HST hot Jupiter transmission spectral survey: evidence for aerosols and lack of TiO in the atmosphere of WASP-12b


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ABSTRACT
We present Hubble Space Telescope (HST) optical transmission spectra of the transiting hot Jupiter WASP-12b, taken with the Space Telescope Imaging Spectrograph (STIS) instrument. The resulting spectra cover the range 2900 to 10300 Å which we combined with archival WFC3 spectra and Spitzer photometry to cover the full optical to infrared wavelength region. With high spatial resolution, we are able to resolve WASP-12A’s stellar companion in both our images and spectra, revealing that the companion is in fact a close binary M0V pair, with the three stars forming a triple-star configuration. We derive refined physical parameters of the WASP-12 system, including the orbital ephemeris, finding the exoplanet’s density is ∼20% lower than previously estimated.

From the transmission spectra, we are able to decisively rule out prominent absorption by TiO in the exoplanet’s atmosphere, as there are no signs of the molecule’s characteristic broad features nor individual bandheads. Strong pressure-broadened Na and K absorption signatures are also excluded, as are significant metal-hydride features. We compare our combined broadband spectrum to a wide variety of existing aerosol-free atmospheric models, though none are satisfactory fits. However, we do find that the full transmission spectrum can be described by models which include significant opacity from aerosols: including Rayleigh scattering, Mie scattering, tholin haze, and settling dust profiles. The transmission spectrum follows an effective extinction cross section with a power-law of index α, with the slope of the transmission spectrum constraining the quantity αT = −3528±660 K, where T is the atmospheric temperature. Rayleigh scattering (α = −4) is among the best fitting models, though requires low terminator temperatures near 900 K. Sub-micron size aerosol particles can provide equally good fits to the entire transmission spectrum for a wide range of temperatures, and we explore corundum as a plausible dust aerosol. The presence of atmospheric aerosols also helps to explain the modestly bright albedo implied by Spitzer observations, as well as the near black body nature of the emission spectrum. Ti-bearing condensates on the cooler night-side is the most natural explanation for the overall lack of TiO signatures in WASP-12b, indicating the day/night cold-trap is an important effect for very hot Jupiters. These finding indicate that aerosols can play a significant atmospheric role for the entire wide range of hot-Jupiter atmospheres, potentially affecting their overall spectrum and energy balance.

Key words: techniques: spectroscopic - planetary systems - planets and satellites: atmospheres - planets and satellites: individual: WASP-12b - stars: individual: WASP-12.
1 INTRODUCTION

Transit events have revolutionised our understanding of hot-Jupiter exoplanets, thanks in large part to atmospheric studies using transmission, emission, and phase curve observations. Even with hundreds of known transiting hot Jupiters, currently only a small handful of exoplanets are capable of having their atmosphere characterised with all three types of observations using current facilities, making these planets prototypes for the rest of the field. Among these planets is WASP-12b, a prototype ‘very hot Jupiter’ which is one of the largest and hottest planets known (Hebb et al. 2009).

Extensive ground and space-based observations have been conducted on this planet over the last few years (Lopez-Morales et al. 2010; Fossati et al. 2010; Chan et al. 2011; Campo et al. 2011; Croll et al. 2011; Maciejewski et al. 2011; Cowan et al. 2012; Haswell et al. 2012; Swain et al. 2013; Crossfield et al. 2012a,b; Zhao et al. 2012; Fossati et al. 2013; Maciejewski et al. 2013; Copperwheat et al. 2013; Stevenson et al. 2013; Föhring et al. 2013).

As a very hot planet, most models predict strong Na, K, H₂O, and TiO/VO features in the atmosphere, with no condensates. WASP-12b has the potential to help address the stratospheric TiO hypothesis, which links the presence of TiO to thermal inversions (Fortney et al. 2008). As one of the largest planets, studying its atmosphere could also help gain insight into the connection between the anomalously large radius and atmospheric features.

Despite all the recent observations, the nature and composition of WASP-12b’s lower atmosphere remains largely elusive, as both ground and space-based transmission spectra have not yet been able to place strong constraints on the presence of specific molecular features or atmospheric constituents (Swain et al. 2013; Copperwheat et al. 2013; Stevenson et al. 2013). Spectral retrieval methods on the day-side emission spectrum indicated the planet contains a high C/O ratio (Madhusudhan et al. 2011), which would have important consequences regarding the planet’s atmosphere (Madhusudhan 2012). However, WASP-12A is now known to have a close M-dwarf stellar companion discovered by Bergfors et al. (2011, 2013), which diluted previously reported transit and eclipse depths, especially in the infrared. After the diluting effects of the nearby M-dwarf have been taken into account, the dayside spectrum appears to largely resemble a black body (Crossfield et al. 2012a; Swain et al. 2013), which weakens the case for a high C/O ratio atmosphere.

Here we present results from a large Hubble Space Telescope (HST) programme for WASP-12b (HST GO-12473; P.I. Sing), which is part of an eight planet optical atmospheric survey of transiting hot Jupiters, with the initial results given in Huíson et al. (2013) for WASP-19b and Wakeford et al. (2013); Nikolov et al. (2013) for HAT-P-1b. The overall programme goals are to detect atmospheric features across a wide range of hot-Jupiter atmospheres enabling comparative exoplanetology, detect stratosphere causing agents like TiO (Hubeny et al. 2003; Fortney et al. 2008), and detect hazes and clouds. In this paper, we present new HST transit observations with the STIS instrument (Space Telescope Imaging Spectrograph), and combine them with existing WFC3 (Wide Field Camera 3) spectra and Spitzer photometry to construct a high signal-to-noise near-UV to infrared transmission spectrum, capable of detecting and scrutinising atmospheric constituents. We describe our observations in Sect. 2, present the analysis of the transit light curves in Sect. 3, discuss the results in Sect. 4 and conclude in Sect. 5.

2 OBSERVATIONS

2.1 Hubble Space Telescope STIS spectroscopy

We observed two transits of WASP-12b with the HST STIS G430L grating during 14 March 2012 and 27 March 2012, as well as one transit with the STIS G750L during 4 September 2012. The G430L and G750L datasets all consist of 53 spectra, each spanning five spacecraft orbits. The G430L grating covers the wavelength range from 2,900 to 5,700 Å, with a resolution $R = \lambda/\Delta\lambda = 530–1,040$ ($\sim$2 pixels; 5.5 Å). The G750L grating covers the wavelength range from 5,240 to 10,270 Å, with a resolution $R = \lambda/\Delta\lambda = 530–1,040$ ($\sim$2 pixels; 9.8 Å). Both the G430L and G750L data were taken with a wide $25'' \times 25''$ slit to minimise slit light losses. This observing technique has proven to produce high signal-to-noise (S/N) spectra which are photometrically accurate near the Poisson limit during a transit event (e.g. Brown 2001; Sing et al. 2011; Huíson et al. 2012). The three visits of HST were scheduled such that the third and fourth spacecraft orbits would contain the transit, providing good coverage between second and third contact, as well as an out-of-transit baseline time series before and after the transit. Exposure times of 279 seconds were used in conjunction with a 128-pixel wide sub-array, which reduces the readout time between exposures to 21 seconds, providing a 93% overall duty cycle.

The dataset was pipeline-reduced with the latest version of CALSTIS and cleaned for cosmic ray detections with custom IBL routines. Cosmic rays typically affect $\sim 5\%$ of the CCD pixels in a typical 279 second exposure and the STScI pipeline is generally insufficient in cleaning the images. Therefore, we adopted the strategy developed by Nikolov et al. (2013) to clean the images. The procedure is based on median-combining difference images to identify cosmic ray events, substituting the affected pixels, and those identified by CALSTIS as “bad”, with flux values interpolated from the nearby point spread function (PSF). The mid-time of each exposure was converted into BJD$_{TDB}$ for use in the transit light curves (Eastman et al. 2010). As the G750L grating suffers from fringing effects red-ward of $\sim$7250 Å, we obtained contemporaneous fringe flats at the end of observing sequence, using them to defringe the science frame images (also see Nikolov et al. 2013).

The spectral aperture extraction was done with IRAF using a 13-pixel-wide aperture with no background subtraction, which minimises the out of transit standard deviation of the white light curves. The extracted spectra were then Doppler-corrected to a common rest frame through cross-correlation, which removed sub-pixel wavelength shifts in the dispersion direction. The STIS spectra were then used to create both a white-light photometric time series (see Fig. 1), and custom wavelength bands covering the spectra, integrating the appropriate wavelength flux from each exposure for different bandpasses. The resulting photometric light curves exhibit all the expected systematic instrumental effects taken during similar high S/N transit observations.
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Figure 1. HST STIS normalised white-light curves for the three WASP-12b transits taken with the G430L (blue - left & middle) and G750L (red - right). Top panels: Raw light curves normalised to the mean raw flux. The light curves experience prominent systematics associated primarily with the HST thermal-breathing cycle (see text for details). Middle panels: Detrended light curves along with the best-fit limb-darkened transit model superimposed with continuous lines. Lower panels: Observed minus modelled light curve residuals, compared to a null (dashed lines) and 1–σ level (dotted lines). A colour version is available in the online version of the journal.

The main instrument-related systematic effect is primarily due to the well known thermal breathing of HST, which warms and cools the telescope during the 96 minute day/night orbital cycle, causing the focus to vary. Previous observations have shown that once the telescope is slewed to a new pointing position, it takes approximately one spacecraft orbit to thermally relax, which compromises the photometric stability of the first orbit of each HST visit. In addition for STIS, the first exposure of each spacecraft orbit has consistently been found to be significantly fainter than the remaining exposures. These trends are continued in our STIS observations, and are both minimised in the analysis with proper HST visit scheduling. Similar to other studies, in our subsequent analysis of the transit we discarded the first orbit of each visit (purposely scheduled well before the transit event). In addition, we set the exposure time of the first exposure of each spacecraft orbit to be 1 second in duration, such that the exposure could be discarded without significant loss in observing time. We find that the second exposures taken for all five spacecraft orbits (each 279 seconds in duration) do not show the first-exposure systematic trend, making the short-exposure strategy an effective choice. However, we note that the first-exposure systematic in new observations of HD 189733 with the STIS G430L (GO 1306, P.I. Pont), persisted despite discarding similar 1 second initial exposures. As the HD 189733 time series exposures were much shorter (64 seconds), the 1-second strategy may only be effective for fainter targets like WASP-12, which have longer exposure times.

2.2 Hubble Space Telescope WFC3 spectroscopy

We also analyse the WFC3 G141 transit data of WASP-12 taken as part of GO 12230 (PI Swain), with results given in Swain et al. (2013). Our re-analysis is motivated by both a need for a consistently derived transmission spectrum with the STIS data, and the subsequent discovery of the M-dwarf companion Bergfors et al. (2011, 2013) which affects the transit and eclipse depths (Crossfield et al. 2012a).

We use the fit outputs from WFC3’s calwf3 pipeline. For each exposure calwf3 conducts the following processes: bad pixel flagging, reference pixel subtraction, zero-read subtraction, dark current subtraction, non-linearity correction, flat-field correction, as well as gain and photometric calibration. The resultant images are in units of electrons per second. The first orbit of the WFC3 data was removed, as it also suffers from thermal breathing systematic effects like STIS, leaving 391 exposures over the remaining four HST orbits, with a total of 175 exposures taken between first and fourth contact.

The spectra were extracted using custom IDL routines similar to IRAF’s APALL procedure, using an aperture of ±9
pixels from the central row, determined by minimising the standard deviation across the aperture. The resulting 18 pixel wide aperture encompasses both WASP-12 and the M-dwarf binary. The aperture was traced around a computed centering profile, found to be consistent in the y-axis with an error of ±0.5 pixels. Background subtraction was applied using a region above and below the spectrum for each exposure. We elected to subtract the M-dwarf flux contribution through post-processing, though we note that nearly identical results can be obtained by instead excluding the M-dwarf flux using PSF fitting techniques (Swain et al. 2013).

For wavelength calibration, direct images were taken in the F132N narrow band filter at the beginning of the observations providing the absolute position of the target star. We assumed that all pixels in the same column have the same effective wavelength, with the extracted spectra covering the wavelength range of 1.077 to 1.704 μm.

2.3 Photometric Monitoring for Stellar Activity

We also observed WASP-12 from the ground with Tennessee State University’s automated Celestron C-14 telescope, located at Fairborn Observatory in southern Arizona. The telescope was equipped with an SBIG STL-1001E CCD camera observing through a Cousins R filter. Fig. 2 shows the Cousins R data for the 2011-2012 and 2012-2013 observing seasons plotted against Heliocentric Julian Date. The observations have been corrected for bias, flat field, differential extinction, and pupil offset. Differential magnitudes are computed against the mean of 17 comparison stars in the same CCD field. Each differential magnitude plotted is the mean of 8 to 10 successive frames on a given night. There are a total of 231 nightly observations, with transit points excluded from the plot. The standard deviation of an individual observation from the grand mean is 2.1 mmag. We find no significant periodicity between one hour and 200 days in these data, with WASP-12A appearing quite constant. In particular, a least-squares sine fit of the C14 observations phased with the radial velocity period has a peak-to-peak amplitude of only 0.00056 ± 0.00041 mm, indicating little, if any, contribution to the radial velocity variations from stellar-surface activity. The late F spectral type of WASP-12 and its relatively low measured vsini (Knutson et al. 2010), also makes it unlikely to have significant star spots, which is confirmed by our photometric monitoring. Alternatively, the low vsini could also be a result of a near pole-on view of the star as seen from the Earth, which is consistent with the spin-orbit misalignment measurement from Albrecht et al. (2012).

3 ANALYSIS

3.0.1 STIS white-light curve fits

Our overall analysis methods are similar to the HST analysis of Sing et al. (2011), Huitson et al. (2013) and Nikolov et al. (2013), which we also describe briefly here. The light curves were modelled with the analytical transit models of Mandel & Agol (2002). For the white-light curves, the central transit time, inclination, stellar density, planet-to-star radius contrast, stellar baseline flux, and instrument systematic trends were fit simultaneously, with flat priors assumed. The period was initially fixed to a literature value, before being updated, with our final fits adopting the value from section 3.1.

Both G430L transits were fit with a common inclination, stellar density and planet-to-star radius contrast. The results from the G430L and G750L white light curve fits were then used in conjunction with literature results to refine the orbital ephemeris and overall planetary system properties (see section 3.2). To account for the effects of limb-darkening on the transit light curve, we adopted the four parameter non-linear limb-darkening law, calculating the coefficients with ATLAS stellar models (T_eff=6500, log g=4.5, [Fe/H]=0.0) following Sing (2010). Varying the stellar model within the known parameter range has a small effect on the output limb-darkening coefficients and fit transit parameters. In particular, we find changing the stellar effective temperature by ±250 K shifts the radius ratios by ~1/3-σ. Further, the shift is typically common to all wavelength channels, and the relative radius ratio differences are largely preserved (to levels of ~0.1-σ in the case of WASP-12b).

As in many past STIS studies, we applied orbit-to-orbit flux corrections by fitting for a fourth-order polynomial to the photometric time series, phased on the HST orbital period. The systematic trends were fit simultaneously with the transit parameters in the fit. Higher-order polynomial fits were not statistically justified, based upon the Bayesian information criteria (BIC; Schwarz 1978). The baseline flux level of each visit was left free to vary in time linearly, described by two fit parameters. In addition, similar to the STIS analysis of Sing et al. (2011), Huitson et al. (2012) and Huitson et al. (2013), we found it justified by the BIC to also linearly fit for two further systematic trends which correlated with the X and Y detector positions of the spectra, as determined from a linear spectral trace in IRAF, as well as the wavelength shift between spectral exposures, measured by cross-correlation.

The errors on each datapoint were initially set to the pipeline values which is dominated by photon noise but also includes readout noise. The best-fit parameters were determined simultaneously with a Levenberg-Marquardt least-
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squares algorithm \cite{Markwardt2009} using the unbinned data. After the initial fits, the uncertainties for each data point were rescaled based on the standard deviation of the residuals and any measured systematic errors correlated in time (‘red noise’), thus taking into account any underestimated errors in the datapoints. The red noise was measured by checking whether the binned residuals followed a $N$ relation, when binning in time by $N$ points. In the presence of red noise, the variance can be modelled to follow a $\sigma^2 = \sigma^2_u/N + \sigma^2_r$ relation, where $\sigma_u$ is the uncorrelated white noise component, and $\sigma_r$ characterises the red noise \cite{Pont2006}. We find that the pipeline per-exposure errors are accurate at small wavelength bin sizes, which are dominated by photon noise, but are in general an underestimation at larger bin sizes. For the STIS white light curves, we find $\sigma_u = 0.00008$ for the G430L and $\sigma_r = 0$ for the G750L. A few deviant points from each light curve were cut at the 3-$\sigma$ level in the residuals.

3.0.2 WFC3 white-light curve fits

The noise properties and systematics of WFC3 G141 spectra are becoming fairly well understood, and are mainly affected by the HST thermal-breathing variation (note the similarities of Figs. 1 & 3) and detector persistence which causes a ramp-effect, also known as the ‘hook’ \cite{Berta2012, Deming2013, Swain2013}. These trends are predominantly either common-mode (i.e. the same in every wavelength channel across the detector) or repeatable orbit-to-orbit, and thus straightforward to remove in a variety of ways without affecting the relative transit depths \cite{Berta2012, Deming2013, Huitson2013}. The amplitude of the ‘hook’ has been studied as a function of exposure level, and reported in \cite{Deming2013}. The authors found that the effect is practically zero when the exposure level per frame is lower than 30,000 electrons/pixel, which is also well within the linear regime of the detector. As the maximum count rates for the WASP-12 WFC3 data are in the range of 38,000 electrons/pixel, thus not substantially higher than the nominal lower threshold, no obvious ‘hook’ systematics are observed \cite{Swain2013}.

We modelled the WFC3 white-light curve using the same analytic transit model and limb-darkening stellar model as used in the STIS analysis. Before the model fits, we subtracted the flux contribution from the M-dwarfs calculated from the WFC3 G141 response and the flux ratio as determined by \cite{Crossfield2012}, which matches well with our STIS analysis of both the M-dwarf spectral type and flux normalisation (see Sect. 3.3). We excluded the ends of the spectrum, where the response drops rapidly, extracting the region from 1.137 to 1.657 µm to use for the white-light curve.

Like in the STIS analysis, the systematic effects of the thermal-breathing were modelled with a fourth order polynomial, phased on the HST orbital period, with the stellar baseline flux free to vary linearly in time. Unlike \cite{Swain2013} we find that higher orders in HST orbital phase are required to more fully remove the systematic errors. An alternative method has been developed by \cite{Berta2012} to correct for detector systematics, which takes advantage of the repetitive nature. Dubbed divide-OOT, the procedure involves creating a template baseline-flux time-series for each subsequent exposure of an HST orbit, determined by averaging the out-of-transit exposures (OOT). The light curve for each of the HST orbits are then divided by the OOT time-series, which removes the systematic error components which are common to each orbit. We find divide-OOT gives very similar results as the parameterised method (as WFC3 exhibits largely common-mode systematics), though shows somewhat higher levels of correlated noise, as there are HST orbital phase mismatches between the sub-exposures of the five HST orbits, leading to residual thermal breathing trends which are evident in the residuals. We adopt the parameterised method both because of the somewhat lower noise values ($\sigma_u = 0.00004$) and it is more straightforward to budget for the affects of the dominant thermal-breathing systematic on the transit depths through the use of the covariance matrix (or alternatively the MCMC posterior distribution). The M-dwarf flux contribution in the WFC3 is 7.16±0.31%, which translates to a systematic uncertainty on the radius ratio when subtracting the flux of 0.00018 $R_p/R_\star$, which is small compared to our final WFC3 white-light curve radius and uncertainly of 0.11977±0.00042 $R_p/R_\star$.

In comparing our results to the literature, a source of disagreement is the overall $R_p/R_\star$ level, which we find significantly higher than \cite{Stevenson2013}, with our levels much closer to those of \cite{Swain2013}. As noted by \cite{Stevenson2013}, this is a result of the exponential function with time which they used to model the instrument systematics, which effectively ‘carves out’ the transit baseline flux leading to smaller fit radii. We see no evidence for a time-dependent exponential function (see Fig. 3), with our raw WFC3 white light curve showing a closer resemblance to the STIS G750L data and its thermal-breathing trends.

3.1 Transit ephemeris

We used the central transit times of our HST data along with the transit times of \cite{Hebb2009, Chan2011, Maciejewski2011, Cowan2012} to determine an updated transit ephemeris. When calculating transit ephemerides from data taken with different instruments in different wavelengths, it is important to use coherent and realistic estimates. \cite{Pont2006} showed how correlated noise could dominate the error budget of system parameter measurements from transit photometry. This issue is especially important for ground-based photometry of WASP-12, given that the M0 dwarf companions lie 1″ from the target star, making very high precision photometry more difficult in changing seeing conditions. As the uncertainties given by \cite{Maciejewski2011} do not account for the effect of correlated noise, as a conservative estimate, we multiplied the error bars by a factor of three, found to be typical for ground-based photometry of transiting planets \cite{Barnes2013}.

We fit the transit times listed in Table 1 and shown in Fig. 4 using a linear function of the period $P$ and transit epoch $E$,

$$T(E) = T(0) + EP.$$  \hspace{0.5cm} (1)

We find a period of $P = 1.09142113 ± 0.0000032$ (days) and a mid-transit time of $T(0) = 2454508.97705 ± 0.00031$ (BJD). A fit with a linear ephemeris is in general an unsatisfactory fit to the data, having a $\chi^2$ of 29 for 9 degrees
of freedom ($\chi^2 = 3.2$), and transit timing variations (TTVs) have been claimed for this system (Maciejewski et al. 2013). We tentatively attribute the high formal reduced $\chi^2$ to unaccounted red noise in the ground-based photometry, rather than actual transit timing variations. We proceed with the linear ephemeris given that our HST transit times are more consistent with a linear fit than a TTV, and the overall problems concerning the red-noise in photometry.

### Table 1. Transit Timing for WASP-12b

<table>
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<tr>
<th>Epoc</th>
<th>BJD$_{TBD}$</th>
<th>BJD error</th>
<th>Notes</th>
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<td>304</td>
<td>2454840.76860</td>
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<td>608</td>
<td>2455172.56182</td>
<td>0.00044</td>
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<td>661</td>
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<td>1527</td>
<td>2456175.57748</td>
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#### 3.2 System parameters

The M-dwarf stellar companion is fully resolved with respect to the WASP-12 primary in our STIS spectroscopy. In combination with the high signal-to-noise, this permits a precise determination of the planetary radius completely free of the flux-dilution effects of the M-dwarf pair. Given that WASP-12b still has one of the largest radii of any transiting planet, a precise radius for this exoplanet, in particular, is crucial for understanding the hot-Jupiter inflation problem (see Baraffe et al. 2010 for a review and the references therein).

We performed a joint fit of the two G430L white light curves in conjunction with the radial velocity data from Hebb et al. (2009) and Husnoo et al. (2011). We used the Markov Chain Monte Carlo (MCMC) suite EXOFAST from Eastman et al. (2013) to perform the joint fit. In the joint fit, EXOFAST utilises the Torres et al. (2010) empirical polynomial relations between the masses and radii of stars, and their surface gravity, effective temperatures, and metallicities. For the fit, we used priors on the orbital period and central transit time from section 3.1 as well as priors on the stellar effective temperature, gravity and metallicity from Hebb et al. (2009). In addition, in order to incorporate the information contained within the G750L and WFC3 light curves, we also put priors on a/R$_*$ and inclination based on the weighted-average transit fits to those datasets. The results are given in Table 2. In addition to finding updated parameters, the EXOFAST fits also serve to help verify the Levenberg-Marquardt transit fits and errors, with all of the fitted parameters and errors consistent at the 1-$\sigma$ level between the two methods, when similar fits are performed, including the values derived for the systematic error parameters described in sections 3.0.1 and 3.0.2.

The resulting planetary radius is in general somewhat larger than past studies (Chan et al. 2011), expected as the M-dwarf serves to dilute the transit depth. With a joint fit using all of the available radial velocity data, our derived absolute radius is also nearly a factor of two more precise than recent ground-based studies (Maciejewski et al. 2013). Consequently, our derived bulk density of $\rho_P = 0.279 \pm 0.019$ (cgs) for the planet is significantly lower than past studies.
Table 2. Best-fit joint parameters for WASP-12

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_*$</td>
<td>Mass (M$_\odot$)</td>
<td>1.362$^{+0.060}_{-0.059}$</td>
</tr>
<tr>
<td>$R_*$</td>
<td>Radius (R$_\odot$)</td>
<td>1.602$^{+0.037}_{-0.035}$</td>
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<tr>
<td>$\rho_*$</td>
<td>Density (cgs)</td>
<td>0.467$^{±0.024}$</td>
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<tr>
<td>$\log(g_\perp)$</td>
<td>Surface gravity (cgs)</td>
<td>4.162$^{±0.016}$</td>
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<tr>
<td>$T_{\text{eff}}$</td>
<td>Effective temperature (K)</td>
<td>6400$^{±190}_{-180}$</td>
</tr>
<tr>
<td>[Fe/H]†</td>
<td>Metallicity</td>
<td>0.159$^{±0.083}$</td>
</tr>
</tbody>
</table>

Planetary Parameters:

| $P$†            | Period (days)           | 1.09142166$^{+0.0000032}_{-0.0000031}$ |
| $a$             | Semi-major axis (AU)    | 0.02300$^{+0.00033}_{-0.00034}$       |
| $M_P$           | Mass (M$_1$)            | 1.417$^{+0.049}_{-0.048}$            |
| $R_P$           | Radius (R$_1$)          | 1.848$^{+0.052}_{-0.049}$            |
| $\rho_P$        | Density (cgs)           | 0.279$^{±0.019}$                    |
| log($g_P$)       | Surface gravity (cgs)   | 3.012$^{+0.019}_{-0.020}$           |
| $T_{\text{eq}}$ | Equilibrium Temp. (K)   | 2578$^{+75}_{-74}$                 |

RV Parameters:

| $K$             | RV semi-amplitude (m/s) | 225.8$^{+3.8}_{-3.9}$            |
| $M_P \sin i$    | Minimum mass (M$_1$)    | 1.406$^{+0.048}_{-0.047}$        |
| $M_P/M_*$       | Mass ratio              | 0.000994$^{±0.000022}$           |
| $\gamma_*$      | Systemic velocity (m/s) | 13.5$^{±2.3}$                    |

Transit Parameters:

| $R_P/R_*$       | Radius of planet        | 0.11852$^{+0.00081}_{-0.00080}$  |
| $a/R_*$         | Semi-major axis         | 3.087$^{+0.052}_{-0.053}$        |
| $i$†            | Inclination (degrees)   | 82.72$^{+0.72}_{-0.73}$          |
| $b$             | Impact Parameter        | 0.391$^{±0.033}$                 |
| $\delta$        | Transit depth           | 0.01405$^{±0.00019}$             |
| $\tau$          | Ingress/egress dur. (days) | 0.01534$^{+0.00062}_{-0.00056}$  |
| $T_{\text{dur}}$| Total duration (days)   | 0.1213$^{±0.0013}_{-0.0012}$     |
| $u_3$           | Linear limb-darkening coeff. | 0.551$^{+0.029}_{-0.028}$        |
| $u_4$           | Quadr. limb-darkening coeff. | 0.220$^{+0.020}_{-0.021}$        |

† parameter makes use of priors, see Sec. 3.2 for details.

(4.5–7° compared to [Chan et al. 2011], further adding to the confirmation of an anomalously large radius for this planet.)

3.3 M-dwarf stellar companions

The M-dwarf companion is well resolved in both the STIS acquisition images (see Fig. 5) and in the STIS spectra. This provides an opportunity to further characterise the properties of the M-dwarf, and its impact on the WASP-12 system. Crossfield et al. (2012a) found that the M-dwarf was consistent with a spectral type of M0V, with an effective temperature of $T_{\text{eff}}=3660$ K using near-IR spectroscopy. In addition, they found that the system may possibly be associated with WASP-12A if the M-dwarf was found to be a close binary pair, but with only low resolution images at the time, they could not firmly conclude its association. However they did note that the ground-based images had an extended PSF profile and that the two objects had a common system radial velocity, pointing toward a binary M-dwarf pair.

In order to align the HST PSF within the STIS longslit, an optical broadband acquisition image was initially taken with the F28x50LP filter, which has a wavelength range between 5490 to 9990 Å and a central wavelength of 7150 Å. With HST’s high resolution, these images immediately reveal the M-dwarf to be a binary pair (see Fig. 5), confirming the suspicions of Crossfield et al. (2012a) and Bergfors et al. (2013). Further, the two components of the M-dwarf binary are observed to have equal brightness, implying equal mass, with a flux contrast between the two estimated from the central pixel intensities to be 1.08$^{±0.07}$ from the acquisition image. The near unity flux contrast between the two stars also match the recent ground-based adaptive optics imaging results of Bechter et al. (2013).

Being spatially well resolved from WASP-12A in STIS spectral images, we also extracted the optical spectrum of the M-dwarf companions (see Fig. 6). The STIS G750L spectrum of the M-dwarf pair matches very well with the $T_{\text{eff}}=3660$ K measurement of Crossfield et al. (2012a), lending further evidence of the two stars possessing the same spectral classification, with the spectral typing of the combined pair consistent between the two studies from the optical to K-band.

Compared to WASP-12A, the flux contrast between the two M-dwarf stars and the WASP-12A primary is 0.0207$^{±0.0004}$ in the HST image, which is close to the $\Delta V$ measurement of Bergfors et al. (2013). Assuming an equal-mass M-dwarf binary, the distance modulus from Crossfield et al. (2012a) is re-evaluated to be 7.85$^{±0.2}$ mag for the M-dwarfs which compares to 7.7$^{±0.2}$ mag for WASP-12A, placing the three stars at the same distance (within the errors), making a triple-star configuration highly likely. At a distance of 427 pc (Chan et al. 2011), the projected separation between WASP-12A and the M-dwarfs is 450 AU, and the M-dwarf binary projected separation is about 40 AU. A final proof of association would be a common proper motion measurement between the three stars (see Bechter et al. 2013).
3.4 Transmission spectrum fits

We extracted various wavelength bins\(^2\) for the STIS G430L, G750L, and WFC3 G141 spectra, to create a broadband transmission spectrum and search for expected narrowband features (see Figs. 7, 8, and 9). In these transit fits, we fixed the transit ephemeris to the results from Sec. 3.1 and fixed the inclination and stellar density to their best-fitting values, allowing \( R_p/R_\star \) to be free as well as the baseline flux and model parameters describing the instrument systematic trends. The WFC3 spectra were M-dwarf flux corrected in the same manner as the white-light curve (see Sec. 3.0.2), with the uncertainty from the correction well under each of our \( 1\sigma \) errors for \( R_p/R_\star \).

The limb-darkening parameters were fixed to the model values, with the four non-linear coefficients for each bin individually calculated from the stellar model, taking into account the instrument response (see Table 3). As a separate direct test of the limb-darkening model used, we fit a light curve with a free limb darkening coefficient in a spectral bin between 4000 to 4500 Å using a linear law, and compared the fit coefficient \( u \) to the stellar model prediction. At these wavelengths, the predicted limb darkening is approximately linear (with a linear law deviating from ATLAS stellar model intensities by no more than 3.2%, except at the very limb), making a direct comparison of the stellar model and transit-fit limb-darkening coefficients straightforward.\(^3\)

The fitted linear coefficient is very close to the stellar model value, with a simultaneous fit of the two G430L transits resulting in \( u = 0.772 \pm 0.023 \) which compares favourably to the ATLAS model prediction of 0.774. Further, we note that our transmission spectrum did not substantially change when fitting the light curves using a linear limb-darkening law with a freely fit coefficient, and the BIC favoured fixing the limb-darkening parameters to the model values.

We handled the modelling of systematic errors in the spectral bins by two methods. In the first method, we allowed each light curve to be fit independently with a parameterised model, as done in the white-light curve analysis. In the second method, we removed the common-mode trends from each spectral bin before fitting for the residual trends, again with a parameterised model but fit with fewer parameters. The common-mode trends were extracted from the white-light curves, by removing the transits from the raw light curves using the parameters derived from the best-fit models. These common-mode trends were then removed from each spectral bin, normalised to preserve the overall flux levels. In particular, removing the common trends reduces the amplitude of the breathing systematics by a considerable margin, as these trends are observed to be very similar wavelength-to-wavelength across the detector.

As found in Nikolov et al. (2013) for the HAT-P-1b STIS transit data, we find that it makes little difference (i.e. deviations of ~1\( \sigma \) or less on the fitted \( R_p/R_\star \) values) whether to include or not the position related trends when fitting for the transit depths, as compared to optimising the systematic trends for each bin individually based on the BIC. In the fully-parameterised method, we elected to fit the same model as used for the white-light curve (4th order in \( HST \) phase and linear in X-position, Y-position, time, and wavelength shift) as a some of the bins did prefer the model, and a uniform model for all wavelength channels helps ensure that residual instrument trends are not differing channel-

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\(^2\) available upon request

\(^3\) Comparing multiple fit limb-darkening coefficients to the stellar models using higher order laws is difficult, as there are degeneracies between the fitted coefficients.

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Table 3. Non-linear limb darkening coefficients calculated for the G430L (top), G750L (middle) and WFC3 G141 (bottom).

<table>
<thead>
<tr>
<th>( \lambda (\text{Å}) )</th>
<th>( c_1 )</th>
<th>( c_2 )</th>
<th>( c_3 )</th>
<th>( c_4 )</th>
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<tr>
<td>2900 - 3800</td>
<td>0.2075</td>
<td>-1.0926</td>
<td>-0.4758</td>
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<td>3800 - 4300</td>
<td>0.2262</td>
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<td>4300 - 4800</td>
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<tr>
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<tr>
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<td>0.0828</td>
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<tr>
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<tr>
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<td>0.6433</td>
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</tr>
<tr>
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<tr>
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<td>0.6756</td>
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<td>-0.4738</td>
<td>0.2539</td>
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</tbody>
</table>

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Evidence for aerosols in the atmosphere of WASP-12b

Figure 7. HST STIS G430L spectral bin transit light curves jointly fit for visit 1 (top) and visit 2 (bottom). (Left) Light curves for the HST STIS G430L spectral bins with the common-mode trends removed, overplotted with the best fitting systematics model. The points have been offset in relative flux, and systematics model plotted with connecting lines for clarity purposes. The light curves are ordered in wavelength, with the shortest wavelength bin shown at the top and longest wavelength bin at the bottom. (Middle) Light curves fully corrected for systematic errors, with the best-fit joint transit model overplotted. (Right) Residuals plotted with 1-σ error bars along with the standard deviation (dotted lines).

Figure 8. The same as Fig. 7, but for the G750L spectral bins.
to-channel, adversely effecting the transit depths. With this method, we reach average precisions of 73% the photon noise limit with the G430L, and 87% for the G750L, with no significant red-noise detected.

In the common-mode analysis, the spectral bins for the two G430L transits were each fit with 3 fewer parameters compared to the fully-parameterised method, as the 3rd and 4th order HST phase trends as well as the linear slope did not justify being fit. Similarly, for the G750L spectral bins, the 4 orders of the HST phase trend polynomial and wavelength shift trend did not need to be fit, reducing the number of nuisance parameters for each light curve from 8 to 3. In addition, the common-mode analysis typically performed comparable or better than the full-parameterised model, with the G430L attaining an average precisions of 80% the photon noise limit, and the G750L attaining 85% the photon noise limit. The biggest improvement is seen where the grating efficiencies are low, as the spectral bins with lower counts are more dominated by photon noise, making it harder for a parameterised model to accurately fit for low-level systematic trends.

As done with STIS, we also fit the WFC3 spectral bins using a fully parameterised model and a common-mode removal analysis. As with the STIS data, the common-mode trends derived from the WFC3 white light curve dramatically reduced the apparent trends in the spectral bins. We report bin sizes which are comparable to the STIS data, 560Å wide, which is courser resolution than reported in Swain et al. (2012b) which is more than 2σ away than our results. With the common-mode analysis, we also find that binning the spectra to wider bandpasses does not significantly degrade the performance relative to the photon limit, as found by Swain et al. (2013) who adopted a linear phase trend polynomial and wavelength shift trend did not need to be fit, reducing the number of nuisance parameters for each light curve from 8 to 3. In addition, the common-mode analysis typically performed comparable or better than the full-parameterised model, with the G430L attaining an average precisions of 80% the photon noise limit, and the G750L attaining 85% the photon noise limit. The biggest improvement is seen where the grating efficiencies are low, as the spectral bins with lower counts are more dominated by photon noise, making it harder for a parameterised model to accurately fit for low-level systematic trends.

For the common-mode analysis, the number of nuisance parameters was reduced from 5 to 2, with a quadratic function of HST phase used to fit the residual trends. With the fully-parameterised method, the precisions attained are close to those of Swain et al. (2013) who reported typical precisions better than our results. The common-mode analysis performed better, with an improvement of about 4% in the residual scatter of the binned light curves with the common-mode method. For both reduction methods, when binning the data similarly as the two aforementioned studies, we find nearly identical transmission spectral results. The one notable exception is the shortest wavelength channel of Swain et al. (2012a) which is more than 2σ higher than our results. With the common-mode analysis, we also find that binning the spectra to wider bandpasses does not significantly degrade the performance relative to the photon limit, as found by Swain et al. (2013) who adopted a linear analysis.

Given the overall better performance with significantly fewer nuisance parameters, we adopt the common-mode analysis for further study, though note that all of the subsequent results would be nearly identical if instead we adopted the fully-parameterised analysis for both the STIS and WFC3 spectra. The broadband spectral results are given in Table 4 and shown in Fig. 10, where we have included the Spitzer transit photometry of Cowan et al. (2012a) as re-evaluated with the M-dwarf dilution correction by Crossfield et al. (2021a). We have chosen the non-prolate value for the 4.5 µm transit depth measurement of Cowan et al. (2012a), which is consistent with the WFC3 eclipse photometry of Swain et al. (2013).

4 DISCUSSION

4.1 Searching for narrowband spectral features

In addition to deriving the broadband spectrum, we searched the STIS data for narrowband absorption signatures, including the expected species of Na, K, Hα, and Hβ, as the line cores of these elements can have strong signatures. In the context of the HST survey, Na has been detected in Hat-P-1b by Nikolov et al. (2013), who found the strongest signal in a 30Å bandpass around the Na doublet.
We find no evidence for Na, either in wide or medium size bandpasses. In a 30 Å wide medium bandpass, we measure a planet-to-star radius difference of $\Delta R_p/R_* = (-0.3 \pm 2.0) \times 10^{-3}$ compared to a 600 Å wide reference region encompassing the Na doublet. Theoretical models which are assumed to be dominated by Na absorption in this region predict features of $4.0 \times 10^{-3}$, so the data can rule out significant Na absorption with about 95% confidence. Any Na feature present in WASP-12b must be confined to a narrow core, similar to HD 189733b or XO-2b (Huitson et al. 2012; Sing et al. 2012).

Similar to Na, we also find no evidence for H$_\alpha$, H$_\beta$, nor K. A 75 Å wide bandpass centred on the K doublet gives a radius difference of $\Delta R_p/R_* = (-2.6 \pm 1.9) \times 10^{-3}$.

4.2 A thorough search for TiO

As one of the most highly irradiated hot Jupiters discovered to date with a zero-albedo equilibrium temperature of $T_{eq}=2580$ K, WASP-12b is a prime target to search for signatures of TiO. TiO has strong opacity throughout the optical, with one of the strongest signatures being a ‘blue edge’ at the short-wavelength end ($\sim 4300$ Å) of the molecule’s optical bandheads, making the STIS G430L an ideal instrument to detect the species. Without the optical-blue wavelength of STIS, ruling out TiO in the atmosphere is not so straightforward. For one, the required optical-blue precisions are difficult to obtain from the ground (Copperwheat et al. 2013). In addition, the overall higher planetary radius levels as seen in the optical-red compared to the near-IR can be reasonably well matched by models which include TiO, especially if the model abundances and temperature profiles are fit (Stevenson et al. 2013).

Our broadband transmission spectrum shows no signs of TiO. In particular, while models expect the radius to drop by $2.4 \times 10^{-3}$ $R_p/R_*$ blueward of 4300 Å, our measured radii instead increase by an average of $(0.9 \pm 0.5) \times 10^{-3}$ $R_p/R_*$ compared to the 4300-4800 Å bin, representing a 6.8σ confident non-detection of TiO at the ‘blue-edge’. Radiative transfer models assuming equilibrium chemistry and solar compositions have strong TiO features, and offer overall unsatisfactory fits to the broadband data, with a [Fortney et al. (2010)] model giving a $\chi^2$ of 44 for 23 DOF (see Fig. 11).

As our broadband spectrum is not optimally configured to detect individual TiO bandheads, we employed custom tailored bins following the TiO ‘comb’ approach of Huitson et al. (2013) which sub-divides the region between 4840 and 7046 Å into two optimal bandpasses. An ‘in’ bandpass specifically covers wavelengths of 8 strong TiO bandheads, while an ‘out’ bandpass covers the wavelength regions between the bandheads. A positive TiO detection would show up as an increased radius in the ‘in’ bandpass compared to the ‘out’, and a positive $[\text{TiO}]_{comb}$ value. In this manner, we are able to use a very large portion of the STIS data to search for specific TiO features, providing good sensitivity. This search also rules out TiO, with the G430L and G750L giving an average $[\text{TiO}]_{comb}$ radius difference of $\Delta R_p/R_* = (-0.51 \pm 0.42) \times 10^{-3}$ while WASP-12b models with TiO predict a difference of $+0.82 \times 10^{-3}$ $R_p/R_*$, representing a 3.2σ confident non-detection of molecular bandheads.

As done in Huitson et al. (2013), we also searched for the
significant difference in altitude was found with a $\Delta$ of TiO drops significantly toward longer wavelengths. No distinct ‘red edge’ at 7396 Å, where the broadband opacity averaged model points are indicated with open circles.

compared to atmospheric models containing TiO from (red) Burrows et al. (2010) and (blue) Fortney et al. (2010). The band-averaged model points are indicated with open circles.

distinct ‘red edge’ at 7396 Å, where the broadband opacity of TiO drops significantly toward longer wavelengths. No significant difference in altitude was found with a $\Delta$ of TiO, measured to be $\text{[TiO]}_{\text{red}} = (-0.87 \pm 0.71) \times 10^{-3}$ between an ‘in’ band from 6616-7396 Å and an ‘out’ band between 7396 and 8175 Å, while models predict a difference of $+1.4 \times 10^{-3} R_p/R_\ast$, a 3.2$\sigma$ confident non-detection of the ‘red edge’.

With three independent tests to search for the molecule giving sensitive null results, significant TiO absorption is decisively ruled out at high confidence as there are no spectral signs of the characteristic ‘blue-edge’, ‘red-edge’, nor its strongest optical bandheads. Similar to Na or K, any TiO absorption features in the transmission spectrum of WASP-12b must be confined to narrowband signatures of the molecule’s strongest optical transitions.

4.3 A search for metal hydrides

Metal hydrides, including TiH and CrH, have been suggested and explored as possible opacity sources in WASP-12b when modelling the red-optical and near-IR data (Swain et al. 2013; Stevenson et al. 2013), with TiH a potentially important Ti-bearing molecule in high C/O ratio atmospheres (Madhusudhan 2012; Stevenson et al. 2013). A complete optical spectrum in this regard helps constrain the presence of metal hydrides. In particular, as TiH has its strongest bandhead near 5300 Å (Sharp & Burrows 2007), the G430L is very sensitive to its presence.

We find no evidence for TiH, with narrower bandpasses around 5300 Å all consistent with the broadband level near 0.1207 $R_p/R_\ast$. The lack of the strong 5300 Å TiH bandhead constrains the presence other longer-wavelength bandhead features of TiH to be at or below the observed optical and near-IR radius. Thus, we conclude TiH can not be a major broadband opacity source for the transmission spectra. The same is true for MgH, which also has its strongest peak in the optical-blue (Sharp & Burrows 2007), which we also do not observe.

Significant opacity by CrH can also be excluded, as abundances needed to match the WFC3 near-IR $R_p/R_\ast$ levels would produce strong features between 8000 and 10,000 Å which would rise to $\sim0.122 R_p/R_\ast$, where the opacity of CrH is strongest (Sharp & Burrows 2007), though no such features are apparent.

In addition to these molecule-specific searches, we also explored a range of different atmospheric models with varying opacity (0.1 to 10 solar) as calculated in Burrows et al. (2010). These models contained significant metal hydride features (including MgH, FeH, and CaH), though none were satisfactory fits to the broadband data (see Table 5).

4.4 Limits on molecular absorption

Despite different reduction techniques and instrument systematic models, the shape of our near-IR transmission spectra agrees very well with other studies (Swain et al. 2013; Stevenson et al. 2013). The data is of sufficient quality to have detected H$_2$O, if it were present at the levels some models predict, with the WFC3 atmospheric H$_2$O detections in WASP-19b and HAT-P-1b a direct example (Huitson et al. 2013; Wakeford et al. 2013). In agreement with the findings of Swain et al. (2013), we find no strong evidence for H$_2$O absorption, though there is a small ‘bump’ at 1.4 μm which is compatible with a small amplitude H$_2$O feature. A straight-line (with 2 free parameters fit in $R_p(\lambda)/R_\ast$ vs. ln(λ)) remains a good fit to the WFC3 data ($\chi^2 = 9$ for 8 DOF).

A small amplitude H$_2$O feature would imply that either the scale height is smaller than expected (requiring lower temperatures), the H$_2$O abundance is low, or that the feature is being covered by other absorbers (including hazes or clouds, also see section 4.5.4), as has been suggested for HD209458b (Deming et al. 2013). We find that the WASP-12b WFC3 transmission spectrum is compatible with H$_2$O-only absorption if the temperature is below 1600 K at 95% confidence. This temperature presents a problem when interpreting the overall broadband spectrum, as smaller scale heights from lower temperatures would lead to a flatter overall spectrum, yet significant broadband radii differences are observed. In addition, as pointed out by Stevenson et al. (2013), the Spitzer data is compatible with smaller radii, even though models with significant H$_2$O (and CO) absorption predict larger radii at those longer wavelengths.

Potentially, HCN could be an important molecule in the atmosphere, especially if WASP-12b were to have a high C/O ratio (Moses et al. 2013; Bilger et al. 2013). However, the cross section of HCN is considerably weaker in the optical and near-IR compared to Spitzer wavelengths (e.g. see Shabram et al. 2011), which places constraints in our broadband spectrum. As found by Stevenson et al. (2013), the near-IR and Spitzer $R_p/R_\ast$ radius levels long-wards of 1.55μm can reasonably reproduced assuming HCN dominates that region, but with a sharp drop in the opacity shortward of 1.55μm, our optical data and the near-IR WFC3 up to that wavelength would need an additional opacity source to explain the larger radius levels. While Stevenson et al. (2013) attributes the higher optical levels in part to TiO or TiH, both molecules are inconsistent with our blue-optical data. With current data, a re-analysis of the secondary eclipse data, taking into account the M0V dilution effects, would likely place stronger overall constraints on the presence of HCN than our transmission spectra.

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Evidence for aerosols in the atmosphere of WASP-12b

4.5 Interpreting the broadband transmission spectrum with aerosols

While most of the expected molecular and atomic features can be confidently ruled out (e.g. TiO, Na, & K) as major contributors to our broadband transmission spectrum, the overall slope of the spectrum shows a significant broadband atmospheric feature, with an overall characteristic slope which spans 0.0031\(R_p/R_\star\) from the optical to the infrared (see Fig. 10). The atmospheric pressure scale height is given by \(H = \frac{R_T}{kT}\), where \(k\) is Boltzmann’s constant, \(T\) is the local gas temperature, \(\mu\) is the mean molecular weight of the atmosphere, and \(g\) is the surface gravity. For WASP-12b, the scale height is estimated to be 700 km at 2100 K, implying that our broadband transmission spectrum spans ~5\(H\) in altitude (3500 km).

Following Lecavelier des Etangs et al. (2008a), we fit the broadband transmission spectrum assuming an atmospheric opacity source(s) with an effective extinction (scattering+absorption) cross section which follows a power law of index \(\alpha\), i.e. \(\sigma = \sigma(\lambda/\lambda_0)^\alpha\). With this assumption, the slope of the transmission spectrum is then proportional to the product \(\alpha T\) given by,

\[
\alpha T = \frac{\mu g}{k} \frac{d(R_p/R_\star)}{d\ln \lambda}.
\]

With these assumptions, we find a good fit to the 24 data points fitting for \(\alpha T\) and the baseline radius, \((\chi^2 = 16.8\) for 22 DOF, \(N_free = 2\)) resulting in \(\alpha T = -352\pm660\) K.

Assuming a temperature mid-way between the dayside and night-side temperatures of 3000 K and 1100 K respectively and allowing a temperature range which encompasses a \(T_{eq}\) of 2578 K, gives a temperature in the range of 2100±500 K. With these adopted temperatures, the slope of the transmission spectrum would imply an effective extinction cross section of \(\sigma = \sigma(\lambda/\lambda_0)^{-1.7\pm0.5}\).

4.5.1 Rayleigh scattering

Assuming that the atmosphere can be described by Rayleigh scattering (\(\alpha = -4\)), as would be the case in a pure H\(_2\) atmosphere or one for an atmosphere dominated by a highly scattering aerosol as observed in HD 189733b (Pont et al. 2008; Lecavelier des Etangs et al. 2008a; Sing et al. 2011), the slope would imply temperatures of 882±165 K. In the H\(_2\) case, the fit gives a reference pressure of 550±470 millibar at \(R_p/R_\star = 0.1195\). This reference pressure is an upper limit representing a clear atmosphere, with any other assumed opacity source for the broadband spectra necessarily residing at lower pressures. With the Rayleigh scattering assumption, the low fitted temperatures serve to reduce the scale height, and decrease the modelled transmission spectral slope to match the data. While this temperature is consistent with the night-side brightness temperature found by Cowan et al. (2012), it is perhaps too low to be representative of the limb, which likely has intermediate temperatures between those of the night and day-side. Such moderate limb temperatures are supported by 3D models, with Fortney et al. (2010) finding that planet-wide average \(T-P\) profiles are a good approximation to the true limb profiles output from 3D simulations.

4.5.2 Mie scattering dust

While Rayleigh scattering can not be excluded, especially if the high-altitude temperatures at the exoplanetary limb are much colder than anticipated, good fits to the data are also possible assuming significant opacity from aerosols. In particular, materials with significant absorptive properties (i.e. a non-negligible complex component to the index of refraction) can fit the observed slope assuming Mie theory. In general, such aerosols can be produced from condensate dust species, or alternatively from photochemistry. For the

\[^4\] The day and night temperatures, \(T_{day}\) and \(T_{night}\), are calculated using the bond albedo and recirculation efficiency from Cowan et al. (2012), the definitions from Cowan et al. (2011), and the parameters in Table 2.
hot day-side temperatures measured for WASP-12b, high
temperature dust condensates such as corundum (Al$_2$O$_3$),
iron oxide (Fe$_2$O$_3$), or perovskite (CaTiO$_3$) are candidate
materials.

We tested various atmospheric models assuming aerosol
dust was the dominant spectral feature at all observed wave-
lengths. We compiled the optical properties of Al$_2$O$_3$ (Koike et al. 1995), Fe$_2$O$_3$ (Triaud, A.), and CaTiO$_3$ (J. W. Ferguson, private communication). Using Mie theory, we
calculated the extinction cross sections as a function of wave-
length for a large range of particle sizes, $a$, then used the
analytical formula of Lecavelier des Etangs et al. (2008a) to
calculate the wavelength-dependant transmission spectrum.
As the cross section is dominated by the largest grain size in
a distribution with $\sigma \propto a^6$ (Lecavelier des Etangs et al. 2008a), the transmission spectrum can be reasonably fit to
first order simply assuming a single grain size.

In fitting Mie scattering dust models against the trans-
mittance spectrum, we found a degeneracy between the grain
size and atmospheric temperatures, which is expected fol-
lowing equation 2, as $a$ is related to $\alpha$ through the cross-
section, and both $\alpha$ and $T$ have an influence on the result-
ning slope. In particular for models assuming Fe$_2$O$_3$, when $a$, $T$, and the baseline altitude were all set to freely fit the
data, the resulting fits favoured sub-micron particle sizes
with low temperatures near 1000 K required, resulting in fits quite similar to the Rayleigh solution. In addition, very
small MgSiO$_3$ and CaTiO$_3$ particles have scattering prop-
ties within the Rayleigh regime, and thus also give good
fits near 1000 K equivalent to those given in section 4.5.1.
A similar fit for Al$_2$O$_3$ ($\chi^2$ of 16.7 for 21 DOF) resulted in
somewhat warmer temperatures of 1400±400 K.

To explore the validity of high temperature condenses at
the expected temperature regime, we also fit Mie scattering
models fixing the $T$ to a value of 2100 K and fitting for $a$ and
the baseline radius. 2100 K temperatures are not only plausible
for the limb of WASP-12b, but are also near the conden-
sation temperatures for the dust species in question. Fe$_2$O$_3$
results in a somewhat less satisfactory fit ($\chi^2$ of 24.8 re-
spectively for 22 DOF) as it contains optical features which
are not apparent in our data which become pronounced at
warmer temperatures (see Fig. 13). As CaTiO$_3$ is highly
scattering throughout the optical, it requires particle sizes
near 0.18$\mu$m ($\chi^2$ of 24.0 respectively for 22 DOF), which
produces a fit similar in quality as Fe$_2$O$_3$. For the dust species

\begin{figure}
\centering
\includegraphics[width=\textwidth]{Figure_13}
\caption{Plotted is the broadband transmission spectral data compared to 6 different aerosol models listed in Table 4 including: Rayleigh scattering (purple), Mie scattering Al$_2$O$_3$ (orange), Settling dust $\beta = -3$ (brown dashed), Mie scattering Fe$_2$O$_3$ (red), Mie Scattering CaTiO$_3$ (gray), Settling Dust $\beta = -0$ (light brown dot-dashed), a partly cloudy model with enhanced Rayleigh scattering Fortney-noTiOEnhancedRayleigh (blue), and Titan tholin (green).}
\end{figure}
tested, Al₂O₃ was the best fit against the transmission spectrum ($\chi^2$ of 16.8 for 22 DOF). As Al₂O₃ does not have strong scattering or absorption features over our wavelength range, with the a-T degeneracy, for sizes below $\sim0.1\mu m$ equally good fits can be found at low, moderate, and high temperatures (e.g. 1000, 2100, 3000 K). For Al₂O₃, grain abundances and corresponding atmospheric pressures for the transmission spectrum are estimated using solar abundances and assuming the condensate is limited by the available number of aluminium atoms. We find corresponding pressures of 0.02 and 0.5 millibar at $R_\ell/R_*$ = 0.1195 if the particle sizes are 0.3 and 0.03 µm respectively. For all assumed temperatures greater than 1450 K, Al₂O₃ remains our best fitting model.

4.5.3 Settling dust

Pont et al. (2013) explored the case where the atmospheric opacity is dominated by Rayleigh scattering from grains of condensates, with the density and maximum size of the grains varying with pressure (settling grains). In this case, the slope of the transmission spectrum, in units of altitude $\beta$ per ln$\lambda$, was found to be $-\frac{1}{2}H$ in the case of a flat distribution of grain sizes ($\beta = 0$), and $-1H$ in the case of an equal partition of mass across all grain sizes ($\beta = -3$), where $\beta$ is a power law index relating the abundance at height $z$ in the atmosphere to the particle size. With a scale height assuming a 2100 K temperature, the $\beta = 0$ case can be excluded from the data as it results in a shallower slope than observed ($\chi^2$ of 29.3 for 22 DOF), though the $\beta = -3$ case results in a better fit ($\chi^2$ of 21.5 for 22 DOF). Allowing the temperature to freely fit can also reproduce a fit equally well as Rayleigh scattering (as it has the effect of increasing the slope), but requires temperatures of 3528 K in even the $\beta = -3$ case.

4.5.4 Partly cloudy

Finally, we explored fitting the data to a suite of Fortney et al. (2010) models which had either an artificially added Rayleigh scattering component simulating a scattering haze, or a ‘cloud deck’ simulated by a grey flat line at different altitudes. These models serve to test the hypotheses that clouds or hazes help cover some, but not all, of the atomic and molecular atmospheric features expected. A 2100 K model lacking TiO with a Rayleigh scattering component with a cross section 100 times larger than that of H₂, resulted in a fit with $\chi^2$ of 31.6 for 22 DOF.

4.5.5 Tholin haze

We tested Mie scattering models assuming that a hydrocarbon haze was the dominant spectral feature, an important feature in solar system planets and a possibility for giant exoplanet atmospheres (Sudarsky et al. 2003). Tholins have a characteristic red colour, as they preferentially absorb at shorter visible wavelengths. We tested the optical properties of a Titan tholin haze from Khare et al. (1984) measured in a N₂ atmosphere, as well as a H₂-atmosphere tholin haze from Khare et al. (1987), whose optical properties are only available between 0.4 to 1 µm and has weaker overall absorptivity. Both tholins absorb strongly in the blue, with similar Mie scattering extinction cross sections which are close to $\sigma = \sigma(\lambda/\lambda_0)^{-4}$ between 0.3 and 2 µm for particles < 0.1µm (also see Howe & Burrows 2012). Similar to the Fe₂O₃ fit, the Titan and H₂ tholin scattering fits with $\alpha$, $T_\ell$, and the baseline radius free were similar to the Rayleigh solution, as the lower ~1000 K temperatures served to mute the tholin’s strong blue absorption through a decreased scale height. Fixing the temperature to 2100 K, the tholins provided satisfactory fits the transmission spectral data (see Table 5 with particle sizes near 0.25µm, which is large enough such that cross section becomes fairly flat over most of the optical and only decreases redward of 1µm (see green model in Fig. 13). We note that Jupiter has similarly sized aerosols in its stratosphere at low latitudes (Zhang et al. 2013). At 2100 K, particle sizes smaller than 0.19µm are ruled out in WASP-12b, as the predicted slope becomes much too steep to fit the data.

4.6 The case for aerosols in WASP-12b’s atmosphere

As indicated in Table 5 our best fitting models are ones which include significant opacity from a Rayleigh or Mie scattering source. Most of the expected aerosol-free models are ruled out at high significance, limiting molecular absorption to a minor role in our broadband transmission spectrum. Potentially, Rayleigh scattering could be produced by gaseous H₂, a possibility explored by Lecavelier des Etangs et al. (2008b) for HD 209458b and Swain et al. (2013) when modelling the WASP-12b WFC3 emission and transmission spectra, though there are several problems with this potential interpretation. For one, a true planetary atmosphere is unlikely to be devoid of all atomic and molecular species, and there is evidence for substantial opacity from metals in the near-UV (Fossati et al. 2010). Furthermore, a pure H₂ atmosphere would have a very high albedo, which is ruled out by the Spitzer observations (Cowan et al. 2012). Sub-micron silicate condensates could also be a source of Rayleigh scat-
terign, as observed for the haze in HD 189733b (Pont et al. 2013). However, the main problem with $H_2$ Rayleigh slope interpretations on WASP-12b are the low implied temperatures (882±165 K) which may not be feasible on this very hot planet, measured to have brightness temperatures near 3000 K. In contrast, the terminator temperatures implied by the Rayleigh scattering slope for HD 189733b are perfectly consistent with day-side and phase curve measurements (Lecavelier des Étangs et al. 2008a; Knutson et al. 2012).

It is possible the condensate scale height is smaller than that of the surrounding gas, which would flatten the resulting transmission spectra and could explain a low measured temperature for aerosols in the Rayleigh scattering regime. Solar system observations and brown dwarf models indicate condensate scale heights which are $\sim$1/3 that of the local gas scale height (Carlson et al. 1994; Marley et al. 2002), a possibility for hot-Jupiter atmospheres as well (Fortney 2005). For WASP-12b, a Rayleigh scattering condensate with a scale height $1/3H$ would imply temperatures $3\times$ higher than found otherwise, or 2646±165 K which is much closer to the expected terminator temperatures. However, we note that the Rayleigh scattering signature on HD 189733b is fully consistent with a condensate scale height which is the same as the gas scale height (Lecavelier des Étangs et al. 2008a).

Our best fit Mie scattering aerosol models are indistinguishable in quality to Rayleigh models, providing an excellent overall fit (see Table 5). Unlike the Rayleigh model, hotter temperature Mie scattering models can fit the data equally well, which is likely necessary for WASP-12b (see Fig. 14). Even with near-UV to IR wavelength coverage, the particle size-temperature degeneracy makes it difficult to confidently constrain the composition, since other aerosol materials with similar optical properties to corundum would also provide equally good fits. Despite the strong degeneracy, we do find the particle sizes for all models are generally sub-micron in size regardless of temperature.

In principle, an aerosol could be the result of condensation chemistry, or alternatively the aerosol may be photochemical in nature (Marley et al. 2013). If the aerosol observed arises from condensation chemistry, WASP-12b would have similarities with late M-dwarfs and brown dwarfs, both of which are thought to have significant dust in their photospheres (Jones & Tsuji 1997; Lodders & Fegley 2006; Helling et al. 2008; Marley et al. 2013).

Hydrocarbons in hot Jupiters models have been explored in several studies including Liang et al. (2004), Zahnle et al. (2009) and Moses et al. (2011). These studies find that polycyclic aromatic hydrocarbon formation generally occurs at high altitudes on the ‘cooler’ hot-Jupiters, which could ultimately lead to the formation of a ‘soot’ aerosol layer (Zahnle et al. 2009). Such a soot layer would be difficult to produce in current models for WASP-12b, without invoking significant transport from the cooler night side or pole regions. In a model of HD 209458b, Liang et al. (2004) found that $C_3H_5$ compounds were lost either primarily by reactions with atomic hydrogen or by photolysis, and such processes would likely be more efficient in the higher irradiated conditions of WASP-12b. However, as discussed in Moses et al. (2011), the chemical models currently invoked assume neutral chemistry, which is not particularly conducive for soot formation, even under ‘cooler’ HD 189733b conditions, and it is possible that ion chemistry plays a role in the formation of complex species, an area which deserves further study.

There are other indications of significant aerosols, namely from secondary eclipse and phase curve observations. The emission spectrum of WASP-12b resembles a black body...
from the optical to the IR (Crossfield et al. 2012a). Such a black body spectrum could be produced from an isothermal atmosphere, but could also be explained by clouds. For non-isothermal atmospheres, more consistent with radiative equilibrium, an observed black body emission spectrum could naturally occur as a result of a cloud deck. The atmosphere could be optically thin at all wavelengths at low pressure above the cloud deck, but then at the pressure level of the cloud, the atmosphere may suddenly become optically thick, making the surface emit from the same altitudes and temperatures at all wavelengths.

The Spitzer phase curve measurements from Cowan et al. (2012) also indicate a low heat recirculation efficiency and a modest Bond albedo, estimated to be $A_B=0.25_{-0.10}^{+0.18}$. As many hot Jupiters have very low albedos (Cowan & Agol 2011), the modest albedo of WASP-12b prompted Cowan et al. (2012) to mention Rayleigh scattering and/or reflective clouds as a possibility. Though the errors on albedo are currently large, if confirmed an aerosol species like corundum could naturally produce such a modest albedo, as its optical properties make the material not overly scattering (like MgSiO$_3$ or CaTiO$_3$) nor highly absorptive (like Fe$_2$O$_3$). Optical secondary eclipse measurements could play an important role in determining the overall pervasiveness of the aerosols, with a direct measurement of the wavelength-dependant albedo a further important constraint on the composition (e.g. see Evans et al. 2013 for the case of HD189733b). For instance, a blue and red optical albedo measurement could help differentiate between a strong Rayleigh scattering dust and tholins, which are preferentially red.

Aerosol species could also be useful in interpreting the observed low recirculation efficiency. As pointed out by Heng et al. (2012) and Pont et al. (2013), the first-order effect of clouds in hot Jupiters is to move the contribution functions and effective photosphere at all wavelengths to higher altitudes and lower pressures. At lower pressures, the timescale of heat loss from the atmosphere will decrease, thereby also decreasing the efficiency of the observed day-to-night heat redistribution.

4.7 The lack of TiO in very hot Jupiters

To date, there has been no substantial evidence for TiO present in the atmosphere for any hot Jupiter, except for the possible bump in the absorption spectrum of HD 209458b between 6200A and ~7000 A (Désert et al. 2008). HST transmission spectra now shows that TiO is absent in the atmospheres of the very hot Jupiters WASP-12b and WASP-19b (Huitson et al. 2013). Both planets also lack strong thermal inversions (Crossfield et al. 2012a; Anderson et al. 2013), which further indicates TiO is not present in either planet at the necessary abundance levels to cause a stratosphere. There are four leading mechanisms to deplete TiO from a hot Jupiter atmosphere: a vertical-cold trap, a day/night cold trap, the effects of stellar activity and high C/O ratios (Spiegel et al. 2009; Showman et al. 2009; Knutson et al. 2010; Madhusudhan 2012). As WASP-19b orbits an active star, experiences a strong day/night contrast, and can also experience a vertical cold trap, it is not immediately clear what the dominant TiO-depletion mechanism is for that planet, though a detection of H$_2$O in the transmission spectrum of WASP-19b disfavours the high C/O scenario (Huitson et al. 2013).

WASP-12b is an ideal test case in many respects. WASP-12A is inactive (see section 2.3), making the activity unlikely. Further, while most hot Jupiters can experience a vertical cold-trap, which would deplete TiO at depth, WASP-12b is hot enough such that it should not experience a cold-trap anywhere throughout its dayside atmosphere (Spiegel et al. 2009). Finally, sensitive non-detections of both TiO and TiH points towards a general lack of Ti-bearing molecules in the broadband spectrum, irrespective of the C/O ratio.

Very hot Jupiters, with equilibrium temperatures greater than 2400 K, are observed to have low circulation efficiencies which leads to very large day/night temperature contrasts (Cowan et al. 2012). The efficiency of redistribution is primarily governed by the ratio of advective to radiative timescales, with hotter planets tend to have shorter radiative timescales and thus larger day/night contrasts (Showman & Guillot 2002; Perna et al. 2012; Cowan et al. 2012; Perez-Becker & Showman 2013). Night-side temperatures cool enough for species such as Ti to be condensed into solids could lead to rain out, which would then drastically deplete the species from the atmosphere. Parmentier et al. (2013) has explored how a strong day/night temperature contrast can lead to depletion of TiO through the use of 3D modelling. In their models, they found that large-scale circulation patterns can produce strong vertical mixing that can keep condensable species lofted, as long as they are trapped in particles of sizes of a few microns or less on the night side. Of note, our transmission spectrum is consistent with sub-micron size particles.

Thus, while it is not entirely clear if the aerosols at the terminator originate from condensation chemistry, in any case, the day/night cold-trap would appear to be the leading explanation for the lack of TiO.

5 CONCLUSION

WASP-12b is now among only a small handful of exoplanets with a full optical to near-IR transmission spectrum measured. With high S/N broadband observations reaching into the near-UV, we are able to decisively rule out prominent absorption by TiO in the exoplanet’s atmosphere. Given WASP-12b’s unique properties, we find that the day/night cold trap is the leading explanation for the lack of the molecule. As other very hot Jupiters also experience similarly strong day/night contrasts, it is likely that few (if any) hot Jupiters will show strong TiO absorption features.

We find a transmission spectrum which lacks any strong broadband molecular or atomic absorption signatures, though it does have a significant slope indicative of scattering by aerosols. This is the first direct indication for the presence of aerosols on a very hot Jupiter. In addition to the transmission spectrum, significant aerosols throughout the entire atmosphere can also help explain the black body nature of the emission spectrum, as well as the modestly bright albedo. An aerosol species on WASP-12b could originate from a high temperature condense analogous to the dusts on brown dwarfs and M-dwarfs, or alternatively the
aerosols could be hydrocarbons which are photochemical in nature.

To date, only the much cooler planet HD 189733b has strong evidence for aerosol species in the atmosphere of a hot Jupiter. The results here for the much hotter planet WASP-12b indicate that the aerosol species can potentially be an important feature for planets across the entire wide range of hot Jupiter planets.

Transmission spectra of exoplanets provides a unique and powerful measurement, with the capability to help identify and constrain high temperature dust species or photochemical products. In this regard, transmission spectra have the potential to also help our understanding of brown dwarfs and M-dwarfs, of which such measurements are not possible. In the future, the mid infrared capabilities of MIRI on JWST could detect the major dust absorption features, which could directly identify aerosol composition.

For the near future, optical albedo measurements can independently help confirm the presence of a reflecting cloud and constrain its composition. In addition, a measure (or model constraints) of the terminator temperature can help constrain the particle composition, and additional thermal phase curve information will be helpful in this regard.

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