DUSK/DAWN ATMOSPHERIC ASYMMETRIES ON TIDALLY-LOCKED SATELLITES II: THERMAL TIDES AND OUTGASSING AT THE GALILEAN SATELLITES Apurva V. Oza[1,2], Francois Leblanc[3], and Robert E. Johnson [4,5], [1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA , [2]Physikalisches Institut, Universität Bern, Bern, Switzerland, (apurva.v.oza@jpl.caltech.edu), [3] LATMOS/CNRS, Sorbonne Université, UVSQ, Paris, France, [4]University of Virginia, Charlottesville, Virginia, [5]New York University, New York, USA

Satellite Tides Background Thermal tides on a tidally-locked satellite have been studied as gas flows on a rotating surface since the '60s [1]. The authors derived two relations $nT^{5/2}$ and nT = constant, by allowing non-uniform gas concentrations (number density (n)-gradients)) to drive lateral flows at a given temperature, T. In effect, when tenuous gas in an exosphere is coupled to a rotating surface, the semidiurnal thermal tide ($\propto$ rotation rate Ω, and temperature gradient $dT/d\phi$) pulls the gas away from the expected thermal flux maxima $\mathcal{F}$ at noon (see Figure 1 sketch, motivated by tidal density perturbations at close-in exoplanets [2]). The expressions studied for lateral transport in planetary exospheres are unable to reproduce the *location* ϕ and *timing* t, of the peak O_2 gas column densities N, simulated on the tidally-locked satellites Europa (JII) [3] and Ganymede (JIII) [4], observed so far only in oxygen emission at JII [5].

Atmospheric Evolution and Escape Model Here, we build on the rotating 1-D mass conservation model (nommé `dishoom` (desorbing interiors via satellite heating to observe outgassing model)) in Paper I (Oza, Johnson, and Leblanc [6]) where we showed that the density peaks consistently at dusk only if a thermal source is used to source the oxygen aurorae observed by the Hubble Space Telescope (HST). Since orbital longitude ϕ probes the axis of time (and the associated surface heating $dT/d\phi$) our analytic model is fundamentally tidal in nature. Thermal tides can therefore be useful in describing the exospheric accumulation of O_2/H_2O and volatiles generally given our recent understanding on the thermal nature of the O_2 population (binding energy, U_s = 0.14 eV (Johnson et al. [7])). Furthermore, recent HST evidence suggests that at the sunlit trailing hemispheres of JII and JIII (Roth et al. [8]) H_2O may generate a locally-collisional atmosphere, whose density remains to be accurately constrained by future ground, space, or in-situ spacecraft. Although, it is generally agreed these O_2/H_2O atmospheres are more tenuous than SO_2 ($\ll 10^{17}$ cm^{-2}) at Io (JI) the simulated near-surface atmospheres at JII & JIII indicate that JI, JII and JIII are all indeed asymmetric towards dusk ((Oza et al. [3]; Leblanc et al. [4]; Walker et al. [9]; Lellouch et al. [10]).

Implications Studying atmospheric evolution on surface-bounded atmospheres is valuable in that properties of the icy surface Johnson et al. [7], and its interior

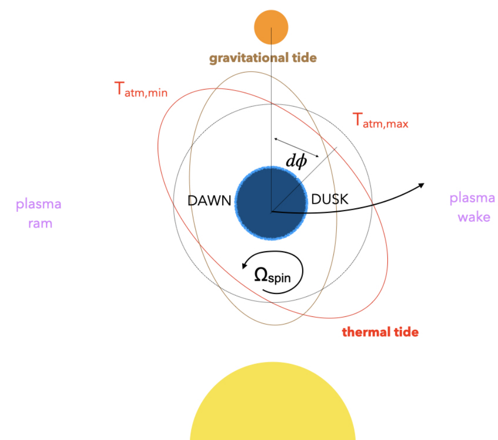

Figure 1: Birds-eye view illustrating the two tidal components acting on a tidally-locked satellite atmosphere/exosphere. Adapted from Arras and Socrates [2].

Hesse et al. [11] can be revealed. These constraints may also be able to inform the formation of primordial icy bodies (e.g comets) in the protosolar nebula (Oza and Johnson [12]).

Thermal Outgassing of O_2/H_2O at Europa, Ganymede, and Callisto Unlike JI, where the freezing point of SO_2 frost (201 K) poses no challenge to our understanding of the Ionian surface-atmosphere boundary layer, the trapped O_2 observed at JII, JIII, and JIV continues to be puzzling (Spencer, Calvin, and Person [13]; Spencer & Calvin 2002) as the trapped O_2 in amorphous or crystalline ice grains must thermally outgas since $P_{vap,O2} \gg P_{JII-JIV}$. Figure 2 provides a model considering the diurnal tide acting on the surface ice, from a range of regolith temperatures representative of the Galilean satellite surfaces. If the diurnal tide is able to sufficiently anneal and release trapped volatiles from inclusions/bubbles Johnson and Jesser [14], this model is a reasonable feedback mechanism for the icy Galilean satellite atmospheres, providing a direct parallel to volcanic SO_2 frost on JI. This continues the idea that O_2 is indeed accessible to the atmosphere as a surface frost in quasi-vapor pressure equilibrium (Paper I).

Summary If a resonance exists between the atmospheric lifetime and rotation rate a dusk-over-dawn at-

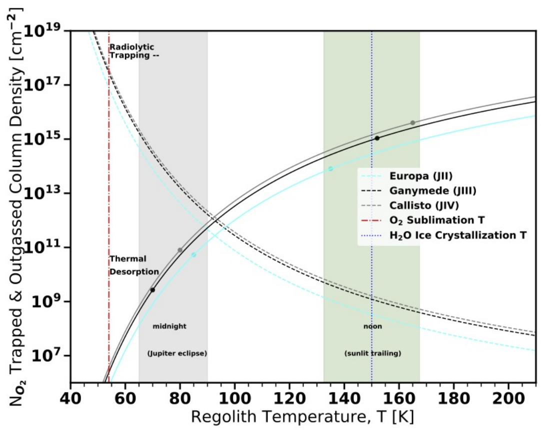

Figure 2: Surface-Atmosphere Exchange system modeled by `dishoom` where the trapped column is estimated following Johnson & Jesser 1997 and Johnson et al. 2019. The sublimation and ice crystallization temperatures are illustrated for O_2 sublimation (54.36 K) and H_2O ice crystallization ($\approx$ 150 K) [15]. Thermal outgassing/sublimation of water is observed in the lab to be significant $\gg$ 150 K [16]. The outgassed column densities are normalized to rough constraints by HST oxygen aurorae observations (Hall et al. 1998).

mospheric asymmetry appears on tidally-locked satellites as shown for ultraviolet HST observations in Paper I [6]. Evidence of thermal outgassing of trapped volatiles may be present in spectra of the newly launched JWST, equipped with the mid-infrared detector MIRI [17]. Future observations may reveal thermal tide signatures, in the form of phase-curve variability as also studied for close-in, asynchronous exoplanets [2])

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