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# The Evolution of Atmospheric Escape of Highly Irradiated Gassy Exoplanets

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**Abstract.**
Atmospheric escape has traditionally been observed using hydrogen Lyman-$\alpha$ transits, but more recent detections utilise the metastable helium triplet lines at 1083nm. Capable of being observed from the ground, this helium signature offers new possibilities for studying atmospheric escape. Such detections are dependent however on the specific high-energy flux received by the planet. Previous studies show that the extreme-UV band both drives atmospheric escape and populates the triplet state, whereas lower energy mid-UV radiation depopulates the state through photoionisations. This is supported observationally, with the majority of planets with 1083nm detections orbiting a K-type star, which emits a favourably high ratio of EUV to mid-UV flux. The goal of our work is understanding how the observability of escaping helium evolves. We couple our one-dimensional hydrodynamic non-isothermal model of atmospheric escape with a ray-tracing technique to achieve this. We consider the evolution of the stellar radiation and the planet's gravitational potential.

**Keywords.** hydrodynamics

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## 1. Introduction

Since the first detections of escaping helium by means of metastable helium triplet 1083nm transit observations (Nortmann et al. 2018; Spake et al. 2018; Allart et al. 2018), there have been over 15 detections as well as constraints set by non-detections. Both theoretically and observationally, K-type host stars have been found to be favourable for producing such detections due to their relatively low mid-UV flux which depopulates the helium triplet state and high EUV flux which populates the state through photoionisations followed by recombinations (Oklopčić 2019; Poppenhaeger 2022). During the lifetime of a planet, the emitted flux and the planetary radii both vary. In Allan et al. (in prep), we study how such evolutionary variations affect the resulting escape and the corresponding helium 1083nm observational signature.

## 2. Solving helium populations self-consistently vs. post-processingly

Our model (Allan et al. in prep) for hydrodynamic escape is an upgraded version of the hydrogen-only version first presented in Allan & Vidotto (2019) which was based on the model of Murray-Clay et al. (2009). We have also updated the ray-tracing technique for simulating spectroscopic transits used in Allan & Vidotto (2019) to be capable of modelling the helium triplet 1083nm signature. We invite the reader to check Allan et al. (in prep) for a more detailed description of the work. Figure 1 briefly summarises our model for hydrodynamic atmospheric escape. In short, our hydrodynamic model uses a

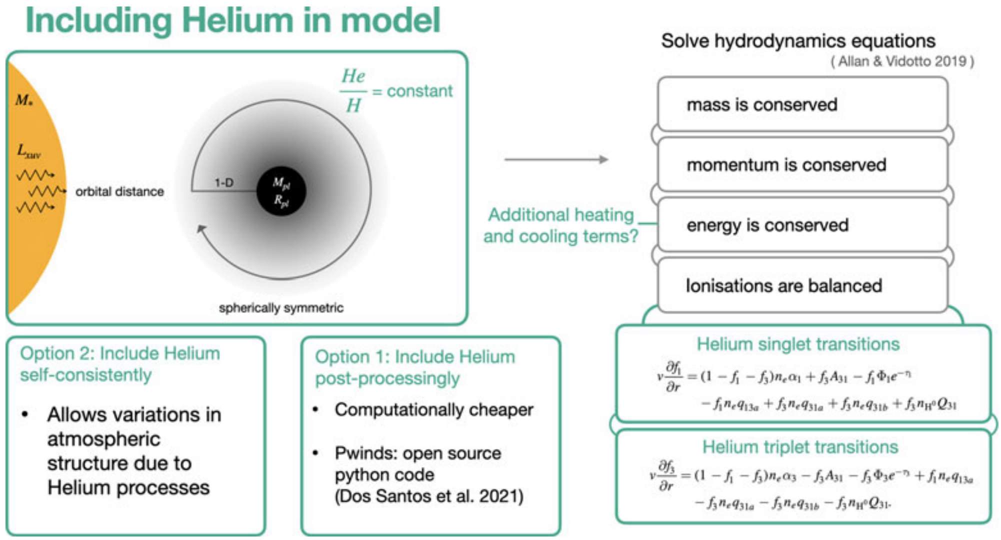


**Figure 1.** A brief summary of our model which will be presented in greater detail in Allan et al. (in prep). In Allan & Vidotto (2019), we present a similar, hydrogen-only version of this model. The main inputs remain similar, with the addition of the X-ray and EUV1 flux inputs as well the assumed hydrogen / helium fraction.

fluid approximation for the atmosphere, numerically solving equations of fluid dynamics in a co-rotating frame, using a shooting method approach based on the model of Vidotto & Jatenco-Pereira (2006). These four coupled differential equations ensure that mass, momentum and energy are conserved and that ionisations are balanced.
In order to model the helium 1083nm signature, the density of helium in the triplet state must be known. To obtain this, we must solve two additional coupled differential equations which account for transitions into and out of the helium singlet and triplet states. These equations are shown in the bottom right of Figure 1 and are discussed in Oklopčić & Hirata (2018). We approach solving these additional equations in two different ways. One option is to solve for the singlet and triplet populations after already solving the fluid dynamics equations. We refer to this approach as solving the helium populations 'post-processingly'. While the helium / hydrogen fraction is considered in the fluid equations, any heating or cooling processes due to helium must be omitted as these processes require predictions of the helium populations. While not used in the models presented here, `P-winds` (Dos Santos et al. 2022) is an open source python code that is capable of solving the coupled helium population equations, either for a given atmospheric structure or from an iso-thermal Parker wind assumption. An alternative approach is to solve all six equations simultaneously or 'self-consistently'. This allows for the inclusion of heating and cooling processes due to helium in the fluid dynamic equations, potentially affecting the resulting atmospheric structure.

## 3. The evolution of atmospheric escape

Allan & Vidotto (2019) previously showed that the evolution of atmospheric escape of a close-in planet depends on two important factors:

(*a*) as the host star evolves, its activity declines due to spin down, resulting in declining fluxes in the X-ray and extreme ultraviolet (XUV) and
(*b*) as the planet evolves, cooling causes it to contract with time.

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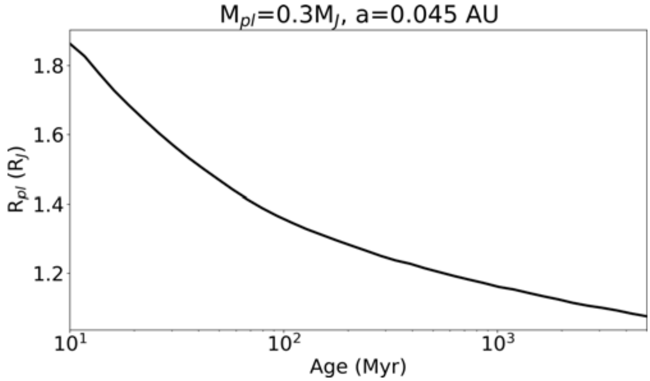


**Figure 2.** Planetary radius with respect to age for a 0.3-$M_{\rm jup}$ warm-Neptune sized planet orbiting a solar-like star at 0.045 au (Fortney & Nettelmann 2010).

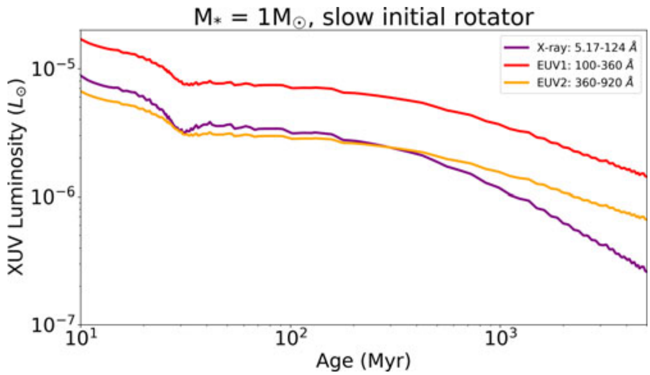


**Figure 3.** Stellar XUV luminosity in various wavelength bins specified in the legend as a function of stellar age. The predictions are obtained by utilising the model of (Johnstone et al. 2021) and normalising the flux in each wavelength channels until they each reproduce their solar value at the solar age.

The level of atmospheric escape and consequently the observational signatures of escaping hydrogen in the Lyman-$\alpha$ and H$\alpha$ lines were found to vary strongly with the evolution of the modelled Hot-Jupiter and warm-Neptune planets, with younger planets exhibiting greater escape. This is the result of a favourable combination of higher irradiation fluxes and weaker gravities. Consequently, Lyman-$\alpha$ and H-$\alpha$ absorption are also greater for the younger planets. In a continuation of this work, we now study how the helium 1083nm signature evolves over the lifetime of a planet. We use the same planetary radius as a function of evolution input (Fortney & Nettelmann 2010) as was used Allan & Vidotto (2019), corresponding to a 0.3 $M_{\rm jup}$ gas-giant orbiting a solar-like star at 0.045 au (see Figure 2). For the XUV flux, we look to Johnstone et al. (2021), from which we obtain the evolution of flux emitted in 3 separate wavelength bins corresponding to X-ray (5.17-124 Å), EUV1 (100-360 Å) and EUV2 (360-920 Å) wavelengths (see Figure 3). Following Murray-Clay et al. (2009) and Allan & Vidotto (2019), we approximate that the flux in each of these bins is concentrated on one representative wavelength, X-ray (50 Å), EUV1 (200 Å) and EUV2 (620 Å).

With the evolving inputs of received XUV flux and planetary radius, we run two versions of our model, either post-processingly or self-consistently solving for the helium triplet fractions as explained in the previous section. Figure 4 displays the resulting mass-loss rate as a function of planetary evolution. As found in Allan & Vidotto (2019),

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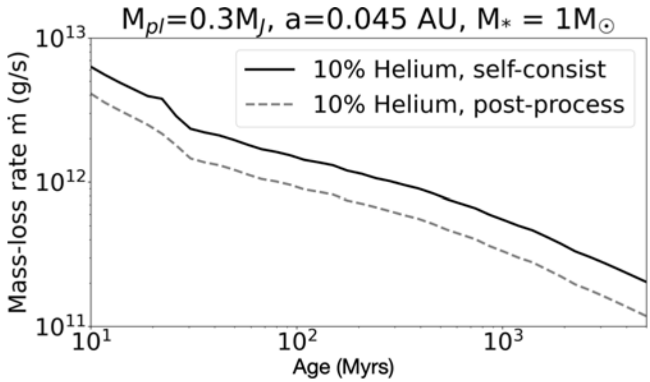


**Figure 4.** Predicted mass loss rate for a 0.3 $M_{\rm jup}$ gas-giant orbiting a slow initial rotator, solar-like star at 0.045 au. The black solid line corresponds to models which solves helium population equations consistently with the fluid dynamic equations, while the dashed grey line denotes models which solve the helium population equations post-processingly. In both cases a helium to hydrogen fraction of 0.1 was used.

the diminishing XUV flux required to heat the planetary atmosphere combined with the growing gravitational potential due to the shrinking planetary radii leads to the decline of atmospheric escape as the planet evolves. Interestingly, helium heating and cooling processes affect the resulting escape. If the helium populations are solved after the fluid dynamic equations are already solved (shown by the dashed grey line in figure 4), meaning heating and cooling effects due to helium are omitted, then the mass-loss rate is under-predicted. In other words, for the chosen planetary parameters, heating arising from the photo-ionisation of helium can further enhance atmospheric escape. In this modelled case, EUV1 photons photo-ionising singlet state helium are the primary contributor although this will likely vary dependant on the chosen stellar and planetary parameters.

## 4. The evolution of the Helium 1083nm signature of atmospheric escape

Naturally, the predicted helium triplet 1083nm signature of atmospheric escape weakens with declining escape as the planet ages. This is clearly seen in figure 5 which compares the predicted 1083nm transmission spectra at 10 Myr (left-panel) and 5000 Myr (right-panel). Allan & Vidotto (2019) found that the hydrogen Lyman-$\alpha$ and H-$\alpha$ signatures of atmospheric escape also follow such a trend with evolution. Solving the helium population equations either post-processingly or self-consistently as shown by the solid black and dashed grey spectra in figure 5 respectively, can also impact the resulting 1083nm signature. This is particularly true during younger planetary ages when the higher flux levels enhance heating through hydrogen and helium photo-ionisations.

## 5. Effects of the assumed helium / hydrogen fraction

An important parameter often featuring in models of hydrodynamic escape which incorporate helium is the fraction of helium / hydrogen in the atmosphere. For simplicity, we assume a constant fraction, both with respect to planetary age and with respect to atmospheric depth. While choosing a helium to hydrogen fraction of 0.1 (black line of Figure 6) or 0.0001 (cyan line) has a negligible effect on the resulting mass-loss rate, this is only true if the helium singlet and triplet populations are solved self-consistently and hence heating due to the photo-ionisation of helium is allowed. Further escape arising from this additional heating is counteracted by the larger gravitational force due to the greater mean molecular weight of helium. Altering the helium / hydrogen fraction

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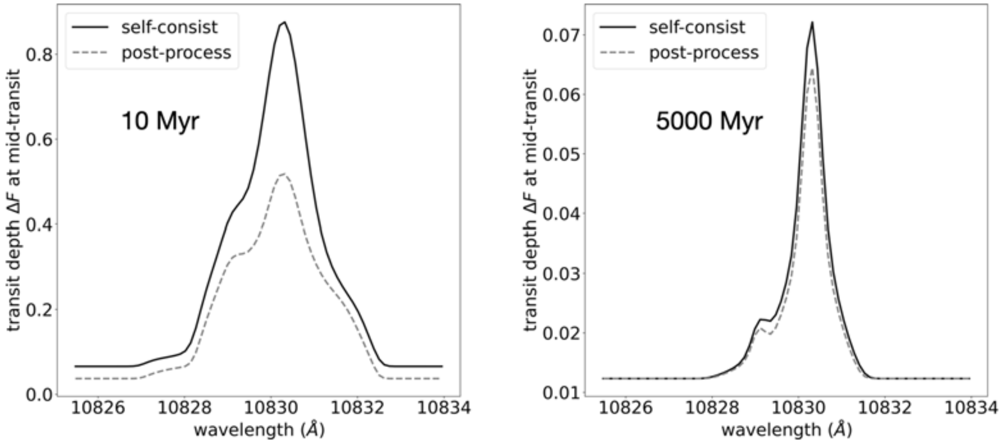


**Figure 5.** Predicted helium triplet 1083nm transmission spectra for a 0.3 $M_{\rm jup}$ gas-giant orbiting a slow initial rotator, solar-like star at 0.045 au. Note the differing scales of the y-axes. The left (right) panel corresponds to an age of 10 (5000) Myr. Solid black lines display spectra for models in which the helium populations were solved self-consistently whereas the dashed grey spectra were obtained through solving the helium populations post-processingly. In all cases, a helium / hydrogen fraction of 0.1 was used.

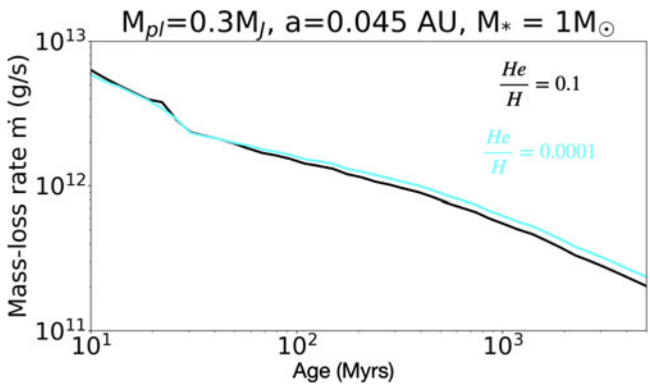


**Figure 6.** Predicted mass loss rate for a 0.3 $M_{\rm jup}$ gas-giant orbiting a slow initial rotator, solar-like star at 0.045 au. The black line corresponds to models which assume a 0.1 helium to hydrogen fraction, while the cyan line denotes models with a fraction of 0.0001, representing the negligible helium case. In both sets of models the helium populations were solved self-consistently.

while neglecting this heating due to helium (as is the case in a post-processing model) would incorrectly exaggerate the dependence of the resulting escape rate on the helium / hydrogen fraction. Despite having only a minor effect on the hydrodynamics of atmospheric escape, the assumed helium / hydrogen fraction remains an important input as it significantly affects the observable metastable helium triplet 1083nm signature.

## 6. Conclusions

As the planet evolves, atmospheric escape declines due to receiving a weaker XUV flux and its growing gravitational potential. The metastable helium triplet 1083nm signature becomes weakens with diminishing atmospheric escape. This is also true for the hydrogen Lyman-$\alpha$ and H-$\alpha$ signatures. When including helium in the modelled atmosphere, it is important to include additional helium heating and cooling processes which can affect the resulting atmospheric structure and escape. Finally, while the assumed helium to

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hydrogen fraction has little effect on the resulting escape, it remains important as the 1083nm signature is heavily dependant upon it.

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