HABITABLE ZONES FOR EXOMOONS AROUND EXOPLANETS. René Heller[1] and Rory Barnes[2,3], [1]Origins Institute, McMaster University, 1280 Main St W, Hamilton (ON) L8S 4M1, Canada, rheller@physics.mcmaster.ca, [2]Astronomy Department, University of Washington, Seattle (WA), USA, rory@astro.washington.edu, [3]NASA Astrobiology Institute, Virtual Planetary Laboratory Lead Team, USA *March 4, 2015*

Context: Predictions of exomoons the size of Mars [1,2] and new possibilities of finding sub-Earth-sized exomoons with the *Kepler* or *PLATO* space telescopes [3,4] naturally make us wonder about the habitability of these worlds. Different from planets, for which surface habitability is mostly constrained by stellar illumination, moons have alternative energy sources. For one thing, a giant host planet of a moon can contribute both stellar reflected light as well as its own thermal emission to a moon's global energy flux budget. Moreover, moons can be subject to tidal heating, which provides an internal, geophysical heat source in the satellite. The combination of all energy sources defines a circumplanetary region, within which a moon can be habitable. Very close to its host planet, a moon in the stellar habitable zone (HZ) can still be in a runaway greenhouse state and therefore uninhabitable [5]. We call the innermost critical orbit around a planet the "habitable edge" [5]. On the other hand, a moon in a close circumplanetary orbit can be habitable beyond the stellar HZ if tidal heating and illumination effects can make up for the weak stellar illumination [6].

Results: We find that Mars- to Earth-sized exomoons, the most massive satellites that are predicted to form in the circumplanetary accretion disks around young super-Jovian planets, can be habitable if they are typically more than about 10 Jupiter radii from their host planet away. Details depend heavily on the orbital eccentricity of the moon, which triggers tidal heating, and on the distance of the planet-moon system to the common host star. At the inner edge of the stellar HZ, moons need to be farther away from their planet to be habitable owing to the strong stellar illumination. Exomoon habitability also depends on the age of the system: if the giant host planet of an exomoon is younger than about 100 Myr, then its substantial thermal emission can make its vicinity uninhabitable in the sense that close-in moons would be subject to a runaway greenhouse effect. For any given parameterization of a star-planet-moon system, we define an "exomoon menagerie" (see figure) [7]. If an exomoon were soon to be found in the HZ around a star, then our global energy flux model would allow a first assessment of the moon's habitability.

References: [1] Canup, R. M. and Ward, W. R. (2006) *Nature*, 441, 834-839 [2] Heller R. and Pudritz, R. (2014) *ApJ (submitted)*, arXiv:1410.5802. [3] Kipping, D. et al. (2012) *ApJ*, 750, id. 115. [4] Heller, R. (2014) *ApJ*, 787, id. 14. [5] Heller, R. and Barnes, R. (2013) *AsBio*, 13, 18-46. [6] Heller, R. and Armstrong, J. (2014) *AsBio*, 14, 50-66. [7] Heller, R. and Barnes, R. (2015) *IJA (in press)*, arXiv:1311.0292.

Figure caption: Exomoon menagerie of an Earth-like moon orbiting a 10 Jupiter-mass planet at 1 AU from a Sun-like star with a circumplanetary orbital eccentricity of 0.001. The planet is in the center of the two plots, respectively. In the left panel, the system is 100 Myr old and illumination from the planet is substantial. In the right panel, at an age of 1 Gyr, the planet has cooled down and the inhospitable circumplanetary region has shrunken. Note that in the "Tidal Venus" (dark red) and "Tidal-Illumination Venus" (light red) states the moon are subject to a runaway greenhouse effect and thus uninhabitable.