

# The GAPS programme at TNG<sup>★</sup>

## XXX. Atmospheric Rossiter-McLaughlin effect and atmospheric dynamics of KELT-20b

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### ABSTRACT

**Context.** Transiting ultra-hot Jupiters are ideal candidates to study the exoplanet atmospheres and their dynamics, particularly by means of high-resolution, high signal-to-noise ratio spectra. One such object is KELT-20b, orbiting the fast rotating A2-type star KELT-20. Many atomic species have already been found in its atmosphere, with blueshifted signals that hints at the presence of a day-to-night side wind.

**Aims.** We aimed to observe the atmospheric Rossiter-McLaughlin effect in the ultra-hot Jupiter KELT-20b, and to study any variation of the atmospheric signal during the transit. For this purpose, we analysed five nights of HARPS-N spectra covering five transits of KELT-20b.

**Methods.** We computed the mean line profiles of the spectra with a least-squares deconvolution using a stellar mask obtained from the Vienna Atomic Line Database ( $T_{\text{eff}}=10\,000$  K,  $\log g=4.3$ ), and then we extracted the stellar radial velocities by fitting them with a rotational broadening profile in order to obtain the radial velocity time-series. We used the mean line profile residuals tomography to analyse the planetary atmospheric signal and its variations. We also used the cross-correlation method to study an already known double-peak feature in the FeI planetary signal.

**Results.** We observed both the classical and the atmospheric Rossiter-McLaughlin effect in the radial velocity time-series. The latter gave us an estimate of the radius of the planetary atmosphere that correlates with the stellar mask used in our work ( $R_{p+atmo}/R_p = 1.13 \pm 0.02$ ). We isolated the planetary atmospheric trace in the tomography, and we found radial velocity variations of the planetary atmospheric signal during transit with an overall blueshift of  $\approx 10$  km s<sup>-1</sup>, along with small variations in the signal's depth and, less significant, in the full width at half maximum (FWHM). We also find a possible variation in the structure and position of FeI signal in different transits.

**Conclusions.** We confirm the previously detected blueshift of the atmospheric signal during the transit. The FWHM variations of the atmospheric signal, if confirmed, may be caused by more turbulent condition at the beginning of the transit, or by a variable contribution of the elements present in the stellar mask to the overall planetary atmospheric signal, or by iron condensation. The FeI signal show hints of variability from one transit to the other.

**Key words.** planetary systems – techniques: spectroscopic – techniques: radial velocities – planets and satellites: atmospheres – stars: individual: KELT-20

### 1. Introduction

A very interesting category of exoplanets is represented by the transiting ultra-hot Jupiters (UHJs; Bell & Cowan 2018), which are highly irradiated Jupiter-size planets with day-side temperatures higher than 2200 K (Parmentier et al. 2018). Transiting UHJs are ideal laboratories to study planetary atmospheres: their inflated atmospheres and high equilibrium temperatures ( $T_{\text{eq}}$ ) result in strong signals and striking peculiar conditions for a planetary body. Their atmospheres are rich in atomic and molecular species: for example, CrII, FeI, FeII, MgII, NaI, ScII, TiII, and YII have been detected in KELT-9b, the hottest UHJ known so far ( $T_{\text{eq}} = 4050$  K), with additional evidence of the presence of CaI, CrI, CoI, and SrII (Hoeijmakers et al. 2018, 2019). Because of the presence of neutral and ionised iron in their atmospheres, UHJs can be used to study the atmospheric

Rossiter-McLaughlin effect (Borsa et al. 2019): in fact the signal coming from their atmosphere correlates with the stellar mask used to compute the mean line profile of the spectra and recover the star's radial velocity (RV), resulting in an additional absorption in the mean line profile that causes an apparent RV variation similar to the classical Rossiter-McLaughlin effect (RML). In addition to that, UHJs have usually very different atmospheric conditions (e.g., in temperature and chemical composition) between day and night side, that may result in day-to-night side wind (Ehrenreich et al. 2020; Heng & Showman 2015): high resolution spectroscopy may be used to study the RV variations of the atmospheric signal in order to search for the presence of winds or any other kind of atmospheric turbulence.

KELT-20b (Lund et al. 2017), *aka* MASCARA-2b (Talens et al. 2018), is a well known ultra-hot Jupiter orbiting a fast rotating A-type star. With a period of 3.47 days and a semi-major axis of 0.0542 au, KELT-20b is highly irradiated by its host star (A2,  $T_{\text{eff}} = 8980$  K,  $m_V = 7.6$ ) and its atmosphere reaches  $T_{\text{eq}} = 2260$  K (see Table 1 for more details on the system).

<sup>★</sup> Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated by the Fundación Galileo Galilei (FGG) of the Istituto Nazionale di Astrofisica (INAF) at the Observatorio del Roque de los Muchachos (La Palma, Canary Islands, Spain).

**Table 1.** Physical and orbital parameters of the KELT-20 system (*aka* MASCARA-2, *aka* HD185603)

Parameter	Symbol	Value
Stellar Parameters		
Spectral type <sup>1</sup>		A2
V-band magnitude <sup>2</sup>	$m_V$	7.6
Effective temperature <sup>3</sup>	$T_{\text{eff}}$	$8980^{+90}_{-130}$ K
Projected rotation speed <sup>4</sup>	$v \sin i_{\star}$	$116.23 \pm 1.25$ km s <sup>-1</sup>
Linear limb darkening <sup>1</sup>	$u$	$0.532^{+0.011}_{-0.014}$
Surface gravity <sup>3</sup>	$\log g$	$4.31 \pm 0.02$ cgs
Metallicity <sup>3</sup>	[Fe/H]	$-0.02 \pm 0.07$ dex
Stellar mass <sup>3</sup>	$M_{\star}$	$1.89^{+0.06}_{-0.05}$ $M_{\odot}$
Stellar radius <sup>3</sup>	$R_{\star}$	$1.60 \pm 0.06$ $R_{\odot}$
Rotation period <sup>4</sup>	$p_{\star}$	$0.695 \pm 0.027$ days
Planetary parameters		
Planet mass <sup>1</sup>	$M_p$	$< 3.51 M_{\text{Jup}}$
Planet radius <sup>3</sup>	$R_p$	$1.83 \pm 0.07$ $R_{\text{Jup}}$
Planet-to-star ratio <sup>1</sup>	$R_p/R_{\star}$	$0.11440^{+0.00062}_{-0.00061}$
Planet-to-star ratio <sup>3</sup>	$R_p/R_{\star}$	$0.115 \pm 0.002$
Equilibrium temperature <sup>3</sup>	$T_{\text{eq}}$	$2260 \pm 50$ K
Surface gravity <sup>1</sup>	$\log g_p$	$< 3.46$ cgs
Overall Fe volume mixing ratio (solar value) <sup>5</sup>	$\log \text{VMR}_{\text{Fe}}$	$-4.27$ cgs
Orbital parameters		
Epoch <sup>3</sup>	$T_P$	$2\,457\,909.5906^{+0.0003}_{-0.0002}$ BJD
Period <sup>3</sup>	$P$	$3.474119^{+0.000005}_{-0.000006}$ days
Transit duration <sup>1</sup>	$T_{\text{dur}}$	$0.14882^{+0.00002}_{-0.00002}$ days
Semi-major axis <sup>1</sup>	$a$	$0.0542^{+0.0014}_{-0.0021}$ au
Inclination <sup>1</sup>	$i$	$86.15^{+0.28}_{-0.27}$ deg
Eccentricity	$e$	0 (fixed)
Projected obliquity <sup>3</sup>	$\lambda$	$0.6 \pm 4$ deg
Stellar RV amplitude <sup>6</sup>	$K_s$	$322.51$ m s <sup>-1</sup>
Systemic velocity <sup>1</sup>	$V_{\text{Sys}}$	$-23.3 \pm 0.3$ km s <sup>-1</sup>
Systemic velocity <sup>3</sup>	$V_{\text{Sys}}$	$-21.3 \pm 0.4$ km s <sup>-1</sup>
Systemic velocity <sup>7</sup>	$V_{\text{Sys}}$	$-22.06 \pm 0.35$ km s <sup>-1</sup>
Systemic velocity <sup>4</sup>	$V_{\text{Sys}}$	$-24.48 \pm 0.04$ km s <sup>-1</sup>

**References.** <sup>1</sup> Lund et al. (2017); <sup>2</sup> Høg et al. (2000); <sup>3</sup> Talens et al. (2018); <sup>4</sup> this work; <sup>5</sup> Asplund et al. (2009); <sup>6</sup> Casasayas-Barris et al. (2019); <sup>7</sup> Nugroho et al. (2020)

Many atomic species such as FeI, FeII, CaII, NaI, HI have been detected in its atmosphere through transit spectroscopy, while there are only tentative detections of MgI and CrII (Casasayas-Barris et al. 2018, 2019; Hoeijmakers et al. 2020; Nugroho et al. 2020; Stangret et al. 2020). There are also hints of the presence of a day-to-night side wind due to the presence of a blueshift of  $-6.3 \pm 0.8$  km s<sup>-1</sup> in the FeI signal, and  $-2.8 \pm 0.8$  km s<sup>-1</sup> in that due to FeII (Stangret et al. 2020; Hoeijmakers et al. 2020; Nugroho et al. 2020).

We observed KELT-20 in the framework of the Global Architecture of Planetary Systems (GAPS) project, which is an Italian project dedicated to the search and characterization of exoplanets (PI G. Micela; Covino et al. 2013). Particularly, one of GAPS' main lines of research focuses on the study of exoplanets' atmospheres using both transmission and emission spectroscopy (Borsa et al. 2019; Pino et al. 2020; Guilluy et al. 2020). Using both our data and public data of KELT-20 taken with the same instrument (HARPS-N), we studied both the classical (Rossiter 1924; McLaughlin 1924) and atmospheric RML effects of KELT-20b from the RV time-series, along with the variations of the atmospheric trace during the planetary transits from the mean line profile tomography.

The dataset used in this work is described in Sec. 2, while the method used to obtain the stellar mean line profiles and the RV time-series is detailed in Sec. 3. Both the classical and atmospheric RML effects are shown in Sec. 4. The variations of the atmospheric trace during the transit and the methods used to detect them from the mean line profile tomography are described in Sec. 5. In Sec. 6 we describe the cross-correlation with a FeI model performed in order to compare our results with those found in the literature. Finally, our conclusions are in Sec. 7.

## 2. Data sample

We analysed five transits of KELT-20b observed with the high-resolution echelle spectrograph HARPS-N (Cosentino et al. 2012) installed at the Telescopio Nazionale Galileo (TNG) at the Roque de los Muchachos Observatory (La Palma, Spain). HARPS-N is an optical spectrograph with resolving power  $R = 115\,000$  and wavelength coverage 383-693 nm. It is a twin of the HARPS spectrograph installed at the 3.6m telescope of the ESO-LaSilla Observatory, down to the Data Reduction Software (DRS) optimised for exoplanet search.

**Table 2.** Data summary. Throughout the paper the transits will be identified by their number (first column).

#	Night	# of spectra	$T_{\text{exp}}$	Mean S/N
1	2017 August 16	90	200s	61
2	2018 July 12	116	200s	93
3	2018 July 19	78	300s	105
4	2019 August 26	30	600s	164
5	2019 September 02	29	600s	176

We observed two transits (2019 August 26 and 2019 September 02) in the framework of the GAPS programme, while the other three transits are public data retrieved from the HARPS-N archive (2017 August 16: PID CAT17A\_38 PI Rebolo; 2018 July 12, and 2018 July 19: PID CAT18A\_34, PI Casasayas-Barris). The GAPS observations were taken in the GIARPS mode (Claudi et al. 2016), that allows the simultaneous use of both HARPS-N and GIANO-B (Oliva et al. 2012; Origlia et al. 2014) spectrographs. GIANO-B is an high-resolution ( $R = 50\,000$ ) near-infrared echelle spectrograph covering the wavelength range from 950 to 2450 nm. For this work, we used only the HARPS-N data

A summary of the acquired HARPS-N spectra in the five transit nights is shown in Table 2. We rejected 14 spectra taken during night 2 because of their low S/N. All five transits are complete, and out-of-transit spectra were taken both before and after the transit in each night. We worked on spectra reduced by the HARPS-N DRS (Cosentino et al. 2014), as such the barycentric correction was already applied.

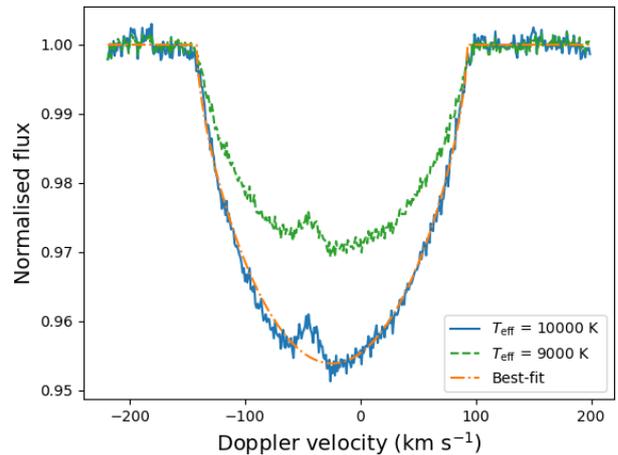
### 3. Mean line profiles

While the HARPS-N DRS is a very powerful tool, it is not optimised for hot stars such as KELT-20: the resulting cross-correlation functions (CCFs) are obtained by using a stellar mask designed to work with a G2-type star, which is the hottest stellar mask available in the DRS mask library.

We decided then to compute the mean line profile using the Least-Squares Deconvolution software (LSD, Donati et al. (1997)) with a stellar mask obtained from the VALD3 database<sup>1</sup> (Piskunov et al. 1995; Ryabchikova et al. 2015). We downloaded stellar masks for  $T_{\text{eff}}=9000$  K and  $T_{\text{eff}}=10000$  K, both with  $\log g=4.31$ , solar metallicity, and micro-turbulence  $v=2$  km s<sup>-1</sup> and wavelength range 3900-7000 Å. While our results are in good agreement using both masks, we show here only those obtained with  $T_{\text{eff}}=10000$  K, where both the stellar and the planetary signals are stronger (see Fig. 1, where the  $T_{\text{eff}}=10000$  K profile is almost twice as deep as the  $T_{\text{eff}}=9000$  K one). This may hint at an higher  $T_{\text{eff}}$  for KELT-20 than previously found.

To apply the LSD, we first normalised all our spectra using a self-developed automated procedure (Rainer et al. 2016). Then, in order to avoid most of the telluric lines contamination and the heavy contribution of the stellar Balmer lines (extremely strong as expected from KELT-20 spectral type, and with a different shape), we cut them, and we kept only the wavelength ranges 4415-4805, 4915-5870, 6050-6265, and 6335-6450 Å. We run the LSD software on each individual spectrum to obtain the mean line profiles.

We fitted all the mean line profiles with a rotational broadening function (see Fig. 1), using the formula in Eq. 1 (Gray 2008):



**Fig. 1.** Mean line profile of a single KELT-20 spectrum obtained with the LSD software and  $T_{\text{eff}}=10000$  K (solid blue line) along with the rotational broadening fit (dashed-dotted orange line). For comparison, the mean line profile of the same spectrum with the  $T_{\text{eff}}=9000$  K is shown (dashed green line). The planet's Doppler shadow is clearly visible as a bump in both lines.

$$f(x) = 1 - a \frac{2(1-u) \sqrt{1 - \left(\frac{x-x_0}{x_l}\right)^2} + 0.5\pi u \left[1 - \left(\frac{x-x_0}{x_l}\right)^2\right]}{\pi x_l \left(1 - \frac{u}{3}\right)}, \quad (1)$$

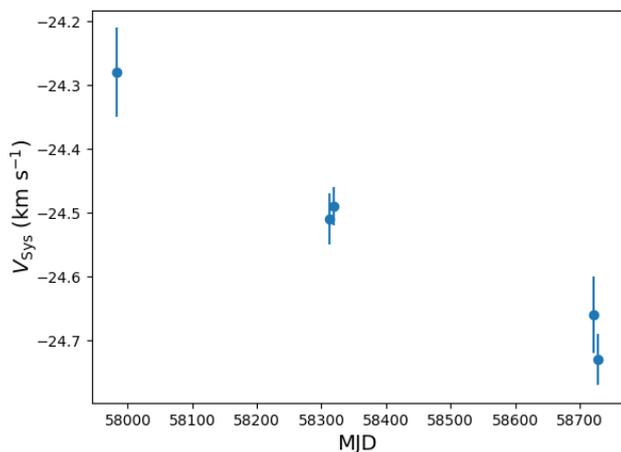
where  $a$  is the depth of the profile,  $x_0$  the centre (i.e., the RV value),  $x_l$  the  $v \sin i_*$  of the star,  $u$  the linear limb darkening (LD) coefficient (listed in Table 1). We thus recovered both the RVs and the projected rotational velocities ( $v \sin i_*$ ) for all observed spectra. We found  $v \sin i_* = 116.7 \pm 0.7$  km s<sup>-1</sup> by averaging the  $v \sin i_*$  of all the out-of-transit spectra. We did not use here the in-transit ones in order to avoid the Doppler shadow affecting our result.

We also computed the  $v \sin i_*$  using the Fourier transform method (Smith & Gray 1976; Dravins et al. 1990): because of the fast rotation of KELT-20 we could use the first three zero positions of the Fourier transform of all our mean line profiles to derive the projected rotational velocity. Using only the out-of-transit spectra, we found an average value of  $v \sin i_* = 116.23 \pm 1.25$  km s<sup>-1</sup>, which aligns well with that obtained by the profile fitting. We note here that, in case of such a fast rotating star, this method is independent from other broadening effects as for example macro-turbulence, and it only depends on the LD coefficient: for this reason, we report this value in Table 1, even if the error is larger than that obtained with the profile fitting. The average value of the ratio of the first two zero positions results in  $q_2/q_1 = 1.805 \pm 0.036$ , which is compatible with a rigid rotation ( $1.72 < q_2/q_1 < 1.83$ , Reiners & Schmitt (2002)).

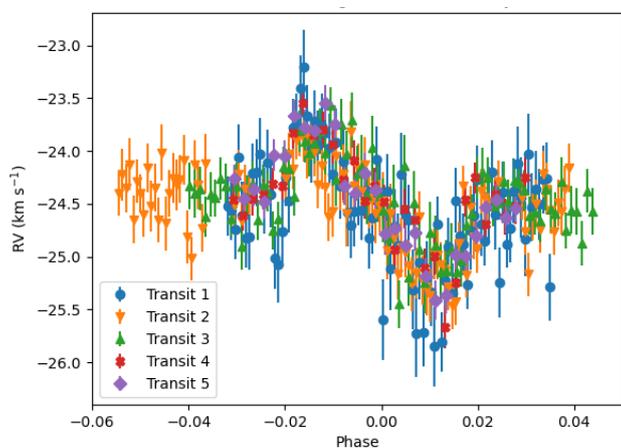
We computed the stellar rotational period as  $p_* = 2\pi R_*/v_{\text{eq}}$ , using  $R_*$ ,  $v \sin i_*$ , and inclination  $i$  from Table 1. We considered the orbit inclination  $i$  equal to the stellar inclination  $i_*$ , seeing as the projected obliquity  $\lambda$  is compatible with a zero value. We found a stellar rotational period of  $0.695 \pm 0.027$  days, which is almost exactly one fifth of the planetary period: this may suggests a resonance between the stellar and planetary rotation.

We performed a linear fit on all the out-of-transit RVs to recover the systemic velocity, and we found  $V_{\text{Sys}} = -24.48 \pm 0.04$  km s<sup>-1</sup>. This value is slightly lower than those found in the literature (see Table 1), but the determination of the systemic velocity

<sup>1</sup> <http://vald.astro.uu.se>



**Fig. 2.** Systemic velocity of the five nights: a small downwards trend is clearly visible.



**Fig. 3.** RVs data phase-folded using the KELT-20b known orbital period ( $P = 3.474119$  days). The RV values were shifted by the difference between the individual  $V_{\text{Sys}}$  of each night and the average  $V_{\text{Sys}}$  value to account for the trend found in our data.

may vary depending on the instrument and method used to estimate it. We also computed  $V_{\text{Sys}}$  independently on the five nights, and we noted a small, but significant downwards trend that may be worth keeping in mind in further studies (see Fig. 2).

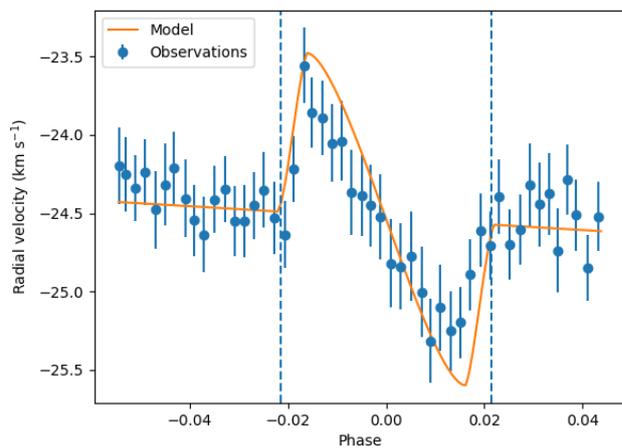
In Fig. 3 we show the RVs corrected for the different  $V_{\text{Sys}}$  (so that the five nights aligns on the average  $V_{\text{Sys}}$  value), and phase-folded using the known orbital value of KELT-20b ( $P = 3.474119$  days, see Table 1). The RML effect is clearly visible.

#### 4. Classical and atmospheric RML effects

The RML effect is visible in all nights of observations (see Fig. 3). We averaged the phase-folded RVs data of all transits using a 0.002 phase bin and we compared them with a theoretical model obtained using the already known system parameters of Table 1, using our value for the systemic velocity. The RML model was computed with the `Rmcl` model class of the `PyAstronomy`<sup>2</sup> package (Czesla et al. 2019) of Python<sup>3</sup> (Van Rossum & Drake Jr 1995), which implements the analytical model RV curves for the RML effect given by Ohta et al. (2005).

<sup>2</sup> <https://github.com/sczesla/PyAstronomy>

<sup>3</sup> <http://www.python.org>



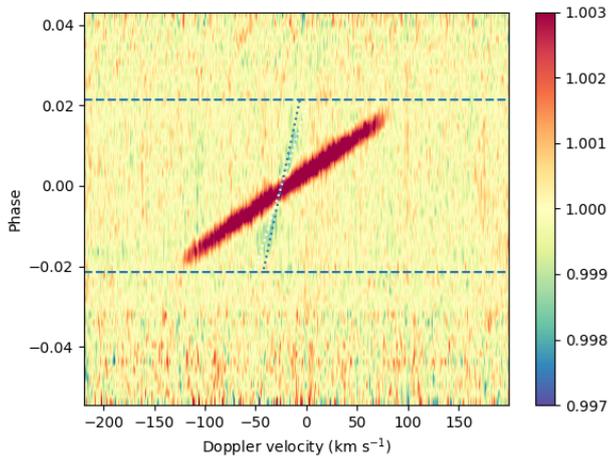
**Fig. 4.** Comparison between the observed RVs averaged with 0.002 phase bin (blue points) and the RML RV model (orange line). The model seems to overestimate the amplitude of the RML effect, while actually the atmospheric RML effect is lowering the amplitude of the signal. The vertical dashed lines show the transit's ingress and egress.

The comparison between the data and the theoretical model is shown in Fig. 4: the model seems to overestimate the amplitude of the RML effect, but we know from a previous study on KELT-9b (Borsa et al. 2019) that the atmospheric RML effect may combine with the classical RML effect and the resulting RVs carry both signals.

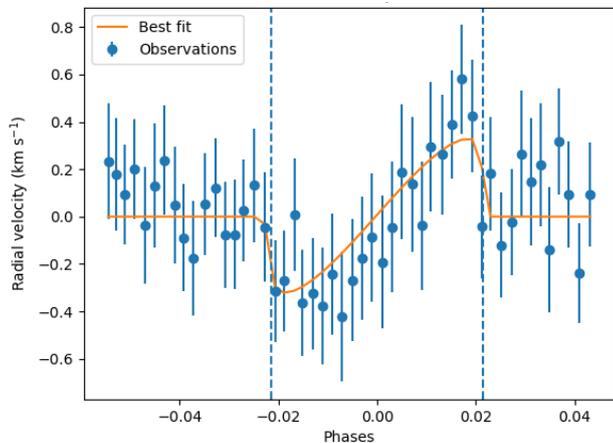
The atmospheric RML effect is akin to the classical one: an apparent stellar RV variation due to the deformation of the stellar lines. While in the classical RML effect the deformation is caused by the occultation of part of the stellar disk by the transiting planet, in the atmospheric RML effect we have an additional absorption signal due to the planetary atmospheric spectrum correlating with the mask used to compute the CCF or the LSD mean line profile. This happens only in the case of extremely hot planetary atmospheres, that show a chemical composition similar to that of late-type stars (in particular due to the presence of neutral or ionised iron), and as such their atmospheric spectrum correlates with the same mask used for the host stars (e.g., in this case the stellar mask contains most of the elements found in the atmosphere of KELT-20b, with more than half of the lines being either FeI or FeII).

Looking at the line profile residuals tomography (Fig. 5, see Section 5 for details), not only the Doppler shadow is visible (red hues), but also the planetary atmospheric trace (blue hues). The latter shifts by the change in planet's orbital RV during transit, confirming that the planet's atmospheric spectrum is correlating with the stellar mask, and thus it shows up in the line residuals as an additional absorption line situated at the planet RV. The Doppler shadow and the atmospheric trace are aligned in such a way that the atmospheric trace is expected to affect the RVs derived from the mean line profiles in the opposite way than the Doppler shadow, so that the net result would be a smaller amplitude of the RML effect, as it is actually seen in Fig. 4.

We then subtracted the RML theoretical model from our data: the resulting RV residuals show the atmospheric RML effect. It goes in the opposite direction from the classical RML effect because it modifies the line profile as an additional absorption instead of a bump. We fit the RV residuals (see Fig. 6) using the `Rmcl` fit class of the same `PyAstronomy` package used before. We interpret the resulting value  $R_p/R_\star = 0.060 \pm 0.002$  given by the fit as  $R_{\text{atmo}}/R_\star$ , where  $R_{\text{atmo}}$  represents the extension of the



**Fig. 5.** Mean line profile tomography: the average stellar line has been removed, but not the systemic velocity. In the residuals both the Doppler shadow (red excess) and the atmospheric trace (blue absorption, evidenced by the blue dotted line) are visible.



**Fig. 6.** RVs residuals show the atmospheric RML effect. The overplotted orange line shows the RML model best fit.

atmosphere that correlates with the stellar mask that we used, if the atmosphere were shaped as a disk. The error on this value was estimated using the `pymc`<sup>4</sup> package of Python. Comparing this result with the planet’s radius  $R_p/R_\star = 0.115 \pm 0.002$ , the atmospheric area is  $\sim 27\%$  of the whole planetary photometric area. If we hypothesize the most simple scenario of a spherical atmosphere, we can then derive  $R_{p+atmo} = 1.13 \pm 0.02 R_p$ , only for the portion of the planetary atmosphere whose spectrum correlates with the stellar mask. This value is in good agreement with the results from Casasayas-Barris et al. (2019), who found  $R_{p+atmo} = 1.11 \pm 0.03 R_p$  for FeII. The slightly larger value found here may be due to the presence of few lines of other elements, such as CaII, for which Casasayas-Barris et al. (2019) found  $R_{p+atmo} = 1.19 \pm 0.03 R_p$ .

We note here that adjusting the classical RML theoretical model by varying the system parameters values inside their error ranges alters only slightly our atmospheric RML result, which remains in agreement with the  $R_{atmo}/R_\star = 0.060 \pm 0.002$  value within the  $1\sigma$  uncertainty.

## 5. Atmospheric trace

We studied the planetary atmospheric trace following the same strategy used with the RVs in Sec. 4, and applying it to the mean line profiles: we combined all five transits, in order to increase the strength of the atmospheric signal and to average out spurious variations due to instrumental or telluric effects.

We averaged all our out-of-transit mean line profiles to obtain a purely stellar mean line profile. Because KELT-20 does not show any significant stellar variations, either due to activity or pulsations, we could then remove the stellar component from our data simply by dividing each mean line profile (both in and out of transit) by the average out-of-transit stellar mean line profile. We then normalised the residuals by dividing them using two different linear fits, one for the points outside the stellar line limits, the other for the points inside the stellar line limits. The latter fit was done avoiding the regions where the Doppler shadow or the atmospheric trace are present. The resulting residuals are shown in Fig. 5; to enhance the signal’s visibility they are binned with a  $0.002$  phase bin and a  $1 \text{ km s}^{-1}$  RV bin.

To isolate and investigate possible variations of the atmospheric trace during transit, we had to remove the Doppler shadow. To be sure that the removal process did not influence our analysis, we proceeded in two different ways:

- by following the method of Hoeijmakers et al. (2019): we selected the residuals where the Doppler shadow signal is far from the atmospheric trace and we fitted it with a Gaussian. Then we fitted the Gaussian parameters with a 2<sup>nd</sup> order polynomial, so that the fit parameters of the Doppler shadow vary smoothly during the transit. We then removed the Doppler shadow Gaussian model from all the residuals. We note here that we obtained a better removals by first shifting all our data in the reference frame of the Doppler shadow, probably because of the geometry of the KELT-20 system. We did this using the estimated Doppler shadow RV obtained from Eq. 2 (Cegla et al. 2016):

$$rv = v \sin i_\star (x_p \cos \lambda - y_p \sin \lambda), \quad (2)$$

where:

$$x_p = a_{R_\star} \sin 2\pi\phi,$$

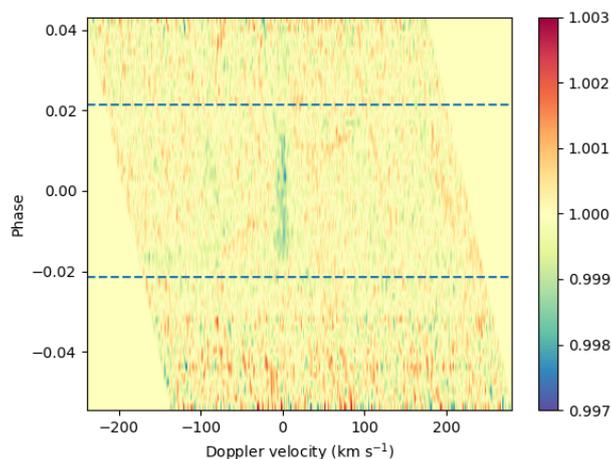
$$y_p = -a_{R_\star} \cos 2\pi\phi \cos i,$$

with  $\lambda$  the projected obliquity in radians,  $a_{R_\star}$  the semi-major axis in units of stellar radius,  $\phi$  the orbital phase and  $i$  the orbital inclination in radians. After this, our Doppler shadow signal was vertically aligned, and we proceeded with the removal as described above;

- by adopting and adjusting the method from Cabot et al. (2020). The original method was applied to the UHJ WASP-121b, which orbits in a near-polar orbit around its host star ( $\lambda = 257.8^{+5.3}_{-5.5}$  deg; Delrez et al. 2016). Because of this, its Doppler shadow in the stellar reference frame is almost completely vertically aligned at the center of the stellar line profile. Cabot et al. (2020) removed it by fitting a 3<sup>rd</sup> degree polynomial on each column of the tomography where the Doppler shadow fell.

Because of the different geometry of the KELT-20 system, we had to modify this approach to suit our data. First of all, we shifted the data in the reference frame of the Doppler shadow as in the original work of Cabot et al. (2020). We could then fit the columns where the Doppler shadow signal fell, and finally we divided each column by its fit. We used

<sup>4</sup> <https://github.com/pymc-devs/pymc>



**Fig. 7.** Line profile residuals after the Doppler shadow’s removal, and after being shifted in the planet reference frame. The atmospheric trace is clearly visible and centered around  $0 \text{ km s}^{-1}$ .

a 5<sup>th</sup> degree polynomial, instead of the original 3<sup>rd</sup> degree one, because it performed a better removal of the Doppler shadow.

We obtained thus two datasets: dataset A, where the Doppler shadow was removed by Gaussian fitting, and dataset B, where the Doppler shadow was removed adapting the Cabot et al. (2020) method. Because the results we obtained with the two datasets are in good agreement, we show here only the work done on dataset A, while the results from dataset B are presented in appendix A.

Once removed the Doppler shadow signal, we shifted the dataset in the planet reference frame: we shifted each spectrum by the combination of  $V_{\text{Sys}}$  and the planet theoretical orbital RV (the barycentric correction was already applied by the HARPS-N DRS), in order to align the atmospheric signal in a vertical position around  $0 \text{ km s}^{-1}$  and to better study its variations (see Fig. 7). The planet orbital RVs were computed for each epoch with the `KeplerEllipse` class of the `PyAstronomy` package using the orbital values of semi-major axis  $a$ , period  $P$ , eccentricity  $e$ , and inclination  $i$  from Table 1. This yields a  $K_p$  of  $169 \pm 6 \text{ km s}^{-1}$ , compatible with the values found in literature (Casasayas-Barris et al. 2019; Nugroho et al. 2020; Stangret et al. 2020).

We then considered each mean line profile to map the velocity variations during transit. Because the atmospheric signal is not very strong, we applied a Savitzky-Golay filter (Savitzky & Golay 1964) to each profile in order to smooth out the noise and increase the signal’s visibility. The Savitzky-Golay filter works by computing a least-squares low-degree polynomial fit (3<sup>rd</sup> degree in our case) in a moving window on the data to estimate the value of the central point of each window, and it is able to smooth the data without greatly distorting the signal. While it was originally created for spectroscopic chemistry, the Savitzky-Golay filter has been successfully applied to several kind of spectroscopic astronomical data (e.g., Deetjen 2000; Dimitriadis et al. 2019; Fleig et al. 2008). We applied the Savitzky-Golay filter by using the `savgol_filter` function of `SciPy`<sup>5</sup> with an optimal window width of 15 pixel. We obtained the window value by applying the method proposed by Sadeghi & Behnia (2018) to our data. In appendix B we show the results of the atmospheric analysis on the unfiltered dataset A, to highlight the improvements

obtained using the filter: the overall behaviour of the signal is clearly the same, but the uncertainties on the estimated values are much lower using the filtered data.

After applying the Savitzky-Golay filter, we fitted the atmospheric signal with a Markov-Chain MonteCarlo (MCMC) sampling and a correlated noise model using Gaussian processes with a Matérn-3/2 covariance kernel. In order to do this, we used the Python packages `emcee`<sup>6</sup> (Foreman-Mackey et al. 2013) and `george`<sup>7</sup> for the noise model. The priors on FWHM, RV, and depth were estimated as an average of the Gaussian fits on the different datasets, with broader widths than the expected uncertainties:  $\text{FWHM}=20 \pm 20 \text{ km s}^{-1}$ ,  $\text{RV}=-5 \pm 20 \text{ km s}^{-1}$ , the initial depth is computed on each dataset as  $\text{depth}=\text{minimum-maximum}$ , and it ranges from  $3 \times \text{depth}$  to 0.1 (to account for normalisation problems). In Fig. 8 we show 24 random posteriors for each of the 20 mean line profile residuals that we have during the transit.

The fit results are shown in Fig. 9: the 0.50, 0.16, and 0.84 quantiles of the posteriors distribution are used as the best values and the upper and lower  $1\sigma$  uncertainties respectively. The vertical dashed orange lines and shaded areas show the mean values of RVs, FWHM and depth and the  $1\sigma$  regions. The RV signal remain stable for most of the transit, and then it blueshifts during egress. Aside from one outlier, the FWHM is more stable: even if it seems to be lower during ingress there is no statistically evident variation from the mean. The depth of the signal increases from the beginning to the center of the transit, and then it decreases in a roughly symmetric way, with some points differing more than  $1\sigma$  from the mean during ingress and egress (a less deep atmospheric signal), and in the middle of the transit (a more deep signal). In all cases, the variations (if any) are mainly found either during ingress, or egress, or both.

Averaging the residuals in the first and the second half of the transit (phases  $[-0.02:0.0]$  and  $[0.0:0.02]$ , see Fig. 10) shows a larger FWHM value in the first half of the transit, but the result is not statistically significant. The depth variation is cancelled out within  $1\sigma$ , and also the RV variation in the averaged signals disappears within  $1\sigma$ . The latter is due to the fact that the major RV variation is caused only by the last three points (and the last one in particular), where the atmospheric signal is smaller (see last panels of Fig. 8) and as such their contribution to the average is lower.

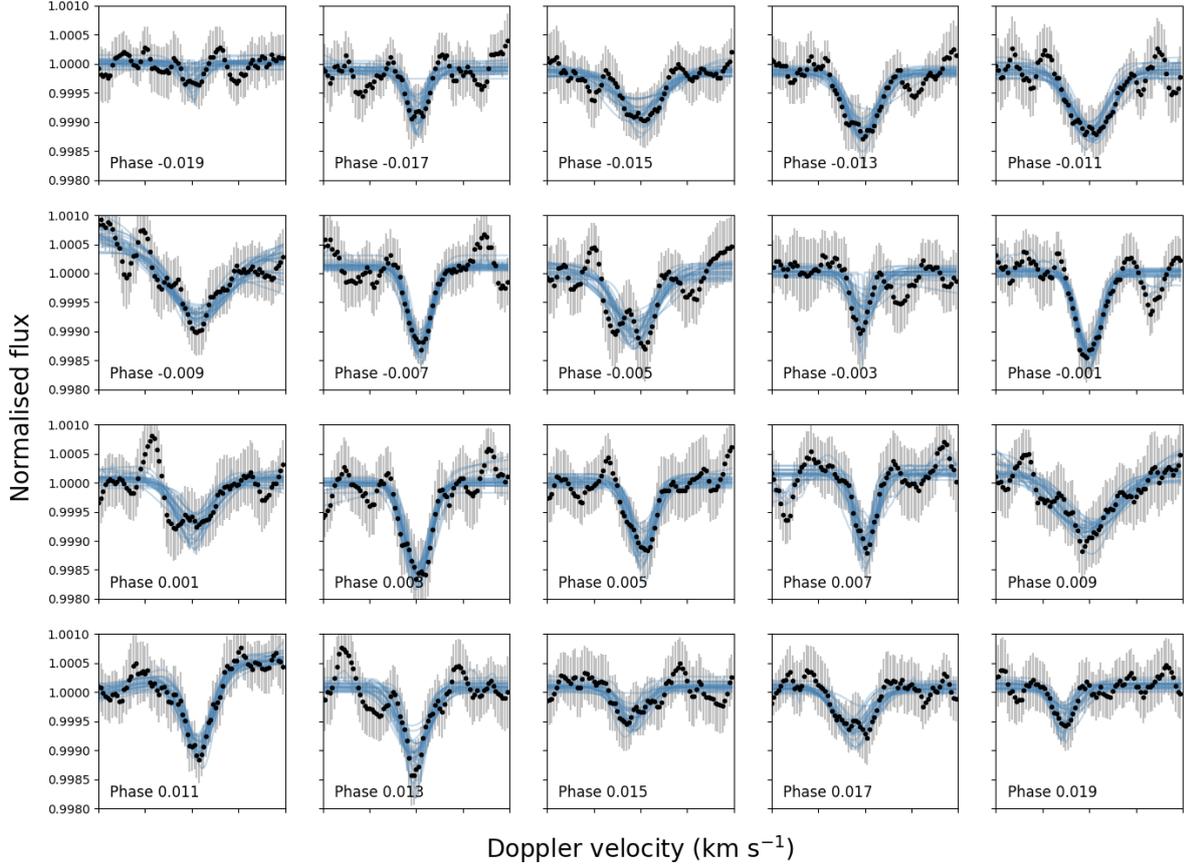
We tried to study the atmospheric trace behaviour in each transit, but the S/N was too low to allow us to follow the finer variations already difficult to see in Fig. 9. However, we were able to determine the overall variations between the first and second half of the transits, and we found interesting results (see Fig. 11). The signal’s depth is stable in all transits aside from night 4, where it decreases from the first to the second half of the transit. The FWHM show variations around  $3\sigma$  level in the last two transits (4 and 5), and just above  $1\sigma$  during transit 2: in all these three nights, the FWHM decreases from the first to the second half of the transit. It may be interesting to note that the FWHM show hints of decreasing also in transit 3, and of increasing in transit 1, but in both cases the variations are not statistically significant. Lastly, the RVs variations are visible only in the last two transits (4 and 5), where the atmospheric signal shows a small but significant redshift.

Even if the FWHM decrease found in our data does not repeat in the same way and with the same strength in every transit, it is still worthwhile to investigate some possible causes of this

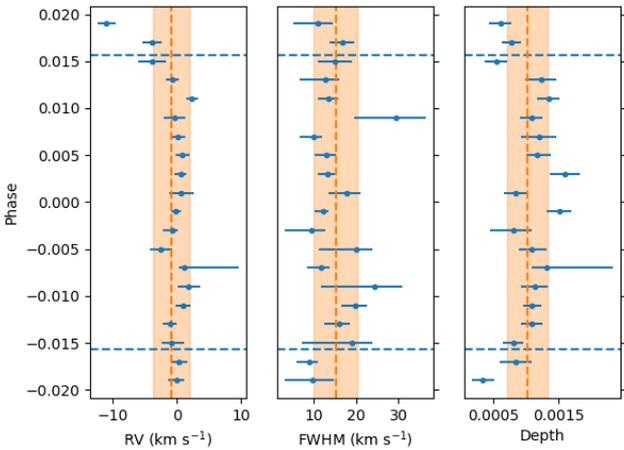
<sup>6</sup> <https://emcee.readthedocs.io/en/stable/>

<sup>7</sup> <https://george.readthedocs.io/en/latest/>

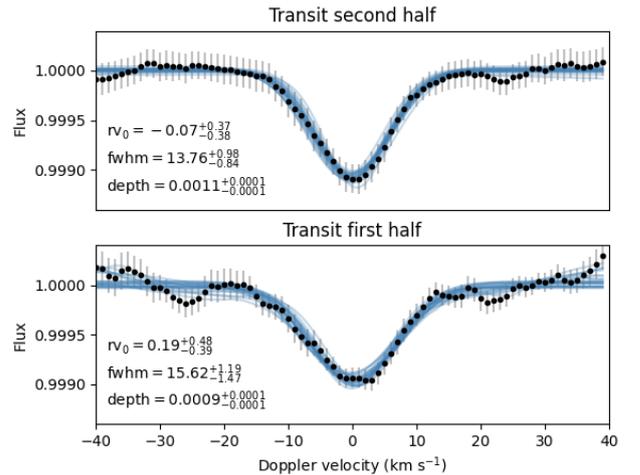
<sup>5</sup> <https://www.scipy.org>



**Fig. 8.** The atmospheric signal found in the line profile residuals and the relative MCMC posteriors. All the graphics have the same abscissa (RVs from  $-40$  to  $40$   $\text{km s}^{-1}$ ) and ordinate (normalised flux from  $0.998$  to  $1.001$ ) to better follow the evolution of the signal. The graphics go from phase  $-0.019$  (upper left panel) to phase  $0.019$  (lower right panel) with a  $0.002$  phase step.



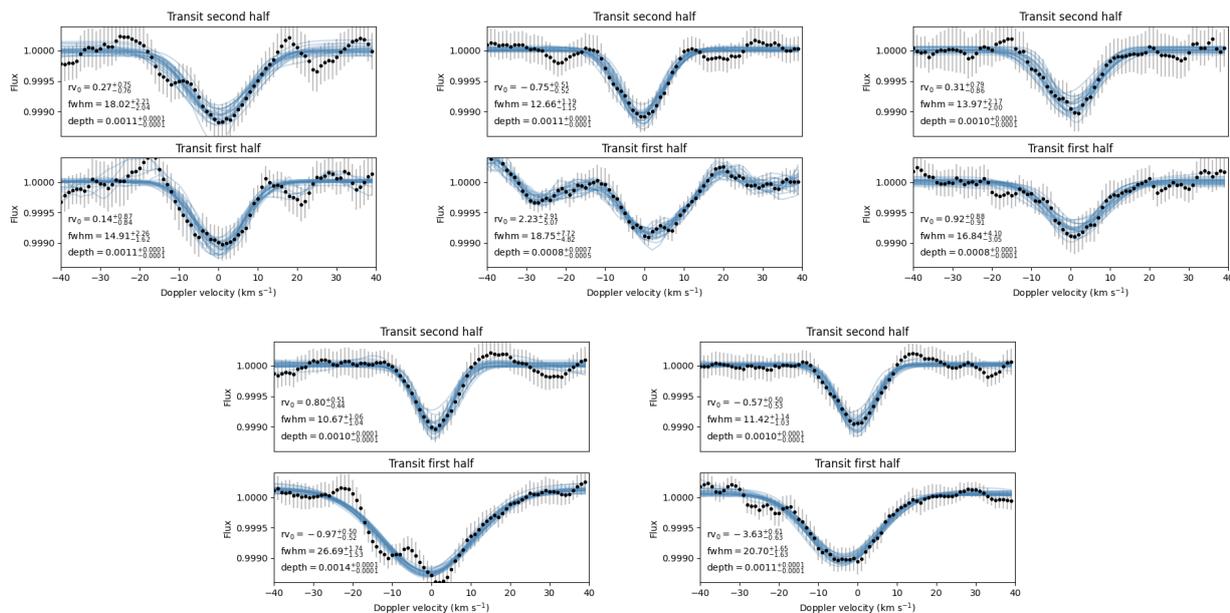
**Fig. 9.** RVs, FWHM and depth of the atmospheric signal shown in Fig. 8 during transit: the vertical dashed orange lines and shaded areas show the mean values and relative standard deviation for each of the three quantities. All the data are comprised between  $t_0$  (start of ingress) and  $t_2$  (end of egress), while the horizontal dashed blue lines indicate  $t_2$  (end of ingress) and  $t_3$  (start of egress).



**Fig. 10.** Averaged atmospheric signal found in the line profile residuals in the first (phase  $[-0.02:0.0]$ ) and second part (phase  $[0.0:0.02]$ ) of the combined transits with relative fit.

behaviour. It is interesting to note that a significant variation of

FWHM has been found between the elements detected in the atmosphere of KELT-20b by Hoeijmakers et al. (2020), varying



**Fig. 11.** Averaged atmospheric signal found in the line profile residuals in the first (phase  $[-0.02:0.0]$ ) and second part (phase  $[0.0:0.02]$ ) of each transit. From top left to bottom right, the graphics show the results for the transits 1, 2, 3, 4, and 5.

from  $5.31 \pm 0.99 \text{ km s}^{-1}$  for CrII to  $33.45 \pm 3.30 \text{ km s}^{-1}$  for MgI. Because our planetary atmospheric trace is obtained through the use of a stellar mask (where several different elements are combined), one possible interpretation for our FWHM variations could arise from a variable contribution of the chemical elements during the transit, due for example to temperature variations that may cause some of them to condense. Still, because FeI and FeII constitute more than half of the mask's lines, another possible cause may be the condensation of iron, similarly to what happens in the UHJ WASP-76b (Ehrenreich et al. 2020). Another interpretation could be the presence of more turbulent atmospheric conditions in the first part of the transit, due for example to a day-to-night side wind, as has been found also in both WASP-76b (Ehrenreich et al. 2020) and WASP-121b (Bourrier et al. 2020).

We stress here that the atmospheric RV variations of KELT-20b are not visible when studying only the first and second half of the transit, even when combining all five transits data (see Fig. 10 and Fig. 11), but they are slightly more visible when tracing the finer atmospheric variations (see Fig. 8 and Fig. 9). Due to the faintness of the signal, this study is possible only in the combined data.

## 6. Cross-correlation with FeI models

Nugroho et al. (2020) detected several elements in the atmosphere of KELT-20b through the CCF method, and they found a peculiar double-peak shape in the  $K_p - \Delta V$  maps of FeI. The peaks have similar  $K_p$ , and they are roughly  $\approx 10 \text{ km s}^{-1}$  apart, with the secondary blueshifted peak weaker than the primary one. They reconstructed the observed structure by simulating two FeI signals with different amplitudes and  $\Delta V$ , and found the best match when masking the weaker signal (at  $\Delta V = -10 \text{ km s}^{-1}$ ) from phase -0.01 and -0.016, simulating a delay in its appearance. This behaviour closely resembled what we observed in the planetary atmospheric RV variations, with a blueshifted signal in the final part of the transit (see Fig. 9).

Since they used the same HARPS-N observations for our first three transits, and we have two additional HARPS-N nights that were not used in their work, we decided to look for the same double-peak signature in our data. We could not use directly our LSD results, because the stellar mask contains several different elements aside from FeI, so we decided to apply the CCF method to obtain our own  $K_p - \Delta V$  maps.

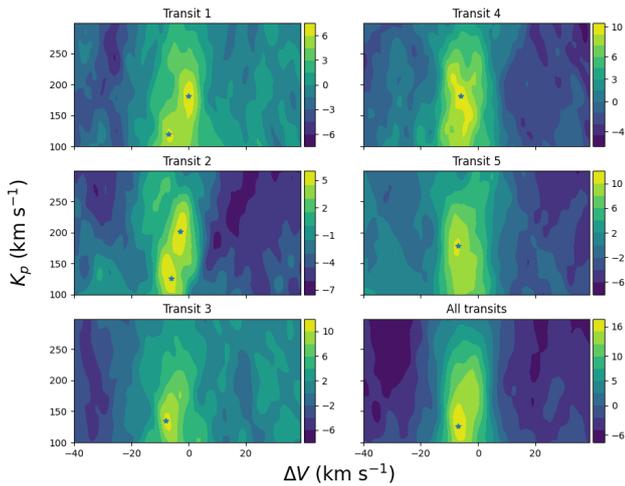
To create our model, we employed the  $\pi\eta$  line-by-line radiative transfer code (Ehrenreich et al. 2006, 2012; Pino et al. 2018). This code was already used for the simultaneous interpretation of HARPS high-resolution spectroscopic observations and HST WFC3 observations (Pino et al. 2018). For this paper, we updated the code to include:

- 1) line opacities from FeI and a continuum by  $\text{H}^-$  following Pino et al. (2020). The FeI lines were taken from the VALD3 database<sup>8</sup>, and modelled as Voigt profiles, accounting for thermal and natural broadening.
- 2) equilibrium chemistry calculations for FeI and  $\text{H}^-$ , to calculate their volume mixing ratios throughout the atmosphere. We employed the publicly available FastChem code version 2 (Stock et al. 2018).

We employed a fixed temperature profile from Lothringer & Barman (2019), representative for a  $T_{\text{eq}} = 2250 \text{ K}$  planet orbiting around an F0-type star ( $T_{\star} = 7200 \text{ K}$ ). The other parameters employed in our model are  $R_{\star}$ ,  $M_p$ ,  $\log \text{VMR}_{\text{Fe}}$ , and  $R_p$  at a reference pressure level of 10 bar (see Table 1). Nugroho et al. (2020) demonstrated that the neutral iron lines in KELT-20b can be well represented with a hydrostatic equilibrium model, provided that the model accounts for a scale factor ( $\alpha$  in their notation). Our cross-correlation scheme is not sensitive to such a scale factor, which is thus fixed to 1.

Because we are now investigating directly the planetary signal, and we are not interested anymore in the stellar contribution used to study the classical and atmospheric RML, we prepared

<sup>8</sup> See Pino et al. (2020) for a full list of references for the case of FeI.



**Fig. 12.** Contour plots of the  $K_p - \Delta V$  maps obtained from the cross-correlation of the residual spectra with the planetary FeI model. All the five transit nights and the combined data (bottom right panel) are shown. The prominent peaks are indicated with star symbols.

our data in a different way than for the LSD analysis. We started again from the whole spectra, including the regions that we cut out in Sec. 3. We then removed the out-of-transit stellar master and telluric contamination, and we performed a cross-correlation in the stellar restframe between the data and our model on each residual spectrum (as in Borsa et al. 2021). Our CCFs are defined as in Eq. 3:

$$CCF(v, t) = \sum_{i=1}^N x_i(t, v) M_i \quad (3)$$

where  $x$  are the  $N$  wavelengths of the spectra taken at the time  $t$  and shifted at the velocity  $v$ , and  $M$  is the model normalised to unity. We impose all the model values smaller than 5% of the maximum absorption line in the considered wavelength range to be at zero (e.g., Hoeijmakers et al. 2019).

We selected a step of  $1 \text{ km s}^{-1}$  and a velocity range  $[-200, 200] \text{ km s}^{-1}$ . The spectra are divided in segments of  $200 \text{ \AA}$  (e.g., Hoeijmakers et al. 2019), then the cross-correlation is performed for each segment. We masked the wavelength range  $5240\text{--}5280 \text{ \AA}$ , which is heavily affected by telluric contamination. Then for each exposure we applied a weighted average between the CCFs of the single segments, where the weights applied to each segment are the sum of the depths of the lines in the model and the inverse of the standard deviation of the segment (i.e., the higher the S/N, the larger the weight). We then averaged all the in-transit CCFs after shifting them in the planetary restframe, for a range of  $K_p$  values from 0 to  $300 \text{ km s}^{-1}$ , in steps of  $1 \text{ km s}^{-1}$ . The shift is performed by subtracting the planetary RV calculated for each spectrum as  $v_p = K_p \times \sin 2\pi\phi$ , where  $\phi$  is the orbital phase. As a last step, we subtracted the  $V_{\text{Sys}}$  from all the averaged CCFs to obtain the  $K_p - \Delta V$  maps. We then created S/N maps by computing the standard deviation of each  $K_p - \Delta V$  map far from the planetary signal (i.e. excluding the region from  $V_{\text{Sys}} = -40 \text{ km s}^{-1}$  to  $V_{\text{Sys}} = 40 \text{ km s}^{-1}$ ), and then dividing the  $K_p - \Delta V$  maps by these values.

Our results are shown in Fig. 12: we identified the strongest peak or peaks in each map with a local maxima algorithm. We found the double-peak feature quite clearly in the first two transits, while only the weaker blueshifted signal is present in transit

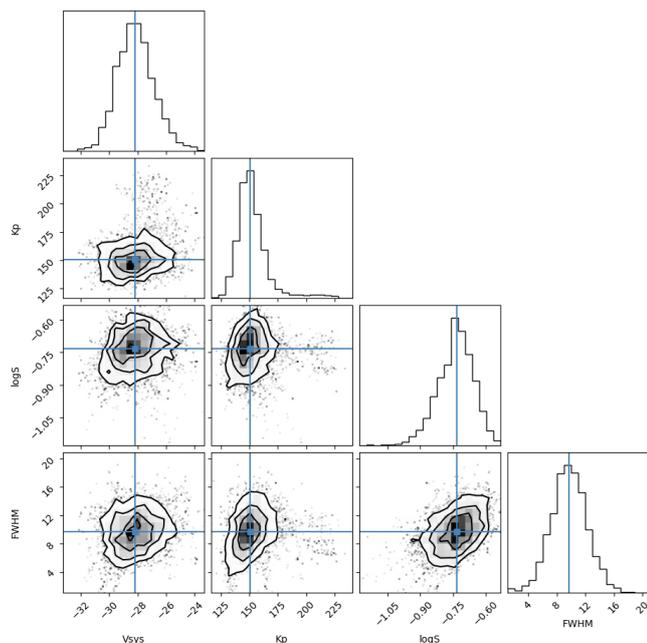
3. We remind that those are the same data analysed by Nugroho et al. (2020). In transits 4 and 5 only the stronger signal is visible.

To further investigate the variability of the FeI signal as a function of transit, we ran MCMC simulations via the Python emcee package and drove their evolution via the likelihood scheme of Brogi & Line (2019). The CCF defined in Eq. 3, and commonly used in stellar radial velocities, is actually called cross-covariance in statistics. Compared to the statistical cross-correlation, it misses a normalisation factor that would force the CCF between  $-1$  (perfect anti-correlation) and  $+1$  (perfect correlation). The quantity in Eq. 3 is thus exactly the same as the cross-covariance  $R$  defined in Eq. 9 of Brogi & Line (2019) and used for the MCMC simulations. However, the likelihood function of Brogi & Line (2019) contains additional terms, namely the data and model variances, which give information about the shape and amplitude of spectral lines. We also note that that the cross-correlation maps in Fig. 12 are converted in S/N by dividing through the standard deviation far from the peak: using the full statistical formula for cross-correlation we would get the same S/N, except for second-order variations of the model variance as a function of  $V_{\text{Sys}}$  and  $K_p$ .

We chose to present here both analyses because the CCF approach is less sensitive to the modelling and thus more appropriate to capture the initial detection of FeI even with an approximate template or a binary mask. The CCFs can also be compared with the existing literature. However, the likelihood approach allows us to better constrain the parameter space and explore the statistical evidence for night-to-night variability, and thus we opted for presenting both analyses.

In our simulations, the likelihood was maximised as a function of four parameters: the two velocities (orbital and systemic), the FWHM of the line profile, and the logarithm of a scaling factor,  $\log S$ . While the measured systemic velocity is consistent within  $1\sigma$  between the nights (aside from the first night), the other three parameters show a clear variability, as reported in Table 3. Here we redefine  $K_p$  as  $K_{p+\text{atmo}}$ , because it combines both the projected orbital velocity of the planet and a contribution from the atmosphere’s physics and dynamics. With this more refined method we found no evidence of the double-peak structure: in Fig. 13 we show the corner plot of the posterior distribution found for the transit night 2, where the double-peak structure is instead clearly visible in Fig. 12. We also investigated the combined data by fixing the FWHM and  $\log S$  to their best-fitting values for each night, and then running an additional MCMC with the five nights combined. Also this further test did not confirm a possible double solution. The posterior in  $K_{p+\text{atmo}}$  appears instead single-peaked, and centered at an intermediate value of  $142 \text{ km s}^{-1}$ . The new results show instead that the values of  $K_{p+\text{atmo}}$  and  $\log S$  are variable over some of the transits. Only the last two transits (4 and 5) yield a  $K_{p+\text{atmo}}$  value fully compatible with the theoretical  $K_p$  estimated in Sec. 5, while in the other transits and the combined data the  $K_{p+\text{atmo}}$  is systematically lower than the theoretical  $169 \pm 6 \text{ km s}^{-1}$  value.

These results hint to the fact that the dynamics probed by the FeI signal, as well as the overall strength of the iron lines, may both change from transit to transit. Furthermore, there is some evidence that the broadening of the line profile also varies, as shown by the retrieved values of FWHM, even if these variations are not strongly statistically significant. Still we note here that, comparing these results with those of Sec. 5, the nights with larger  $K_{p+\text{atmo}}$  (4 and 5) are those with the larger FWHM variations of the atmospheric trace between the two half of the transit, while the night 1 is the one with the more deviant values, and also the only one where the atmospheric trace shows a pos-



**Fig. 13.** Corner plot of the posterior distribution found with MCMC simulations and Brogi & Line (2019) likelihood for the transit 2, where the double-peak structure is clearer in the  $K_p - \Delta V$  contour maps. No evidence of such structure is found here.

**Table 3.** Signal position, and width and model’s scale factor found with the MCMC simulations and the likelihood from Brogi & Line (2019)

Night	$K_p$ ( $K_{p+atmo}$ ) ( $\text{km s}^{-1}$ )	$\Delta V$ ( $\text{km s}^{-1}$ )	FWHM ( $\text{km s}^{-1}$ )	$\log S$
1	$99.5^{+13.6}_{-20.2}$	$-1.0^{+1.7}_{-1.4}$	$16.7^{+4.2}_{-2.8}$	$-0.20^{+0.05}_{-0.05}$
2	$150^{+13.0}_{-9.1}$	$-3.7^{+1.4}_{-1.3}$	$-9.7^{+2.3}_{-2.6}$	$-0.73^{+0.08}_{-0.09}$
3	$129.7^{+4.4}_{-7.2}$	$-6.0^{+0.7}_{-0.6}$	$-6.4^{+3.8}_{-1.9}$	$-0.55^{+0.07}_{-0.06}$
4	$163.1^{+21.3}_{-15.2}$	$-3.3^{+0.8}_{-0.9}$	$-12.7^{+1.8}_{-1.8}$	$-0.40^{+0.04}_{-0.05}$
5	$161.1^{+4.9}_{-4.9}$	$-4.9^{+0.5}_{-0.5}$	$-9.7^{+1.2}_{-1.2}$	$-0.33^{+0.03}_{-0.03}$
All data	$142^{+7}_{-6}$	$-4.7^{+0.3}_{-0.3}$		

sible increase of the FWHM from the first to the second half of the transit (see Fig. 11). The difference between the values of FWHM found here and those of the atmospheric trace may arise from the fact that the atmospheric trace described in Sec. 5 is caused by a combination of the different elements found in the stellar mask. Additionally, we confirm the blueshift of the FeI signal found also in literature (Stangret et al. 2020; Hoeijmakers et al. 2020; Nugroho et al. 2020),

## 7. Conclusions

Because of its high  $T_{eq}$  ( $2260 \pm 50$  K), the atmospheric spectrum of the ultra-hot Jupiter KELT-20b correlates with the stellar mask used to compute the host star mean line profiles. We were thus able to detect and characterise the atmospheric RML effect present in the stellar RV time-series, which resulted in an estimation of the size of the planetary atmosphere that correlates with the mask ( $R_{p+atmo}/R_p = 1.13 \pm 0.02$ ). This is in agreement with literature values from metal line-depths, confirming the reliability of the atmospheric RML method. In addition to that, we could isolate the atmospheric trace in the mean line profile tomography: the high-resolution, high S/N of our data allowed us

to fit the atmospheric signal and follow its variations during the transit.

We found possible variations of RV, FWHM and depth of the atmospheric signal during the combined transit data and a different behaviour during different transits. There is a decrease of the FWHM during two transits, and just above  $1\sigma$  level during a third one, while in another transit and in the combined data the measured decrease may be present, but it is not statistically significant. This possible greater FWHM spread during the first part of the transit may hint at turbulent conditions, that become more stable in the second part of the transit. This behaviour resembles that found by Ehrenreich et al. (2020) in WASP-76b, and Bourrier et al. (2020) in WASP-121b, and confirms the existence of different structures between morning and evening terminators, as suggested by Hoeijmakers et al. (2020): in their work, they analysed only one transit and so they could not exclude a spurious nature for the RV variability. Another possible interpretation for the FWHM variations may be the variable contribution of elements to the overall atmospheric signal during the transit: because the stellar mask contains different elements, all of them contribute to the resulting atmospheric trace, but their relative abundances may change during the transit due to, for example, temperature variations that may cause some of them to condense. This may result in a FWHM variation due to the significant FWHM differences between the elements detected in KELT-20b atmosphere (Hoeijmakers et al. 2020). Seeing as more than half of the stellar mask lines are FeI and FeII line, the condensation of iron (Ehrenreich et al. 2020) may play a role in this situation.

The RV variations are more visible in the combined data of the atmospheric trace, that confirms the presence of atmospheric dynamics with a blueshift of the signal during egress. These RV variations led us to explore the results from Nugroho et al. (2020), who found a double-peak feature in their FeI  $K_p - \Delta V$  maps. This feature consisted of a primary peak at  $\Delta V = 0 \text{ km s}^{-1}$  and a weaker secondary peak at  $\Delta V = -10 \text{ km s}^{-1}$ . Their best match with simulated signals indicated a delayed appearance of the weaker blueshifted signal, which agrees well with the blueshift we found in the second part of the transit. The atmospheric trace that we studied in Sec.5 was found in the mean line profiles obtained using the LSD software with a stellar mask suited for the host star KELT-20, and as such we could not directly compare our results with those of Nugroho et al. (2020). We decided then to create our own  $K_p - \Delta V$  maps using the standard cross-correlation method with a planetary atmospheric FeI model. Initially we found the same double-peak structure in transits 1 and 2 with a simple contour analysis, but a more refined study using MCMC simulations driven via the likelihood scheme of Brogi & Line (2019) showed only a single significant peak per night. Nevertheless, we did find some indication of the variability of the signal from one transit to another, that aligns well with the tentative results from the line profile tomography.

To conclude, we used different methods (line profile tomography and FeI CCFs) to search independently for variability in the atmospheric signal of KELT-20b, and we found indication of FWHM and RV variability during some of the transits. We also confirm the blueshift of the FeI signal and the reliability of the atmospheric RML method to estimate the atmospheric extension.

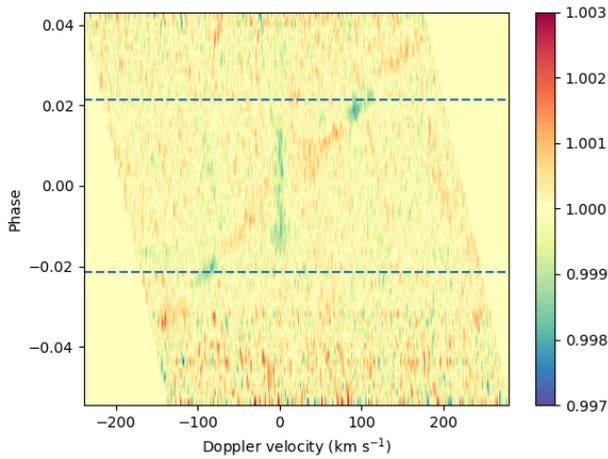
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**Fig. A.1.** Dataset B: line profile residuals after the Doppler shadow’s removal, and after being shifted in the planet reference frame. The atmospheric trace is clearly visible and centered around 0 km s<sup>-1</sup>. There is still a visible Doppler shadow residual.

## Appendix A: Atmospheric trace analysis on dataset B

In order to ensure that the removal of the Doppler shadow did not unduly affect the study of the atmospheric trace, we performed the removal with two methods, which generated two datasets. While the results from dataset A are shown in the paper, we show here the same analysis performed on dataset B.

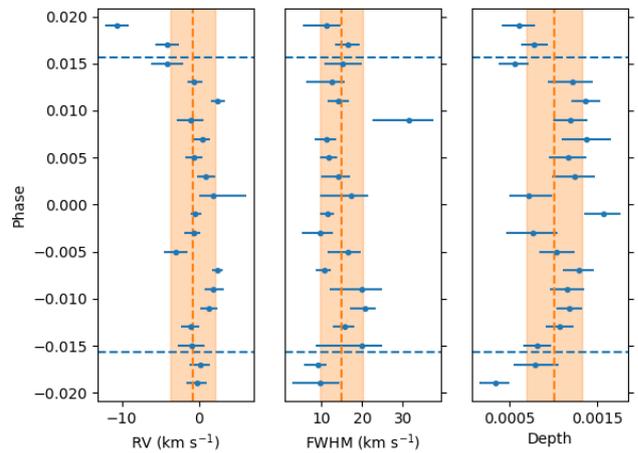
The line profile residuals after the Doppler shadow’s removal are shifted in the planetary reference frame and shown in Fig. A.1). It is clearly evident that the Doppler shadow’s removal was less efficient in this case than in dataset A (see Fig. 7), as evidenced by the large residuals left in the tomography. We then smoothed each in transit residual by applying a 3<sup>rd</sup> degree Savitzky-Golay filter with a 15 pixels window, and we fitted the atmospheric signal using MCMC with a correlated noise model.

The resulting RVs, FWHMs and depths are shown in Fig. A.2. As for dataset A, we found a blueshift during egress, while the FWHM is more stable (aside from the same outlier found in dataset A) and the depth shows a symmetric increase and subsequent decrease during transit.

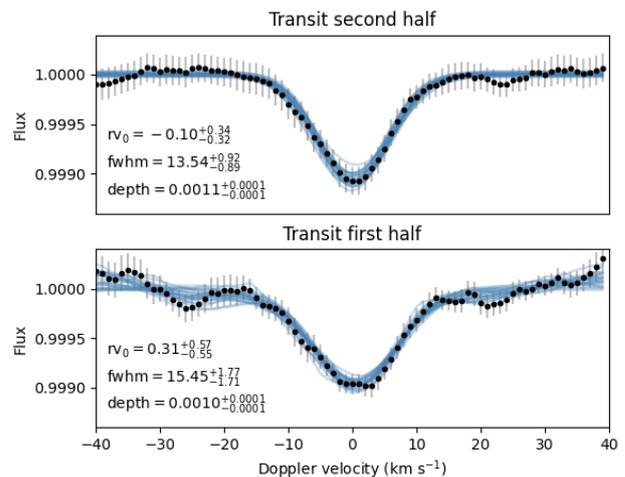
We studied the overall variations during transit by averaging all residuals in the first and second half of the transit (phases [-0.02:0.0] and [0.0:0.02]), see Fig. A.3. We performed the same study also on each individual night (see Fig. A.4). We found mostly the same results of dataset A: the atmospheric depth is stable in all transit nights (also during night 4 the variation falls exactly at 1 $\sigma$  level), the RV variations are statistically significant only in night 4, where a small redshift is visible, and the FWHM decreases during the transit in nights 2 (just above 1 $\sigma$  level), 4, and 5 (around the 3 $\sigma$  level). The results are qualitatively identical to those obtained with dataset A, showing that the choice of the Doppler shadow removal method does not influence our work.

## Appendix B: Atmospheric trace analysis on unfiltered dataset A

We performed the same analysis shown in Sec. 5 on the unfiltered dataset A, combining all five transits together. While the atmospheric trace signal is much noisier, the overall behaviour of its FWHM, RV and depth, shown in Fig. B.1, closely resem-



**Fig. A.2.** RVs, FWHM and depth of the atmospheric signal during transit using dataset B: the vertical dashed orange lines and shaded areas show the mean values and relative standard deviation for each of the three quantities. All the data are comprised between  $t_0$  (start of ingress) and  $t_2$  (end of egress), while the horizontal dashed blue lines indicate  $t_2$  (end of ingress) and  $t_3$  (start of egress)

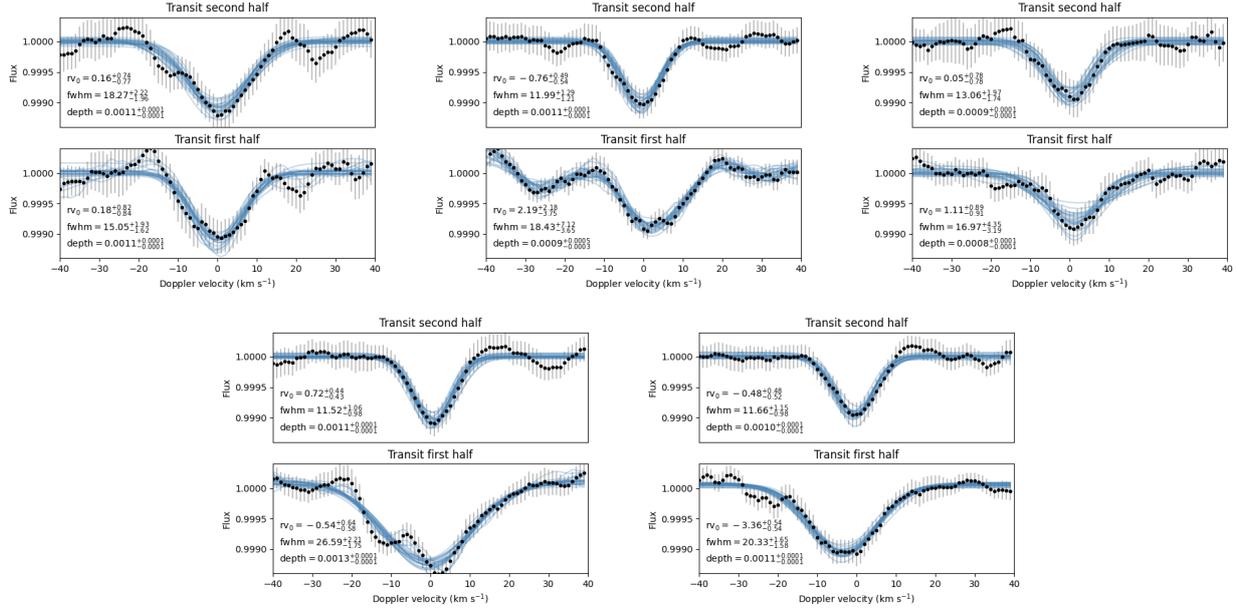


**Fig. A.3.** Averaged atmospheric signal in the first (phase [-0.02:0.0]) and second part (phase [0.0:0.02]) of the transit with relative fit using dataset B.

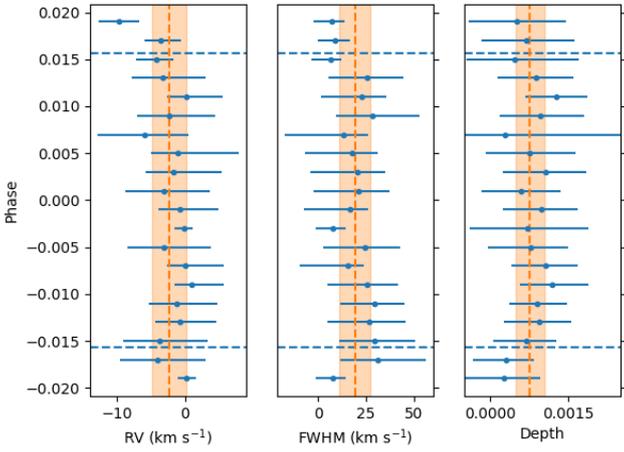
bles that found in the filtered data (Fig. 9), as can be seen from the direct comparison shown in Fig. B.2.

Also the overall variations during the transit (Fig. B.3), arising from comparing the atmospheric signal in the first and second half of the transit, are similar to those found in the filtered data (Fig. 10). For example, in the unfiltered data the FWHM decreases from 16.27<sup>+3.5</sup><sub>-2.9</sub> to 14.78<sup>+4.6</sup><sub>-3.3</sub> km s<sup>-1</sup>, while in the filtered data it decreases from 15.46<sup>+1.4</sup><sub>-1.6</sub> to 13.96<sup>+0.9</sup><sub>-0.9</sub> km s<sup>-1</sup>: in both cases the decrease amounts to 1.5 km s<sup>-1</sup>, while the slightly larger FWHM values found in the unfiltered dataset may be due to the excess noise.

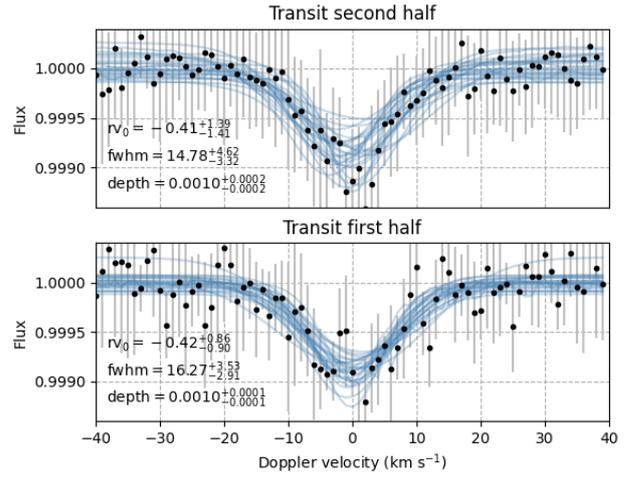
We can reliably confirm that the Savitzky-Golay filter behaves as expected, preserving the signal’s behaviour and lowering the uncertainties thanks to the cleaned out noise.



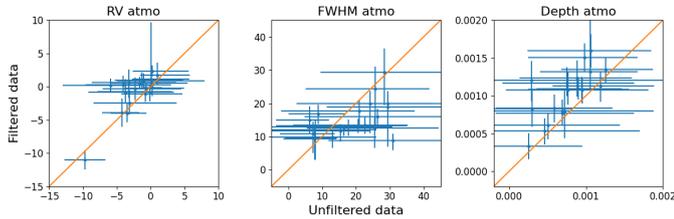
**Fig. A.4.** Averaged atmospheric signal in the first (phase  $[-0.02:0.0]$ ) and second part (phase  $[0.0:0.02]$ ) of each transit using dataset B. From top left to bottom right, the graphics show the results for the nights 1, 2, 3, 4, and 5.



**Fig. B.1.** RVs, FWHM and depth of the atmospheric signal during transit using the unfiltered data: the vertical dashed orange lines and shaded areas show the mean values and relative standard deviation for each of the three quantities. All the data are comprised between  $t_0$  (start of ingress) and  $t_2$  (end of egress), while the horizontal dashed blue lines indicate  $t_2$  (end of ingress) and  $t_3$  (start of egress)



**Fig. B.3.** Averaged atmospheric signal in the first (phase  $[-0.02:0.0]$ ) and second part (phase  $[0.0:0.02]$ ) of the transit with relative fit using the unfiltered data.



**Fig. B.2.** Comparison between the atmospheric trace values of RV, FWHM and depth found in dataset A using the unfiltered data (x-axis) and filtered data (y-axis). The orange lines show the one-to-one correlation.