Habitable Evaporated Cores

Converting Mini-Neptunes into Super-Earths in the Habitable Zone of M Dwarfs

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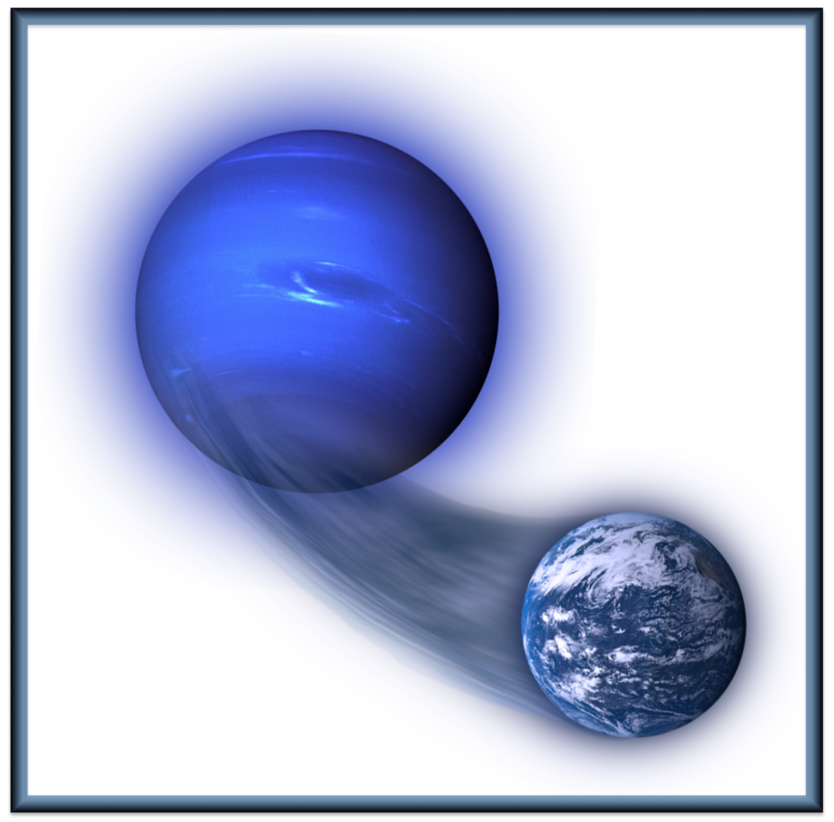

The low masses and luminosities of M dwarfs make them ideal targets for the detection of terrestrial planets in the habitable zone (HZ[1]). However, studies suggest that planets formed only from material in the HZs of these stars are likely to be small and dry[2,3]. Moreover, the long contraction phase of M dwarfs results in these stars being superluminous for as long as 1 Gyr **(Figure 3)**, exposing planets that will eventually be in the HZ to extreme levels of radiation. Earth-like planets in this regime will enter a runaway greenhouse and may be completely desiccated by H loss to space, particularly around late M dwarfs **(Figure 4)**.

As a result, habitable planets around M dwarfs may preferentially form from bodies that migrate into the HZ from beyond the snow line. These planets are enhanced in volatiles and may have accreted large H/He envelopes, which could help shield the surface from the extreme radiation environment early on. In this study, we show that photoevaporation and Roche lobe overflow of migrating "mini-Neptunes" can lead to the complete loss of their gaseous envelopes, transforming them into potentially habitable worlds, which we call ***habitable evaporated cores* (HECs)**. We couple planet structure evolution models[4] with a simple Roche lobe overflow scheme and an extreme ultraviolet (XUV)-induced mass loss model[5,6]. We also couple the orbital effects of anisotropic mass loss with tidal evolution[7] and show that this coupling can lead to orbital changes that significantly enhance the mass loss rate.

HECs are most likely to form from small mini-Neptunes ($\lesssim 4\ M_\oplus$) with large ($\lesssim 50\%$) initial hydrogen fractions orbiting M4 stars and later. Given the steep decrease in stellar XUV flux with time[8], mass loss is negligible after ~1 Gyr, at which point a habitable evaporated core is capable of degassing and maintaining a secondary atmosphere. This process may be one of the dominant formation mechanism for habitable planets around M dwarfs, and may be discovered by missions such as TESS and PLATO.

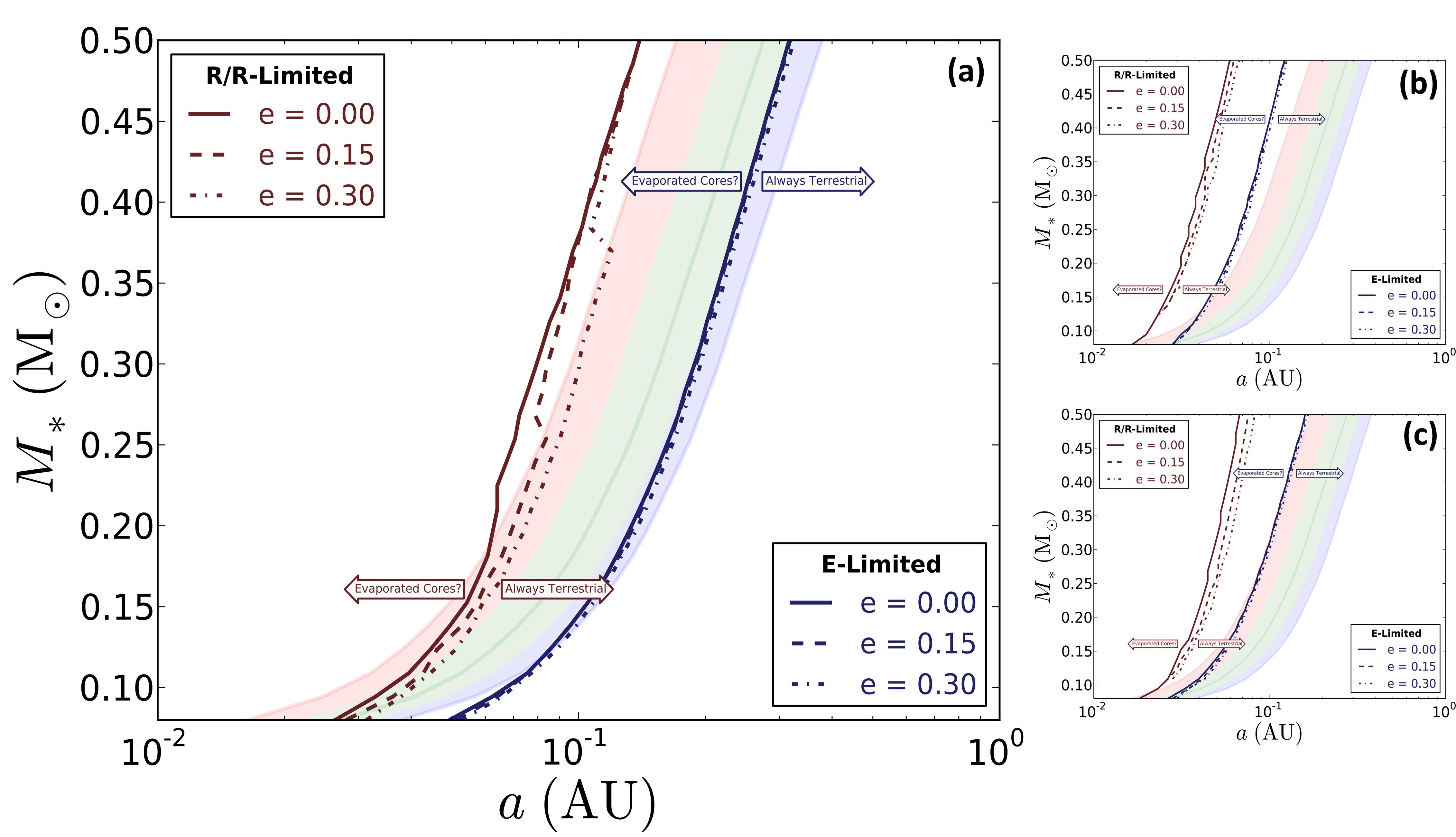

Figure 1: Regions of parameter space that may be populated by HECs. Terrestrial planets detected today occupying the space to the *left* of each contour line could be the evaporated cores of gaseous planets. Planets detected to the *right* of the contour lines have always been terrestrial/gaseous. Dark red lines correspond to mass loss dominated by radiation/recombination-limited escape, while dark blue lines correspond to the more vigorous energy-limited mechanism. Which mechanism operates will depend on the ratio of stellar EUV to X-ray luminosity[9]. Different line styles correspond to different eccentricities today. Terrestrial planets detected at higher eccentricity (dashed and dash-dotted lines) could be evaporated cores at slightly larger orbital separations than planets detected on circular orbits (solid lines). In the energy-limited regime, all $1 M_\oplus$ terrestrial planets in the HZ of low-mass M dwarfs could be habitable evaporated cores. **(a): The default run**, for $M_{core} = 1 M_\oplus$ and $M_H \leq 1 M_\oplus$. **(b): Weak XUV run**, for $t_{sat} = 0.1$ Gyr and $\varepsilon_{XUV} = 0.15$. **(c): Super-Earth**, with $M_{core} = 2 M_\oplus$ and $M_H \leq 2 M_\oplus$.

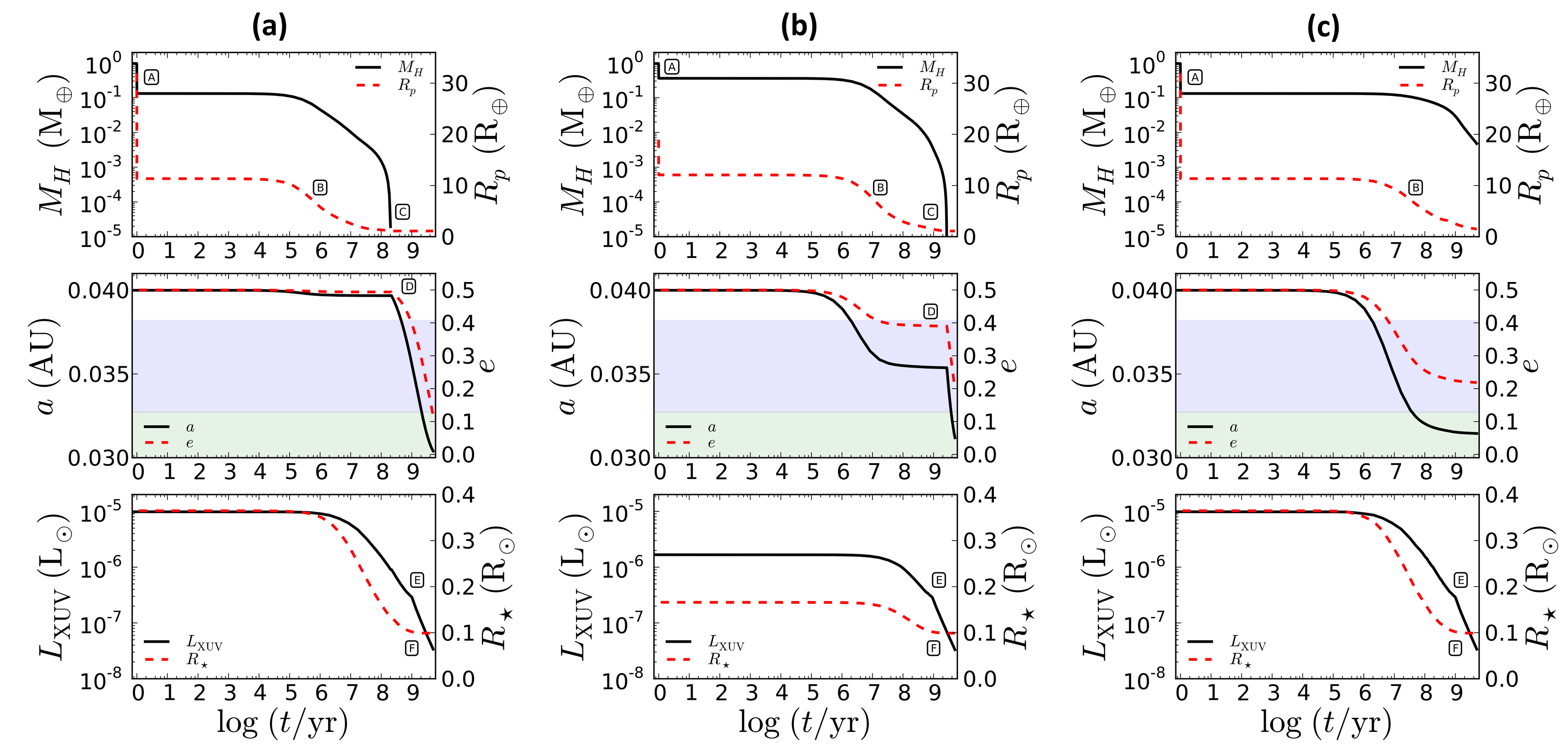

Figure 2: Three sample integrations of our code, showing envelope mass (M_H), planet radius (R_p), semi-major axis (a), eccentricity (e), stellar XUV luminosity (L_{XUV}) and radius (R_*) as a function of the time t since formation. The planet is initially a 1 $M_\oplus$ core with a 1 $M_\oplus$ envelope orbiting a 0.08 $M_\odot$ M-dwarf with $e = 0.5$ at a semi-major axis of 0.04 AU, just outside the OHZ (outer HZ; light blue shading). As it loses mass and tidally evolves, it migrates into the CHZ (center HZ; light green shading). **(a): Energy-limited escape.** The planet loses its entire envelope at $t \approx 100$ Myr. **(b): Late migration**, with $t_0 = 100$ Myr. While the envelope still completely evaporates, this occurs at a much later time, $t \approx 2$ Gyr. **(c): Radiation/recombination-limited escape.** Here, the envelope does not fully evaporate and tidal migration is noticeably weaker.

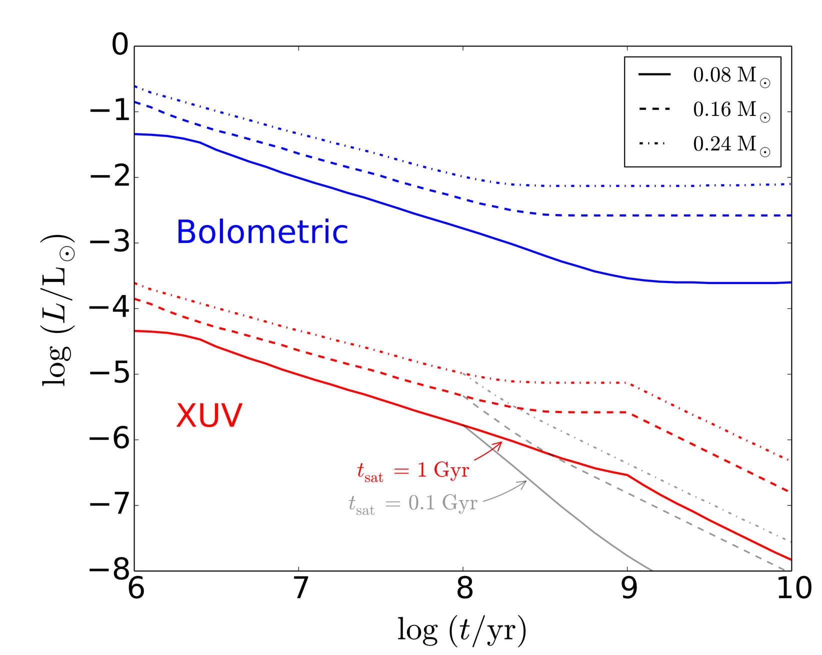

Figure 3: Evolution of the bolometric (blue) and XUV (red) luminosity for three different stellar masses (solid: $0.08 M_\odot$; dashed: $0.16 M_\odot$; dash-dotted: $0.24 M_\odot$) as a function of time. Two XUV saturation times are shown: 1 Gyr (red) and 0.1 Gyr (grey). Note the several order-of-magnitude drop in the first ~1 Gyr for the latest M dwarfs.

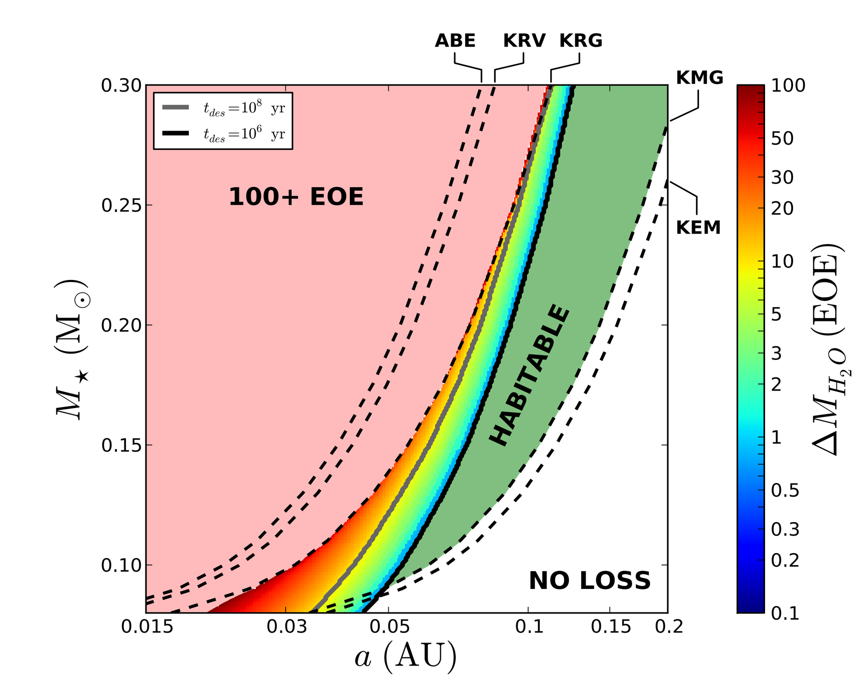

Figure 4: Mirage Earths? Because of the long contraction phase of late M dwarfs, Earths formed in situ in the HZ may lose several Earth Ocean Equivalents (EOE) of water in the first ~100 Myr, rendering them dry and uninhabitable. The latest M dwarfs may not have a HZ for Earths formed in situ.

Parameter	Range	Default
$M_\star(M_\odot)$	$0.08 - 0.4$	-
$M_p(M_\oplus)$	$1 - 10$	-
$R_{XUV}(R_p)$	$1.0 - 1.2$	1.2
a	IHZ - OHZ	-
e	0.0 - 0.9	-
$P_{0,\star}$ (days)	$1.0 - 100$	30.0
f_H	$10^{-6} - 0.5$	-
ϵ_{XUV}	$0.1 - 0.4$	0.3
ξ_{min}	$1 + 10^{-5} - 3$	3
Atmos. esc.	R/R-Lim / E-Lim	-
Tidal model	CPL/CTL	CTL
$Q_\star$	$10^5 - 10^6$	10^5
Q_p	$10^1 - 10^5$	10^4
$\tau_\star$ (s)	$10^{-2} - 10^{-1}$	10^{-1}
τ_p (s)	$10^{-3} - 10^3$	10^{-1}
β	$0.7 - 1.23$	1.23
t_{sat} (Gyr)	$0.1 - 1.0$	0.1
t_0 (Myr)	$10.0 - 100.0$	10.0
t_{stop} (Gyr)	$0.01 - 5.0$	5.0

Table 1: A list of free parameters and their ranges, as well as default values used in the plots.

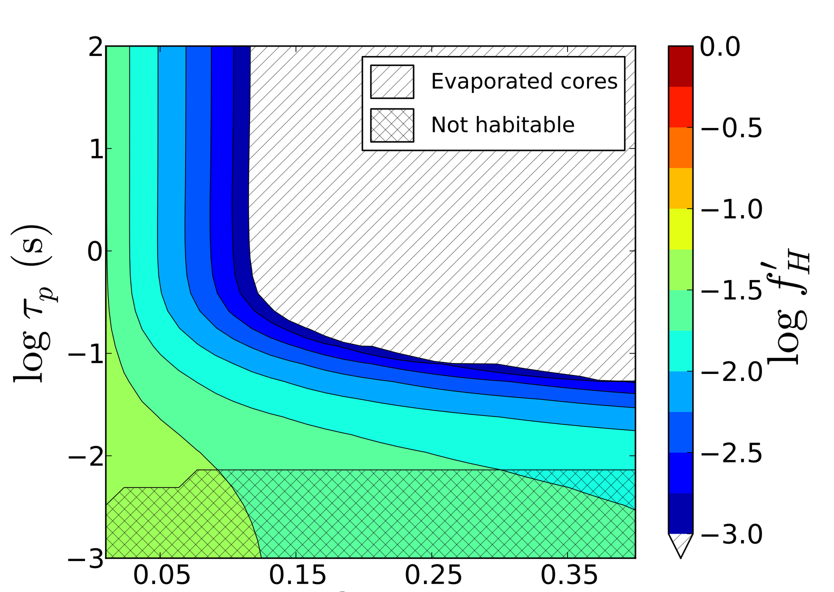

Figure 5: Final H fraction as a function of XUV absorption efficiency and tidal time lag for a sample run of our code. Mass loss and tidal evolution are strongly coupled in these systems.

References

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