# The Role Atmospheric Escape Plays in Sculpting Planet Populations: The Kepler 36-b Case

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## Contents

# 1 Introduction

Since the launch of NASA's Kepler/K2 mission and subsequently the NASA TESS mission, thousands of exoplanets have been discovered and have shed light on interesting planet populations. For example, planets that are close-in to their host star and fall between 8.0 - 24 Earth radii are considered Hot-Jupiters, planets ranging from 1.0 - 1.7 Earth radii are referred to as Super-Earths while 1.7 - 4.0 Earth radii are categorized as Sub-Neptunes (Weiss et al., 2023). Analysis of theses of these discovered planets have revealed interesting features such as the radius valley, a dearth of planets between 1.5 - 2.0 earth radii (Fulton et al., 2017). The origin of these populations remains widely debated but theories involving atmospheric escape processes have been proposed to explain their emergence. One such process is photoevaporation or XUV irradiation and occurs when the radiation from a host star strips the planet's atmosphere. The other process is core-powered mass loss which is a combination of the stellar bolometric flux and the remaining thermal energy from planet formation released from the core to the atmosphere. The key difference between both of these processes is the timescale at which they happen - photoevaporation is said to occur during the first few million years, when the host star's radiation is the strongest, as opposed to the billion-year timescale proposed by the core-powered mass loss theory. A deeper understanding of how these aforementioned processes sculpt planet populations or give rise to new populations can help improve our theories of planet formation and evolution. In this paper, we will focus on the photoevaporation theory and briefly explore two types of different atmospheric escape models that simulate stellar irradiation over time.

# 2 Modeling The Effects of Atmospheric Escape Caused by Stellar Irradiation

## 2.1 The Photoevaporation Theory

Photoevaporation is the process by which stellar irradiation (XUV and X-rays) heats the upper layers of a planet's atmosphere to the point where it begins dissipating or "escaping" into space. Specifically, the host star's intense radiation interacts with the gas in the planet's upper atmosphere and begins to ionize it to the point where these gas molecules reach the planet's escape velocity and are ejected from the atmosphere into space. Over time, a planet can be completely stripped of its atmosphere due to the continuous amount of radiation it receives from its host star. The amount of time it takes for this to happen can vary with the planet's mass, proximity to its host star among other factors.

## 2.2 The VPLanet 'Atm Esc' Model

The 'Atm Esc' model from VPLanet is based on the energy-limited model (Watson et al., 1981), which describes the physical process of planet atmospheric escape due to stellar

XUV photons (1-1000 Angstroms) energizing the upper atmosphere. Specifically, the model calculates the rate particles are escaping the planet's atmosphere depending on the atmospheric composition. For a hydrogen-dominant atmosphere, the model becomes:

$$F_{\mathrm{EL}} = \frac{\epsilon_{\mathrm{XUV}} \mathcal{F}_{\mathrm{XUV}} R_p}{4 G M_p K_{\mathrm{tide}} m_{\mathrm{H}}} \tag{1}$$

where $F_{\mathrm{EL}}$ is the particle escape rate, $\mathcal{F}_{\mathrm{XUV}}$ is the XUV energy flux, $\epsilon_{\mathrm{XUV}}$ is the XUV absorption efficiency, $R_p$ is the planet radius, $M_p$ is the planet mass, $K_{\mathrm{tide}}$ is the tidal correction term of order unity (Erkaev et al., 2007) and $m_{\mathrm{H}}$ is the mass of a hydrogen atom. The equation can vary on the type of atmosphere

## 2.3 Using Two Different Types of Atmospheric Escape Models

When using VPL, you have the option of changing many of the default features of the 'Atm Esc' model, such as the stellar model in charge of tracking the evolution of stellar properties such as the luminosity, XUV luminosity, effective temperature, or radius. The input of the planet properties can also be modified and modeled differently depending on the atmosphere type desired (a hydrogen atmosphere envelope or a water vapor atmosphere envelope). In our case, we will focus on a hydrogen-dominated atmosphere and use two different models that calculate the atmospheric escape rate slightly differently. The first model is from Lopez et al. (2012), where they investigate how thermal evolution and XUV-driven atmospheric mass loss shape the compositions of low-mass exoplanets, such as super-Earths and sub-Neptunes. Here, the energy-limited rate of XUV-driven atmospheric escape is defined as,

$$\dot{M}_{e\text{–lim}} \approx \frac{\epsilon \pi F_{\mathrm{XUV}} R_{\mathrm{XUV}}^3}{G M_p K_{\mathrm{tide}}} \tag{2}$$

$$K_{\mathrm{tide}} = \left(1 - \frac{3}{2\xi} + \frac{1}{2\xi^3}\right) \tag{3}$$

$$\xi = \frac{R_{\mathrm{Hill}}}{R_{\mathrm{XUV}}} \tag{4}$$

where $K_{\mathrm{tide}}$ is a correction factor that accounts for the reduced gravitational binding at the Hill radius, where mass only needs to reach this distance to escape (Erkaev et al., 2007). The second model is from Lehmer & Catling (2017), where the energy-limited rate of XUV-driven atmospheric escape is defined as,

$$\frac{dM}{dt} = \frac{\eta \pi F_{\mathrm{XUV}} R_{\mathrm{XUV}}^3}{G M_p} \tag{5}$$

$$R_{\mathrm{XUV}} = \frac{R_s^2}{H \ln(p_{\mathrm{XUV}}/p_s) + R_s} \tag{6}$$

$$R_s = 1.3 M_p^{0.27} \tag{7}$$

where $R_{\text{XUV}}$ is defined as the radial distance from the planetary center where the optical depth for broadband XUV radiation equals unity, H is the scale height, $p_{\text{XUV}}$ is the pressure at the base of the thermosphere, and $P_S$ is the pressure at the surface, $R_S$ is the surface radius of the rocky core. In Lehmer & Catling (2017), they found a 1.8 Earth radii cutoff for close-in (100 day orbits) rocky planets affected by stellar XUV irradiation, consistent with observations found by Fulton et al. (2017).

### 2.4 Our VPL "Atm Esc" Model Setup

For this work, we choose to compare the Lopez et al. (2012) and Lehmer & Catling (2017) models to see the differences in their atmospheric escape rate calculations. For the Lehmer & Catling (2017) model, the key parameter is $R_{\text{XUV}}$ and is directly calculated using a hydrostatic equilibrium model, assuming a fixed pressure at the base of the thermosphere. They integrate this value into the escape rate formula, where $R^3_{\text{XUV}}$ dominates the rate. For the Lopez et al. (2012) model, the most important parameter is the $K_{\text{tide}}$ parameter and is most significant when the host star is young (first few million years), when the XUV radiation is at its strongest. During this time, the radius of the planet is also at its largest due to its newly formed conditions therefore leading to large stripping of the planet's atmosphere. Some limitations the Lopez et al. (2012) model presents is the uncertainty involving the EUV spectrum (100 - 1200 Angstroms). The observations do not account for this part of the spectrum for stellar ages between 10 - 100 Myr and therefore it cannot be reliably said that the XUV radiation is constant or saturated during the entire first Gyr. The limitation for the Lehmer & Catling (2017) model lies with the percentage amount of the gas envelope. Within both models, the only parameter varied was the XUV absorption efficiency, $\epsilon_{\text{XUV}}$, between values 0.01 and 1.0 (the default value being 0.1). This parameter represents the fraction of the incident XUV energy that is effectively used to heat the atmosphere and drive hydrodynamic escape and therefore has a directly correlation to the escape rate.

## 3 VPLanet Model Results

In Figure 1, we reproduce the results found in Lopez & Fortney (2013) using the same models used by that work, showing the percentage of Kepler 36-b's atmosphere envelope stripped due to XUV-driven atmospheric escape as a function of the planet's core mass, initial envelope mass and initial total mass (the core mass + envelope mass). Based on their results, the core mass has the greatest influence as to whether or not a planet is ultimately able to maintain its atmosphere and/or how quickly it loses it. In Figure 2, the model now reflects the one used in the Lehmer & Catling (2017). In Figure 3, 4, 5, and 6, we now vary the XUV efficiency factor, $\epsilon_{\text{XUV}}$, between the values 0.01 and 1.0 for both the Lopez & Fortney (2013) and Lehmer & Catling (2017) models.

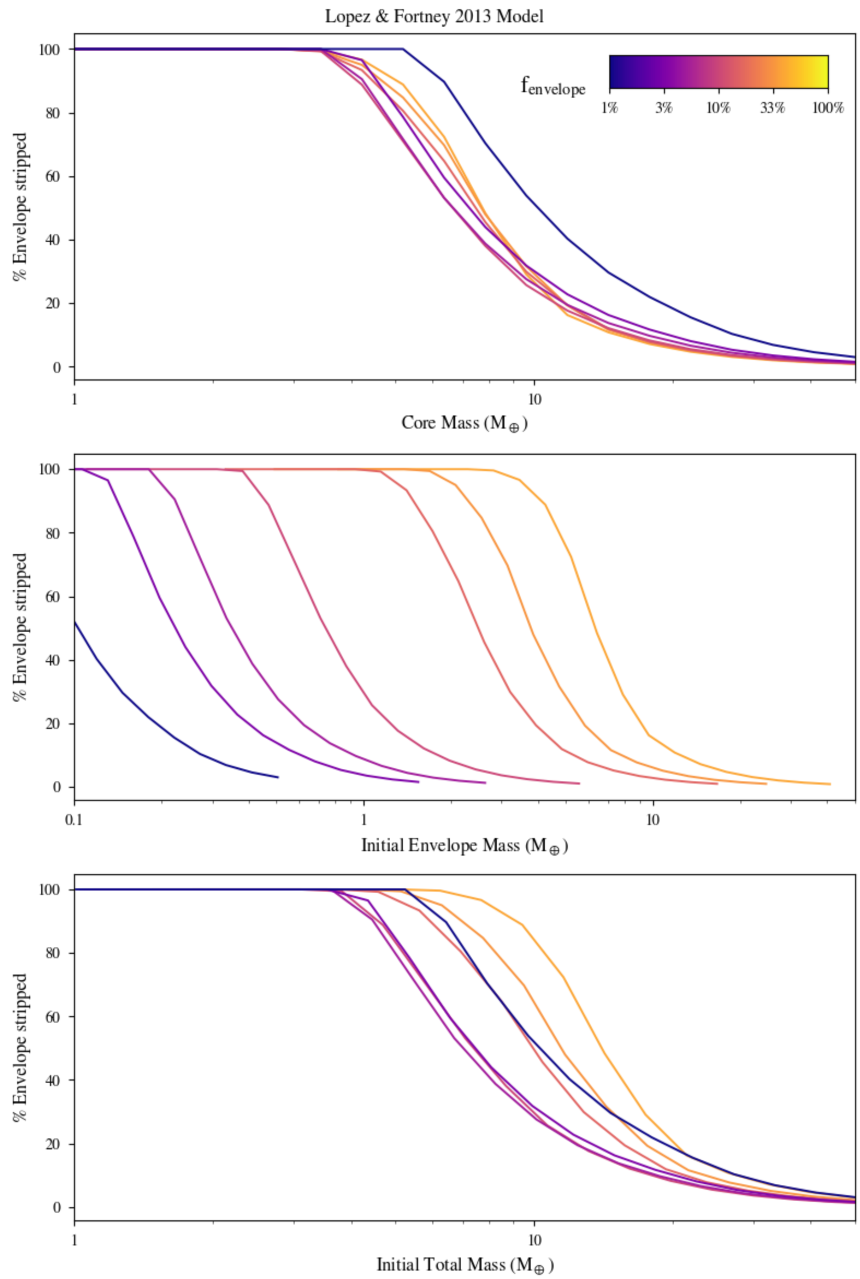


Figure 1: The % of the atmospheric envelope stripped as a function of core mass, initial envelope mass and initial total mass using the Lopez et al. (2012) model.

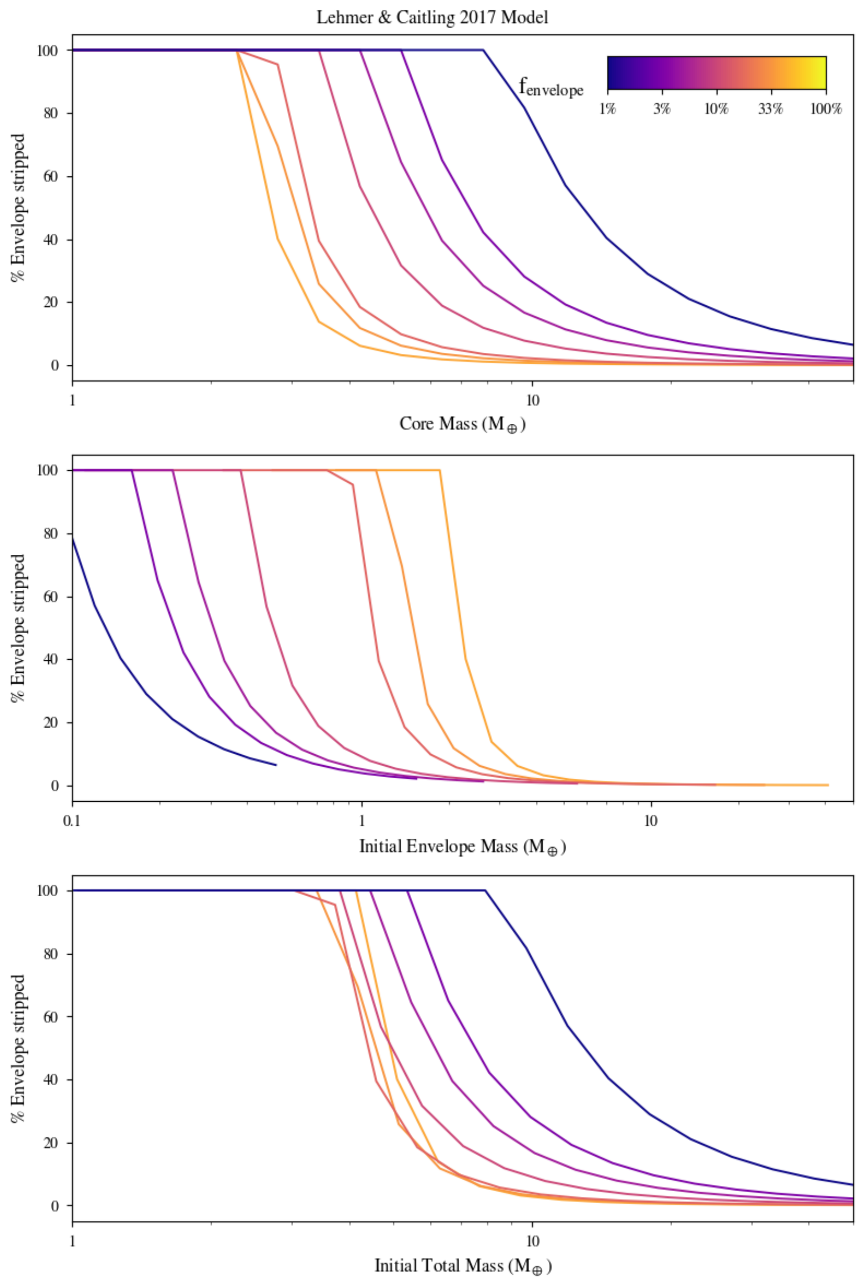


Figure 2: Like in Figure 1, but using the Lehmer & Catling (2017) model instead.

# 4 Discussion and Summary

## 4.1 Discussion

One of the primary observations is the strong dependence of atmospheric stripping on the XUV absorption efficiency ($\epsilon_{XUV}$). For higher $\epsilon_{XUV}$ values (e.g., $\epsilon_{XUV} = 1.0$), planets with low core masses experience rapid and near-complete envelope loss, highlighting their susceptibility to stellar irradiation. Conversely, at lower $\epsilon_{XUV}$ values ($= 0.01$), atmospheric retention increases substantially across all core masses, reducing the degree of atmospheric escape. For our analysis, we chose to focus solely on the core mass since its found to be the dominant parameter influencing atmospheric retention. Based on the results from Figures 3, 4, 5, and 6, it can be observed that it takes much longer for the planet to lose its atmosphere at $\epsilon_{\mathrm{XUV}}$ = 0.01 compared to when $\epsilon_{\mathrm{XUV}}$ = 1.0, consistent with the findings in the Lopez & Fortney (2013) and Lehmer & Catling (2017). A noticeable transition occurs for planets with core masses exceeding approximately $5M_{\oplus}$, where the percentage of stripped atmosphere drops significantly, indicating their increased resilience to photoevaporation. This trend is evident in both models but is more pronounced in the Lehmer & Catling (2017) model due to its explicit dependence on the radial distance of the atmosphere ($R_{XUV}$). The Lopez et al. (2012) model predicts a more gradual decrease in atmospheric stripping with increasing core mass, which is influenced by the tidal correction factor ($K_{tide}$). This factor becomes particularly relevant for younger systems where XUV radiation is at its peak and planetary radii are larger. In contrast, the Lehmer & Catling (2017) model predicts more aggressive stripping for low-mass planets, with its results aligning with observational studies such as the radius valley at $1.8R_{\oplus}$. This model emphasizes the role of atmospheric height ($R_{XUV}$) in determining escape rates, capturing key physical processes that dominate in close-in planetary environments. The fraction of the initial atmospheric envelope ($f_{envelope}$) also plays a critical role. Planets with larger initial envelopes ($f_{envelope} > 33\%$) tend to lose a significant portion of their atmospheres, while those with smaller envelopes are more resistant to complete erosion. This finding underscores the importance of initial atmospheric conditions in determining a planet's long-term evolution and habitability. These results support the hypothesis that photoevaporation is a key mechanism shaping planetary populations, particularly in the creation of the radius valley. Planets near the $1.8R_{\oplus}$ boundary are likely remnants of substantial atmospheric stripping, consistent with the predictions of both models. However, the differences between the models indicate the need for further observational constraints, particularly on XUV luminosity histories and atmospheric compositions, to refine our understanding of these processes.

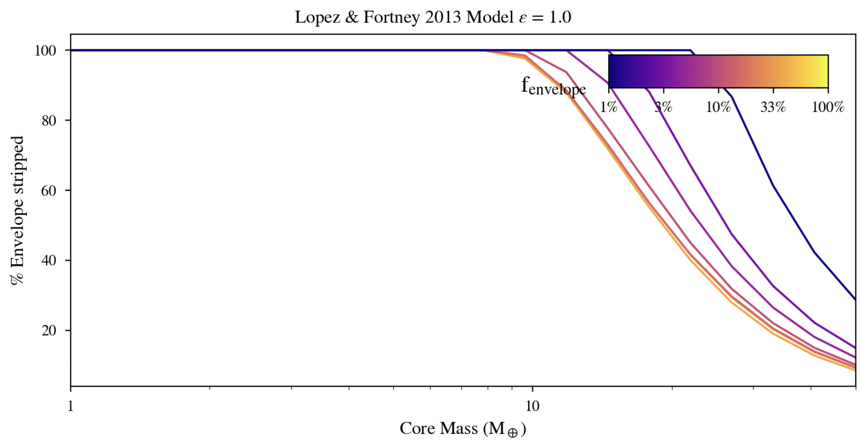


Figure 3: The % of the atmospheric envelope stripped as a function of core mass using the **?** with $\epsilon_{XUV}$ = 1.0

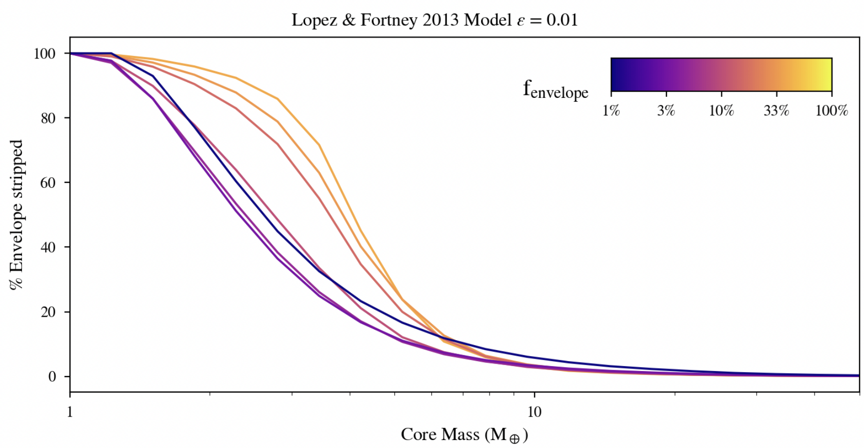


Figure 4: The % of the atmospheric envelope stripped as a function of core mass using the **?** model with $\epsilon_{XUV}$ = 0.01

## 4.2 Summary and Conclusions

In conclusion, this study demonstrates that both the Lopez & Fortney (2013) and Lehmer & Catling (2017) models offer valuable insights into the impact of photoevaporation on planetary atmospheres. While variations in their methodologies result in differing predictions, the role of core mass and XUV absorption efficiency is consistently emphasized as critical factors in determining the degree of atmospheric loss. These findings contribute to our broader understanding of planetary formation and evolution, providing a framework for interpreting future exoplanet observations.

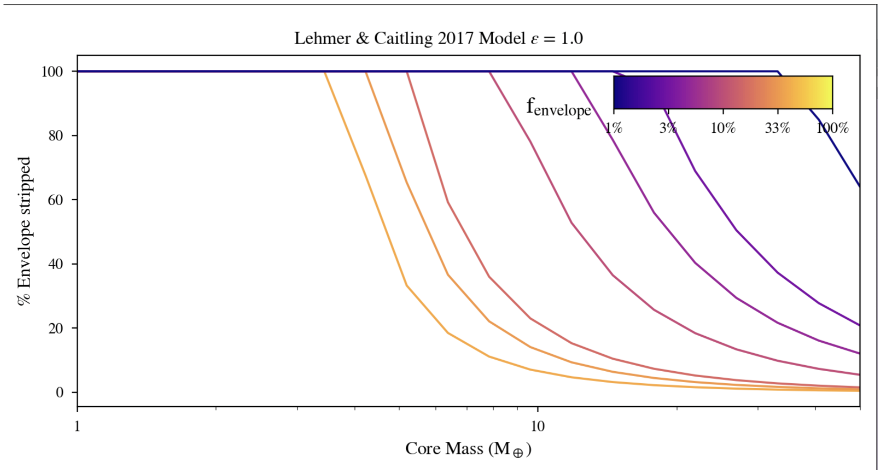


Figure 5: The % of the atmospheric envelope stripped as a function of core mass using the Lehmer & Catling (2017) model with $\epsilon_{\mathrm{XUV}} = 1.0$

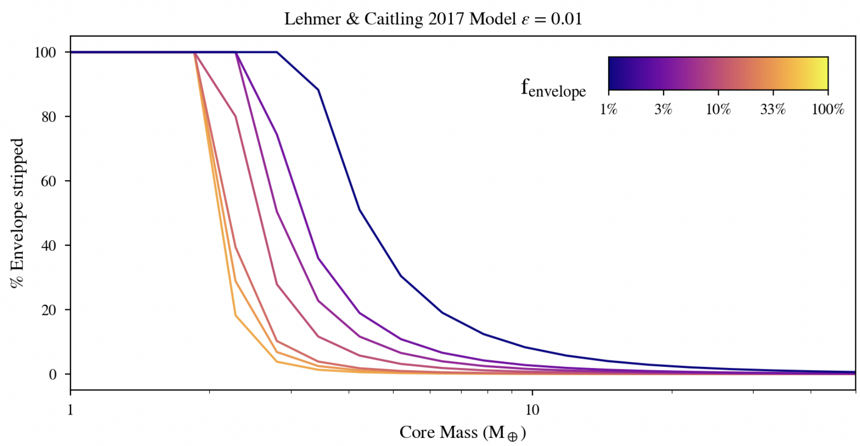


Figure 6: The % of the atmospheric envelope stripped as a function of core mass using the Lehmer & Catling (2017) model with $\epsilon_{\mathrm{XUV}} = 0.01$

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