Transmission spectroscopy of the ultra-hot Jupiter MASCARA-4 b

Disentangling the hydrostatic and exospheric regimes of ultra-hot Jupiters

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ABSTRACT

Context. Ultra-hot Jupiters (UHJs), rendering the hottest planetary atmospheres, offer great opportunities of detailed characterisation with high-resolution spectroscopy. MASCARA-4 b is a recently discovered close-in gas giant belonging to this category.

Aims. We aim to characterise MASCARA-4 b, search for chemical species in its atmosphere, and put these in the context of the growing knowledge on the atmospheric properties of UHJs.

Methods. In order to refine system and planet parameters, we carried out radial velocity measurements and transit photometry with the CORALIE spectrograph and EulerCam at the Swiss 1.2 m Euler telescope. We observed two transits of MASCARA-4 b with the high-resolution spectrograph ESPRESSO at ESO’s Very Large Telescope. We searched for atomic, ionic, and molecular species via individual absorption lines and cross-correlation techniques. These results are compared to literature studies on UHJs characterised to date.

Results. With CORALIE and EulerCam observations, we update the mass of MASCARA-4 b ($M_\text{p} = 1.675 \pm 0.241 M_{\text{Jup}}$) as well as other system and planet parameters. In the transmission spectrum derived from ESPRESSO observations, we resolve excess absorption by H\(\alpha\), H\(\beta\), Na I D1&D2, Ca II H&K, and a few strong lines of Mg I, Fe I, and Fe II. We also present the cross-correlation detection of Mg I, Ca I, Cr I, Fe I, and Fe II. The absorption strength of Fe II significantly exceeds the prediction from a hydrostatic atmospheric model, as commonly observed in other UHJs. We attribute this to the presence of Fe II in the exosphere due to hydrodynamic outflows. This is further supported by the positive correlation of absorption strengths of Fe II with the H\(\alpha\) line, which is expected to probe the extended upper atmosphere and the mass loss process. Comparing transmission signatures of various species in the UHJ population allows us to disentangle the hydrostatic regime (as traced via the absorption by Mg I and Fe I) from the exospheres (as probed by H\(\alpha\) and Fe II) of the strongly irradiated atmospheres.

Key words. planets and satellites: atmospheres – techniques: spectroscopic

1. Introduction

Transmission spectroscopy of close-in giant planets provides great opportunities to characterise the composition, structure, and dynamics of exoplanet atmospheres (Charbonneau et al. 2002; Redfield et al. 2008; Snellen et al. 2010; Huitson et al. 2012; Madhusudhan 2019). These strongly irradiated planets undergo significant atmospheric escape as traced by absorption signatures from exospheres extending beyond the Roche limit (Vidal-Madjar et al. 2003, 2004; Spake et al. 2018). The mass loss drives the evolution of close-in planets and shapes the exoplanet population as observed today (Owen 2019).

Ultra-hot Jupiters (UHJs) represent a subclass of close-in hot Jupiters that are extremely irradiated, with day-side temperatures above 2200 K. As a result of such high temperatures, their day-side atmospheres are predicted to be cloud-free and with effective thermal dissociation of molecules such as H\(_2\)O to produce OH (Parmentier et al. 2018; Nugroho et al. 2021; Landman et al. 2021). The transmission spectra are dominated by neutral and ionized atomic species in the optical, similar to the photosphere of dwarf stars (Kitzmann et al. 2018; Lothringer et al. 2018), which are well suited for atmospheric characterisation. The dissociation of hydrogen combined with electrons from metal ionisation to form H\(^+\), adds strong continuum opacity which plays an important role in shaping the spectra (Arcangeli et al. 2018). The extreme irradiation also makes UHJs interesting targets for studying the mass loss via hydrodynamic escapes (Fossati et al. 2018; Sing et al. 2019).

Transmission spectra under high spectral resolution ($R = \lambda/\Delta\lambda \sim 10^5$) provide unique access to the information contained in resolved absorption lines, such as Na I D lines, H\(\alpha\) Balmer series, and He I triplet, allowing better constraints on the atmospheric structure and the escaping process (e.g. Wytenbach et al. 2015, 2017; Yan & Henning 2018; Allart et al. 2018; Nortmann et al. 2018; Casasayas-Barris et al. 2019;
We describe the observations and data reduction in Sect. 2. The analyses are presented in Sect. 3, including fitting the spin–orbit misalignment angle, modeling the Rossiter-McLaughlin (RM) effect, extracting transmission spectra, and carrying out cross-correlation. We then present in Sect. 4 the detection of planetary absorption signals in the transmission spectrum from both single-line and cross-correlation analysis. In Sect. 5, we put the results of MASCARA-4 b in context of the UHJ population and discuss trends of absorption strengths among UHJs that may shed light on the atmospheric structures.

2. Observations and data reduction

2.1. Radial velocity measurements with CORALIE and updated planet mass

To refine the mass of MASCARA-4 b, 20 high-resolution spectra were obtained with the CORALIE spectrograph (Baranne et al. 1996; Queloz et al. 2000) at the Swiss 1.2 m Euler telescope at La Silla Observatories, Chile. The observations took place between January 4, 2020, and February 10, 2021. The S/N per pixel at 550 nm varied between 55 and 90, according to sky condition and exposure time (20–30 min depending on target visibility and scheduling requirements).

Radial velocity (RV) measurements were extracted by cross-correlating the spectra with a binary A0 mask. The shape of the cross-correlation functions (CCFs) were dominated by rotational broadening ($FWHM \approx 55 \text{ km s}^{-1}$) and a linear slope across the continuum due to imperfect flux correction across the CCF window. Similar to the approach demonstrated for WASP-189 (Anderson et al. 2018), we fitted a rotational profile with a linear slope to the CCFs (for more information, see Sect. 2.3.3 in Nielsen 2021). The inverse bisector-span (BIS; Queloz et al. 2001) was computed on the continuum-corrected CCFs.

The RV fitting were carried out with the Data and Analysis Center for Exoplanets web platform (DACE)

1. The Keplerian model described in Delisle et al. (2016) was fit to the RV data points using a Markov chain Monte Carlo (MCMC) algorithm (Diaz et al. 2014, 2016), while applying Gaussian priors on the stellar mass and planetary orbit ($P$, $T_0$, and $i_p$) from Table 1. When allowing for an eccentric orbit, we found an eccentricity consistent with zero and adopted a circular model to avoid overestimating the eccentricity (Hara et al. 2019). A traditional RV fit yielded a moderate anti-correlation between the RV-residuals and BIS (weighted Pearson coefficient $R_{BP} = -0.68$). We, therefore, applied a linear detrending of the RVs with BIS in the model. The final RV analysis derives a semi-amplitude of the stellar reflex motion of $165.9 \pm 23.7 \text{ m s}^{-1}$, corresponding to a planet mass of $1.675 \pm 0.241 \ M_{\text{Jup}}$. We tested the fitting without the detrending step and found no sensible change in the resultant semi-amplitude. The phase folded data, detrended with BIS, is shown in Fig. 1 along with the Keplerian model. The planet mass deviates by $2\sigma$ from the previous measurement of $3.1 \pm 0.9 \ M_{\text{Jup}}$ (and RV semi-amplitude $310 \pm 90 \text{ m s}^{-1}$) in Dorval et al. (2020), which relied on one particular data point with large uncertainty. Hence we adopt the revised values.

2.2. Photometry with EulerCam

We observed two transits of MASCARA-4 b on February 12 and 29, 2020 using EulerCam, the CCD imager installed at the

1 https://dace.unige.ch/
Table 2. Observing log of MASCARA-4 b with ESPRESSO.

<table>
<thead>
<tr>
<th>Night</th>
<th>Date</th>
<th>Exposure time (s)</th>
<th>N_{spectra}</th>
<th>On-target time (h)</th>
<th>Airmass</th>
<th>Seeing (″)</th>
<th>S/N at 580 nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Feb 12, 2020</td>
<td>360</td>
<td>85</td>
<td>7.5</td>
<td>1.34–1.99</td>
<td>0.34–0.87</td>
<td>~212</td>
</tr>
<tr>
<td>2</td>
<td>Feb 29, 2020</td>
<td>300</td>
<td>96</td>
<td>7.9</td>
<td>1.34–2.46</td>
<td>0.32–0.77</td>
<td>~208</td>
</tr>
</tbody>
</table>

Fig. 1. CORALIE radial velocity measurements of MASCARA-4, phase folded on the planetary orbital period and corrected for stellar activity. The best-fit Keplerian model to the data is shown as a solid grey line. The semi-amplitude of the stellar reflex motion is 165.9 ± 23.7 m s\(^{-1}\), corresponding to a planet mass of 1.675 ± 0.241 M\(_{\text{Jup}}\).

1.2 m Euler telescope located at La Silla. The observations were scheduled to be simultaneous with the two nights of observations with ESPRESSO (see Sect. 2.3), delivering updated transit parameters for the analysis of transmission spectroscopic data. For more details on the instrument and associated data reduction procedures the reader is referred to Lendl et al. (2012). As the star is brighter (V \sim 8.19) than exoplanet hosts usually observed with EulerCam (V \sim 10–14, Lendl et al. 2012, 2013, 2019), using a broad-band filter would lead to saturation of the detector. We therefore used a narrower band to avoid saturation issues, namely the Geneva VI filter (Rufener & Nicolet 1988), which peaks at 539 nm and has a transmission above 50% from 509 nm to 562 nm (accounting for detector quantum efficiency). The telescope was also defocused slightly to improve PSF sampling and observation efficiency. An exposure time of 20 s was used throughout both sequences. The light curves shown in Fig. 2 were obtained using relative aperture photometry with two bright reference stars and apertures of 26 pixel (5.6″) radius. The night of February 12, 2020 was affected by recurrent cloud passages, leading to gaps in the observed data.

We used the EulerCam data to compute the physical system parameters and in particular derive a planetary radius in the Geneva VI band, which is comparatively close in wavelength observed with ESPRESSO. TESS (Ricker et al. 2015) has previously observed MASCARA-4 b, revealing a slightly asymmetric transit shape created by gravity darkening on the host star and a misaligned planetary orbit (Ahlers et al. 2020). Our ground-based observations do not possess sufficient precision to reveal this effect. However, to propagate the information encoded in the TESS data into our fit, we place Gaussian priors on the transit duration (T\(_{14}\)) and the impact parameter (b) corresponding to the values presented by Ahlers et al. (2020). We used a Markov chain Monte Carlo approach as implemented in CONAN (Lendl et al. 2020) to derive the system parameters, fitting for R\(_p\)/R\(_\star\), b, T\(_{14}\), T\(_{0}\) and P. With the exception of b and T\(_{14}\) for which broad uniform priors were assumed. We assumed a quadratic limb-darkening law with parameters derived with LDCU\(^2\) (Deline et al. 2022). Correlated noise was modelled individually for each light curve using approximate Matérn-3/2 kernels implemented through celerite (Foreman-Mackey et al. 2017). For the light curve of February 12, 2020, we included an evident correlation between the residual flux and the stellar FWHM as a linear trend fitted together with the transit model. The unbinned data points are shown in light blue, while the dark blue points show the data binned into 2-min intervals.

Fig. 2. EulerCam light curves of MASCARA-4. Top panel: raw differential photometry together with the transit and systematic model corresponding to the median posterior values. The top two light curves are the data, while the bottom two light curves show the residuals to these models. Bottom panel: systematics-corrected, phase-folded data together with the transit model. The unbinned data points shown in light blue, while the dark blue points show the data binned into 2-min intervals.

To derive planetary parameters, we used our derived radial velocity amplitude of 165 ± 23 m s\(^{-1}\) as presented in Sect. 2.1 and pulled values from a corresponding Normal distribution at each MCMC step. Similarly, normal distributions for M\(_p\) and R\(_p\) were

\(^2\) https://github.com/delinea/LDCU
assumed corresponding to the values inferred from our spectral analysis. The raw and phase-folded light curves are shown in Fig. 2, and the resulting updated parameters are given in Table 1.

2.3. High-resolution transmission spectroscopy with ESPRESSO

We observed two transits of MASCARA-4b with ESPRESSO on February 12 and 29, 2020 under ESO program 0104.C-0605 (PI: Wytenbach). ESPRESSO is a fiber-fed, ultra-stabilized echelle high-resolution spectrograph installed at the incoherent combined Coudé facility of the VLT. The observations were taken with the single-UT HR21 mode, providing a spectral resolving power of $R \sim 138,000$, covering the optical wavelength range of 380–788 nm. The observations are summarised in Table 2. The exposure time during transit was 360 s and 300 s length range of 380–788 nm. The observations are summarised (Table 2).

We took the sky-subtracted 1D spectra extracted with the Data Reduction Software (DRS) pipeline, and then corrected for telluric absorption features caused by H$_2$O and O$_3$ in the Earth’s atmosphere following Allart et al. (2017) using the ESO sky tool molecfit (version 4.2, Smette et al. 2015). The tool uses a line-by-line radiative transfer model (LBLRTM) to derive telluric atmospheric transmission spectra and accounts for molecular abundances, instrument resolution, continuum level, and wavelength solution that can best fit observations, whereas other telluric or interstellar contamination such as the absorption of Na I was not removed with this correction.

We also used the ESPRESSO DRS to generate stellar cross-correlation functions (CCFs) with an A0 mask as presented in Wytenbach et al. (2020). The stellar CCFs outside of the transit were average-combined to build a master out-of-transit CCF, representing the unocculted stellar line shape. We measured the projected spin velocity $v \sin i$, and systemic velocity $V_{\text{sys}}$, of the target by fitting a rotationally broadened model (Gray 2005) to the line shape. We found the $V_{\text{sys}}$ of $43.0 \pm 0.1 \text{ km s}^{-1}$ and the $V_{\text{sys}}$ of $58.68 \pm 0.09 \text{ km s}^{-1}$. We then obtained the residual CCFs by subtracting the CCF at each phase from the master out-of-transit CCF. The residual CCFs were used later to extract Rossiter–McLaughlin information as detailed in Sect. 3.2.

Fig. 3. Map of the residual CCFs at different orbital phases before (top panel) and after (bottom panel) the correction of stellar pulsation. Data of two transits were binned in orbital phase with a step size of 0.002. The horizontal dotted lines denote the timings of four transit contacts. The slanted yellow streak during transit delineates the deformation of stellar lines as the planet moving across the stellar disk. The ripples seen in the out-of-transit residual CCFs in the top panel are attributed to stellar pulsation.

3. Data analysis

3.1. Stellar pulsations

In residual CCFs we note a strong rippled pattern caused by the stellar pulsations as shown in Fig. 3. The pulsations generate streak features throughout the course of observations, entangling with the Rossiter–McLaughlin and planetary signal during transit. We empirically mitigated the stellar pulsation pattern in CCFs following Wytenbach et al. (2020). To achieve this, we suppose the pulsation features in the two-dimensional diagram (Fig. 3) stay static in terms of radial velocity, which can be approximated with positive or negative Gaussian profiles. We co-added the out-of-transit residual CCFs before ingress and after egress respectively, where the pulsation pattern appears symmetric before and after transit. We fit a Gaussian profile to the strongest peak in the combined out-of-transit residual CCFs and subtracted the fitted Gaussian component from all the individual out-of-transit CCFs, while the rest in-transit spectra remain untouched. Then the steps above were repeated to iteratively remove one Gaussian component at a time, until the major pulsation features were cleaned (5 iterations in our case, and the results are not sensitive to the number of iterations). The pulsation signal is mitigated while some structure remains visible in Fig. 3 bottom panel.

3.2. Rossiter–McLaughlin reloaded

The Rossiter–McLaughlin (RM) effect (also known as the Doppler shadow) is the deformation of the stellar lines as a result of the planet blocking part of the stellar disk during transit. It encodes information of the stellar rotation $v \sin i$, and the projected misalignment angle $\lambda$ between the planet’s orbital axis and the star’s rotation axis. We used the reloaded RM method (Cegla et al. 2016) to model the Doppler shift of the CCF profiles due to the occultation by the planet during transit. To extract RM information from the data, we combined the residual CCFs from both transits by binning in orbital phase with a step size of 0.002 and then fit the residual CCF at each phase with a Gaussian profile to determine the local RV of the occulted stellar surface. The measured local RVs plotted against orbital phases are shown in Fig. 4. We model the local RVs by computing the brightness-weighted average rotational velocity of the stellar surface blocked by the planet at each phase. Here we fixed the parameters such as $\alpha/R_*, R_0/R_*$, and $i_0$ to the values listed in Table 1, while making the spin–orbit angle $\lambda$, the stellar spin velocity $v$, inclination $i_*$, and rotational diffusion rate $\alpha$ free parameters. Fitting the model to the measured local RVs, we derived $\alpha = 0.09 \pm 0.03$, $\lambda = 250.34 \pm 0.14^\circ$, and $v \sin i_* = 46.2^{+7.7}_{-2.5} \text{ km s}^{-1}$. The values are consistent with the previous measurement of $\lambda = 244.9^{+2.7}_{-3.0}$ and $v \sin i_* = 45.66^{+1.3}_{-0.9} \text{ km s}^{-1}$ by Dorval et al. (2020), with the slight difference in the spin–orbit angle likely resulting from the systematic differences in $P$ and $T_0$. Since we updated $P$ and $T_0$ from the simultaneous photometry as the spectroscopic observations, the updated epoch is more reliable for our analysis of the local RVs. We caution that
the uncertainties quoted here are underestimations because they did not account for systematics in the transit epoch and system parameters.

3.3. Modeling RM and CLV effects

To disentangle the stellar signal from the planetary signal, we modeled the transit effects on stellar lines, including the Rossiter–McLaughlin (RM) and center-to-limb variation (CLV) effects, following (Yan et al. 2017; Casasayas-Barris et al. 2019). We first computed synthetic stellar spectrum at different limb-darkening angles (μ) using Spectroscopy Made Easy tool (Valenti & Piskunov 1996) with VALD line lists (Ryabchikova et al. 2015). The stellar disk was divided into cells of size 0.01 R∗ × 0.01 R∗, each assigned with a spectrum obtained by the interpolation to its corresponding μ and applying a radial velocity shift according to its local rotational velocity. We then integrated the whole stellar disk while excluding the region blocked by the planet during transit. We divided the integrated spectrum at each phase through the out-of-transit stellar spectrum, resulting in the model of RM+CLV effects such as shown in Fig. 5b. The system and stellar parameters used in the modeling are presented in Table 1, including the best-fit parameters α = 0.09, i = 250.3°, and v sin i = 48.6 km s⁻¹ obtained via RM reloaded method in Sect. 3.2.

3.4. Transmission spectrum

Using the telluric corrected 1D spectra, we extracted the transmission spectrum following the similar procedure in previous studies (such as Wytenbach et al. 2015; Casasayas-Barris et al. 2019). It is summarised as follows. The spectra were median-normalised and shifted to the stellar rest frame. The out-of-transit spectra were co-added to build the master stellar spectrum, which was then removed from each individual spectrum via division. In the residuals, there remained sinusoidal wiggles as also seen in other ESPRESSO data (Tabernero et al. 2021; Borsa et al. 2021; Casasayas-Barris et al. 2021; Kesseli et al. 2022). We applied a Gaussian smoothing filter with a width of 5 Å to each exposure and removed it to correct for the low-frequency noise. Moreover, outliers exceeding 4σ threshold in a sliding 25 Å window were corrected through linear interpolation over nearby pixels. Finally, we combined the data of both transits by binning in orbital phase with a step size of 0.002.

The in-transit residuals at this stage contain the variation due to RM + CLV effects and the absorption of the planet. Following Yan & Henning (2018), we fit the data with a model composed of both the stellar effects (as detailed in Sect. 3.3) and the planetary absorption signal (modeled as a Gaussian profile) assuming the expected planetary orbital motion amplitude (Kp) as listed in Table 1. The free parameters include the Gaussian amplitude (h), Gaussian width (FWHM), wind speed (twind), and a scaling factor of the stellar effects (f) to account for the fact that the effective absorption radius can be larger than the nominal planet radius used in the RM + CLV model. The fitting process was performed with PyMultiNest (Buchner et al. 2014), a Python interface for the Bayesian inference tool MultiNest (Feroz et al. 2009). Once obtaining the best-fit values, we removed the stellar RM+CLV effects from the residuals, which were then average-combined in the planet rest frame to form the 1D transmission spectrum such as presented in Fig. 5e.
3.5. Cross-correlation analysis

In addition to inspecting individual lines, we carried out cross-correlation analyses (Snellen et al. 2010; Brogi et al. 2012) to co-add hundreds of absorption lines in the full range of the optical transmission spectrum to search for atoms (Hoeijmakers et al. 2018, 2019; Kesseli et al. 2022). We computed transmission models of different atoms and ions (Fe i, Fe ii, Mg i, etc.) for cross-correlation analysis using the radiative transfer tool petitRADTRANS (Mollière et al. 2019). Here we assumed an isothermal temperature profile of 2500 K, a continuum level of 1 mbar, and a gray cloud deck at 1 mbar. The volume mixing ratios (VMR) were set to the solar abundance. We utilized the formula for cross-correlation as presented in Hoeijmakers et al. (2018, 2019, 2020a),

\[
c(v, t) = \frac{\sum_i x_i(t) T_i(v)}{\sum_i T_i(v)}. \tag{1}
\]

where \(x_i(t)\) is the observation at time \(t\), \(T_i(v)\) is the transmission model of the species shifted to a radial velocity \(v\), such that the CCF effectively is a weighted average of multiple absorption lines, representing the average strength of the absorption. Following this convention allows us to compare the line strengths across different ultra-hot Jupiters presented in previous cross-correlation studies. However, we caution that such CCF amplitudes depend on the specific models used. This will be further discussed in the comparison to other planets in Sect. 5.1.

The transmission templates were cross-correlated with the telluric corrected spectra in the wavelength range of 380–685 nm (beyond which the spectra are heavily contaminated by telluric lines, therefore excluded in the analysis). This led to the stellar CCFs dominated by signals from the stellar spectra. We then obtained the residual CCFs by removing the average out-of-transit CCF and mitigated the stellar pulsation pattern following Sect. 3.1. Similar as the transmission spectrum, the residual CCFs contains both the stellar RM+CLV effects and the planetary signal. We carried out the same cross-correlation analysis on the synthetic stellar spectra computed in Sect. 3.3 to simulate the RM+CLV contribution to the residual CCFs, which was multiplied by a scaling factor \(f\) and then removed from the data to obtain the final CCFs originating from the planetary absorption. The values of free parameters including \(f\), the Gaussian amplitude of the absorption signal \(h\), the Gaussian FWHM and the central velocity offset \(v_{\text{wind}}\) were determined similarly as presented in Sect. 3.4.

4. Results

4.1. Detection of individual lines of H i, Na i, Ca ii, Mg i, Fe i, Fe ii

We report the detection of individual absorption lines of H α, H β, Na i D1&2, Ca ii H&K, Mg i, Fe i, and Fe ii in MASCARA-4 b. The transmission spectra around these absorption lines are shown in Fig. 6, and the measured properties are summarised in Table 3.

The centre of the absorption features generally agree with zero, while H α, H β, and Na i doublet appear blueshifted by up to \(-4\) km s\(^{-1}\), which is usually interpreted as the evidence of day-to-night side wind (Snellen et al. 2010; Brogi et al. 2016; Hoeijmakers et al. 2018; Casasayas-Barris et al. 2019; Seidel et al. 2021). The various velocity offsets of different species may indicate that the lines probe distinct atmospheric layers dominated by different dynamic processes.
Table 3. Summary of individual line detection in the transmission spectrum of MASCARA-4 b.

<table>
<thead>
<tr>
<th>Line</th>
<th>( \lambda_0 ) (Å)</th>
<th>( h ) (%)</th>
<th>( N_{sc} )</th>
<th>S/N</th>
<th>( FWHM ) (km s(^{-1}))</th>
<th>( v_{wind} ) (km s(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hα</td>
<td>6564.61</td>
<td>-0.317 ± 0.021</td>
<td>48.4 ± 3.3</td>
<td>14.8</td>
<td>1.89</td>
<td>31.4 ± 2.4</td>
</tr>
<tr>
<td>Hβ</td>
<td>4862.72</td>
<td>-0.143 ± 0.030</td>
<td>21.9 ± 4.5</td>
<td>4.8</td>
<td>1.49</td>
<td>27.2 ± 8.1</td>
</tr>
<tr>
<td>Ca II H</td>
<td>3969.59</td>
<td>-0.705 ± 0.082</td>
<td>107.6 ± 12.6</td>
<td>8.6</td>
<td>1.48</td>
<td>23.0 ± 3.0</td>
</tr>
<tr>
<td>Ca II K</td>
<td>3934.77</td>
<td>-0.844 ± 0.082</td>
<td>128.9 ± 12.5</td>
<td>10.3</td>
<td>1.31</td>
<td>29.6 ± 3.1</td>
</tr>
<tr>
<td>Na I D1</td>
<td>5897.55</td>
<td>-0.168 ± 0.014</td>
<td>25.6 ± 2.2</td>
<td>11.9</td>
<td>1.32</td>
<td>28.6 ± 2.8</td>
</tr>
<tr>
<td>Na I D2</td>
<td>5891.58</td>
<td>-0.214 ± 0.017</td>
<td>32.7 ± 2.6</td>
<td>12.4</td>
<td>1.37</td>
<td>19.9 ± 2.1</td>
</tr>
<tr>
<td>Mg I</td>
<td>5174.12</td>
<td>-0.151 ± 0.017</td>
<td>23.0 ± 2.6</td>
<td>8.7</td>
<td>1.04</td>
<td>22.6 ± 3.5</td>
</tr>
<tr>
<td>Mg II</td>
<td>5185.05</td>
<td>-0.125 ± 0.019</td>
<td>19.1 ± 2.9</td>
<td>6.5</td>
<td>1.08</td>
<td>25.2 ± 5.8</td>
</tr>
<tr>
<td>Fe I</td>
<td>4046.96</td>
<td>-0.162 ± 0.025</td>
<td>24.8 ± 3.8</td>
<td>6.6</td>
<td>1.04</td>
<td>27.8 ± 4.4</td>
</tr>
<tr>
<td>Fe I</td>
<td>4384.78</td>
<td>-0.135 ± 0.016</td>
<td>20.6 ± 2.5</td>
<td>8.3</td>
<td>1.16</td>
<td>29.2 ± 4.1</td>
</tr>
<tr>
<td>Fe II</td>
<td>4925.30</td>
<td>-0.226 ± 0.022</td>
<td>34.5 ± 3.3</td>
<td>10.3</td>
<td>1.13</td>
<td>13.1 ± 1.7</td>
</tr>
<tr>
<td>Fe II</td>
<td>5019.83</td>
<td>-0.211 ± 0.020</td>
<td>32.2 ± 3.0</td>
<td>10.8</td>
<td>1.11</td>
<td>19.1 ± 2.5</td>
</tr>
</tbody>
</table>

Notes. \( \lambda_0 \) is the central wavelength of the line in vacuum. \( h \), FWHM, and \( v_{wind} \) are the amplitude, width, and center of the best-fit Gaussian profile to the planetary absorption. S/N is simply calculated as the value of \( h \) divided by its uncertainty. \( N_{sc} \) represents the number of atmospheric scale heights that the peak absorption corresponds to. \( f \) is the scaling factor applied to the stellar RM+CLV model.

The wind velocity offset for the Na I doublet differs from each other by \(-2\sigma\). We suppose this may be systematics as a result of multiple sodium absorptions by the interstellar medium located around 13–24 km s\(^{-1}\) away from the line center. We mitigated the effect by excluding this velocity range at the barycentric rest-frame when calculating the transmission spectrum, but some artefacts might still persist to contribute to the line offset.

We also note in Fig. 9c the ‘gap’ in the absorption signal when the planetary trail intersects the Doppler shadow, meaning that the planetary transmission lines overlap with the stellar lines from the region blocked by the planet. At this moment, the effective size of the planet appears larger because of the absorption, therefore enhancing the RM effect. This is not accounted for in our RM+CLV modelling, so we commonly see such under-correction that leads to the gap near the overlapping orbital phases. We quantified the effect of the under-correction on the planetary absorption depths by excluding the overlapping orbital phases (e.g. from \(-0.015\) to 0.015) when fitting the planetary signal and co-adding the transmission spectra. We found that the absorption amplitude increases by \(-20\%\)–25% for lines such as Hα, sodium, and ionised iron, typically around 2σ of our measurements. The nominal uncertainties shown in Table 3 did not account for such systematic noise, therefore likely to be underestimations.

4.2. Detection of species in cross-correlation

In addition to elements with individual lines detected in the transmission spectrum, we performed cross-correlation analyses for a range of atoms, ions, and molecules, guided by their observability at high spectral resolution as presented in Kesseli et al. (2022). Here we present the detection of Mg I, Ca I, Cr I, Fe I, and Fe II in Fig. 7 and Table 4. We found no evidence of other species such as Ti I, Ti II, V I, V II, Mn I, Co I, Ni I, TiO, VO.
The lack of detection of Ti I, Ti II, and TiO are commonly seen in UHJs, although not well understood. Temperatures in the atmosphere seem to play a key role in determining the chemical composition. For example, KELT-9 b shows strong Ti II at the extreme temperature of 4000 K (Hoeijmakers et al. 2018). The detection of Ti in any form. This has been proposed to be due to Ti being trapped in condensates on the night side of those cooler temperatures (including WASP-76 b, WASP-121 b, HAT-P-70 b and WASP-189b). For instance, super-rotational jets may be present in the lower atmospheres of MASCARA-4 b and MASCARA-2 b, resulting in broadened Fe II signatures. Whereas, the atmosphere of HAT-P-70b may undergo strong outflow in the upper atmosphere, broadening Fe II signal instead.

5. Discussion

5.1. Disentangling the hydrostatic atmosphere and extended exosphere of UHJs

As the detection of atoms with high-resolution transmission spectroscopy accumulates quickly, a small sample of ultra-hot Jupiters starts to build up, providing us with the opportunity to study potential trends of atomic signatures in the UHJ population. Among various species, H I, Na I, Mg I, Ca II, Fe I, and Fe II, have been commonly detected in a handful of UHJs, including KELT-9b (Yan & Henning 2018; Cauley et al. 2019; Borsa et al. 2019; Hoeijmakers et al. 2019; Yan et al. 2019; Turner et al. 2020; Wittenbach et al. 2020), MASCARA-2b (Casasayas-Barris et al. 2020; Hoeijmakers et al. 2020a; Nugroho et al. 2020; Stangret et al. 2020), WASP-121b (Cabot et al. 2020; Gibson et al. 2020; Hoeijmakers et al. 2020b; Borsa et al. 2021; Merritt et al. 2021), WASP-76b (Tabernero et al. 2021; Seidel et al. 2021; Casasayas-Barris et al. 2021; Kesseli et al. 2022), WASP-189b (Prinoth et al. 2022), HAT-P-70b (Bello-Arufe et al. 2022). We compile properties of the detections (including the transmission amplitude h and the FWHM of each species) in Table B.1.

Figure 8 shows the sample of UHJs with the absorption amplitude (h) of each species plotted against the typical transmission amplitude $2H_0 R_p/R_\star^2$. Under the assumption of hydrostatic atmospheres, we expect the line strength of one species to be proportional to the typical transmission amplitude $2H_0 R_p/R_\star^2$, if the absorption forms at a similar pressure level. In this case, the slope of the linear correlation represents the vertical extent of the atom in UHJ atmospheres in units of scale height $H_0$. According to Fig. 8, near metal species such as Mg I, Fe I, (and possibly Na I) follow the trend well, with the Pearson correlation coefficients $r$ close to 1. The number of scale heights (see the slopes in Fig. 8) probed by Na I, Mg I, and Fe I decreases with the atomic mass of the element. Another underlying assumption for the linear correlation is that the abundances of the neutral species do not vary.
significant in all the UHJs. The good correlations shown in Fig. 8 seem to hint at the validity of this hypothesis, which could be verified by future retrieval analysis to constrain the abundances in these UHJs.

On the other hand, \(H\alpha\) and \(Fe\text{II}\) are two apparent exceptions of the correlation. In particular, although the scale height of WASP-76b is large, only upper limits have been estimated for \(H\alpha\) and \(Fe\text{II}\) (Casasayas-Barris et al. 2021; Kesseli et al. 2022). Instead, this agrees with the argument that the absorption of \(H\alpha\) probes extended upper atmospheres where the hydrostatic and LTE assumptions no longer apply. Hence, the \(Fe\text{II}\) signatures, with such a similar behaviour as \(H\alpha\), likely also originate from UHJ exospheres.

In this light, we find a positive correlation of absorption signals between \(Fe\text{II}\) and \(H\alpha\) as shown in Fig. 9, consolidating that they probe the similar atmospheric region and process. The planet WASP-76b, with only an upper limit detection of the \(H\alpha\) absorption, also show no evidence of \(Fe\text{II}\), well in line with the correlation. WASP-121b is a baffling case where the detection of \(Fe\text{II}\) in the optical is debated (the tentative detection was claimed in Ben-Yami et al. 2020; Borsa et al. 2021; Merritt et al. 2021, but contradicted in Hoeijmakers et al. 2020b; Gibson et al. 2020), while the strong detection in the NUV (Sing et al. 2019) does suggest its presence in the extended exosphere up to 2\(R_p\). Based on the strong \(H\alpha\) detection in WASP-121b (Cabot et al. 2020; Borsa et al. 2021), we expect significant \(Fe\text{II}\) absorption if it follows the trend. Further observations are needed to unravel this. We also note that in order to ensure the trend is not obstructed by the model-dependency of the CCF signal, we compared individual \(Fe\text{II}\) lines in transmission spectra of KELT-9b (Cauley et al. 2019; Hoeijmakers et al. 2019), MASCARA-2b (Casasayas-Barris et al. 2020), and MASCARA-4b (this work), and confirm that the correlation with \(H\alpha\) still holds.

Therefore, our comparison of atomic transmission features among the UHJ population hints at two distinct regimes of origin, the hydrostatic lower atmosphere and the extended atmosphere. The linear correlation between the absorption strengths of metals (such as \(Na\text{I}\), \(Mg\text{I}\), and \(Fe\text{I}\)), and the expected transmission amplitudes under the hydrostatic assumption validates their origin from the hydrostatic lower atmosphere. On the other hand, hydrogen and ions such as \(Fe\text{II}\) deviate from the scale height correlation, possibly because of the prevailing contribution from hydrodynamic outflows in the upper atmosphere. The positive relation of absorption strength between \(Fe\text{II}\)
and Hα is further indicative of their exospheric origins (as discussed in Sect. 5.2). The overall picture for Ca II is less clear, probably involving contribution of both regimes. The absorption strengths of Ca II are commonly large enough to be attributed to the extended upper atmospheres, sometimes even beyond the Roche lobe (Borsa et al. 2021; Bello-Arufe et al. 2022). Yet we find no clear correlation between Ca II and Hα, while the linear trend with scale heights still hold to some extent (see Fig. 8). Our speculation is that both lower and upper atmosphere regimes contribute to the absorption, considering Ca I atoms are prone to be readily ionized in the lower atmosphere in contrast to Fe I, the ionization of which may only be significant in the upper atmosphere. A larger sample size is required to draw more solid conclusions.

We caution that studying an ensemble of UHJs is challenging because of two aspects. First, it is difficult to account for the uncertainty of measurements either from different instruments or from different data reduction. For instance, systematic differences have been found in Hα in KELT-9b (Yan & Henning 2018; Cauley et al. 2019; Turner et al. 2020; Wyttenbach et al. 2020) and MASCARA-2b (Casasayas-Barris et al. 2019). However, the systematics are not expected to be large enough to break the general trend that we show here. Second, the model-dependency of cross-correlation signals presents challenges for the comparison of the UHJ population. Previous studies of individual UHJs use cross-correlation templates that are modeled differently. A standard set of models such as presented in Kitzmann et al. (2021) will be beneficial if it can be commonly used in such analyses. Yet the choice of temperature in the model affects the relative weights assigned to weak versus strong lines, which changes the amplitude of CCFs by up to a factor of two.

5.2. Hydrodynamic exospheres as probed via Hα and ions

The positive correlation of absorption signals between Fe II and Hα as shown in Fig. 9 indicates that both species trace the similar atmospheric region in UHJs. H I and He I absorption lines have been previously modeled as a probe for the escaping exosphere (Huang et al. 2017; Allan & Vidotto 2019; García Muñoz & Schneider 2019; Wyttenbach et al. 2020; Yan et al. 2021; Oklopcić & Hirata 2018; Lampón et al. 2021; Dos Santos et al. 2022), which is expected to be the consequence of hydrodynamic outflows driven by stellar X-ray, extreme Ultraviolet (EUV) or NUV radiation. The driving mechanism may depend on the stellar type, as early A type stars are not expected to emit strongly at EUV (Fossati et al. 2018), while having high levels of NUV flux (García Muñoz & Schneider 2019). The modeling of outflows also extends to heavy atoms such as C, O, Si by Koskinen et al. (2013), suggesting that heavy elements dragged to the upper atmospheres stay well mixed as a result of collisions with rapidly escaping hydrogen. Gebek & Oza (2020) modeled Na and K in evaporative exospheres to interpret high-resolution transmission observations. Furthermore, the strong Mg I, Mg II, and Fe II lines in the NUV are discussed as tracers of upper atmospheres and hydrodynamic escapes (Bourrier et al. 2014; Sing et al. 2019; Dwivedi et al. 2019), while the optical lines have not been explored. Based on the presented correlation of absorption signals between Fe II and Hα, we suggest that Fe II lines in the optical also probe exospheres of UHJs. Therefore, further modeling of Fe II in exosphere can help constrain the structure of upper atmosphere, outflows, and the mass loss process.

Without the intention to model any particular atmosphere in detail, we aim to get insights into the trend in the UHJ population by some simplified estimations as follows. We examine the role of hydrodynamic outflows and photoionisation of atoms in the absorption signals of H I and Fe II in UHJs. For a rough estimation, we assume the extended exosphere as a homogeneous optically thin cloud subject to stellar high energy radiation. In the optically thin limit, the absorption level is proportional to the total mass of the absorbing material regardless of the shape of the cloud (Hoeijmakers et al. 2020b; Gebek & Oza 2020). Hence, the absorption signal depends on the mass loss rate \( \dot{M} \) that determines the inflow of absorbing material to the exosphere and the ionisation degree \( f_X \) of the element. More details of the estimation can be found in Appendix A. We find that the photoionisation plays a marginal role in the discrepancy of absorption strengths because the degree of ionization is expected to vary by less than a factor of a few among different UHJs. Instead, the amount of absorption is dominated by the planetary mass loss \( \dot{M} \) driven by the stellar EUV or NUV flux, which usually varies by orders of magnitudes from system to system. Therefore, we argue that the dominant outflow drives the positive correlation between the Hα and Fe II absorption (see Fig. 9), and they likely trace the exospheres of UHJs. The absorption level reflects the properties of individual planets such as the mass loss rate and the irradiation environment.

Although the sample size of UHJs with detailed spectral characterisation is still small, we suggest that the correlation between Fe II and Hα absorption signal is expected from the analytical estimation. It therefore calls for more future observations on UHJs to populate this plot. Detailed modeling of individual planets will be valuable for constraining the hydrodynamic outflows and mass loss rate as traced by atomic absorption lines in the optical.

6. Conclusion

With the purpose of detailed characterisation of the ultra-hot Jupiter MASCARA-4b, we carried out transit photometry and radial velocity measurements using EulerCam and CORALIE at the 1.2 m Euler telescope, delivering a refined planet mass of \( 1.675 \pm 0.241 \, \text{M}_{\text{Jup}} \), together with other updated system and planet parameters. We analysed the optical transmission spectrum of MASCARA-4b observed with the high-resolution spectrograph ESPRESSO at the VLT and report the detection of various species in the atmosphere, including H I, Na I, Mg I, Ca I, Ca II, Cr I, Fe I, and Fe II. This adds MASCARA-4b to the ensemble of UHJs showing a profusion of atomic absorption features. Putting the measurements into perspective, we explored the trends of atomic absorption features within the UHI population, indicating two distinct atmospheric regimes as probed through different absorption signatures. The absorption by metals such as Mg I and Fe I appears to trace the hydrostatic region of atmospheres as the line strengths correlate well with the scale heights of different planets. The Hα and Fe II absorption strengths, which deviate from the scale height correlation, yet show a positive relation with each other among the UHI population. Through analytical estimations, we suggest that the correlation is consistent with the exospheric origin of Fe II and Hα absorption in UHJs, driven by the dominant outflows subject to stellar high-energy radiation. This shows the potential of using both species as probes for the hydrodynamic escape and mass loss of UHJs. Studying the diverse atomic transmission signatures allows us to disentangle the hydrostatic and the exospheric regime of the extremely irradiated planets.

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Appendix A: Analytical estimation of atomic absorption in exospheres

We consider the gas composed of atomic hydrogen in the upper atmosphere (exosphere) escaping the planet with a velocity of \( u \) and a constant mass loss rate \( M \). The conservation of mass provides

\[
M = 4\pi R_p^2 \rho \dot{m},
\]

where \( R_p \) is the size of the exobase, \( \rho \) is the density of hydrogen, and \( u = n_0 v_{\text{esc}} \) is a fraction of the planet’s escape velocity \( v_{\text{esc}} = \sqrt{2GM_{\text{p}}/R_p} \).

The energy-limited mass loss rate following Erkaev et al. (2007) is given by

\[
M = \frac{\pi R_p^2 F_{\text{EUV}} \epsilon}{\Phi_0 K},
\]

where \( F_{\text{EUV}} \) is the planet radius, \( F_{\text{EUV}} \) is the stellar EUV flux at the location of the planet, \( \epsilon \) is the heating efficiency, \( \Phi_0 \) is the gravitational potential at the planetary radius \( (\Phi_0 = GM_{\text{p}}/R_p) \), and \( K(R) \) is the coefficient accounting for the potential difference between the Roche lobe boundary \( (R_R) \) and the planetary surface \( (R_p) \) as a result of stellar tidal forces.

Combining Equation A.1 and A.2, we get the number density of H atom in the exosphere as a result of outflows

\[
\rho = \frac{eF_{\text{EUV}}}{2\pi n_0 K v_{\text{esc}}} \rho_0 \left( \frac{eF_{\text{EUV}}}{F_0} \right) \left( \frac{v_0}{v_{\text{esc}}} \right)^3,
\]

where \( F_0 = 450 \text{ erg cm}^{-2} \text{ s}^{-1}, v_{\text{esc}} = 60 \text{ km s}^{-1}, \) and \( \rho_0 = 10^{-15} \text{ g cm}^{-3} \), as informed by previous simulations such as Murray-Clay et al. (2009); Allan & Vidotto (2019).

Equation A.3 suggests that under the assumption of the energy-limited mass loss, the exospheric density \( \rho \) scales with the planet’s escape velocity (or gravitational potential) and the EUV flux received.

In addition to the outflow, the photoionisation of species also plays a role in determining the level of transmission signal. For a rough estimation of the photoionisation, we simply assume the extended exosphere as a homogeneous optically thin cloud subject to stellar EUV radiation. The characteristic temperature of the exosphere is determined by the balance of heating (\( Q \)) and cooling (\( C \)) following Murray-Clay et al. (2009).

\[
Q = eF_{\text{EUV}} \sigma_{n_0} n_0,
\]

where \( \sigma_{n_0} \) is the cross section for the photoionisation of hydrogen and \( n_0 \) is the number density of neutral hydrogen. For the cooling term, we assume it is driven by radiative losses resulting from collisional excitation of Ly\( \alpha \) line

\[
C = 7.5 \times 10^{-19} n_+ n_e \alpha_{\text{rec}} \exp[-1.183 \times 10^5/T],
\]

where \( n_+ \) is the number density of protons, equivalent to the number density of electrons.

Considering the photochemistry of H\( I \), we solve for the ionisation balance (the rate of photoionisation and radiative recombination) to estimate the degree of ionization \( f_{\text{H}} \).

\[
\frac{F_{\text{EUV}} \sigma_{n_0} n_0}{e_{\text{in}}} = n_+ n_e \alpha_{\text{rec}},
\]

where \( \sigma_{n_0} = 1.89 \times 10^{-18} \text{ cm}^2 \) is the cross section for photoionisation of hydrogen (Spitzer 1978); the recombination coefficient \( \alpha_{\text{rec}} = 2.7 \times 10^{-13} / (T/10^4)^{0.9} \) taken from Storey & Hummer (1995); \( n_+ = n_e = n_f \) and \( n_+ = n_I = n - n_f \), where \( n = \rho / m_0, m_0 \) is the mass of H atom; \( e_{\text{in}} \) is the input photon energy, assumed to be 20 eV, and the heating efficiency is \( \epsilon = 1 - 13.6 eV / e_{\text{in}} = 0.32 \).

Combining Equation A.3, A.4, A.5, and A.6, we solve for the ionization degree of hydrogen and the temperature as follows

\[
\frac{1}{f_{\text{H}}} = 1 + 0.015/(T^{0.9} \exp[-1.183 \times 10^5/T]),
\]

\[
\frac{1}{f_{\text{Fe}}} = 0.4\rho_0 \left( \frac{v_0}{v_{\text{esc}}} \right)^3 \exp[-1.183 \times 10^5/T].
\]

Similarly, for other species such as Fe\( I \), the ionisation balance of Fe combined with Equation A.6 gives

\[
\frac{1}{f_{\text{Fe}}} = 1 + \frac{f_{\text{H}} \sigma_{\text{rec,Fe}}}{\sigma_{\text{Fe}}} \left( f_{\text{H}} \right)^{0.15},
\]

where \( \sigma_{\text{rec}} = 3.66 \times 10^{-18} \text{ cm}^2 \) (Verner et al. 1996), the recombination coefficient \( \sigma_{\text{rec,Fe}} = 3.7 \times 10^{-12} \text{ cm}^2 \) (Woodall et al. 2007).

Hence, the exospheric temperature and degree of ionisation depend on the planet’s potential in terms of \( v_{\text{esc}} \) in our simplified model, as shown in Fig. A.2.

In the optically thin limit, the equivalent width of absorption is proportional to the total mass of the absorbing material (Hoeijmakers et al. 2020b; Gebek & Oza 2020). For neutral hydrogen and ionised iron, they can be written as follows

\[
T_{\text{H}} \sim \rho (1 - f_{\text{H}}) \sim \rho_0 \left( \frac{eF_{\text{EUV}}}{F_0} \right) \left( \frac{v_0}{v_{\text{esc}}} \right)^3 (1 - f_{\text{H}}),
\]

\[
T_{\text{Fe}} \sim \rho_{\text{fe}} f_{\text{Fe}} \sim \rho_0 \left( \frac{eF_{\text{EUV}}}{F_0} \right) \left( \frac{v_0}{v_{\text{esc}}} \right)^3 A_{\text{Fe}} f_{\text{Fe}},
\]

where a constant mixing of the metal species is assumed, \( A_{\text{Fe}} \) is the mass fraction of iron. We note that the photoionisation term \( (f_{\text{H}} \text{ and } f_{\text{Fe}}) \) can result in variations of the signal strength from different planets by a factor of 4 at most (see Fig. A.2). Whereas, equation A.9 contains the linear term of \( F_{\text{EUV}} \) that usually varies by orders of magnitudes from system to system. Therefore, the absorption signal from the exosphere is dominated by the planetary outflow \( M \) induced by the EUV flux, which drives the positive correlation between \( \text{H}\alpha \) and Fe\( \Pi \) as we note in Section 5.1. Hence such correlation is indeed expected, which reflects properties such as the mass-loss rate and EUV irradiation of different UHJs.

For simplicity we did not take into account the fraction of atoms at the right state (e.g. the principal quantum number \( n = 2 \) for \( \text{H}\alpha \) absorption). This requires non-local thermal equilibrium (NLTE) calculation of the radiation field and gets even more complicated for the case of Fe\( \Pi \) where we combined multiple lines in the observation. The ionisation of Fe\( \Pi \) is also ignored here. We do not attempt to make detailed interpretation of observed lines in any particular system. Instead, our aim is to draw the relation between \( \text{H}\alpha \) and Fe\( \Pi \) across the UHJ population. These assumptions hopefully do not deter the overall trend, yet we need to rely on detailed simulations for a definite answer.

Appendix B: Summary of UHJs with detailed characterisation with high-resolution transmission spectroscopy

A47, page 12 of 13
Y. Zhang et al.: MASCARA-4b

Table B.1. Properties of atomic absorption features detected in transmission spectra of ultra-hot Jupiters.

<table>
<thead>
<tr>
<th>$R_p/R_\star$</th>
<th>HAT-P-70b</th>
<th>KELT-9b</th>
<th>MASCARA-2b</th>
<th>MASCARA-4b</th>
<th>WASP-76b</th>
<th>WASP-121b</th>
<th>WASP-189b</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_p/R_\star$</td>
<td>0.099</td>
<td>0.082</td>
<td>0.113</td>
<td>0.087</td>
<td>0.109</td>
<td>0.125</td>
<td>0.061</td>
</tr>
<tr>
<td>$T_{eq}$ (K)</td>
<td>2562 ± 52</td>
<td>3921 ± 182</td>
<td>2260 ± 50</td>
<td>2250 ± 62</td>
<td>2228 ± 120</td>
<td>2358 ± 52</td>
<td>2641 ± 31</td>
</tr>
<tr>
<td>$T_e$ (K)</td>
<td>8450 ± 690</td>
<td>9600 ± 400</td>
<td>8980 ± 130</td>
<td>7800 ± 200</td>
<td>6329 ± 65</td>
<td>6586 ± 59</td>
<td>8000 ± 100</td>
</tr>
<tr>
<td>$R_p$ ($R_{Jup}$)</td>
<td>1.87 ± 0.15</td>
<td>1.926 ± 0.047</td>
<td>1.83 ± 0.07</td>
<td>1.515 ± 0.044</td>
<td>1.865 ± 0.083</td>
<td>1.865 ± 0.044</td>
<td>1.619 ± 0.021</td>
</tr>
<tr>
<td>$M_p$ ($M_{Jup}$)</td>
<td>&lt; 6.78</td>
<td>2.88 ± 0.35</td>
<td>&lt; 3.5</td>
<td>1.675 ± 0.241</td>
<td>0.894 ± 0.014</td>
<td>1.183 ± 0.064</td>
<td>1.99 ± 0.16</td>
</tr>
<tr>
<td>$h_e$ (km)</td>
<td>&gt; 184</td>
<td>704 ± 95</td>
<td>&gt; 302</td>
<td>430 ± 66</td>
<td>1206 ± 102</td>
<td>967 ± 65</td>
<td>485 ± 40</td>
</tr>
<tr>
<td>$h_{H\alpha}$ (%)</td>
<td>1.560 ± 0.150</td>
<td>1.150 ± 0.050</td>
<td>0.765 ± 0.090</td>
<td>&lt; 0.317 ± 0.021</td>
<td>&lt; 0.470</td>
<td>1.700 ± 0.048</td>
<td>0.13 ± 0.02</td>
</tr>
<tr>
<td>FWHM $H\alpha$ (km s$^{-1}$)</td>
<td>32.1 ± 3.9</td>
<td>51.2 ± 2.6</td>
<td>16.8 ± 3.4</td>
<td>17.1 ± 2.4</td>
<td>-</td>
<td>40.9 ± 1.7</td>
<td>27.4 ± 4.6</td>
</tr>
<tr>
<td>$h_{Fe I}$ (%)</td>
<td>0.037 ± 0.003</td>
<td>0.016 ± 0.001</td>
<td>0.057 ± 0.002</td>
<td>0.0150 ± 0.0001</td>
<td>0.049 ± 0.003</td>
<td>0.039 ± 0.002</td>
<td>0.0075 ± 0.0004</td>
</tr>
<tr>
<td>FWHM $Fe I$ (km s$^{-1}$)</td>
<td>9.7 ± 1.0</td>
<td>20.1 ± 1.0</td>
<td>12.39 ± 1.69</td>
<td>22.5 ± 0.2</td>
<td>8.6 ± 0.7</td>
<td>15.9 ± 1.1</td>
<td>15.3 ± 1.0</td>
</tr>
<tr>
<td>$h_{Fe II}$ (%)</td>
<td>0.437 ± 0.017</td>
<td>0.183 ± 0.004</td>
<td>0.130 ± 0.011</td>
<td>0.0444 ± 0.0011</td>
<td>&lt; 0.063</td>
<td>-</td>
<td>0.023 ± 0.002</td>
</tr>
<tr>
<td>FWHM $Fe II$ (km s$^{-1}$)</td>
<td>13.7 ± 0.6</td>
<td>21.8 ± 0.7</td>
<td>8.54 ± 0.87</td>
<td>16.5 ± 0.4</td>
<td>-</td>
<td>-</td>
<td>14.1 ± 1.2</td>
</tr>
<tr>
<td>$h_{Na I \ D}$ (%)</td>
<td>0.655 ± 0.150</td>
<td>&gt; 0.095 ± 0.007</td>
<td>0.320 ± 0.050</td>
<td>0.191 ± 0.017</td>
<td>0.360 ± 0.050</td>
<td>0.480 ± 0.047</td>
<td>0.153 ± 0.031</td>
</tr>
<tr>
<td>$h_{Mg I}$ (%)</td>
<td>0.131 ± 0.018</td>
<td>0.056 ± 0.005</td>
<td>0.062 ± 0.005</td>
<td>0.0221 ± 0.0009</td>
<td>0.114 ± 0.016</td>
<td>0.123 ± 0.015</td>
<td>0.018 ± 0.002</td>
</tr>
<tr>
<td>$h_{Ca II}$ (%)</td>
<td>3.750 ± 0.370</td>
<td>0.780 ± 0.040</td>
<td>0.560 ± 0.050</td>
<td>0.775 ± 0.082</td>
<td>2.440 ± 0.340</td>
<td>4.700 ± 0.180</td>
<td>0.40 ± 0.05</td>
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<td>References</td>
<td>(1),(2)</td>
<td>(3)-(10)</td>
<td>(11)-(15)</td>
<td>(16)-(18)</td>
<td>(19)-(24)</td>
<td>(25)-(28)</td>
<td>(29)-(31)</td>
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</tbody>
</table>

Notes. For the calculation of the lower atmosphere scale height $H_0$, we assume a mean molecular weight $\mu$ of 2.3. The amplitude of Na I absorption ($h_{Na I \ D}$) takes the average value of the Na I doublet at 5891 and 5897 Å. The $h_{Ca II}$ takes the average value of the Ca II H & K lines at 3969 and 3934 Å. Properties of Mg I, Fe I, and Fe II are taken from cross-correlation outcomes.


![Fig. A.1](image-url) Schematic of a transiting ultra-hot Jupiter with a hydrostatic lower atmosphere and an optically-thin escaping exosphere.

![Fig. A.2](image-url) Estimated temperature and degree of ionization of H and Fe for different planets with a range of $v_{esc}$. The ionisation fractions are not expected to vary drastically across different UHJs.