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# TOWARD THE CHARACTERIZATION OF UPPER ATMOSPHERES WITH A 3D COUPLED THERMOSPHERE-EXOSPHERE MODEL

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**Abstract.** Atmospheres of exoplanets are our main observing window into the physical and chemical properties of these remote worlds. Spectacular progress has already been made on the atmospheric characterisation of exoplanets, highlighting a huge diversity compared to our Solar System planets. In particular, hot exoplanets found very close to their stars have been found to lose a substantial fraction of their atmospheres, because of the tremendous stellar irradiation they receive. It is surmised that such planets could be entirely stripped from their atmospheres, raising questions as to the possibility that gaseous planets in milder irradiation regimes could give birth to smaller planets with residual, Earth-like atmospheres. The study of atmospheric escape is thus essential to our understanding of exoplanet evolution, and the origins and stability of habitable worlds.

Upper atmospheres (thermosphere + exosphere) give rise to spectacular spectroscopic signatures in the UV and more recently in the IR. The metastable helium lines (10832.1, 10833.2 and 10833.3 Å) represent recent tracers of escape in a wavelength range where the spectra of the star and of the planetary atmosphere are more easily observed than in the UV. Observations of exospheres in the UV only yield part of the information about the escaping gas which need to be completed by probing the thermosphere in the IR. It is thus essential to simulate self-consistently thermosphere and exosphere with the most relevant codes, to interpret accurately observations of these layers. The joint interpretation can be done using sophisticated simulations with the model of upper atmosphere that we developed to the description of both gaseous and ultra-hot rocky planets, EVaporation of Exoplanets (EVE). This model is a 3D model simulating the different atmospheric layers of exoplanets: the lower layers, described in a fluid regime, are modelled with a high-resolution Cartesian grid containing millions of cells. The upper atmospheric layers are modelled in a collisionless regime, with tens of millions of particles of gas. The main purpose of the EVE code is to calculate the absorption of stellar light across the simulated atmosphere. The better coupling of thermospheric and exospheric structure allow us to re-interpret and in greater details available UV (HST) and IR (CARMENES, GIANO, SPIRou, Keck/NIRSPEC) observations of upper atmospheres. We also aim to interpret and predict signatures of escape in near-infrared JWST spectra of small exoplanets, and in near-infrared and optical spectra respectively obtained by the GTOs of the NIRPS and ESPRESSO spectrographs.

Keywords: atmosphere, exoplanets, helium, model, escape

## 1 Introduction

The Neptune Desert is not an observational bias but can be explained by some physical processes, such as orbital migration (Mazeh et al. 2016) and atmospheric evaporation (Lopez et al. 2012; Jin et al. 2014; Kurokawa & Nakamoto 2014; Owen & Wu 2017). Focusing on atmospheric evaporation, upper atmosphere models try to better characterize the escape rate of planets at the edge of the Desert in order to understand its origins. The helium infrared signature can be observed without interstellar medium absorption compared to hydrogen which makes it an interesting signature to find back the total escape rate of a planet.This requires to extend the upper atmospheric models to lower levels than the exosphere. Thermospheric models needs to be taken into account, improved and coupled with exospheric models.

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## 2 Understanding H/He signatures with 1D models

Using a Parker winds approximation thanks to the python package p-winds (Santos et al. 2021), we can establish a 1D structure for the upper atmosphere. This gives a density and velocity profile as well as the hydrogen and helium profile for a given set of parameter depending on the planet but also some assumption on temperature and the total mass loss rate. Figure 1 shows the velocity, density and helium profiles for a simulation of HAT-P-11b ($R_p = 0.39 R_{jup}; M_p = 0.087 M_{jup}$) with a temperature of 10,153.8 K and a total mass loss rate of $2.40 \times 10^{11} g.s^{-1}$. HAT-P-11b is a transiting, warm Neptune-class exoplanet orbiting its star in 4.89 days. Its orbit is near the edge of the evaporation desert, a region at close orbital distances characterized by a lack of observed Neptune-mass exoplanets (Allart et al. 2019).

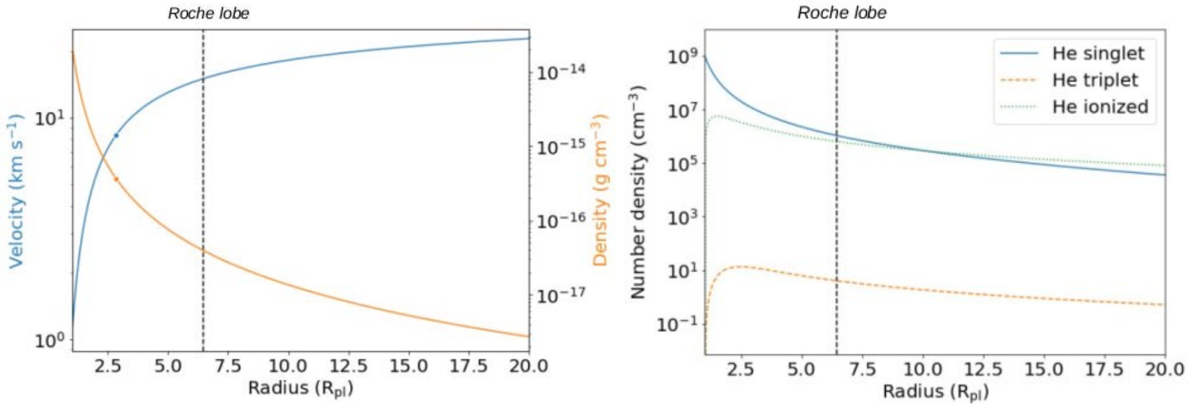

**Fig. 1.** HAT-P-11b p-winds simulation for T = 10,153.8 K and $\dot{M} = 2.40 \times 10^{11} g.s^{-1}$ **Left:** Density and velocity profile. **Right:** Helium profile.

The parameter space can be explored in order to simulate different conditions and so different helium transmission signatures that can be compared to the observations. In a large range of temperature and total mass loss rate, the transmission spectra of HAT-P-11b from Allart et al. (2019) have been compared to the theoretical simulation with the $\chi^2$ method to determine the best fit. Figure 2 shows the $\Delta\chi^2$ map with a close range to the best fit given by T = 10,153.8 K and $\dot{M} = 2.40 \times 10^{11} g.s^{-1}$, and the resulting transmission spectra compared to the observation.

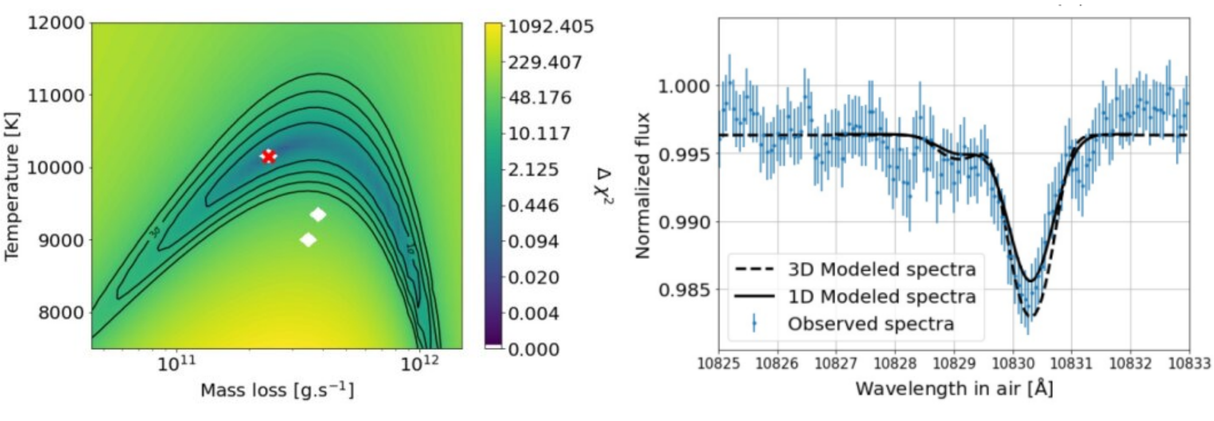

**Fig. 2.** HAT-P-11b p-winds simulation with best fit at T = 10,153.8 K and $\dot{M} = 2.40 \times 10^{11} g.s^{-1}$ **Left:** $\Delta\chi^2$ map with best fit pointed by a red cross. **Right:** Observed spectra compared to best fit simulated spectra with 1D p-winds model and 3D EVE model.

This first approach is fast but not accurate to take into account the 3D geometry and dynamic. However, it is perfect to explore rapidly the parameter space and focus the 3D model.

## 3 Understanding H/He signatures with 3D models

The EVaporating Exoplanets code (EVE) (Bourrier & Des Etangs 2013) is a 3D model simulating the different atmospheric layers of exoplanets: the lower layers, described in a fluid regime, are modelled with a high-resolution Cartesian grid containing millions of cells. The upper atmospheric layers are modelled in a collisionless regime, with tens of millions of particles of gas. The main purpose of the EVE code is to calculate the absorption of stellar light across the simulated atmosphere. Compare to 1D model, it takes into account the orbit and planet geometry, the stellar surface rotation, the limb darkening and the surface stellar line variation.

EVE thermosphere layer has been improved by using p-winds instead of constant or hydrostatic model. This makes a first step forward considering a homogeneous 1D profile with a 3D structure, see Figure 3. Figure 2 shows that for the best fit the 3D structure change the transmission spectra due to the 3D effects. This highlight that the retrieved parameter and so the calculated escape rate of a planet can change compare to previous study which approximated the structure with 1D models. Figure 3 shows the $\Delta\chi^2$ map using the 3D model, trying to derive the new best fit. Such model are more computational expensive and the exploration is consequently slower.

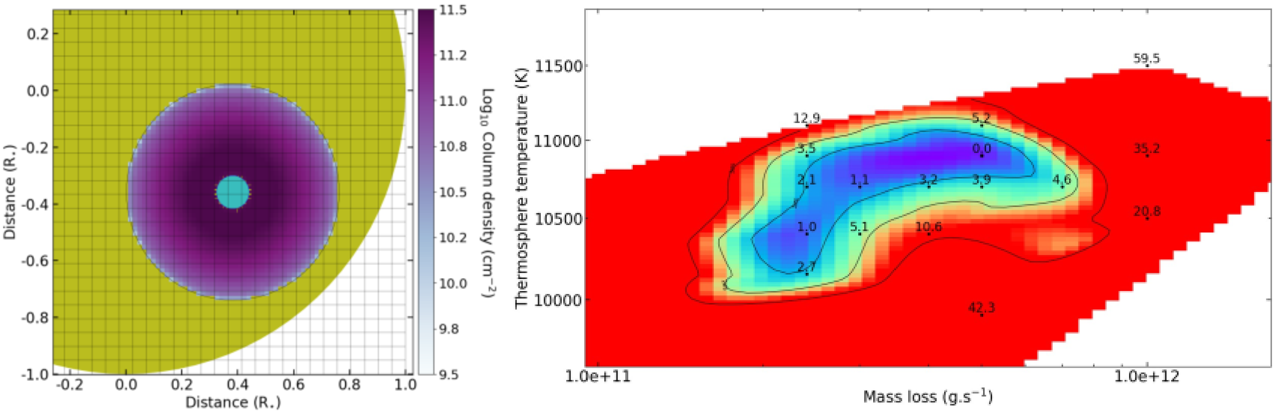

**Fig. 3.** HAT-P-11b EVE simulation **Left:** Helium thermospheric abundance. **Right:** $\Delta\chi^2$ map.

The next step is to extend the 1D homogeneous EVE thermosphere to a 2D structure. This will add dynamic effects such as winds, transportation and irradiation geometry effects. It is an ongoing work.

## 4 Conclusions

Observed helium signatures can be quickly characterized by the 1D p-winds model in order to constrain the range of temperature and escape rate close to the best fit. Then, the EVE 3D model offers the possibility to determine more precisely the temperature and escape rate which fit the best the observation. This allows us to improve the escape rate constraint on planets to better understand the Neptune desert. An evolution towards an even more complex 2D thermosphere is underway.

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