



Dusk/Dawn Atmospheric Asymmetries on Tidally-Locked Satellites II: Thermal Tides and Outgassing at the Galilean Satellites

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DUSK/DAWN ATMOSPHERIC ASYMMETRIES ON TIDALLY-LOCKED SATELLITES II: THERMAL TIDES AND OUTGASSING AT THE GALILEAN SATELLITES Apurva V. Oza^{1,2}, Francois Leblanc³, and Robert E. Johnson^{4,5}, ¹Jet Propulsion Laboratory, California Institute of Technology, Pasadena, USA, ²Physikalisches Institut, Universität Bern, Bern, Switzerland, (apurva.v.oza@jpl.caltech.edu), ³ LATMOS/CNRS, Sorbonne Université, UVSQ, Paris, France, ⁴University of Virginia, Charlottesville, Virginia, ⁵New 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 $nT = \text{constant}$, 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 ($\ll 10^{17} \text{ cm}^{-2}$) 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

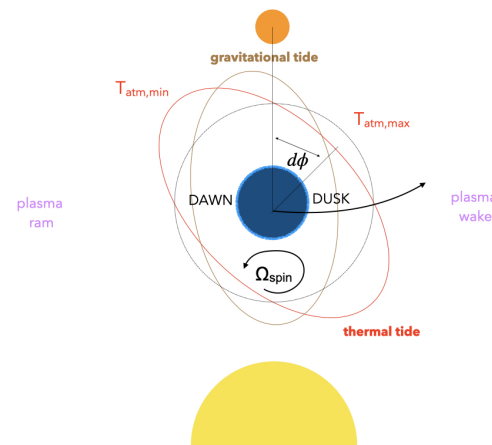


Figure 1: Birds-eye view illustrating the two tidal components acting on a tidally-locked satellite atmosphere/exosphere. Adapted from Arras and Socrates [2].

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 $P_{vap,O_2} \gg P_{JII-JIV}$. 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-

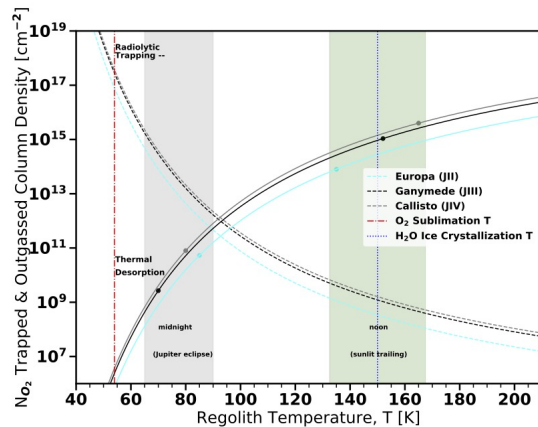


Figure 2: Surface-Atmosphere Exchange system modeled by dishoom where the trapped column is estimated following Johnson & Jessor 1997 and Johnson et al. 2019. The sublimation and ice crystallization temperatures are illustrated for O₂ sublimation (54.36 K) and H₂O ice crystallization (\approx 150 K) [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).

ospheric 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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References: [1] R. R. Hodges Jr. and F. S. Johnson. “Lateral transport in planetary exospheres”. In: 73 (1968), p. 7307. DOI: [10.1029/JA073i023p07307](https://doi.org/10.1029/JA073i023p07307). [2] Phil Arras and Aristotle Socrates. “Thermal Tides in Fluid Extrasolar Planets”. In: 714.1 (May 2010), pp. 1–12. DOI: [10.1088/0004-637X/714/1/1](https://doi.org/10.1088/0004-637X/714/1/1). arXiv: [0912.2313](https://arxiv.org/abs/0912.2313) [astro-ph.EP]. [3] Apurva V. Oza et al. “Dusk over dawn O₂ asymmetry in Europa’s near-surface atmosphere”. In: 167 (Mar. 2019), pp. 23–32. DOI: [10.1016/j.pss.2019.01.006](https://doi.org/10.1016/j.pss.2019.01.006). arXiv: [1804.10582](https://arxiv.org/abs/1804.10582) [astro-ph.EP]. [4] F. Leblanc et al. “On the orbital variability of Ganymede’s atmosphere”. In: 293 (Sept. 2017), pp. 185–198. DOI: [10.1016/j.icarus.2017.04.025](https://doi.org/10.1016/j.icarus.2017.04.025). [5] L. Roth et al. “Europa’s far ultraviolet oxygen aurora from a compre-

hensive set of HST observations.” In: *J. Geophys* 261 (Nov. 2015), pp. 1–13. DOI: [10.1016/j.icarus.2015.07.036](https://doi.org/10.1016/j.icarus.2015.07.036). [6] Apurva V. Oza, Robert E. Johnson, and François Leblanc. “Dusk/dawn atmospheric asymmetries on tidally-locked satellites: O₂ at Europa”. In: 305 (May 2018), pp. 50–55. DOI: [10.1016/j.icarus.2017.12.032](https://doi.org/10.1016/j.icarus.2017.12.032). [7] R. E. Johnson et al. “The Origin and Fate of O₂ in Europa’s Ice: An Atmospheric Perspective”. In: 215.1, 20 (Feb. 2019), p. 20. DOI: [10.1007/s11214-019-0582-1](https://doi.org/10.1007/s11214-019-0582-1). arXiv: [1804.10589](https://arxiv.org/abs/1804.10589) [astro-ph.EP]. [8] Lorenz Roth et al. “A sublimated water atmosphere on Ganymede detected from Hubble Space Telescope observations”. In: *Nature Astronomy* 5 (July 2021), pp. 1043–1051. DOI: [10.1038/s41550-021-01426-9](https://doi.org/10.1038/s41550-021-01426-9). arXiv: [2106.03570](https://arxiv.org/abs/2106.03570) [astro-ph.EP]. [9] Andrew C. Walker et al. “A parametric study of Io’s thermophysical surface properties and subsequent numerical atmospheric simulations based on the best fit parameters”. In: 220.1 (July 2012), pp. 225–253. DOI: [10.1016/j.icarus.2012.05.001](https://doi.org/10.1016/j.icarus.2012.05.001). [10] E. Lellouch et al. “Detection and characterization of Io’s atmosphere from high-resolution 4- μ m spectroscopy”. In: 253 (June 2015), pp. 99–114. DOI: [10.1016/j.icarus.2015.02.018](https://doi.org/10.1016/j.icarus.2015.02.018). arXiv: [1502.05620](https://arxiv.org/abs/1502.05620) [astro-ph.EP]. [11] M. Hesse et al. “Transport of surface oxidants into internal oceans by brine migration through ice shells”. In: *Bulletin of the American Astronomical Society*. Vol. 53. Mar. 2021, 1041, p. 1041. [12] A. Oza and R. Johnson. “A common origin of oxygen at Jupiter’s icy moons and comets: Modeling thermal outgassing at Europa”. In: *AAS/Division for Planetary Sciences Meeting Abstracts*. Vol. 52. AAS/Division for Planetary Sciences Meeting Abstracts. Oct. 2020, 215.01, p. 215.01. [13] John R. Spencer, Wendy M. Calvin, and Michael J. Person. “CCD Spectra of the Galilean Satellites: Molecular Oxygen on Ganymede”. In: 100.E9 (Sept. 1995), pp. 19049–19056. DOI: [10.1029/95JE01503](https://doi.org/10.1029/95JE01503). [14] R. E. Johnson and W. A. Jessor. “O₂/O₃ Microatmospheres in the Surface of Ganymede”. In: 480.1 (May 1997), pp. L79–L82. DOI: [10.1086/310614](https://doi.org/10.1086/310614). [15] R. A. Vidal et al. “Oxygen on Ganymede: Laboratory studies”. In: *Science* 276 (Jan. 1997), pp. 1839–1842. DOI: [10.1126/science.276.5320.1839](https://doi.org/10.1126/science.276.5320.1839). [16] B. D. Teolis et al. “Ozone Synthesis on the Icy Satellites”. In: 644.2 (June 2006), pp. L141–L144. DOI: [10.1086/505743](https://doi.org/10.1086/505743). [17] Pierre-Olivier Lagage. “Characterisation of exoplanet atmosphere with the JWST and then ARIEL”. In: *Planets 2020, Ground and Space Observatories: a Joint Venture to Planetary Science*. Mar. 2020, 13, p. 13. DOI: [10.5281/zenodo.4435587](https://doi.org/10.5281/zenodo.4435587).