



**HAL**  
open science

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

Apurva V Oza, François Leblanc, Robert E Johnson

► **To cite this version:**

Apurva V Oza, François Leblanc, Robert E Johnson. Dusk/Dawn Atmospheric Asymmetries on Tidally-Locked Satellites II: Thermal Tides and Outgassing at the Galilean Satellites. 53rd Lunar and Planetary Science Conference, Mar 2022, the Woodlands, United States. pp.LPI Contribution No. 2678, 2022, id.2862. insu-04477245

**HAL Id: insu-04477245**

**<https://insu.hal.science/insu-04477245>**

Submitted on 26 Feb 2024

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

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

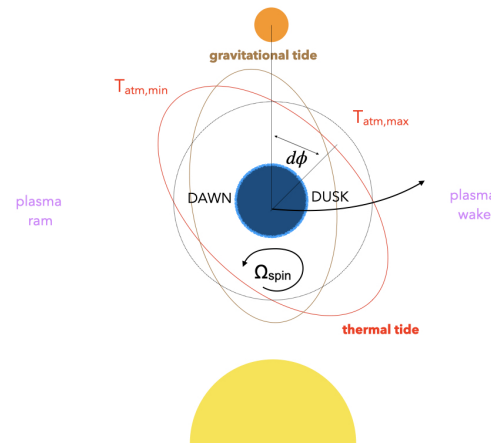


Figure 1: Birds-eye view illustrating the two tidal components acting on a tidally-locked satellite atmosphere/exosphere. Adapted from Arras and Socrates [2].

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-

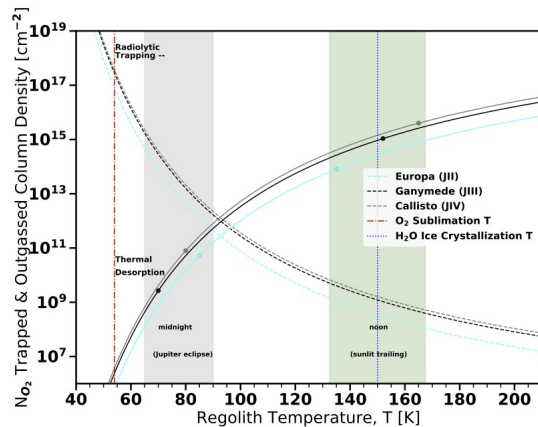


Figure 2: Surface-Atmosphere Exchange system modeled by *dishoom* where the trapped column is estimated following Johnson & Jesser 1997 and Johnson et al. 2019. The sublimation and ice crystallization temperatures are illustrated for  $O_2$  sublimation (54.36 K) and  $H_2O$  ice crystallization ( $\approx 150$  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).

atmospheric 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])

#### Acknowledgments:

Part of this work was conducted at the Jet Propulsion Laboratory, California Institute of Technology, under contract

**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  $O_2$  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:  $O_2$  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  $O_2$  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- $\mu$ 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. Jesser. “ $O_2/O_3$  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).