

**EXTREME WATER LOSS AND ABIOTIC O<sub>2</sub> BUILDUP IN THE HABITABLE ZONES OF M DWARFS.**

R. Luger<sup>1,2,3</sup> and R. Barnes<sup>1,2</sup>, <sup>1</sup>Department of Astronomy, University of Washington, Box 351580, Seattle WA 98195, <sup>2</sup>NASA Astrobiology Institute – Virtual Planetary Laboratory Lead Team, USA. <sup>3</sup>E-mail: rodluger@uw.edu.

**Introduction:** Classically, the boundaries of the habitable zone (HZ) are calculated based on the instantaneous stellar flux received by a planet [1]. However, because of stellar evolution, the limits of the HZ are not static. Their evolution is particularly drastic during the pre-main sequence (PMS) phase of the star, prior to the onset of fusion in the core. During this period, the star contracts in an attempt to establish hydrostatic equilibrium; as a result, its inflated radius results in a luminosity several times larger than its value on the main sequence. While the PMS phase of Sun-like stars lasts a few tens of Myr [2], and is therefore over by the time the terrestrial planets form [3], the PMS phase of M dwarfs can last up to ~1 Gyr [2]. Given that terrestrial planets probably form more quickly around these stars [3,4], the PMS phase poses severe problems for the habitability of M dwarf planets. In particular, Earths and super-Earths in the HZ of M dwarfs today were not in the HZ when they formed, and may have experienced prolonged runaway greenhouse phases, during which water photolysis and loss of hydrogen to space could have desiccated their surfaces.

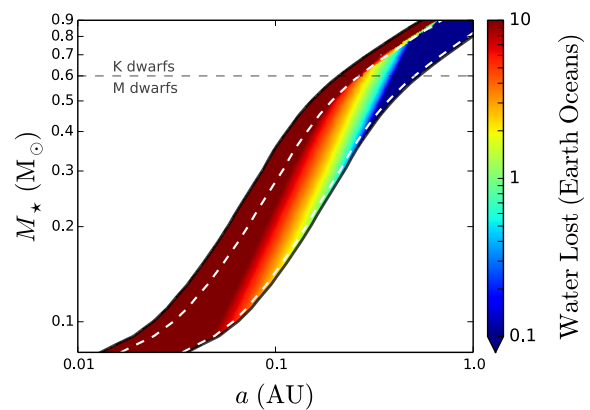
**Model Description:** We couple stellar evolution models [2,5] to energy-limited and diffusion-limited models of hydrodynamic escape from planetary atmospheres [6,7] to determine the evolution of the water content of terrestrial planets in the HZ of M dwarfs. We explore water loss on a grid of planet masses in the range 1-5M<sub>Earth</sub>, formation ages in the range 1-100 Myr, and stellar spectral types M9-K0.

**Results:** We show that because of the prolonged PMS phase of M dwarfs, planets in the HZs of these stars may have lost >10 Earth oceans of water early on. Water loss is significant around all M dwarfs, particularly from planets close to the inner edge of the HZ (Fig. 1), and could lead to complete desiccation of their surfaces. The escape of hydrogen to space also leads to the buildup of hundreds to thousands of bars of O<sub>2</sub> (Fig. 2). Such large amounts of oxygen could overwhelm surface sinks, leading to long-lived O<sub>2</sub>-rich atmospheres. This could pose a serious problem for biosignature detection on these planets [8].

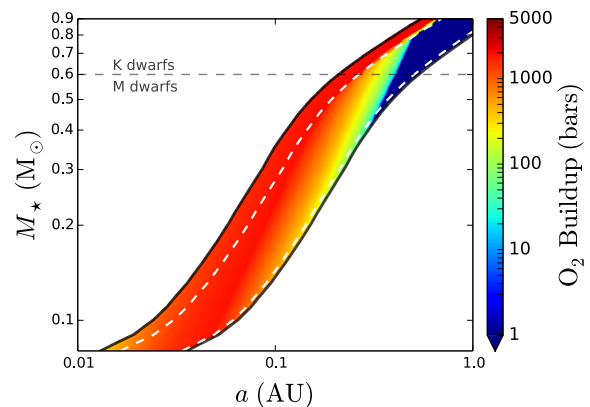
We find that both water loss and O<sub>2</sub> buildup scale with planet mass, and are particularly severe for super-Earths. As a result, many recently discovered super-Earths in the HZs of M dwarfs, such as GJ 667Cc, could be completely desiccated and/or have massive oxygen atmospheres. Because of the extended PMS

phase, the habitability of many M dwarf planets may be compromised.

**References:** [1] Kopparapu, R. et al. (2013) *ApJ*, 765, 131. [2] Baraffe, I. et al. (1998) *A&A*, 337, 403-412. [3] Raymond, S. et al. (2007) *ApJ*, 669, 606-614. [4] Lissauer, J. (2007) *ApJL*, 660, 149-152. [5] Ribas, I. et al. (2005) *ApJ*, 622:680-694. [6] Watson, A. et al. (1981) *Icarus*, 48:150-166. [7] Hunten, D. et al. (1987) *Icarus*, 69:532-549. [8] Schwieterman, E. et al., *in prep.*



**Fig. 1** Maximum water loss from a 5M<sub>Earth</sub> super-Earth in the HZ during the PMS phase of its host star. From left to right, the HZ is bounded by the Recent Venus and Early Mars limits; the dashed white lines are the Runaway Greenhouse and Maximum Greenhouse limits. Dark blue corresponds to negligible water loss; dark red corresponds to >10 Earth oceans. Nearly all planets in the HZs of M dwarfs may lose several oceans during the PMS phase of their stars.



**Fig. 2** Total amount of photolytic O<sub>2</sub> (in bars) retained by the planets in Fig. 1, after accounting for hydrodynamic drag of O<sub>2</sub> to space. Super-Earths around most M dwarfs may build up over 2000 bars of abiotic oxygen during the star's PMS phase.