to the present day tiger stripes, the ice shell may have rotated ~45° since tiger stripe initiation. Assuming a constant NSR rotation rate between 100,000 and 1 Myr, the present-day active tiger stripes could be as young as ~12,500 - 125,000 years. Shorter NSR periods may not allow enough time for the tiger stripes to accumulate plume fallout material and develop into the prominent features we see today. Longer periods will rotate the orientations of the NSR stresses so that the tiger stripes would be in compression today and thus no longer able to relieve the tensile NSR stress component.

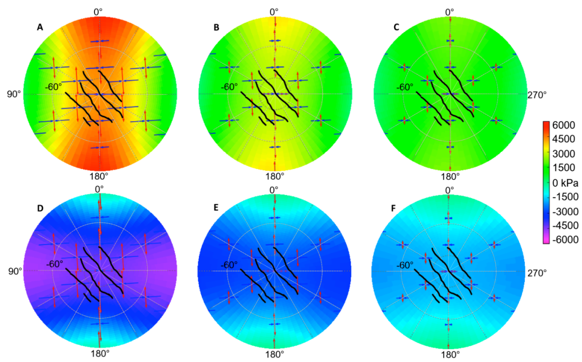

Fig. 2: Orientations and magnitudes of NSR stresses in a south polar stereographic projection. Center of the images are at the south pole and the outer edge is at 40°S. Figures A-C show the maximum tensile stress and D-F show the maximum compression. Stresses are shown for a 1 Myr NSR period and upper ice layer thicknesses of 3 km (A and D), 5 km (B and E), and 8 km (C and F). All models have a 21 km thick lower ice layer. Background colors show the magnitude of the maximum tensile (top) and compressional (bottom) stresses, where warm colors are more tensile and cool colors are compressional. Locations of the tiger stripes are shown as black lines.

The difference in stress magnitude between thin and thick ice shells (Fig. 2) may help explain why the south polar region is heavily fractured but the regions to the north are older and less fractured. The ice shell near the south pole could be thinner than the rest of the satellite [17-19] by 40 km [20] resulting in larger NSR stresses. Alternatively, the lower, less viscous ice layer could be closer to the surface resulting in a thinner upper ice layer, making the SPT more prone to fracturing. The thinning could be related to the excess heat generated within the ice shell, as observed by Cassini [21, 22], making the colder and more brittle ice layer thinner than other parts of the moon. Stresses for different ice shell configurations could be interpreted to imply that models with larger stresses (i.e. upper ice layer is 3 km thick and the lower ice layer viscosity is 10^{14} Pa s) may be applicable to the SPT where the induced NSR stress is on the order of, or greater than, the tensile strength of ice. Conversely, the north polar ice shell could have a thicker or colder ice shell resulting in NSR tensile stresses that are smaller. These smaller resultant stresses make fracturing due to the NSR stress less likely, albeit still possible, as is suggested by recent observations [23]. Additionally, the larger stresses near the south pole due to the thinner ice shell will allow for fractures to propagate farther down towards the liquid layer. Therefore, we suggest the brittle portion of the ice shell in the SPT has a thickness between 3-4 km, making fracturing more likely in that region, whereas outside of the SPT, it is 6-8 km thick, making fractures less likely to form and less likely to fracture.

Summary: Diurnal tidal stresses are likely too small to initiate fracturing on Enceladus. Instead, the fracture patterns observed near the south pole and the modeled stresses induced by NSR suggest the initial fracturing of the ice shell is most likely to have occurred as a result of NSR stress. A NSR period of ~1 Myr would produce stresses that are large enough to fracture the ice and would result in an age of the tiger stripes on the order of, ~125,000 yrs. The ice shell is not likely globally uniform in thickness; instead, the brittle portion of ice shell is 3-4 km thinner near the south pole than ice in the more northern regions.

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