The stability of oceans against escape on warm Ganymedes and Europas around migrated giant planets in the habitable zone. David C. Catling[1], Kevin J. Zahnle[2], [1]University of Washington, Box 351310, Dept. Earth & Space Sciences / cross-campus Astrobiology Program, Seattle WA, USA (dcatling@uw.edu). [2]MS 245-3, Space Science Division, NASA Ames Research Center, Moffett Field, CA, USA.

Introduction: The Solar System has several examples of *Clausius-Clapeyron (C-C) atmospheres*, where the thickness of a whole atmosphere is determined by vapor equilibrium with a condensed phase. N_2 air on Triton and Pluto is in saturation vapor pressure equilibrium with surface N_2 ice at the prevailing temperature on each body. The martian atmosphere is arguably another C-C atmosphere—buffered to ~600 Pa surface pressure by ~148 K CO_2 ice caps [1] (but see [2] for an alternative explanation). Given these instances and other likely possibilities, we suggest that exomoon and exoplanet C-C atmospheres will surely exist and may be detectable in the future.

An interesting case of a C-C atmosphere is an icy exomoon orbiting a giant planet that has migrated into the habitable zone (HZ). The surface of such a moon would melt, creating potentially habitable "water worlds". Very deep oceans are possible given that ~40-50% water can make up the bulk mass of such moons. But would oceans (even deep ones) on relatively small moons be stable against escape to space? Low gravity and relatively high stellar flux would allow a vapor atmosphere to expand into the vacuum of space hydrodynamically. Would such moons remain potentially habitable even in the HZ?

Methods: To develop physical intuition about the evaporation of exomoon oceans using semi-analytic physics, we did some preliminary calculations starting with an isothermal hydrodynamic wind approximation. Radiative cooling is then simply σT^4 (where σ is the Stefan-Boltzmann constant and T is temperature), allowing a straightforward formulation of escape versus radiative cooling. Of course, if stellar heating is strong, a watery exomoon will reach a runaway greenhouse state, which needs to be borne in mind.

The global energy balance for a watery exomoon is between incoming stellar flux versus the energy flux lost to vaporizing the condensable, lifting molecules out of the gravity well, and radiative cooling, i.e.,

$$\tfrac{1}{4}\left(1-A\right)F_S = \left(GM/r_s + L_v\right)\rho_s u_s + \sigma T^4 \qquad (1)$$

Here, $r = r_s$ is the lower boundary condition where the atmospheric density is ρ_s, such that $\rho_s u_s$ is the escape flux, given an outward velocity u_s. In addition, A is the albedo, F_S is the stellar flux available for absorption, and L_v is the latent heat of vaporization. An equation for $\rho_s u_s$ was derived from hydrodynamic theory (e.g., Ch. 5 in Ref. [3]) . We also assumed a surface density set by the C-C equation for the saturation vapor pressure of water. This system of equations was solved for the velocity profile of the exomoon wind, the critical radius where the speed of sound is attained, and the isothermal temperature.

Results: An example calculation of ocean longevity is shown in Fig. 1. Oceans escape in less time than the age of the Solar System on a warm Europa throughout the HZ. In contrast, oceans on warm Ganymedes (~2 lunar masses) or larger exomoons survive for long periods in the mid-outer HZ. Oceans persist essentially indefinitely on moons of ~4 or more lunar masses. Of course, calculations are sensitive to assumed ocean mass fraction and albedo. Preliminary non-isothermal wind calculations tend to have lower loss rates but do not change the qualitative conclusions. Additional gases that are heavier than water, such as CO_2 can also slow the escape, if available, e.g., from a melted Callisto.

Discussion: Initial calculations suggest that warm Ganymedes in the HZ have long-lived oceans at stellar fluxes ~$S_\odot$, whereas warm Europas tend to lose their oceans. Further calculations will explore the parameter space and sensitivities, as well as runaway cases.

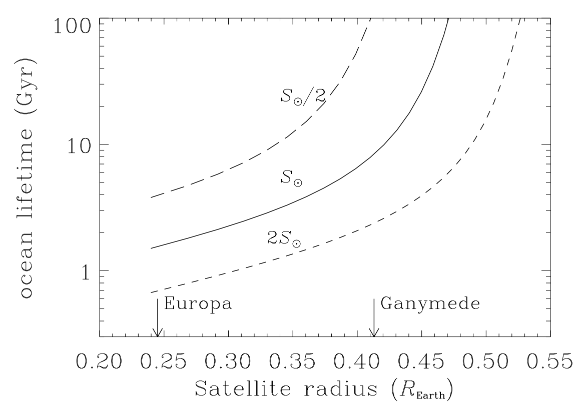

Fig. 1. The lifetime of deep oceans on melted icy exomoons for different levels of stellar flux, where $S_\odot$ is the solar flux at 1AU. Bounds roughly correspond to flux at orbits of Mars (long dash) and Venus (short dash). Here we assume that the ocean mass to be evaporated is 40% of the satellite mass. Albedo was a liquid water value of 0.1.

Refs: [1] Leighton R. B., Murray B. C. (1966) *Science* 153, 136. [2] Kahn R. (1985) *Icarus* 62, 175. [3] Catling D. C., Kasting J. F. *Atmospheric Evolution on Inhabited and Lifeless Worlds*. (CUP, New York), in press.