The near-UV transit of HD 189733b with the XMM-Newton Optical Monitor

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ABSTRACT
We present analysis of XMM-Newton Optical Monitor observations in the near-ultraviolet of HD 189733, covering twenty primary transits of its hot Jupiter planet. The transit is clearly detected with both the UVW2 and UVM2 filters, and our fits to the data reveal transit depths in agreement with that observed optically. The measured depths correspond to radii of 1.059\(^{+0.046}_{-0.050}\) and 0.94\(^{+0.15}_{-0.17}\)\(\times\) the optically-measured radius (1.187\(R_J\) at 4950 Å) in the UVW2 and UVM2 bandpasses, respectively. We also find no statistically significant variation in the transit depth across the 8 year baseline of the observations. We rule out extended broadband absorption towards or beyond the Roche lobe at the wavelengths investigated, although observations with higher spectral resolution are required to determine if absorption out to those distances from the planet is present in individual near-UV lines.

Key words: planets and satellites: individual: HD 189733b – ultraviolet: planetary systems – planets and satellites: atmospheres

1 INTRODUCTION
One of the key aspects in characterising discovered exoplanets is investigating their atmospheric composition. Transiting planets are particularly good targets for this as the apparent transit depth varies as a function of wavelength. This variation is driven by the bulk elemental composition, molecular, and particulate species present in any atmosphere maintained by the planet. This method of “transmission spectroscopy” has been widely applied to discover numerous species in the atmospheres of hot Jupiters (e.g. Sing et al. 2016). Attempts to explore much smaller super-Earths (e.g. Kreidberg et al. 2014; Edwards et al. 2020) and even Earth-sized planets (e.g. de Wit et al. 2018) are now being made.

The near-ultraviolet (NUV) is an intriguing wavelength range to target for transmission spectroscopy. There are numerous lines of metallic species that may be observable in absorption (Lothringer et al. 2020), including neutral and singly ionised Fe and Mg. Such absorption can arise from materials in an extended or escaping atmosphere (Fossati et al. 2010; Haswell et al. 2012; Sing et al. 2019; Cubillos et al. 2020). As such, NUV transits could provide insight into mass loss from exoplanets, complementing observations at other wavelengths such as Ly \(\alpha\) (e.g. Vidal-Madjar et al. 2003; Lecavelier des Etangs et al. 2012; Ehrenreich et al. 2015). Additionally, optically-measured Rayleigh scattering slopes may extend into the NUV.

The NUV has been largely underexplored. Ground-based measurements can only be made down to about 3000 Å. Furthermore, where observations have been taken, it can be challenging to interpret the results due to the relatively small number of strong, unblended lines, as compared to other wavelengths more commonly used for exoplanet investigations. From space, the Hubble Space Telescope (HST) is capable of observing in the NUV with its COS, STIS, and WFC3/UVIS instruments (Fossati et al. 2010; Haswell et al. 2012; Vidal-Madjar et al. 2013; Sing et al. 2019; Wakeford et al. 2020; Cubillos et al. 2020), though the majority of transmission spectroscopy experiments performed with HST have focused on the optical, near-infrared, and some FUV (e.g. Kreidberg et al. 2014; Ehrenreich et al. 2015; Sing et al. 2016).

In the last few years, both the XMM-Newton Optical Monitor (OM) and Swift Ultraviolet/Optical Telescope (UVOT) have been used to detect planetary transits in the NUV. While both facilities are primarily used to make high-energy observations, the 30 cm diameter OM and UVOT observe simultaneously with the various X-ray and gamma-rays telescopes, and both have a range of broad-band filters in the optical and NUV. King et al. (2018) made the first detection of a NUV transit with the OM, using the UVW1 filter to observe a transit of WASP-80b. While consistent with the optically measured transit depth, there was a hint of it being shallower, a result also suggested by an earlier ground-based U-band observation (Turner et al. 2020).
The detection using UVOT was reported for WASP-121b by Salz et al. (2019), with the measured transit depth deeper at the 2-σ level than in the optical.

Here, we analyse data taken with the XMM-Newton OM across twenty primary transits of the prototypical transiting hot Jupiter HD 189733b, wherein we detect the transit in two different broadband NUV filters.

1.1 The HD 189733 system

The discovery of HD 189733b was reported by Bouchy et al. (2005), and it remains the closest transiting hot Jupiter to Earth, orbiting a relatively active K1 dwarf at a distance of just 19.775±0.013 pc (Gaia Collaboration et al. 2018). This fact has led to HD 189733b being one of the most popular targets for both theoretical studies, and follow-up observations to characterise its atmosphere. We give the parameters of the system adopted in this study in Table 1.

At optical wavelengths, the transmission spectrum of HD 189733b shows a steep-gradient slope (e.g. Pont et al. 2008; Sing et al. 2011; Gibson et al. 2012). Excess absorption has been noted in the Na i doublet (e.g. Redfield et al. 2008; Huitson et al. 2012; Wyttenbach et al. 2015; Louden & Wheatley 2015; Khalafinejad et al. 2017), and there is evidence for a K i absorption feature (Pont et al. 2013; Keles et al. 2019, 2020). In the near-infrared, water (Birkby et al. 2013; McCullough et al. 2014; Brogi et al. 2016, 2018) and CO (de Kok et al. 2013; Rodler et al. 2013; Brogi et al. 2016) have both been detected. The subdued amplitude of both the water and wings of the sodium line features, together with the steep optical slope, point towards the presence of high-altitude aerosols in the atmosphere (Pont et al. 2013; Sing et al. 2016). The planet is also one of an increasing number to have a helium excess measured in the metastable 10830 Å triplet (Salz et al. 2018; Guillory et al. 2020).

HD 189733b’s atmosphere has also been studied at shorter wavelengths, with Ly α transit observations showing that H i is moving beyond the Roche lobe and escaping the atmosphere (Lecavelier des Etangs et al. 2010; Lecavelier des Etangs et al. 2012; Bourrier et al. 2013, 2020). The transit depths at Ly α wavelengths of up to 15 per cent have been observed to be variable (Lecavelier des Etangs et al. 2012). Additionally, Ben-Jaffel & Ballester (2013) measured a 6.4 per cent transit in O i, and there is a time-variable absorption signature in the Si iii line that could arise from a bow-shock formed ahead of the planet in its orbit (Bourrier et al. 2013, 2020). In X-rays Poppenhaeger et al. (2013) presented evidence of the X-ray transit possibly being as deep as 8 per cent. Our analysis of the simultaneously taken X-ray data will be published separately (Wheatley et al., in prep; King et al., in prep). Taken together, these observations show that the XUV heating of HD 189733b has led to its atmosphere being extended, and in at least the case of H i, escaping. As is thought to be the case for almost all hot Jupiters (e.g. Owen & Jackson 2012; Bourrier & Lecavelier des Etangs 2013), the rate of escape of material becoming unbound to the planet is not high enough to significantly change the planet’s structure.

2 OBSERVATIONS & DATA REDUCTION

XMM-Newton has observed HD 189733b on 25 separate occasions from 2007 through 2015, with twenty of these covering a primary transit. In Table 2, we present details of these twenty transit observations (the PI in each case was P. Wheatley).

Our analysis here focuses on the data taken with the Optical Monitor, a 30 cm aperture telescope with a photon-counting instrument at Cassegrain focus, operating in the visual and NUV (Mason et al. 2001). The observations presented in the work exploited the rare ultraviolet capabilities of the OM, using the UBV1, UBV2, and UVM2 filters1. All twenty of these observations were taken in imaging mode, along with a single, small fast mode window to capture the light from HD 189733 at 11 ms resolution.

As per their definition in Table 2, observations 1 and 2 employed the UVM2 (effective wavelength = 2910 Å; width = 830 Å) and UBV1 (2310 Å; 480 Å) filters, respectively, while the other 18 all used the UBV2 (2120 Å; 500 Å) filter. The observation 2 data were rendered unusable by the brightness of the source resulting in excessive coincidence losses that could not be corrected. We do not analyse or discuss this observation any further. The UVM2 filter choice for observation 1 lead to a count rate of 9.4 s⁻¹, and the 18 observations that employed the UBV2 filter had an average count rate of 4.9 s⁻¹.

We reduced the data using the standard software omc1chain and omchain within the Scientific Analysis System, for the image and fast mode data, respectively. Although the fast mode data is captured at 11 ms resolution, in practice, the standard reduction pipeline produces a time-series file at 10 s resolution by default, a setting which we do not alter. Following the running of the chains, we corrected each observation’s photometric data using the procedure as described in King et al. (2018), wherein we correct the fast mode time series using the image mode data.

3 DATA ANALYSIS & RESULTS

3.1 UBV2 observations

The bulk of our analysis efforts focused on the 18 observations taken with the UBV2 filter. We restrict our analysis to the phases where there are data for at least 16 of the 18 observations: 0.9142–1.0508. Visual inspection of the binned, phase-folded light curve, shown in Fig. 1 revealed a clear transit detection at the expected time, according to the optical ephemeris. The light curve however shows structure in the out of transit data. By examining the individual observation

Table 1. Adopted stellar and planetary parameters for HD 189733(b).

| Parameter | Symbol | Value | Unit | Ref. |
|-----------|--------|-------|------|------|
| Stellar mass | $M_*$ | $0.823 \pm 0.029$ | $M_\odot$ | 1 |
| Stellar radius | $R_*$ | $0.780^{+0.017}_{-0.024}$ | $R_\odot$ | 2 |
| Planet to star rad. | $R_p/R_*$ | $0.1564 \pm 0.00010\dagger$ | | 3 |
| Orbital period | $P_{\text{orb}}$ | $2.185875200(77)$ | d | 4 |
| Transit centre | $T_0$ | $2453955.525511(88)$ | BJD$_{\text{TDB}}$ | 4 |

References: (1) Triaud et al. (2009); (2) Gaia Collaboration et al. (2018); (3) Sing et al. (2011); (4) Baluiev et al. (2015); (5) Agol et al. (2010); (6) Bouchy et al. (2005).

1 For more information about the filters of the OM, see the XMM-Newton Users Handbook: http://xmm-tools.cosmos.esa.int/external/xmm_user_support/documentation/uhb/omfilters.html

2 The width of a filter with a constant transmission equal to that at the effective wavelength, and which has the same effective area as the real OM filter in question.
We accounted for the out of transit trends by multiplying the transit model by a quadratic, $a_j t^2 + b_j t + c_j$, allowing the coefficients to vary across the different observations, $j$. However, in order to help constrain the coefficients and avoid them going off to erroneous values, we initially performed a fit using a single quadratic that was the same for each observation, yielding $a = -0.997^{+0.697}_{-0.676}$, $b = 2.02^{+1.33}_{-1.37}$, and $c = -0.016^{+0.676}_{-0.018}$. In our final fits, we placed uniform priors on the quadratic coefficients for each observation, forcing them to be within 2-$\sigma$ of this initial single quadratic fit. Additionally, at this same step, we ran a second, similar fit in which the only difference was that we allowed the mid-transit time $t_0$ to vary, in order to verify there was no offset in this value from the ephemeris present in the data. The best-fit $t_0$ was consistent to within 1-$\sigma$ of the optical ephemeris (in phase, $t_0 = 1.0005^{+0.0001}_{-0.0002}$). In all of our following analyses, we accordingly fixed $t_0$ according to the optically-measured ephemeris.

Our three final fits investigated the measured planet radius in the UVW2 band ($R_p/UVW2$). In the first of these, we allowed $R_p/UVW2/R_*$ to change between all of the observations, applying...
Figure 3. Measured value of the ratio of the planet and stellar radius, \( R_p/\text{UVW2}/R_* \), at each of the four defined epochs (see main text). The solid horizontal line depicts the measured value of \( R_p/R_* \) at optical wavelengths.

a wide uniform prior, \( 0 < \frac{R_p/\text{UVW2}}{R_*} < 1 \), to prevent unphysical values. As we were interested in the relative changes of \( R_p/\text{UVW2} \) across each observation, in this fit we fixed the values of \( i, a/R_*, u_1, \) and \( u_2 \), as opposed to utilising the Gaussian priors. In Fig. 2, we plot the measured \( R_p/\text{UVW2}/R_* \) as a function of observation number. This plot shows that the individual UVW2 transit depths are consistent with each other, and with the transit depths observed in the optical (see Table 1). The mean and median of these 18 measurements are \( R_p/\text{UVW2}/R_* = 0.1555 \pm 0.0071 \) and 0.159, respectively. In terms of \( R_p/\text{UVW2}/R_{p,\text{opt}} \), where \( R_{p,\text{opt}} \) is the optically measured radius (at 4950 Å), these values are 0.994 ± 0.045 and 1.00. We statistically tested for variation of \( R_p/\text{UVW2}/R_* \) by comparing against a constant model equal to the mean of the 18 values, 0.15722. This gave \( \chi^2_{\text{red}} = 0.71 \) and a p-value of 0.79, indicating that the values are consistent with being constant within the uncertainties.

In the second fit, we further investigated variation in the transit on longer timescales, by forcing \( R_p/\text{UVW2}/R_* \) to be the same for each observation within (but not between) the following defined epochs: "Autumn 2013" (Observations 3 and 4 in Table 2), "Spring 2014" (Observations 5 to 9), "Autumn 2014" (Observations 10 to 17), and "Spring 2015" (Observations 18 to 20). The same wide uniform prior as before was used for each of the four \( R_p/\text{UVW2}/R_* \) values, while \( i, a/R_*, u_1, \) and \( u_2 \) were again fixed for this fit. In Fig. 3, we plot the measured \( R_p/\text{UVW2}/R_* \) for each of these four epochs. Although the final epoch for the Spring 2015 data shows a hint of a larger \( R_p/\text{UVW2}/R_* \) compared to the other three epochs, the four points are consistent with a constant model equal to the mean, with \( \chi^2_{\text{red}} = 1.47 \) and a p-value of 0.22.

Following these findings, we ran an MCMC wherein we forced \( R_p/\text{UVW2}/R_* \) to be the same across all 18 transits. The Gaussian priors on \( i, a/R_*, u_1, \) and \( u_2 \) were restored. In Fig. 4, we plot the phase folded light curve with the best fit model from this MCMC plotted over the top. In this plot, the best-fitting out-of-transit trends have been removed from each observation’s light curve before phase folding and binning. Parameter details for this MCMC run are given in Table 3. Most notably, this run gives a best-fitting value of \( R_p/\text{UVW2} = 1.059^{+0.046}_{-0.050} R_{\text{opt}} \), a value which is consistent with the optical radius of the planet to just outside 1-σ.

Figure 4. Top panel: binned, phase folded OM light curve for the 18 UVW2 observations, with the best fitting out of transit quadratic trends removed. Plotted in orange is the best fit model, where \( R_p/\text{UVW2} \) was forced to be the same across all 18 light curves. Bottom panel: residuals of the model.

Table 3. Parameters used for and obtained from the final, best MCMC run for each OM filter’s observations. In the case of UVW2, this is the fit where \( R_p/\text{UVW2}/R_* \) was forced to be the same across all observations.

| Parameter      | UVW2    | UVM2    | Unit |
|----------------|---------|---------|------|
| \( u_1 \)     | 0.0594 ± 0.0200 | 0.0618 ± 0.0250 |       |
| \( u_2 \)     | 0.0160 ± 0.0200 | 0.0204 ± 0.0250 |       |
| \( a/R_* \)   | 8.863 ± 0.020 | 8.97 ± 0.024 |       |
| \( i \)       | 85.710 ± 0.024 |           |      |
| \( t_0 \)     | 1.0      | 1.0     | phase|

3.2 UVM2 observation

The observation on 17/18 April 2007 (observation 1 in Table 2) was taken using the UVM2 filter. The resulting light curve, displayed in Fig. 5, showed evidence of a transit dip at the expected phase. We ran an MCMC fit to the time series data binned to 10 s. We used a similar procedure to that outlined for the UVW2 data, with the same priors on \( R_p/\text{UVM2}/R_* \), \( i, a/R_* \). The out of transit trend was again accounted for by multiplying the transit model by a quadratic in time. We derived limb darkening coefficients for the UVM2 filter using Limb Darkening Toolkit of \( u_1 = 0.0618 ± 0.0250 \) and \( u_2 = 0.0204 ± 0.0250 \), again using these values to place a Gaussian prior on the fit coefficients.

The light curve and the best fitting model from the MCMC are plotted in Fig. 6, with the best fitting out of transit quadratic having

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that transmission spectrum will eventually flatten at shorter wavelengths (Powell et al. 2019). Both the UVM2 and UVW2 data points are consistent with that scenario, although the errorbars are also too large to concretely prove or rule out enhanced absorption from other sources, such as FeII and MgII (Turner et al. 2016; Salz et al. 2019; Lothringer et al. 2020).

The measurements unquestionably rule out average opaque region sizes across these bandpasses similar to or exceeding the size of the Roche lobe (3 $R_{\text{opt}}$). Opaque region sizes measured at other wavelengths (e.g. Ly $\alpha$; Lecavelier des Etangs et al. 2012; Bourrier et al. 2013; McCullough et al. 2014). In Fig. 7, we also plot two recent transit spectra derived from simulations of the HD 189733b atmosphere, extended to 2000 Å. The 1-D model from Lavvas & Arfaux (2021) includes disequilibrium chemistry and radiative feedback from photochemical hazes, which dominate the NUV opacity of the upper atmosphere, 0.1 mbar and above. They found that hazes also work to heat the upper atmosphere above 1 mbar, which increases the effective scale height at short wavelengths. Utilising soot opacities, their model (green curve in Figure 7) provides a good fit to the steep transmission curve for wavelengths less than 6000 Å. The 3-D model from Steinrueck et al. (2020) features a GCM derived HD 189733b transmission spectrum that includes the effects of a non-homogeneous distribution of photochemical hazes at the terminator. Assuming a uniform particle size of 3 nm and utilizing soot opacities, they find that enhancing the vertical mixing in the GCM (dashed black curve in Figure 7) is required to approach the steep slope observed at short wavelengths, but their 3-D model fits the observed transmission spectrum at wavelengths longer than 6000 Å better than the 1-D models.

4 DISCUSSION

The transmission spectrum of HD 189733b exhibits a steep optical slope that may arise from either the presence of atmospheric aerosols or contamination from starspots (Pont et al. 2008; Sing et al. 2011; Pont et al. 2013; McCullough et al. 2014). In Fig. 7, we plot a transmission spectrum of HD 189733b. In addition to the two broadband filter measurements presented here, we include optical data blue-wards of 6500 Å (Pont et al. 2013; McCullough et al. 2014; Sing et al. 2016). The single observation UVM2 point is not particularly informative as to whether the steep slope continues into the UV, given the large size of the error bar. One thing to note is that detailed simulations of aerosol formation in hot Jupiter atmospheres predict
The UVW2 measurement across 18 transits hints at a continuation of the steep blue slope into the NUV. However, the uncertainties on our measurement mean that a flattening out of this feature, as seen in the 1-D model (see Fig. 7) cannot be ruled out. We can however decisively rule out the average transmission region size across the UVW2 bandpass being similar in size to the Roche lobe, which is interesting in the context of previous studies of the neutral and singly-ionised Fe and Mg lines a few hundred Angstroms either side of 2500 Å. Transits in these areas have previously been used to detect these species in the exospheres of exoplanets (Fossati et al. 2010; Sing et al. 2019; Cubillos et al. 2020). However, we cannot determine without higher resolution observations or further modelling whether there is no detectable exosphere Fe and Mg at these wavelengths, or if the broadness of the bandpasses used in this work have sufficiently washed out the deeper transits expected in those narrow lines.

5 CONCLUSIONS

We have observed the near-UV transit of prototypical hot Jupiter HD 189733b in three broadband filters across twenty observations taken with the XMM-Newton Optical Monitor. We successfully detected transits in two of these filters, UVW2 (18 observations) and UVM2 (1 observation), with the star proving too bright in the single UVW1 observation and saturating the camera. HD 189733b is the third planet to have a near-UV transit detection by XMM-Newton or Swift.

With MCMC fits to the data using batman transit light curve models, we measured transit depths for UVW2 and UVM2 that are statistically consistent with the optically measured radius of the planet. The same conclusion was also reached when Swift taken with Horizon 2020 research and innovation programme (project ST/P000495/1 and ST/T000406/1. DE has received funding from the European Research Council (ERC) under the European Union’s Horizon 2020 research and innovation programme (project SPIRE DUNE; grant agreement No 947634). This project has also been carried out in the frame of the National Centre for Competence in Research PlanetS supported by the Swiss National Science Foundation (SNSF).
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