Hydrogen and Sodium Absorption in the Optical Transmission Spectrum of WASP-12b

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Received 2018 July 25; revised 2018 August 20; accepted 2018 August 21; published 2018 September 12

Abstract

We have obtained >10 hr of medium-resolution (R ~ 15,000) spectroscopic exposures on the transiting exoplanet host star WASP-12, including ~2 hr while its planet, WASP-12b, is in transit, with the Hobby-Eberly Telescope. The out-of-transit and in-transit spectra are coadded into master out-of-transit and in-transit spectra, from which we create a master transmission spectrum. Strong, statistically significant absorption features are seen in the transmission spectrum at Hα and Na I (the Na D doublet). There is the suggestion of pre- and post-transit absorption in both Hα and Na I when the transmission spectrum is examined as a function of phase. The timing of the pretransit absorption is roughly consistent with previous results for metal absorption in WASP-12b, and the level of the Na I absorption is consistent with a previous tentative detection. No absorption is seen in the control line of Ca I at $\lambda$6122. We discuss in particular whether or not the WASP-12b Hα absorption signal is of circumplanetary origin—an interpretation that is bolstered by the pre- and post-transit evidence—which would make it one of only a small number of detections of circumplanetary Hα absorption in an exoplanet to date, the most well-studied being HD 189733b. We further discuss the notable differences between the HD 189733 and WASP-12 systems and the implications for a physical understanding of the origin of the absorption.

Key words: planetary systems – planets and satellites: atmospheres – planets and satellites: gaseous planets – techniques: spectroscopic

1. Introduction and Background

1.1. The Hot Jupiter WASP-12b

WASP-12b is a very short-period hot Jupiter (Hebb et al. 2009) discovered with the SuperWASP program (Pollacco et al. 2006). At the time of its discovery, it was the most highly irradiated and shortest-period planet in the literature, and it has been the subject of significant attention ever since. Shortly after its discovery, Fossati et al. (2010b) found evidence suggestive of absorption by Mg II and other metals in WASP-12b’s atmosphere through HST/COS observations. These results include an indication of pretransit absorption, potentially signifying that WASP-12b has a significant extended atmosphere. Haswell et al. (2012) presented a second HST/COS visit that bolstered the results of Fossati et al. (2010b), including a detection of Fe II. The Haswell et al. (2012) results showed that the required interpretation of the system was more complex, especially given that the ingress of the second visit began significantly earlier than the first visit in Fossati et al. (2010b). The depth of the transits indicate that the planet’s Roche lobe is overfilled (Lai et al. 2010; Debrecht et al. 2018), and there is also observational and theoretical evidence that material from WASP-12b forms a torus- or disklike structure around the star (Haswell et al. 2012; Fossati et al. 2013; Debrecht et al. 2018).

The C/O ratio and water content of WASP-12b have also been the focus of much study, especially the possibility that the planet is carbon-rich rather than oxygen-rich. Evidence of a high C/O ratio and a weak thermal inversion was found by Madhusudhan et al. (2011). More recently, Kreidberg et al. (2015) found evidence for water in the Hubble Space Telescope/Wide Field Camera 3 (HST/WFC3) transmission spectrum of WASP-12b. This detection is potentially consistent with high C/O ratios (>1) under certain assumptions but strongly favors a C/O ratio closer to 0.5.

Another question of interest is whether WASP-12b has an absorbing layer of TiO/VO. The nominal expectation from using the classification system of Fortney et al. (2008) is that WASP-12b should have TiO/VO in its atmosphere that masks Na I absorption. However, Sing et al. (2013) found evidence of a lack of TiO in WASP-12b in HST observations. Recently, Burton et al. (2015) tentatively detected Na I in WASP-12b’s atmosphere through defocused transmission spectroscopy at the level of $0.12\% \pm 0.03\% \pm 0.3\%$, with the error in brackets representing additional systematic uncertainty; accounting for the uncertainty, they state that 0.15% is a better representation of their absorption measurement. This detection of Na I is consistent with the Sing et al. (2013) results and further indicates that WASP-12b does not fit neatly into the Fortney et al. (2008) classification system. Furthermore, Sing et al. (2013) found that their transmission spectrum can be fit equally well by either Rayleigh or Mie scattering. However, Mie scattering is a much better fit to the expected atmospheric temperatures (and the observed blackbody emission spectrum) and implies a high-altitude haze. This subsequently means that any observed line absorption must occur at high altitudes above the haze.

One final recent WASP-12b observation is relevant to the current work: a search for He I absorption at 10833 Å by Kreidberg & Oklopič (2018). They found a transit depth of $59 \pm 143$ ppm relative to the adjacent wavelength bands in the HST/WFC3 G102 grism data. This nondetection does constrain certain models for WASP-12b’s atmosphere and indicates that any helium absorption in WASP-12b is smaller...
than a recent detection in WASP-107b (Spake et al. 2018). However, the measurement is made over an integration band of 70 Å (the instrumental resolution) and does not rule out the possibility that significant absorption might be observed with a higher instrumental resolution.

1.2. Observations of Hydrogen in Exoplanets

Observations of broad hydrogen envelopes measured in ground-state absorption (specifically in Lyα) have been made in multiple planets, including the well-studied planets HD 209458b (Vidal-Madjar et al. 2003, 2004) and HD 189733b (Lecavelier des Etangs et al. 2010, 2012). Such observations give insight into the possibility of star-planet interactions and atmospheric escape. However, exoplanetary Lyα measurements pose significant observational difficulties. First, Lyα is in the UV, and UV-capable facilities with adequate throughput and spectral resolution are a very limited resource; only HST is capable of such observations in Lyα at the current time. Second, certain stars are not bright at Lyα, especially Sun-like stars. Furthermore, interstellar Lyα absorption is significant and absorbs stellar Lyα; this absorption poses difficulties for all observations of exoplanetary Lyα and makes them completely impractical in lines of sight longer than 50 pc or so. In short, only certain relatively nearby systems will have adequate observable Lyα flux available to perform exoplanetary transmission spectroscopy. The aforementioned detection of He I at 10833 Å in WASP-107b (Spake et al. 2018) is one promising observational strategy for observing extended exoplanetary atmospheres without UV facilities. Another option is to directly observe hydrogen, albeit not in the ground state, through its Balmer series of transitions at visible wavelengths.

In a series of papers (Redfield et al. 2008; Jensen et al. 2011, 2012, hereafter Papers I, II, and III), the current authors examined the Hobby-Eberly Telescope (HET) transmission spectra of four hot Jupiter-like planets for absorption due to Na I, K I, and Hα. Paper I made the first ground-based observation of an exoplanetary atmosphere by detecting Na I in HD 189733b. Paper II confirmed previously observed atmospheric Na I absorption in HD 189733b (Paper I) and HD 209458b (Charbonneau et al. 2002) and found the hint of possible Na I absorption in HD 149026b. In Paper III, Hα was detected in HD 189733b’s transmission spectrum, the first-ever such detection of exoplanetary Hα. Because the HET observations do not lend themselves to complete light curves that encompass an entire transit, observations with Keck 1/HIRESr were obtained to observe a full transit of HD 189733b. The first observations, in 2013, confirmed the Hα transit absorption and found corresponding H β and H γ transit absorption, along with a significant pretransit signal in all three lines (Cauley et al. 2015). Subsequent observations in 2015 found strong variation in the pretransit and transit signals, leading to an uncertain physical model for the geometry of the absorption (Cauley et al. 2016).

Barnes et al. (2016) challenged the circumplanetary interpretation of the Hα absorption observed in HD 189733b, presenting an alternate interpretation that the transmission spectrum is dominated by contrast effects during transit. Any star’s spectrum will vary over its disk (due to spots or other active regions), and it is possible that a transiting planetary disk may result in differential spectroscopy that mimics excess absorption in certain lines. However, there remain two significant arguments for a circumplanetary origin of the Hα absorption in HD 189733b. First, short-cadence monitoring of HD 189733’s stellar Hα shows that variation at the level of the observed pretransit signals (which cannot be explained by the contrast effect) is uncommon (Cauley et al. 2017a). Second, modeling of the stellar contrast effect that might mimic absorption during transit demonstrates that creating the absorption signal seen in HD 189733b requires a highly constrained distribution of active regions distributed mainly along the transit chord and/or a potentially implausible level of stellar activity for HD 189733 (Cauley et al. 2017b).

As of early 2018, HD 189733b was the only exoplanet with a published detection of Hα absorption. However, there are two recent detections of Hα in exoplanetary atmospheres, both in planets around A stars: KELT-9b (Yan & Henning 2018) and MASCARA-2b/KELT-20b (Casasayas-Barris et al. 2018). Yan & Henning (2018) detected 1.15% of extra absorption in the Hα line center in KELT-9b and attributed the Hα absorption to a hot extended atmosphere that is driven by the intense UV radiation of the star. In addition to finding Hα, Casasayas-Barris et al. (2018) detected Na I in KELT-20b. They found that a temperature higher than equilibrium (4210 K versus 2260 K, respectively) is required in order to explain the observations, which could be explained by the large amount of UV energy delivered by the central star.

1.3. WASP-12b and Comparative Planetology

In this paper, we present the HET transmission spectrum of WASP-12b. This target was selected for HET observations as a point of comparison to the Paper III HD 189733b Hα detection (and prior to the Keck follow-up in Cauley et al. 2015, 2016). The central star, WASP-12, has been classified as a G0V star by Bergfors et al. (2013); however, Fossati et al. (2010a) found a temperature of 6250 ± 100 K, consistent with the value Hebb et al. (2009) derived, which would suggest a spectral type of approximately F7. In any case, as it pertains to the possibility of Hα absorption, WASP-12b is closer to a hotter central star than HD 189733 and thus more highly irradiated. On the other hand, HD 189733 is a later-type (KOV) star that is presumably more active than WASP-12, and its Lyα emission is likely to be both stronger and more variable. This is significant as Huang et al. (2017) modeled the Hα emission in HD 189733b and found that stellar Lyα emission and Lyman continuum emission play an important role in creating the n = 2 hydrogen population, although collisional excitation also plays a role (Christie et al. 2013). Furthermore, Huang et al. (2017) suggested that HD 189733’s activity may be the cause of the variation in the Hα transit depth between Cauley et al. (2015, 2016). Thus, any Hα detected in WASP-12b, given its intermediate spectral type and different physical conditions, would immediately be an interesting data point to enable comparative planetology for any exoplanets exhibiting transit-correlated Hα absorption, including HD 189733b, KELT-9b, and KELT-20b. Table 1 provides information on the WASP-12 system.

In Section 2, we describe our observations and data reduction, and in Section 3, we describe our analysis methods. Our results are presented in Section 4. We discuss our results and possible future work in Section 5.
2. Observations and Data Reduction

2.1. Description of the Observations

Observations of the WASP-12 system were obtained with the HET in 2012 March and April. Spectra were observed with the High-Resolution Spectrograph (HRS) at its lowest-resolution setting of \( R \sim 15,000 \) with a 2" fiber. This is a lower resolution than that used in Papers I–III due to the relative faintness of WASP-12 \( (V = 11.7) \) as compared to the targets in those papers. Exposures for WASP-12 were 600 s in length. The star HR 2866 was used as a telluric standard star; exposures of 60 s were used for this target. This star has celestial coordinates close to WASP-12 in order to reduce differences in air mass and water vapor content in the time between the primary target and telluric observations. In addition, the instrumental setup used two 2" sky fibers.

We initially obtained 63 total exposures of WASP-12. Of these, 12 were while the planet was transiting the star’s disk. Several (14) of these observations needed to be discarded due to low signal-to-noise ratio (S/N) or other miscellaneous reduction issues; however, only one of these 14 was an in-transit observation (discarded due to very low S/N), for a total of 38 out-of-transit exposures and 11 in-transit exposures. An additional out-of-transit exposure was discarded in the echelle order containing Na I due to an uncertain reduction in that order. Figure 1 indicates where the observations were taken relative to the planet’s light curve as described in Hebb et al. (2009). Note that the out-of-transit observations are distributed in phase such that there are many observations far from transit, as well as many pre- and post-transit observations that are very close to transit. Based on this, and the possibility of pre- or post-transit absorption, we discuss in additional detail which observations should be considered “in” versus “out” of transit in Section 4.1.

2.2. Data Reduction

The HRS instrument on the HET is an echelle spectrograph. We used standard IRAF procedures for the removal of the bias level and scattered light, field flattening, aperture tracing, and wavelength calibration from the ThAr comparison lamp exposures. We then summed the apertures to one-dimensional spectra for the primary target (WASP-12), telluric standard (HR 2866), and ThAr lamp exposures. The ThAr lamp exposures were used to set the wavelength scale of the primary and telluric observations.

An attempt was made to extract the sky fiber apertures to one-dimensional spectra. However, the sky background was very often faint enough that a conventional aperture trace through standard IRAF procedures failed (the trace was lost). As a result, we did not complete the sky extraction or perform sky subtraction, and we evaluated through different methods whether or not a variable sky background impacted our final measurements. This is discussed more in Section 3.4.

After the extraction of the apertures, each relevant order of each observation was normalized using a high-order spline function to remove the blaze function of the echelle. Flux errors are calculated based on photon and read noise and scaled by this normalization.

3. Analysis

3.1. Transmission Spectra

The primary goal of our measurements is to determine the “transmission spectrum” of WASP-12b,

\[
S_T = \frac{F_{\text{meas}}}{F_{\text{ref}}} - 1,
\]

where \( S_T \) is the transmission spectrum, \( F_{\text{meas}} \) is a measurement of the flux that we want to consider, and \( F_{\text{ref}} \) is an appropriate reference flux. We will refer to either \( F_{\text{meas}} \) or \( F_{\text{ref}} \) generally as a “flux spectrum” to distinguish it from the transmission spectrum. Note that by this terminology, a flat “flux spectrum” is normalized to a value of 1, while a flat “transmission spectrum” is normalized to a value of zero. Commonly, e.g., in Papers I–III, \( F_{\text{meas}} = F_{\text{in}} \) (i.e., the in-transit flux) and \( F_{\text{ref}} = F_{\text{out}} \) (i.e., the out-of-transit flux). We will refer to a transmission spectrum that includes all observations categorized as either “in” or “out” as a “master” transmission spectrum, though in Section 4.1, we will discuss whether it is appropriate to determine this solely by the transit of the planet’s disk.

In order to create a flux spectrum \( (F_{\text{meas}} \) or \( F_{\text{ref}} \)) that will be used to calculate a transmission spectrum, we take the normalized individual spectra and coadd them (weighted by the normalized flux errors). Prior to coaddition, simple profile fits of the stellar lines are performed in order to determine the line centroids; spectra are then shifted linearly to align the stellar features. Higher-order resolution and wavelength

\[
\begin{array}{c|c|c|c|c|c|c}
\text{Parameter} & \text{WASP-12/WASP-12b} & \text{Unit} \\
\hline
\text{Transit midpoint} & 2,454,508.97682 & \pm 0.0002 & \text{HJD} \\
\text{Period} & 1.09142245 & \pm 3 \times 10^{-7} & \text{days} \\
\text{Transit duration} & 0.122 & \pm 0.001 & \text{days} \\
R_p & 1.79 & \pm 0.09 & R_{\text{Jup}} \\
R_e & 1.63 & \pm 0.08 & R_{\text{Jup}} \\
R_e/R_p & 2.98 & \pm 0.154 & \text{N/A} \\
b & 0.375 & \pm 0.042 & \text{N/A} \\
i & 82.5 & \pm 0.9 & \text{deg} \\
\hline
\end{array}
\]
corrections that were applied in Papers I–III are not necessary due to the $\sim 4 \times$ lower resolution of the WASP-12b observations. Furthermore, as explored in Paper II, observed time-based variations in the resolution of the HET HRS decreased significantly after 2007 December.

The flux spectra, $F_{\text{meas}}$ and $F_{\text{ref}}$, are then used to create the transmission spectrum $S_T$ as in Equation (1); this is done for the orders of interest containing Hα (6563 Å), Hβ (4861 Å), Na I (5890 and 5896 Å), and Ca I (6122 Å). Unlike the targets in Papers II and III, the instrumental setup of the WASP-12 observations was shifted to shorter wavelengths to include Hβ, at the expense of potentially exploring K I (7699 Å).

We also define the equivalent width, $W_\lambda$, in terms of a transmission spectrum to be

$$W_\lambda = \int S_T \, d\lambda,$$

(2)

where the integration is carried over some appropriate wavelength range; $W_\lambda$ has wavelength units. We then use $W_\lambda$ as a measurement of merit for a given transmission spectrum. Obviously, $W_\lambda = 0$ indicates a transmission spectrum that is flat, on average, while $W_\lambda < 0$ indicates net absorption and $W_\lambda > 0$ indicates net emission.

Our definitions of $F_{\text{meas}}$ and $F_{\text{ref}}$ are more general in Equation (1) than in the examples of Papers I–III in order to allow for variations of the transmission spectrum as a function of phase that may not necessarily occur during the disk transit of the planet. For example, Cauley et al. (2015, 2016) calculated a light curve of Hα absorption (equivalent widths $W_\lambda$) as a function of phase in order to observe the possibility of pre- and/or post-transit absorption. Each Hα $W_\lambda$ is based on a corresponding “transmission spectrum,” even where $F_{\text{meas}}$ is not necessarily calculated from in-transit spectra. Again, this is in contrast with Papers I–III, where the focus was on the master transmission spectrum as defined previously. The difference between these two sets of papers was due to the lower S/N of the HET observations compared to the Keck observations, as well as the limited periods of time for which the HET can track an object; no single night of our HET observations provides a complete transit with adequate out-of-transit baseline time. We note, however, that single-exposure transmission spectra were considered briefly in Paper III. In the current paper, we will examine the transmission spectrum as a function of phase and also consider the aggregate master transmission spectrum; results are presented in Section 4.

3.2. “Empirical Monte Carlo” Error Analysis

The process of normalizing individual spectra, coadding them to create flux spectra, and creating a transmission spectrum involves many possible systematic effects. In order to quantify our transmission spectrum errors, in Papers I–III and Cauley et al. (2015, 2016), we performed an “empirical Monte Carlo” (EMC) analysis of our results. The EMC is similar to a “jackknife” method (Paper II; Wall & Jenkins 2003). In short, the fundamental process of the EMC is to select a subset of individual spectra, coadd them to create the $F_{\text{meas}}$ flux spectrum, and then compare $F_{\text{meas}}$ to an appropriate $F_{\text{ref}}$ flux spectrum to create the transmission spectrum as defined in Equation (1). The transmission spectrum is then characterized by a measurement of $W_\lambda$, as in Equation (2). The distribution of $W_\lambda$ measurements, carried out over many different subset combinations, is then used to estimate the uncertainty in the “master” measurement (the $W_\lambda$ of the $S_T$ from comparing the master in-transit spectrum versus the master out-of-transit spectrum).

In Papers I–III, three variations on the EMC were used. The “out–out” method used random subsets of the out-of-transit exposures to create $F_{\text{meas}}$ and the master “out” flux spectrum as $F_{\text{ref}}$. The “in–out” method used random subsets of the in-transit exposures to generate $F_{\text{meas}}$ and $F_{\text{ref}} = F_{\text{out}}$ to calculate $S_T$. Finally, the “in–in” method used in-transit exposure subsets to generate $F_{\text{meas}}$ and then created $S_T$ with $F_{\text{ref}} = F_{\text{in}}$. The resulting “out–out” and “in–in” EMC distributions (measurements of $W_\lambda$) should be centered at zero, while the “in–out” EMC $W_\lambda$ distribution should be centered at the same value as the $W_\lambda$ measurement of the master transmission spectrum. The widths of the distributions can then be used to estimate the overall uncertainty in the measurement of the $W_\lambda$ measurement of the master transmission spectrum.

For WASP-12b, we have 11 in-transit and 38 out-of-transit exposures (37 out-of-transit exposures for Na I). As compared to Papers I–III, we perform the EMC analysis with two small but key differences. First, for the various iterations, we do not use the same master spectrum for $F_{\text{ref}}$ but instead create $F_{\text{ref}}$ from a subset of the appropriate spectra. For example, using the “out–out” method, we select a subset of “out” observations to create $F_{\text{meas}}$, and then we use all remaining “out” observations (the complement of those selected for the “in”) to create $F_{\text{ref}}$. Note that this is how the “in–in” and “out–out” EMC calculations were done in Cauley et al. (2015, 2016). Second, in the earlier papers, the number of spectra used to generate individual measurements was selected based on the overall ratio of in-transit to out-of-transit observations; e.g., if there were 25% as many in-transit observations as out-of-transit observations, we would maintain that same ratio for the “in–in” and “out–out” EMC analyses. However, especially when considering the possibility of exospheric or pretransit absorption, we cannot take this definition of “in” versus “out” for granted. Therefore, in Section 4, we put this to the test; additionally, in that section, we also discuss the sample sizes (i.e., number of spectra) and numbers of iterations for each method.

Finally, we note that an EMC analysis that is based on a subset of a larger sample should provide a somewhat conservative error estimate. The EMC analysis is intended to characterize both systematic and statistical errors simultaneously. If statistical errors dominate, then the actual error in the $W_\lambda$ of a transmission spectrum $S_T$ should scale with the number of observations involved in $S_T$ relative to the EMC analysis. Assuming each individual spectrum has a constant uncertainty $\sigma$, then the scaling between the error in a given transmission spectrum and the error from an EMC distribution width is as follows:

$$\sigma_{S_T} = \sigma_{\text{EMC}} \times \sqrt{\frac{1}{N_{\text{meas, } S_T}} + \frac{1}{N_{\text{ref, } S_T}}}$$

where $\sigma_{S_T}$ is the uncertainty we are trying to find, $\sigma_{\text{EMC}}$ is the error from the EMC, and the values of $N$ are the numbers of individual measured and reference spectra used in $S_T$ and the EMC. However, this scaling may underestimate the overall error if systematic errors are significant (i.e., there are errors that are nonnormal and/or have nonzero covariance).
3.3. Telluric Removal in Individual Spectra

Papers I–III used certain reduction and analysis techniques, such as “cleaning” the telluric standard spectra from weak stellar and interstellar lines. These techniques are unnecessary in the present work due to WASP-12’s faintness and the subsequent lower S/N and resolution as compared to the targets and instrumental setup in those papers. In fact, this extends to the subtraction of telluric absorption itself. We used the Molecfit program (Smette et al. 2015) to fit the telluric lines seen in our observations of our telluric standard target HR 2866. We then applied the fit model to the primary WASP-12 spectra, using the model as a basis to fit the telluric lines in the WASP-12 spectra. This fit allows for a variation in the wavelength shift and optical depth. However, the modeled telluric lines are generally weaker than the noise of individual WASP-12 spectra, and the resulting fit parameters for the optical depth variation are not particularly physically reasonable (e.g., optical depths more than twice the original optical depth fit of the telluric spectra taken in close spatial and temporal proximity, as the weak, narrow lines “lock on” to features in the noise). An example of the telluric spectrum near Hα is shown in Figure 2.

In order to test the possible effect of telluric contamination, we present our first transmission spectrum, with \( F_{\text{meas}} = F_{\text{in}} \) compared against \( F_{\text{ref}} = F_{\text{out}} \) for a region with a few telluric lines to the red of the Hα line (note that for “in” and “out,” we use the “pre/post” case that we will define in Section 4.1). This is shown in Figure 3. Note that the two strongest telluric lines in this region, at \( \sim 6571 \) and \( \sim 6575 \) \( \text{Å} \), are not immediately visible in either the transmission spectrum or the reference spectrum. A corresponding EMC analysis (Figure 4) indicates marginal surplus flux over this limited region, approximately 1\( \sigma \) different than zero, where \( \sigma \) is estimated from the width of the out–out EMC distribution. The fact that a slight, statistically insignificant excess is observed rather than a deficit indicates that forgoing telluric subtraction will not result in a false positive for absorption at our lines of interest (Hα, Hβ, Na I, and Ca I) that we discuss in Section 4. The width of the telluric lines versus our target lines must also be considered, as the telluric lines are narrower than the stellar lines and what we might expect for the planetary atmosphere lines.

3.4. Stellar and Solar Contamination

In addition to understanding the effect of the sky background (Section 2.2), another consideration that must be taken into account is that WASP-12 is a hierarchical triple-star system; the primary is a late-F star (see discussion in Section 1.1) orbited by a pair of M3V stars that orbit each other (Bechter et al. 2014 and references therein). Our instrumental setup used the 2\( \theta \) fiber setup, which is more precisely a 1\( \theta \)93 fiber (P. McQueen, 2017 private communication). The separation of the dwarfs from the primary is 1\( \alpha \)047, meaning that the stars’ centroids will nominally be just off the edge of the fiber, and some nontrivial fraction of their flux may fall within the fiber.

In order to rigorously quantify the possible effects of inadequate sky subtraction and the stellar companions, we took modeled stellar spectra and simulated a transmission spectrum where either \( F_{\text{meas}} \) or \( F_{\text{ref}} \) (it does not particularly matter which) is contaminated by another stellar source. This other stellar source is either a faint solar spectrum (to approximate the sky spectrum) or the additional M dwarf stars in the system. These
sources are scaled by an estimate of the sky background from our observations and an extrapolation of the known magnitudes of the stars, respectively. We can see in Figure 5 the effect that sky contamination has on our transmission spectra. The 18.75 km s⁻¹ radial velocity of WASP-12 (Gaia Collaboration et al. 2016) adjusted for the Earth’s motion during March and April (approximately −28 km s⁻¹, varying by only a few km s⁻¹) results in a relatively constant, approximately 47 km s⁻¹ offset between the solar lines (causing sky contamination and to the blue) and WASP-12’s stellar lines (to the red); additional radial velocity (RV) considerations of WASP-12 due to the planetary influence are much smaller and can be safely ignored. The simulations show the \( S_T \) resulting from a 6300 K WASP-12 stellar model for both \( F_{\text{meas}} \) and \( F_{\text{ref}} \), but \( F_{\text{ref}} \) has been contaminated with a 5800 K solar model at 1%, 2%, and 5% levels; the solar contamination has been offset according to the above discussion. This result in an absorption feature at the wavelength of the stellar line core but also a significant emission feature to the blue. Importantly, this simulation assumes an extreme, unfavorable contamination level: the sky background is ∼1%–2% of WASP-12’s brightness in our observations, but these simulations assume a fully biased out-of-transit contamination with “clean” in-transit observations. For more realistic, random combinations, we would reasonably expect the contamination effect to be much smaller. We further note that in a simulation of no velocity offset between the solar and stellar lines (not shown), the similarity of the 5800 K solar model and the 6300 K WASP-12 model results in a broad, shallow feature rather than the significant narrow features shown. While the zero-offset case is not representative of our data, it demonstrates that sky contamination for this target in our data set cannot produce a false absorption line without the corresponding emission spike.

The same issue is explored for the companions of WASP-12 (Bechter et al. 2014). The two companions have \( J \) magnitude differences of 3.81 and 3.92 from WASP-12, respectively. We extrapolate this to \( R \)-band flux ratios based on Ducati et al. (2001) and estimate that the flux ratio of each companion to the primary is 1.8%. As noted above, the stars will have centroids that are nominally just outside the edge of the fiber, reducing but not eliminating any contamination effect. The pointing accuracy of the HET ranges from approximately 0 ′′ 1 to 0 ′′ 5, while the point spread function (PSF) FWHM ranges from about 1 ′′ 2 to 2 ′′ 5, depending on seeing, with a median of 1 ′′ 7 (P. McQueen, 2017 private communication). These PSF FWHM ranges are consistent with the measured values in the HET night reports for our observations. This indicates that the median flux falling in the fiber is 45%. The fiber will also not catch all of the flux of the primary. If perfectly centered, approximately 82% of the primary’s flux will fall in the fiber on a night of median seeing; for poor centering (and median seeing), this value drops to approximately 71%.

In total, these values indicate that an ∼2% flux ratio between the companions and the primary is a reasonable upper limit. As in the previous simulation, the representative values in Figure 6 assume a pessimistic perfect anticorrelation of maximum contamination for the out-of-transit observations and no contamination for the in-transit signals. No velocity offset has been assumed between WASP-12 and the companion stars; while velocity information is not available for the companion stars, all three stars in the system are resolved at a distance of approximately 430 pc (Gaia Collaboration et al. 2018), implying that any orbital velocities must be small. As before, in practice, we expect a significantly smaller net contamination due to randomness. We have also simulated the case in which contamination mimics absorption rather than emission; both are equally probable. The lack of velocity offset results in a more straightforward absorption feature as compared to the sky contamination case; these worst-case scenarios can still be compared to our results in Section 4.

### 3.5. Interstellar Absorption

As noted in Section 3.3, in Papers I–III, it was necessary to remove interstellar absorption (as well as stellar absorption) from the telluric observations. This is because the telluric observations are adjusted for wavelength and line depth during the process of being subtracted from the primary (using standard IRAF procedures). However, as the stellar and interstellar lines are fixed in depth and wavelength relative to the telluric lines in the telluric spectra, making these adjustments to the telluric spectra then subtracting them from the primary spectra can introduce artifacts.

In the present work, even though WASP-12 is at a distance of approximately 430 pc (Gaia Collaboration et al. 2018)
interstellar lines may be significant, the lines have fixed depth and velocity offsets relative to the stellar lines of WASP-12 (RV variations for WASP-12 are small enough that they can safely be ignored). Therefore, there is no need to remove interstellar lines prior to the calculation of $S_T$, where they will naturally be removed in the same way that stellar lines are. In addition, while interstellar lines in general may be significant for WASP-12 due to its distance, this is not necessarily true of all the specific absorption lines explored in this paper: interstellar lines from the NaI D doublet should be present, but we would not expect detectable interstellar Balmer lines of hydrogen.

4. Results

In this section, we first present our results for a preliminary phase curve of H$\alpha$ that was calculated in order to assess whether or not there is evidence for pre- or post-transit absorption. From this, we wish to better determine which spectra to include in $F_{\text{meas}}$ and $F_{\text{ref}}$ for our master $S_T$ and EMC analyses (Section 4.1). Using this information, we then analyze H$\alpha$ and H$\beta$ (Section 4.2), NaI (Section 4.3), and the CaI control line (Section 4.4). We briefly discuss the velocity shifts of observed absorption in Section 4.5.

4.1. Preliminary Phase Curve

As noted in Section 1.1, Fossati et al. (2010b) and Haswell et al. (2012) provided evidence of metal absorption occurring in pretransit observations of WASP-12b, with significant theoretical follow-up (e.g., Lai et al. 2010; Vidotto et al. 2010; Llama et al. 2011). In Cauley et al. (2015, 2016), evidence for pretransit H$\alpha$ in HD 189733b was presented. Therefore, as discussed in Section 3.1, we should not take for granted that absorption might only occur during the disk transit of WASP-12b. To evaluate this, we create a light curve of the H$\alpha$ absorption using all out-of-transit observations to generate $F_{\text{ref}}$ with subsets of three or more spectra, grouped by orbital phase, to generate the various $F_{\text{meas}}$ and subsequent $S_T$.

In Figure 7, we see a very clear correlation with transit that extends to before and after transit. The earliest indication of absorption is around a phase of $-0.1$, where a phase of zero is defined as the transit midpoint. There is an indication of absorption just beyond transit at a phase of approximately 0.07. Notably, nearly all but one of the remaining out-of-transit points (where the phase absolute value is less than 0.1) are above the baseline. This is sensible, as it indicates that the default master out-of-transit flux spectrum used for $F_{\text{ref}}$ has been diluted by the inclusion of the observations near transit.

In Fossati et al. (2010b), the indication of metal absorption (e.g., Mg II) occurs as early as a phase of $-0.08$, which is roughly consistent with what we see here. The early absorption is most pronounced in the NUVA band (2539–2580 Å), which includes resonance lines of Na I, Al I, Sc II, Mn II, Fe I, and Co I (Morton 1991, 2000; Fossati et al. 2010b); a NUVA time-tag data point at a phase of approximately $-0.09$ in Fossati et al. (2010b) does not show absorption. Haswell et al. (2012) showed evidence for early absorption in the NUVA and NUVC (2770–2811 Å) in phases as early as $-0.16$. As discussed in Section 1.1, the combined results of Fossati et al. (2010b) and Haswell et al. (2012) are evidence for a time-variable ingress. It is also not a given that H$\alpha$ absorption should precisely correlate with the absorption in the NUVA and NUVC bands in those papers.

In addition to being evidence for possible pre- and/or post-transit absorption, this is an indication that we should shift our definitions of “in-transit” and “out-of-transit” for our calculations of $F_{\text{meas}}$ and $F_{\text{ref}}$ in either our determination of $S_T$ or when performing our EMC analyses. We will henceforth refer to two cases: (1) the “disk transit” case, where we define in-transit and out-of-transit observations based on whether they occur during the white-light transit of WASP-12b’s disk, and (2) the “pre/post” case, where we define any observation with a phase between $-0.1$ and 0.1 to be in-transit and all others to be out-of-transit based on the combination of our preliminary light-curve results and the Fossati et al. (2010b) and Haswell et al. (2012) results. Our discussion will focus primarily on the “pre/post” case.

4.2. H$\alpha$ and H$\beta$ Transmission Spectra

In Figure 8, we show the modified version of the light curve for H$\alpha$ assuming the pre/post case; this is the same as Figure 7 but shifted, so the clear correlation with transit, including some evidence of absorption during pre- and post-transit phases, remains intact. As discussed in Section 1.2, evidence for the circumplanetary nature of H$\alpha$ in HD 189733b was presented in Cauley et al. (2017a, 2017b) on the basis of short-cadence stellar H$\alpha$ monitoring and simulations of the contrast effect. While we have not performed similar investigations of the WASP-12 system, both concepts are relevant here. WASP-12 has a very low value of log $R_{\text{HK}}$ (Knutson et al. 2010), indicating anomalously low stellar activity; however, Fossati et al. (2013) argued that material in the WASP-12 system may have a significant impact on the observed core absorption in the Ca II H and K lines, and WASP-12 may in fact have a more normal activity level for its spectral type. In either case, the activity level of WASP-12 is expected to be smaller than that of HD 189733 based on spectral type, which is relevant for conclusions about absorption in the transmission spectrum.
First, the contrast effect should be small. Second, it strengthens the case that any apparent pre- or post-transit absorption, which cannot be explained by contrast effects, is due to circumplanetary absorption rather than stellar variability in the Hα line.

Figure 9 shows the master transmission spectrum at Hα, again assuming the pre/post case. The presence of a line is very clear and striking, larger than the corresponding observations for other planets where Hα has been observed (HD 189733b, KELT-9b, and KELT-20b). The depth of the feature is stronger than the simulated worst-case scenarios in Figures 5 and 6. In addition, no obvious strong emission feature to the blue is seen as in Figure 5, though there are slight excesses to both the red and blue of the central absorption.

The master transmission spectrum is integrated over a 2 Å band, resulting in a $W_l$ at Hα, or $W_{\text{Hα}}$, of $-64.9$ mA. We used an EMC analysis (Section 3.2) to evaluate the error on the master transmission spectrum. In the pre/post case, we have 25 in-transit and 24 out-of-transit spectra. In our EMC analysis, we select random subsets of approximately half of the available spectra for each iteration; in this case, we have 25 in-transit spectra, and thus $C_{25}^{25} = 5,200,300$ combinations of 13 spectra are available. This is an unwieldy number of combinations, so we choose to explore 5000 iterations for the “in–in” method— in each iteration, $F_{\text{meas}}$ is a random combination of 13 individual spectra and $F_{\text{ref}}$ is the complement, i.e., the combination of the remaining 12 individual spectra. Similar numbers are applicable for the “out–out” method, with the change that there are only 24 total spectra, but we use combinations of 12 spectra to create $F_{\text{meas}}$ and the complementary 12 spectra to create $F_{\text{ref}}$; this is done for 5000 iterations (combinations). For the “in–out” method, we choose random subsets of 13 of the in-transit spectra to create $F_{\text{meas}}$ and random subsets of 12 of the out-of-transit spectra to create $F_{\text{ref}}$ again for 5000 iterations.

We show our EMC analysis in Figure 10. In that figure, the “in–in” and “out–out” distributions are both centered at zero, which is what we expect. In addition, the “in–out” distribution is centered at roughly the master transmission spectrum, also what we expect.

We assume that the distribution of $W_l$ measurements is Gaussian and allow the measured Gaussian σ to represent an estimate of the error in our master $W_l$ measurements, keeping in mind that we may wish to scale the errors by Equation (3). The

![Figure 8](image-url) **Figure 8.** Revised light curve of $W_l$ measurements for Hα absorption in WASP-12b. The format is the same as Figure 7, except that this figure is for the pre/post case as defined in Section 4.1. In addition, note that the two points above the baseline of zero are the only points that are created from more than three individual spectra, due to how the observations are binned; the point at a phase of approximately 0.46 is comprised of four observations, and the point at a phase of approximately 0.28 is comprised of five observations.

![Figure 9](image-url) **Figure 9.** Master transmission spectrum of WASP-12b at Hα. The format is the same as in Figure 3.

![Figure 10](image-url) **Figure 10.** The EMC results for Hα in WASP-12b. The format is the same as in Figure 4.

| Table 2 | WASP-12b Absorption Results |
| --- | --- |
| Line | Bin | $W_l$ | $\text{"In–In" } \sigma$ | $\text{"In–Out" } \sigma$ | $\text{"Out–Out" } \sigma$ | Scale Factor |
| --- | --- | --- | --- | --- | --- | --- |
| Hα | 2.0 | $-64.9$ | 9.0 | 9.1 | 17.3 | 0.714 |
| Hβ | 2.0 | $-3.1$ | 2.8 | 2.7 | 4.0 | 0.714 |
| Na Iα | 2.0 | $-52.6$ | 15.2 | 14.9 | 29.2 | 0.707 |
| Ca Iα | 2.0 | $-2.3$ | 3.3 | 2.5 | 3.3 | 0.714 |

**Notes.**

a The $W_l$ for Na I is the total of both lines in the doublet, each with an integration width of 2.0 Å, as described in the text.

b The factor by which the error in the master $W_l$ measurements should be scaled based on Equation (3); e.g., the out–out width for Hα would correspond to an actual error of $(17.3 \text{ mÅ}) \times 0.714 = 12.3 \text{ mÅ}$. The results of the integration of the master transmission spectrum and the errors derived from the EMC are shown in Table 2; results are given for Hα along with Hβ, Na I, and Ca I. For Hα, the “out–out” distribution is broader than the “in–in” and “in–out.” As seen in the revised phase curve (Figure 8), there is some variation in the baseline, which contributes to the broader width of the “out–out” distribution. The source of this variation is not immediately obvious, but the EMC analysis is intended to characterize systematic effects such as stellar variation or variability in the normalization of individual spectra. We note here that in Papers II and III, it can be seen that the EMC distributions of strong lines such as Hα and Na I are somewhat broader than the EMC distributions of weaker lines like Ca I, likely because these two factors (stellar variation and difficulty
in normalization) are more significant for lines that are broader and stronger in the stellar spectrum.

Next, we present similar figures for the H$\beta$ phase curve (Figure 11), master transmission spectrum (Figure 12), and EMC analysis (Figure 13), all based on the pre/post case in order to be consistent with H$\alpha$. There is no obvious correlation in the H$\beta$ phase curve with transit, and the transmission spectrum of H$\beta$ does not show any obvious absorption near line center. There are some additional artifacts in the transmission spectrum at other wavelengths, but based on the EMC analysis, absorption at H$\beta$ is roughly consistent with zero at the 1$\sigma$ level.

Notably, Cauley et al. (2015, 2016) saw H$\beta$ and H$\gamma$ absorption in Keck observations of HD 189733b, while in Paper III, the HET observations did not cover these wavelengths. However, the absorption ratios in the different Balmer lines (H$\alpha$, H$\beta$, and H$\gamma$) vary significantly between Cauley et al. (2015, 2016). In Cauley et al. (2015), the H$\alpha$/H$\beta$ absorption ratio is smaller, indicating some degree of optical thickness. However, in Cauley et al. (2016), H$\beta$ is much weaker, closer to the optically thin limit, and H$\gamma$ is not observed at a statistically significant level. The oscillator strength of the H$\beta$ transition is more than five times smaller than H$\alpha$ (Goldwire 1968). In Figure 12, we also show the binned H$\alpha$ transmission spectrum from Figure 9, scaled by wavelength and f-value. This would represent an estimate of the expected H$\beta$ profile in the optically thin limit. While we do not see a clear feature this large at H$\beta$, the estimate is not substantially above the remaining noise and other artifacts.

The H$\beta$ $W_0$ measurement and EMC error estimates in Table 2 suggest a very small, statistically insignificant (~1$\sigma$) amount of absorption at H$\beta$, which would be inconsistent with the H$\alpha$ absorption, even accounting for the differing oscillator strengths (note that, in addition to f-value, $W_0$ is also proportional to $\lambda^2$). However, given the errors on both H$\alpha$ and H$\beta$, the results are not mutually exclusive at a level of approximately 2$\sigma$ if we assume the optically thin case.

Sing et al. (2013) presented a transmission spectrum of WASP-12b using HST STIS G430L and G750L. In that paper, the transmission spectrum at H$\alpha$ is not explicitly shown. Sing et al. (2013) instead showed broadband transmission spectral results in wavebands hundreds of Å in width. The bin covering H$\alpha$, from 6300 to 6800 Å, has a slightly larger transit depth than the surrounding wavebands, though not by a statistically significantly amount. Sing et al. (2013) also searched for H$\alpha$, H$\beta$, Na I, and K I in narrower bandpasses and did not find any evidence for absorption. They noted that their results for Na I do not rule out absorption confined to the narrow core, as observed for HD 189733b in the varying results of Papers I-II, Huitson et al. (2012), and Sing et al. (2012). Our observations here resolve the core of the stellar H$\alpha$ line, which is critical for sensitivity to detecting absorption in the core. The STIS G750L, at a resolution of $R \sim 500$, does not resolve the core; Figure 9 covers less than two G750L instrumental resolution elements. It is ultimately unsurprising that the H$\alpha$ signal we see here is not observed in the HST data.

In Section 1.3, we discussed the differences between the WASP-12 and HD 189733 systems. At the time of its discovery, WASP-12b was the most highly irradiated exoplanet known. However, as a late-F star, WASP-12 is expected to be less active and have less Ly$\alpha$ emission than the K0V star HD 189733. In 2013, this model modeled the 2$\sigma$ population in the atomic hydrogen layer between pressures of 5 x 10$^{-5}$ and 10 $\mu$bar, high in the atmosphere (for more discussion, see Yelle 2004). This model indicates that radiative excitation from Ly$\alpha$ dominates over excitation mechanisms for hydrogen. Thus, it is superficially surprising to see H$\alpha$ absorption in WASP-12b if stellar Ly$\alpha$ is the dominant driver of the n = 2 hydrogen population.

One possibility is that WASP-12b has insufficient cooling, perhaps due to an underabundance of coolants, which would allow for an increased n = 2 hydrogen population even with limited Ly$\alpha$ flux coming from the star. However, the Fossati et al. (2010b) and Haswell et al. (2012) results indicate that magnesium, an important coolant, is present in the upper atmosphere. To model this issue in detail is beyond the scope.
of this paper, but our results provide motivation for undertaking such modeling. We note here that the HD 189733b models of Huang et al. (2013) and Christie et al. (2017) find that Hα absorption occurs over a relatively small range of radii. However, our observations—both the magnitude of the absorption and the evidence for pre- or post-transit absorption—indicate that Hα absorption occurs over a larger range of radii. This difference may be important for understanding the mechanism of $n = 2$ creation. While we do not have a detailed model for understanding the Hα absorption, the broader strokes of our observations, especially the early ingress times and the implication that absorption occurs at very high altitudes, are not surprising in light of the previous observational results (Fossati et al. 2010b; Haswell et al. 2012; Sing et al. 2013).

The lack of observed Hβ absorption is the biggest challenge to our interpretation of the Hα transmission spectrum as showing absorption as a real astrophysical signal from a circumplanetary source. However, there is some possibility that we have underestimated errors for the Hβ nondetection in particular, and even with our current errors, the two results are not inconsistent at high statistical significance. What we can conclude is that the lack of clear Hβ absorption suggests that the Hα absorption in WASP-12b, if it is of circumplanetary origin rather than some sort of artifact, is optically thin. Ultimately, it is not clear if this represents a difference with respect to HD 189733b or not.

### 4.3. Na I Transmission Spectrum

Our results for Na I in the pre/post case are shown in Figures 14 (phase curve), 15 (master transmission spectrum), and 16 (EMC analysis). Our master transmission spectrum $W_0$ is $-52.6$ mA and significant to $\sim 5\sigma$ using either the in–in or in–out EMC distribution widths for the error (and scaled by a factor of 0.707) but approximately $2.5\sigma$ using the very broad, scaled out–out width. As with Hα, it is not immediately obvious why the out–out width is so broad, other than that we see in the phase curve that there is significant variation in the out-of-transit observation. In the disk transit case (not shown), absorption is still observed, albeit with a weaker value and an EMC that is similarly broad, such that the overall measurement has marginal statistical significance ($\sim 1\sigma$) at best.

Burton et al. (2015) used defocused transmission spectroscopy to make a tentative detection of Na I in WASP-12b using a 2 Å integration window over each line of the doublet, initially finding an absorption fraction of $0.12\% \pm 0.03\%$. This value is revised to $0.15\% \pm 0.05\%$ after an attempt to remove a systematic feature in mid-transit; the final reported value is $0.12\% \pm 0.03\% \pm 0.03\%$, with the additional error in brackets reflecting the potential effect of this systematic issue.

Converting the absorption value in Table 2 from equivalent width to percentage absorption, we find a value of $0.59\%$ (total for both lines of the doublet) using the disk transit criteria and $1.32\%$ if we include pre- and post-transit up to phases of $\pm 0.1$. However, these values are not directly comparable to the Burton et al. (2015) result. Our method takes an average of the transmission spectrum as follows:

$$\langle S_T \rangle_{\text{(this paper)}} = \langle \frac{F_{\text{in}}}{F_{\text{in}}} \rangle - 1.$$  \hspace{1cm} (4)

In contrast, for a single in-transit or out-of-transit spectrum, Burton et al. integrated and compared their integration window to surrounding continuum windows and then compared the in-transit and out-of-transit integrations. In essence, their average transmission spectrum can be described as

$$\langle S_T \rangle_{\text{(Burton et al.)}} = \langle \frac{F_{\text{in}}}{F_{\text{out}}} \rangle - 1.$$  \hspace{1cm} (5)

The difference in the order of operations of the averages is not trivial. The Burton et al. (2015) method will typically result in smaller values because our point-by-point values of $S_T$ will have a larger absolute value in the line cores where $F_{\text{ref}}$ is small. When performing the integration in the manner of Burton et al. (2015), we get an absorption value of $0.18\%$ across the two lines of Na I in the disk transit case, reasonably consistent with their value—although, as mentioned, our disk transit result is of marginal statistical significance. It is more
appropriate to use our disk transit case results for this comparison because Burton et al. (2015) did not indicate that they included any pre- or post-transit values in their calculation. However, our pre/post case result, integrated in this same manner, gives us an absorption value of 0.56%. Errors on this value will scale with the errors in the EMC results in Table 2.

4.4. Ca I Transmission Spectrum

We use the Ca I line at 6122 Å as a control line where planetary absorption is not expected, as was done in Papers I–III. This is based on the assumption that Ca I will condense out of the planets’ atmospheres based on the pressure–temperature relationships for brown dwarfs given by Lodders (2003). WASP-12b has a higher temperature than any of the targets in those papers, so first we must evaluate this assumption. Stevenson et al. (2014) derived a terminator temperature of 1870 ± 130 K. Based on Lodders (2003), we estimate that Ca I will not condense to CaTiO$_3$ at this temperature as long as the pressure is greater than ~0.1 bar. Stevenson et al. (2014) did not explicitly specify the reference pressure for this temperature but noted elsewhere that they usually set the reference pressure at ~1 bar. We also note that Stevenson et al. (2014) did find alternate model retrievals that fit their data with similar $\chi^2$ for higher temperatures and relatively lower reference pressures, but they ultimately favored the lower temperature.

In any case, we do not see any clear evidence for transit-correlated absorption in either the phase curve (Figure 17) or the transmission spectrum for Ca I (Figure 18), as the latter shows no obvious features. There is a small dip near line center that is largely washed out by 4 pixel binning, and the integration is consistent with zero at the ~1σ level in our EMC error analysis (Figure 19). These figures show the pre/post case, but the disk transit case (not shown) is not substantially different; any apparent absorption is even weaker and statistically insignificant.

4.5. Absorption Velocities

As described in Section 2.1, we used the HET’s HRS at its $R \sim 15,000$ setting. This corresponds to a velocity resolution of ~20 km s$^{-1}$ near H$\alpha$ and Na I. As shown in Figure 1, the observations are weighted toward the first half of transit. We calculate that for a simple filled Roche lobe model, assuming that hydrogen absorption matches the planet’s radial velocity, any absorption should be dominated by observations corresponding to approximately ~50 km s$^{-1}$ (relative to the star). In

5. Conclusions

5.1. Discussion

As we have stated, detection of H$\alpha$ in exoplanetary atmospheres is rare. The H$\alpha$ in HD 189733b (Paper III; Cauley et al. 2015, 2016) is by far the best studied. There are
also a handful of nondetections of Hα, such as for HD 209458b in Winn et al. (2004) and HD 147506b and HD 149026b in Paper III. Recent additional detections in KELT-20b (Casayas-Barris et al. 2018) and KELT-9b (Yan & Henning 2018) are intriguing, especially considering that they are around A stars, but they are not as well-studied as HD 189733b.

Salz et al. (2016) modeled the atmosphere of several hot Jupiter planets and found a mass-loss rate for WASP-12b that is large (3.4% per Gyr) but significantly smaller than previous results (Lai et al. 2010; Li et al. 2010), thus resolving the prior implication that the planet was short-lived and its discovery statistically improbable. The mass-loss rate found by Salz et al. (2016) indicates a very large hydrogen envelope and a large theoretical Lyα signal that absorbs over 80% of the incoming flux at line center and spans hundreds of km s\(^{-1}\). This model includes absorption that is significant well beyond the Roche lobe. Given the abundance of hydrogen, the detection of Hα is not particularly surprising, nor is the fact that we detect pre- and possibly post-transit absorption. The primary open question remains what mechanisms generate \(n = 2\) in significant amounts, and whether these mechanisms can explain the observational details, particularly the depth and velocity range, of the Hα absorption.

What creates \(n = 2\) hydrogen in hot Jupiter atmospheres? The HD 189733b Hα detection has been modeled in detail by Christie et al. (2013) and Huang et al. (2017). The former used a hydrostatic atmosphere model, but the Lyα radiation was not modeled in detail. Christie et al. (2013) found that a reasonably constant \(n = 2\) hydrogen density within the atomic layer could be created if collisional excitation dominated. Huang et al. (2017) expanded on the work of Christie et al. (2013) by including a more detailed treatment of the Lyα radiative transfer. By considering Lyα coming from recombinations within the atmosphere, the radiative excitation rate can exceed the collisional excitation rate, meaning that the excitation can occur at significant levels deeper within the atmosphere at greater \(n = 1\) hydrogen densities.

Given that WASP-12’s Lyα emission is presumably weaker than HD 189733’s, it is unclear how significant \(n = 2\) could exist. However, WASP-12b’s atmosphere should be more extended than HD 189733b’s, with a larger scale height. WASP-12b’s lower atmosphere is certainly hotter than HD 189733b’s, though this may not necessarily be the case at higher altitudes (Salz et al. 2016). If and where WASP-12b’s atmosphere is hotter, it is possible that even with weaker EUV radiation, collisions will contribute significantly to \(1s \rightarrow 2s\) excitation.

Our results also must be understood in the context of the evidence for a torus- or disklike structure around WASP-12 made up of material from WASP-12b (Lai et al. 2010; Haswell et al. 2012; Fossati et al. 2013; Debrecht et al. 2018). We show a clear correlation with transit for Hα and Na I, which argues for some asymmetry in the disk, such as a collision between the accretion stream from the planet and the disk (Lai et al. 2010), which could be the source of early ingress. Understanding the early ingress also has significant implications as a potential probe of the magnetic field (Vidotto et al. 2010; Llama et al. 2011). The evidence for late egress in our observations is not as compelling as the evidence for early ingress, but it is also worth further study.

In Section 1.2, we noted that there are observational challenges to relying on Lyα as a diagnostic of extended exoplanetary atmospheres. First, UV instrumentation that covers Lyα at adequate S/N and resolution is essentially restricted to HST at the current time. Second, the stellar flux at Lyα varies significantly as a function of spectral type. Active late-type stars have significant line emission at Lyα; this includes K stars like HD 189733b. Late-F stars like WASP-12 have line emission at Lyα, but it is weaker (relative to the star’s continuum) than Lyα emission for K or M stars, while earlier-type stars like the A stars KELT-9b and KELT-20b will have significant UV continuum flux. Third, even with adequate UV instrumentation and stellar flux at Lyα, the observation of Lyα transit absorption is complicated by interstellar absorption and airglow in the Earth’s atmosphere, issues that are not present for Hα.

Given that Hα also probes the structure of a planet’s upper atmosphere, and its location in the visible red portion of the spectrum makes it accessible from the ground, Hα is an arguably underutilized diagnostic for observing extended atmospheres. Specifically, while not all exoplanets with observable Lyα signatures will have corresponding observable Hα absorption (e.g., HD 209458b), using both can be complementary approaches insofar as Lyα observations are flux-limited. This is the case with WASP-12b; at a distance of approximately 430 pc (Gaia Collaboration et al. 2018), interstellar absorption prevents Lyα observations of WASP-12 with HST. The recent He I detection by Spake et al. (2018) is another way in which extended atmospheres may potentially be observed without UV observations of Lyα. Furthermore, the far- and near-UV metal-line observations discussed in Section 1.1 represent another significant way in which extended atmospheres may be probed. In addition to being in different wavebands, all of these methods represent at least somewhat different diagnostics of exoplanetary atmospheres, and therefore they are all useful as different probes of exoplanetary characteristics.

5.2. Summary

We have presented the transmission spectrum of WASP-12b from HET observations in 2012 March/April. The spectrum shows clear features at Hα (Figure 9) and Na I (Figure 15), while no obvious features are observed at Ca I (Figure 18, intended as a control line) or H/β (Figure 12). The Hα absorption marks only the fourth such detection in an exoplanetary atmosphere after HD 189733b, KELT-20b (Casayas-Barris et al. 2018), and KELT-9b (Yan & Henning 2018), while the Na I absorption is roughly consistent with previous results by Burton et al. (2015) and likewise one of the larger, but still limited, number of exoplanetary Na I detections. Phase curves of Hα (Figure 8) and Na I (Figure 14) indicate the possibility of pre- and post-transit absorption, roughly consistent with the results of Fossati et al. (2010b) and Haswell et al. (2012) for metals in the extended atmosphere of WASP-12b. The evidence for pre- and post-transit absorption suggests that stellar effects such as the contrast effect are not an adequate explanation for our observations. The lack of H/β absorption at a level that would be consistent with the strong Hα signal is somewhat puzzling and the biggest challenge to our interpretation of the Hα transmission spectrum as a real astrophysical signal from WASP-12b’s circumplanetary material; however, our results for the Hα/H/β ratio are not ruled out to high statistical significance in the optically thin case.
5.3. Future Work

As with HD 189733b, the transit-correlated Hα absorption cannot be fully understood with our track-limited observations made by the HET. The Hα profile of WASP-12b needs to be observed at high S/N over an entire single transit in order to get a better picture of what the correlation between transit and absorption actually is. Our previous work has shown that absorption detected through the HET can be well-characterized through a large telescope that observes continuously through transit, e.g., with Keck (Cauley et al. 2015, 2016). Such observations would also allow us to more rigorously characterize the suggestion of pre- and post-transit absorption in our observations, as was noted in HD 189733b by Cauley et al. (2015, 2016).

This work was completed with support by NASA Exoplanet Research Program grant 14-XRP14-2-0090 to the University of Nebraska at Kearney (PI: AGJ) and National Science Foundation Astronomy and Astrophysics Research Grant AST-1313268 to Wesleyan University (PI: SR). The authors thank C. Huang, M. Swain, and P. McQueen for many helpful discussions. We also thank P. Arras and C. Duncan for providing feedback on the manuscript. Finally, we thank the anonymous referee for insight and several helpful comments.

The Hobby-Eberly Telescope is a joint project of the University of Texas at Austin, Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen and is named in honor of its principal benefactors, William P. Hobby and Robert E. Eberly. This work made use of IDL, the Interactive Data Language; IRAF, the Image Reduction and Analysis Facility; the SIMBAD Database; the Exoplanet Data Explorer; and the Exoplanet Transit Database.

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