Characterisation of the hydrodynamic atmospheric escape of HD 209458 b, HD 189733 b and GJ 3470 b

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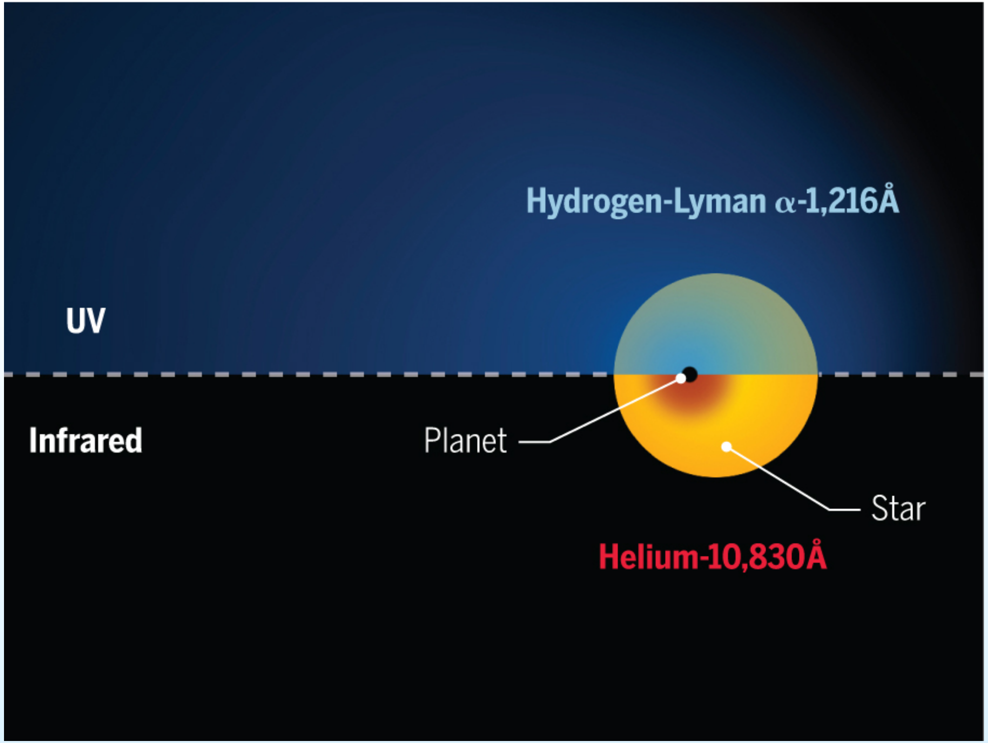
Hydrodynamic escape is the most efficient atmospheric mechanism of planetary mass loss and has a large impact on planetary evolution. However, the lack of observations remained this mechanism poorly understood. Therefore, new observations of the He I triplet at 10830Å provide key information to advance hydrodynamic escape knowledge. In this work, we analyse the hydrodynamic escape of three exoplanets, HD209458 b, HD189733 b, and GJ 3470 b via an analysis of He triplet absorptions recently observed by the CARMENES high-resolution spectrograph, and their available Ly-alpha measurements, involving a 1D hydrodynamic model. We characterise the main upper atmospheric parameters, e.g., the mass-loss rate, the temperature, the composition (H/He ratio), and the radial outflow velocity. We also study their hydrodynamic regime and show that HD209458 b is in the energy-limited regime, HD189733 b is in the recombination-limited regime, and GJ 3470 b is in the photon-limited regime. Details of this work can be found in Lampón et al. (2020, 2021a,b).

Introduction

The He triplet absorption at 10830Å, He(2^3S), offers a new window for studying the atmospheric escape of exo-atmospheres (Nortmann et al., 2018).

Atmospheric hydrogen and helium gases of exoplanets that orbit close to their host stars can escape after suffering strong irradiation at XUV.

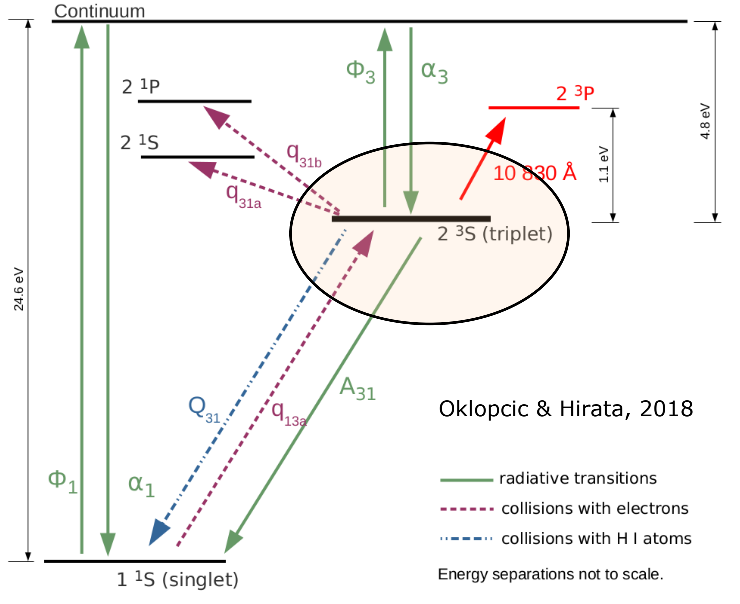
So far the evaporation has been studied using the H Ly-α in the UV. The He NIR line provides more information since its directly probes the region where the escape is originating (see Figure).



Brogi, 2018

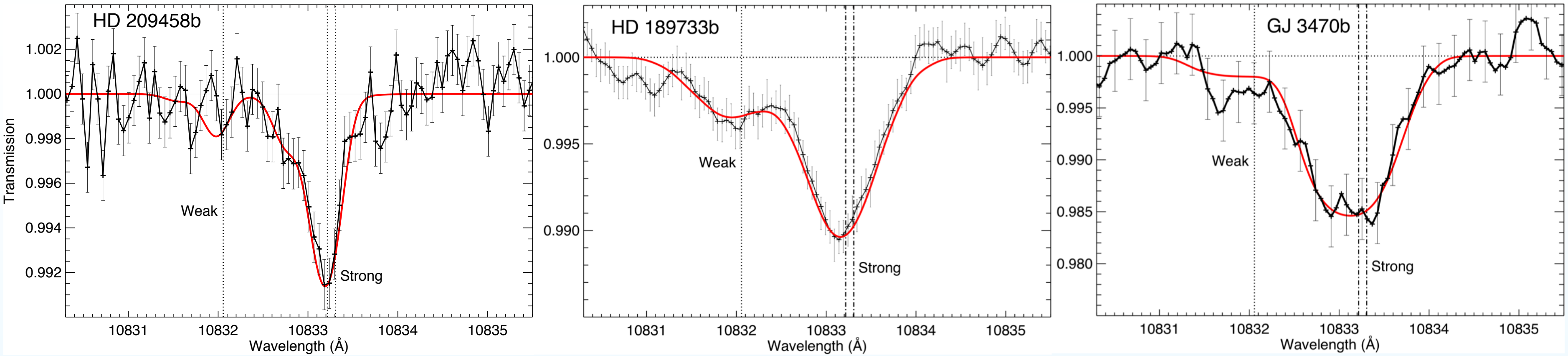
Observations and Modelling

- We analyse the observations of the He(2^3S) absorption of HD209458b, HD189733b, and GJ3470b measured with the high-resolution spectrograph CARMENES at the 3.5m Calar Alto Telescope (Alonso-Floriano et al., 2019; Salz et al., 2018; and Pallé et al., 2020).
- We developed a 1D hydrodynamic model of the thermosphere, with spherical symmetry, and coupled with a non-LTE model that calculates the density profiles of H, H^+, He, He^+ and He(2^3S).
- Hydrodynamic continuity equations are solved assuming a constant speed of sound, similar to the isothermal Parker wind model (Parker, 1958).
- The inputs of the model are temperature (T), mass-loss rate (MLR) and the H/He composition.



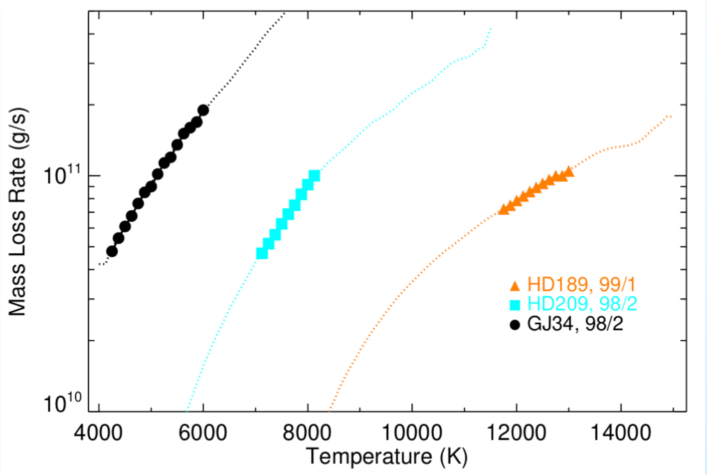
- The production and loss processes of He(2^3S) are sketched in the figure.
- With the He(2^3S) density, we computed synthetic spectra and compared to that measured.

Results and Discussion (1)



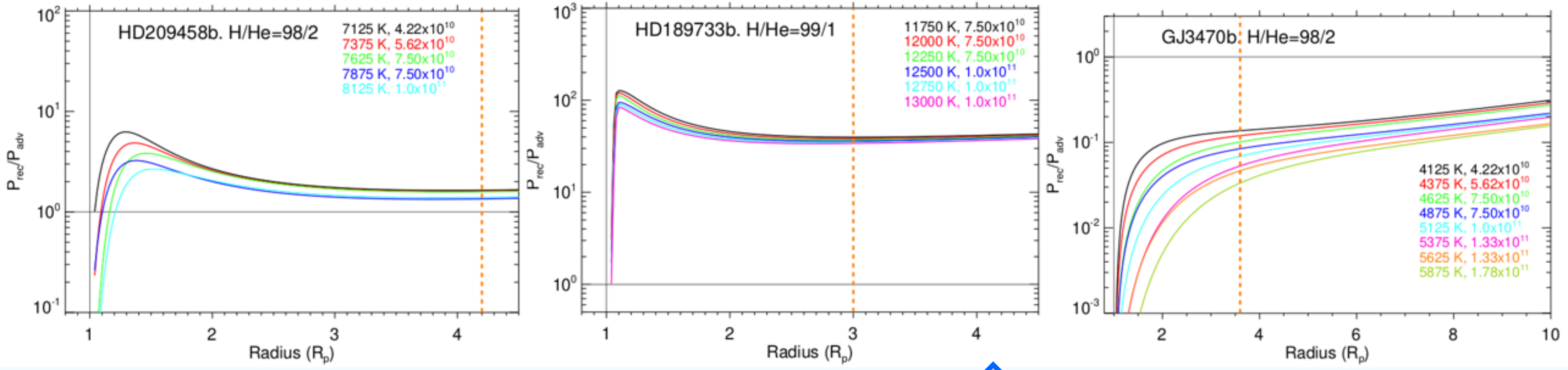
Spectral transmission of the He(2^3S) at mid-transit (black lines and error bars) and the synthetic spectrum (red lines).

Ranges of T-MLR and H/He ratios derived for the three planets. Dotted lines show extended T-MLR ranges, and symbols the derived T-MLR.

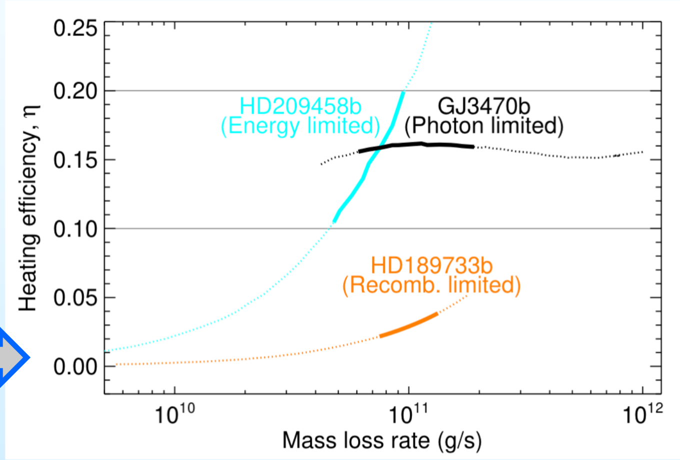


Our results also suggest an H/He composition > 97/3, higher than the solar 90/10.

Results and Discussion (2)



- To differentiate the hydrodynamic escape regimes, we use two criteria, a) ratios of recombination to the advection of H and b) heating efficiency.
- **a) Top figures**: Ratios of recombination to the advection of H, derived from the measured He(2^3S) absorption spectra. The vertical dashed orange lines indicate the mean Roche lobes.
- **b) Right figure**: Heating efficiency versus MLR derived for the three planets. Dotted lines show extended T-MLR ranges, and thick lines the derived T-MLR.



Conclusions

- **HD 189733 b** has a rather compressed and hot upper atmosphere, almost fully ionized, and with low radial velocities.
- **GJ 3470 b**, with smaller gravitational potential, exhibits a very extended atmosphere, relatively cold, not strongly ionized and with large radial outflow velocities. Its MLR is comparable to that of HD 189733 b, despite it is much less XUV-irradiated.
- **HD 209458 b** is in between those exoplanets, with temperature, density, ionization profile, and gas radial velocities with intermediate values. However, its MLR is comparable.
- Our results suggest that the upper atmosphere of giant planets undergoing hydrodynamic escape tend to have a **very low mean molecular mass** (H/He > 97/3), **significantly higher than the solar** 90/10 ratio.
- We have found **observational evidence of the three escape regimes theoretically predicted** in giant planet H/He atmospheres: **energy-limited** (HD 209458 b), **recombination-limited** (HD 189733 b) and **photon-limited** (GJ 3470 b).