HABITABLE EVAPORATED CORES: VIGOROUS ATMOSPHERIC ESCAPE FROM MINI-NEPTUNES IN THE HABITABLE ZONES OF M DWARFS.
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Introduction: Among the groundbreaking discoveries of the *Kepler* mission is the finding that planets larger than the Earth but smaller than Neptune are extremely common in exoplanetary systems, particularly on orbits with periods less than 100 days [1]. A likely formation scenario for these so-called "mini-Neptunes" is assembly of rocky/icy cores with gaseous envelopes followed by inward disk-driven migration [2]. Because of the extended pre-main sequence phase of M dwarfs, characterized by high extreme ultraviolet emissions [3,4], mini-Neptunes in close-in orbits around these stars may experience vigorous atmospheric escape. We study the atmospheric evolution of mini-Neptunes in the habitable zone (HZ) of M dwarfs and whether or not they may completely shed their envelopes and become "habitable evaporated cores" (HECs).

Model Description: We couple stellar evolution models [3,4] to energy-limited and radiation/ recombination-limited models of hydrodynamic escape from planetary atmospheres [5,6] to determine the evolution of the gaseous envelopes of mini-Neptunes and super-Earths in the HZs of M dwarfs. We account for thermal evolution of the envelope [7] and orbital evolution due to tidal effects [8]. We explore the evolution of mini-Neptunes on a grid of planet masses in the range 1-5M_{Earth}, envelope mass fractions between 10^{-6} and 0.5, formation/migration times in the range 1-100 Myr, stellar spectral types M9-M0, and varying semi-major axes, eccentricities, tidal quality factors, and atmospheric escape efficiencies.

Results: We find that HECs can form throughout a large portion of the HZ of M dwarfs, though the total amount of mass that a mini-Neptune can lose is highly dependent on the X-ray/extreme ultraviolet evolution of the host star, the time of migration into the HZ, the atmospheric escape efficiency, the initial orbital parameters, and the planetary surface gravity. HECs are most likely to form from mini-Neptunes less massive than about 2M_{Earth}, especially close to the inner edge of the HZ (**Fig. 1**). At higher planet masses, mini-Neptunes with more than a few percent H/He by mass cannot be evaporated within the age of the system, unless processes such as impact erosion or stellar flares are able to remove significant amounts of hydrogen. Therefore, large terrestrial super-Earths in the HZs of M dwarfs may have always been terrestrial.

Given that planets formed *in situ* in the HZs of M dwarfs may be uninhabitable [9,10], evaporation of low-mass mini-Neptunes could be a major formation mechanism for potentially habitable worlds in these environments.

References: [1] Fressin, F. et al. (2013) *ApJ*, 766:81. [2] Rogers, L. et al. (2011) *ApJ*, 738:59. [3] Baraffe, I. et al. (1998) *A&A*, 337, 403-412. [4] Ribas, I. et al. (2005) *ApJ*, 622:680-694. [5] Erkaev, N. et al. (2007) *A&A,* 472:329-334. [6] Murray-Clay, R. et al. (2009) *ApJ,* 693:23-42. [7] Lopez, E. and Fortney, J. (2014) *ApJ*, 792:1. [8] Barnes, R. et al. (2013) *Astrobiology*, 13:225-250. [9] Lissauer, J. (2007) *ApJL*, 660, 149-152. [10] Luger, R. and Barnes, R. (2015) *Astrobiology,* 15:119-143.

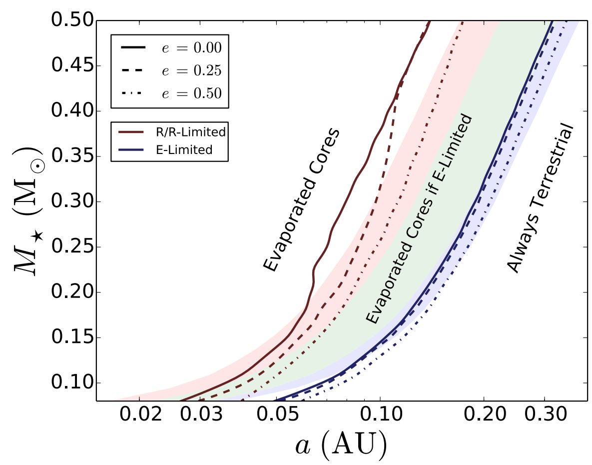

Fig. 1 Results of a grid of evolution models of 2M_{Earth} mini-Neptunes in the HZ of M dwarfs. The red, green, and blue shaded regions denote the inner, central, and outer HZ, respectively. Contour lines separate regions where mini-Neptunes can be completely evaporated (to the left) from regions where their gaseous envelopes are always retained (to the right). Red lines correspond to radiation/ recombination-limited escape; blue lines correspond to energy-limited escape. Line styles correspond to different initial eccentricities. In the energy-limited regime, HECs can form throughout most of the HZ of M dwarfs. However, if escape is limited by radiation/recombination, HECs can only form close to the inner edge of the HZ of low mass M dwarfs and/or from mini-Neptunes on highly eccentric initial orbits. At higher planet masses, HEC formation is similarly inhibited.