Photodissociation-Driven Mass Loss from Young and Highly-Irradiated Exoplanets

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Abstract

The most widely-studied mechanism of mass loss from extrasolar planets is photoevaporation via XUV ionization, primarily in the context of highly irradiated planets. However, the EUV dissociation of hydrogen molecules can also theoretically drive atmospheric evaporation on low-mass planets. For temperate planets such as the early Earth, impact erosion is expected to dominate in the traditional planetesimal accretion model, but it would be greatly reduced in pebble accretion scenarios, allowing other mass loss processes to be major contributors. We apply the same prescription for photoionization to this photodissociation mechanism and compare it to an analysis of other possible sources of mass loss in pebble accretion scenarios. We find that there is not a clear path to evaporating the primordial atmosphere accreted by an early Earth analog in a pebble accretion scenario. Impact erosion could remove ~2,300 bars of hydrogen if 1% of the planet's mass is accr eted as planetesimals, while the combined photoevaporation processes could evaporate ~750 bars of hydrogen. Photodissociation is likely a subdominant, but significant component of mass loss. Similar results apply to super-Earths and mini-Neptunes. This mechanism could also preferentially remove hydrogen from a planet's primordial atmosphere, thereby leaving a larger abundance of primordial water compared to standard dry formation models. We discuss the implications of these results for models of rocky planet formation including Earth's formation and the possible application of this analysis to mass loss from observed exoplanets.

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Motivation:

The theory of atmospheric loss from highly-irradiated exoplanets is predominantly focused on X-ray and EUV photoionization of hydrogen early in the planet's history, starting with Watson et al. (1981). However, longer-wavelength FUV radiation can also cause atmospheric loss through photodissocation of hydrogen. The FUV flux from sun-like stars is greater than the XUV flux and continues throughout their lives, potentially resulting in greater mass loss than has previously been predicted (Claire et al., 2012). This process has long been studied for Solar System planets (e.g. Dayhoff et al., 1967), but not for exoplanets. In conventional models of planet formation, impact erosion resulting from planetesimal accretion will dominate over photoevaporation (ionization and dissociation) for less irradiated planets (Schlichting et al., 2015), but in pebble accretion models, in which planets are formed before the gas disk dissipates via the streaming instability (Bitsch et al. 2015), impact erosion is probably less important, and photoevaporation processes should be considered.

Model:

We modeled six important atmospheric loss mechanisms for a young, Earth-like planet that forms with 2% hydrogen by mass. These processes are illustrated below: (a) Jeans escape, (b) thermal wind and outflow, (c) stellar wind ablation, (d) impact erosion, (e) photoionization, and (f) photodissociation. (We do not consider magnetic effects in this work.) The colors in Fig. 1 are arbitrary and have been chose to illustrate the difference between photo-ionization and photodissociation.

Using analytic and semi-analytic approximations, we estimated the expected mass loss over the early life (500 Myr years) and then the full lifespan of a planet. By varying the amount of stellar irradiation and the ratio of (thermal) FUV to XUV, we are able to model planets orbiting at different distances from stars of different types.

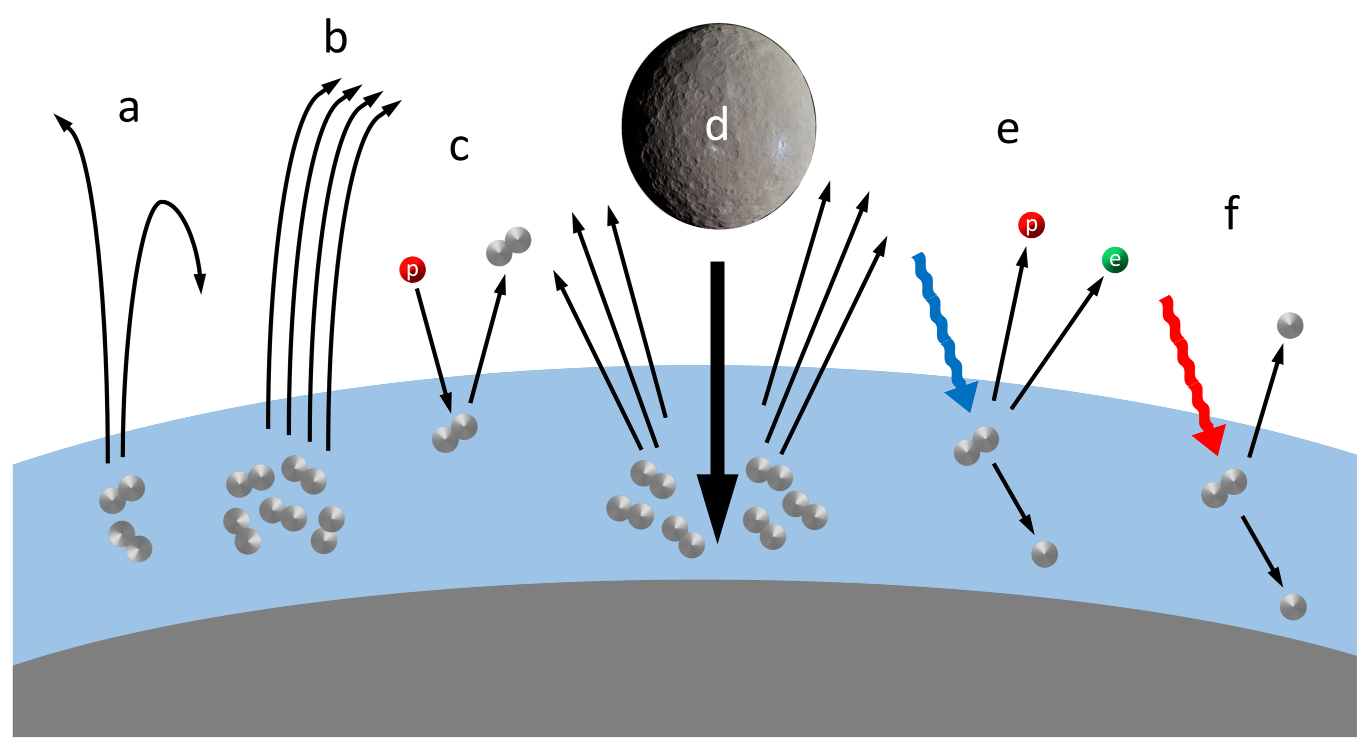

Figure 1: Atmospheric mass loss processes considered in our simulations.

Results:

In a pebble accretion scenario, ***photodissociation is a significant contributor the atmosphere loss from a young, Earth-like planet***,

Process	Mass Removed (bars)	Mass Removed ($10^{-6}\,M_\oplus$)
Jeans Escape	0.6	50
Stellar Wind Ablation	20	8
Impact Erosion[1]	2,300	2,000
Photoionization	712	619
Photodissociation	34	30
Total	3,067	2,700

The computed mass loss due to various processes for a young Earth-analog planet. We employ a plausible upper bound of 0.01 $M_\oplus$ of the planet's mass delivered as giant impactors (cf. Liu et al, 2019). In contrast, this is a *lower* bound for photodissociation, assuming the combined heating efficiency for photoionization and dissociation ~10%. As there are two pathways involved, the total efficiency my be significantly higher.

Starting from a quasi-uniform planetary population over the parameter space observed by e.g. *Kepler* and *TESS* (Fig. 2), we model photoevaporation for Earth-analog planets with a standard efficiency of 10% (Fig. 3) and an optimistic efficiency of 25% (Fig. 4) incorporating photodissociation. The "evaporation valley" (Owen & Wu, 2017) is marked in blue.

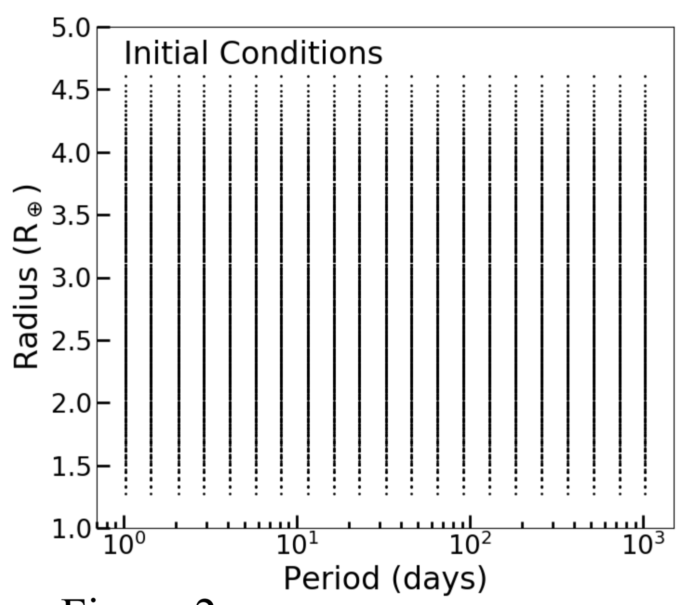

Figure 2

Our model is consistent with observations of the evaporation valley (Owen & Wu, 2017). (Based on the density of the final mass-radius distributions. Discrepancies in the "sub-Neptune desert" are caused by the non-naturalistic initial population.) This pattern may be different for M-dwarfs or for giant impacts.

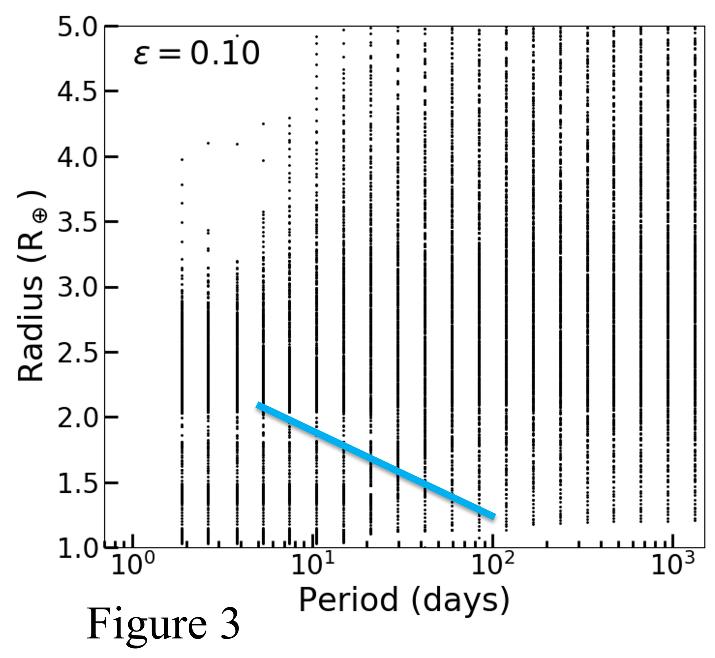

Figure 3

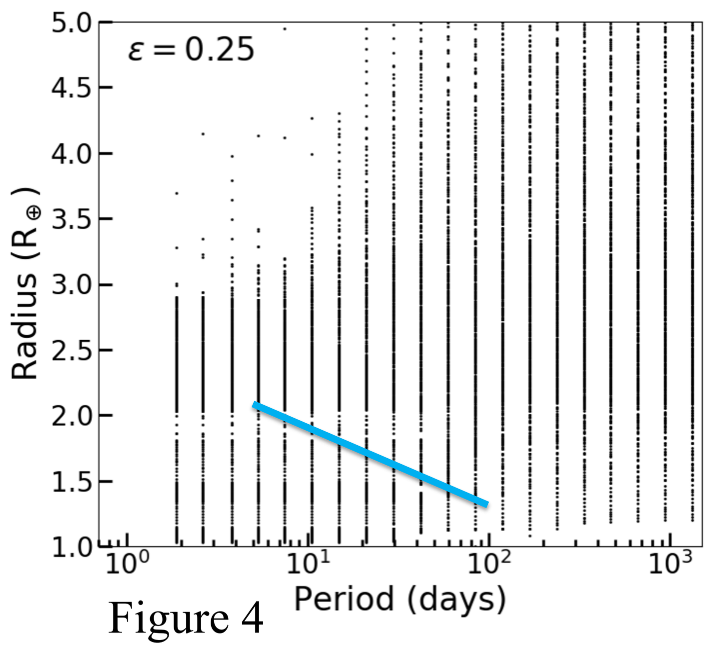

Figure 4

Take-away Message:

- ***Photodissociation of molecular species can be a significant source of mass loss in the early evolution of temperate planetary atmospheres in addition to photoionization.***
- There is no clear path to evaporating bulk primordial hydrogen and helium from an early Earth.
- Impact erosion may be a significant process in pebble accretion models.
- Better UV measurements of M-dwarfs and the mass-radius-period distribution for M-dwarf planets will help test more accurate mass loss models.
- ***FUV dissociation predicts mass loss on young, hot planets that is consistent with the observed evaporation valley.***

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More information can be found at:
https://sites.lsa.umich.edu/feps/

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