Tidal Heating Effects on Habitable Zone Widths due to Non-Synchronous Spin and Eccentric Orbits. W. G. Henning[1,2,3] and T. J. Taylor[1], [1]University of Maryland, [2]NASA Goddard Space Flight Center, [3]Sellers Exoplanets Environments Collaboration.

Introduction: When occurring at significant levels, tidal heating in terrestrial exoplanets has the ability to modify the position and width of classical habitable zones (HZ) [1], particularly in the vicinity of low luminosity host stars. Classical HZs are defined here as the region where the surface of a terrestrial body can sustain a temperature between 0 and 100 degrees Celsius, a vital condition for liquid water. Relative to a habitable zone width (HZW) for an equivalent planet at zero eccentricity, HZ widths may be reduced for an eccentric orbit by up to 40 %, but never by a greater degree, due to the outward shift of the HZ position.

Results: We calculated tidal heating [2] and its effects on HZs for a wide range of stellar and planetary systems. We focused on simple modifications to surface temperatures due to different orbits and spin rates, and included discussion of melting and other secondary effects.

HZ tidal effects for eccentric orbits. Tides can significantly reduce HZs for eccentric orbits around typical low-mass stars for reasonable eccentricities. For dim hosts, eccentric tides can generate significant heating on their own, even creating small HZs without a host star.

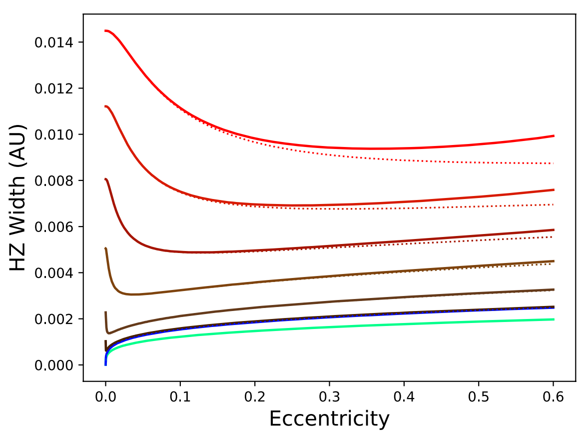

Figure 1: HZ modifications due to eccentricity. Curves range from low-mass red dwarf stars at the top to brown-dwarf and super-Jupiter massed primaries at the bottom. All secondaries here are Earth-mass satellites.

HZ effects on spin-synchronized worlds. Spin-synchronization is shown to have minimal impact on the phenomenon of tidal HZ width reduction, which will occur for synchronized, pseudo-synchronized, and non-synchronized cases, as well as planets with localized surface habitable zones, and planets with localized concentrations of tidal heat expression.

HZ tidal effects due to non-synchronous spin. Tidal heating due to non-synchronous spin, when relevant, is also demonstrated to modify habitable zone widths with significant reductions possible. Small-integer spin-orbit resonances, in particular the 1:2 and 3:2 resonances, are particularly vital to HZ widths. More complex outcomes are demonstrated for cases with combined non-synchronous rotation, nonzero eccentricity, and a model planet using the viscoelastic Andrade rheology. For non-luminous primaries such as large gas giants and brown dwarfs, tides due to NSR can generate habitable zones where none existed before, similar to eccentricity tides. This is particularly relevant for icy moons of planets that receive little to no solar radiation which can generate significant amounts of tidal heat, possibly allowing for favorable surface or subsurface conditions due to tides alone.

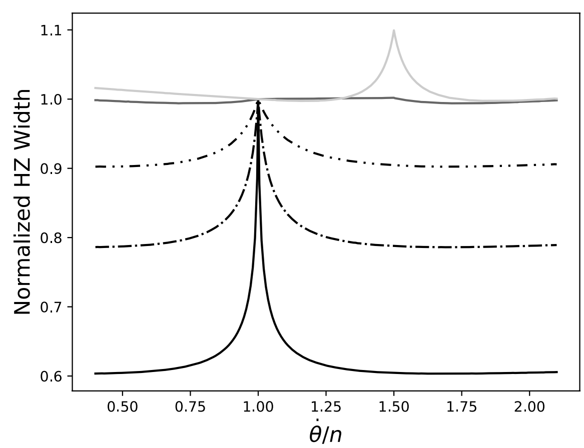

Figure 2: HZ modifications around a low-mass red dwarf due to the non-synchronous spin of an Earth-sized orbiting body. HZW is normalized to the width at synchronous spin, and plotted for eccentricities of $e = 0$ (solid black curve), 0.05 (dashed black curve with one dot), 0.10 (dashed black curve with two dots), 0.25 (solid dark gray curve), and 0.50 (solid light gray curve). Notably, the dominant resonance peak (minimum in tidal heat and maximum in HZW) shifts from a the 1:1 resonance for low eccentricity to a smaller beneficial peak at the 3:2 resonance.

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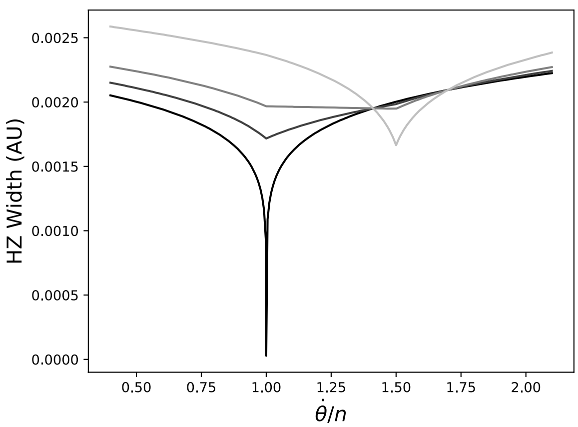

Figure 3: Non-luminous host Habitable Zone production via NSR tides blended with eccentricity tides. Host is a super-Jupiter with an Earth-sized satellite. The different eccentricities used are: 0.00, 0.15, 0.25, and 0.50, ranging from 0 for the darkest curve and getting lighter for each more eccentric calculation. In the absence of eccentricity, any non-luminous HZ collapses to zero size without tidal heating (or other internal heating) at 1:1 spin-orbit resonance. With nonzero *e*, this dip shifts towards the 3:2 spin-orbit resonance, though the effect is more marginal. Overall, even modest NSR can generate non-zero HZs around non-luminous hosts.

Modifications to HZs when considering the parameters of the secondary. We primarily utilized the fixed-Q rheology to calculate heating values due to tides in this work. We also implemented the Andrade rheology [3] which features a more realistic frequency response as a comparison. We found that results largely mirrored the fixed-Q results, with only minor modifications to the depth and severity of spin-orbits resonances in terms of the HZ widths. In general, the size of the secondary plays a large role. Larger secondaries generate proportionally more tidal heat, leading to a further decrease in HZW around luminous hosts and a larger generation of HZs around dim hosts. Some of the best candidates for habitable worlds around brown dwarfs or super-Jupiters are therefore large moons that can generate more of their own heat through tides.

Modifications to HZs for different tidal heat rates and other sources of surface heat. Using different fixed-Q values for our model secondary can drastically change the tidal heat generated. As a result, the HZs can change in width drastically, with large decreases for luminous hosts and large increases for non-luminous hosts. This further supports the idea that tides are almost universally beneficial to habitability for systems with limited insolation and are largely detrimental to HZ widths around stars.

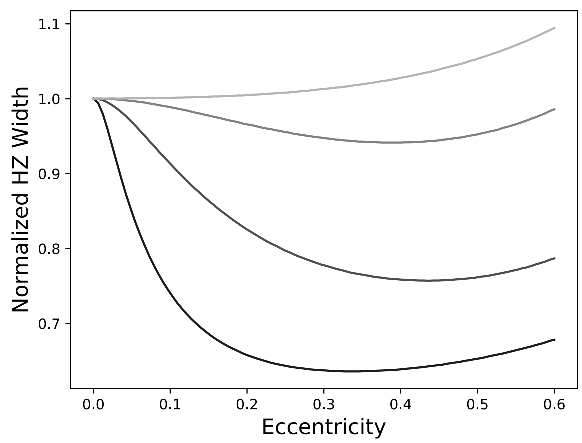

Figure 4: Plot of HZ width as a function of eccentricity of an Earth-sized secondary orbiting a star 20% the mass of the Sun for Q values of 1, 10, 100, and 1000. Widths are normalized to baseline values at e = 0. The darkest curve corresponds to Q = 1, with each lighter curve representing the next higher value of Q. Lower Q values correspond to greater tidal heating. Note the general profile of HZW reduction and then gradual recovery. For the highest Q case, tidal heating is significantly reduced, leading to a monotonic HZW increase dominantly driven by the insolation eccentricity correction. These effects are similar to the effect of increasing the radius of the orbiting body on HZWs, which increases tidal heat in a similar way to decreasing the Q value.

We modeled the impact of other sources of heat such as greenhouse effects or radiogenic production as an added amount of heat to the overall production of the orbiting body. Only non-physically high values of radiogenic heating changed our results, indicating that radiogenics play little role in determining the HZ width of a planet around a star -- the heat provided by insolation, and possibly by tides, is generally much more significant. Radiogenics may play an outsized role on cold ocean worlds capped by an icy shell, maintaining a consistent layer of liquid water under the surface for significant lengths of time (e.g., Europa, Pluto, or Charon).

References:

[1] Kasting, J. F., Whitmire, D. P., & Reynolds, R. T. (1993), Icarus, 101, 108. [2] Efroimsky, M., & Makarov, V. V. 2014, The Astrophysical Journal, 795, 6. [3] Shoji, D., & Kurita, K. 2014, The Astrophysical Journal, 789, 3.