A transmission spectrum of HD 189733b from multiple broad-band filter observations

David H. Kasper,1★ Jackson L. Cole,1,2 Cristilyn N. Gardner,1,3★ Bethany R. Garver,1,4
Kyla L. Jarka,1,5 Aman Kar,1 Aylin M. McGough,1 David J. PeQueen,1,6
Daniel I. Rivera,1,7 Hannah Jang-Condell,1 Henry A. Kobulnicky,1★ Adam D. Myers1 and Daniel A. Dale1

1Department of Physics & Astronomy, University of Wyoming, Laramie, WY 82072, USA
2Physics and Astronomy Department, Middle Tennessee State University, Murfreesboro, TN 37132, USA
3Department of Physics, California State University San Bernardino, San Bernardino, CA 92407, USA
4Physics Department, Seattle Pacific University, Seattle, WA 98119, USA
5Physics Department, Colorado College, Colorado Springs, CO 80903, USA
6Department of Physical Sciences, Embry-Riddle Aeronautical University, Daytona Beach, FL 32114, USA
7Department of Astronomy, San Diego State University, San Diego, CA 92182, USA

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ABSTRACT
We present new multibroadband transit photometry of HD 189733b obtained at the Wyoming Infrared Observatory. Using an ensemble of five-band Sloan filter observations across multiple transits we have created an ‘ultra-low’ resolution transmission spectrum to discern the nature of the exoplanet atmosphere. The observations were taken over three transit events and total 108 $u'$, 120 $g'$, 120 $r'$, 110 $i'$, and 116 $z'$ images with an average exposure cadence of seven minutes for an entire series. The analysis was performed with a Markov-Chain Monte Carlo method assisted by a Gaussian processes regression model. We find the apparent planet radius to increase from 0.154+0.00092−0.00096 $R_*$ at $z'$ band to 0.157+0.00074−0.00078 $R_*$ at $u'$ band. Whether this apparent radius implies an enhanced Rayleigh scattering or clear or grey planet atmosphere is highly dependent on stellar spot modelling assumptions, but our results are consistent with the literature for HD 189733b. This set of observations demonstrates the ability of our 2.3-m ground-based observatory to measure atmospheres of large exoplanets.

Key words: methods: observational – techniques: photometric – planets and satellites: atmospheres – planets and satellites: individual: HD 189733b.

1 INTRODUCTION
From the first photometric confirmation of a transiting extrasolar planet (Charbonneau et al. 2000; Henry et al. 2000) the possibility of observing transit events spectrally to further characterize the exoplanet was discussed. The known number of transiting exoplanets has increased dramatically (NASA Exoplanet Archive, Akeson et al. 2013), and transit observation techniques (Everett & Howell 2001) and analysis techniques (Mandel & Agol 2002) have been developed. In particular, transmission spectroscopy has become a powerful tool for probing giant exoplanet atmospheres, as it reveals the absorption and scattering by the exoplanetary atmosphere on the host star’s light during a transit (Seager & Sasselov 2000; Brown 2001). The infrared and optical signatures of the atomic, molecular, and particulate components have revealed the composition of dozens of giant exoplanet atmospheres to date (recent e.g. Sing et al. 2016; Tsiaras et al. 2018).

Space-based observations are the ‘gold-standard’ for exoplanet transmission spectroscopy (Charbonneau et al. 2002; Pont et al. 2013; Kreidberg et al. 2014). The spectrophotometric precision required to measure typical transmission effects is at the level of one part in $10^4$ or better – a regime where space-based observations excel, especially at near-infrared wavelengths where Earth’s atmospheric transmission can be poor and highly variable. Specialized observation techniques and heroic calibration efforts have permitted detections of exoplanet transmission features more recently to levels of few parts in $10^5$ (Deming et al. 2013; Line et al. 2016; Tsiaras et al. 2016). Transmission spectroscopy of giant exoplanets has detected, for example, atomic species including Na I in HD 209458b (Charbonneau et al. 2002), a conspicuous lack of Na I in WASP-12b (Sing et al. 2013), and molecular species including H$_2$ in HD 209458b (Levacher Des Etangs et al. 2008a), and H$_2$O in...
for example in HD 209458b, thereby demonstrating the capability of ground-based transmission spectroscopy (Redfield et al. 2008). Ground-based observations have since made original contributions, such as measurement of atmospheric circulation on HD 209458b (Snellen et al. 2010) and a continuum slope consistent with Rayleigh scattering in GJ 3470b (Chen et al. 2017). Recently, many survey programs have been implemented to increase the number of high-quality broad-coverage transmission spectra, creating a statistically significant sample to understand atmospheric properties and their connection to planetary characteristics. (Murgas et al. 2014; Nikolov et al. 2016; Huitson et al. 2017; Rackham et al. 2017).

Multicolour broad-band photometry is also a fruitful technique to investigate exoplanetary atmospheres (de Mooij et al. 2012; Turner et al. 2017). This observational method principally measures the apparent variation of the planet radius as a function of wavelength, effectively creating an ‘ultra-low’ resolution transmission spectrum. Some observational programs have employed dichroics to record a transit in multiple filters simultaneously, typically with large (>4 m) telescopes (Nascimbeni et al. 2013; Nikolov et al. 2013; Bento et al. 2014). Other programs have utilized single near-ultraviolet filters where effects of Rayleigh scattering are most pronounced (Turner et al. 2016; Mallonn & Wakeford 2017). Additionally some coordinated campaigns utilizing several (typically ≤1 m) observatories have also produced multiband transmission photometry (de Mooij et al. 2012; Mancini et al. 2013; Cáreres et al. 2014; Dragomir et al. 2015). The highest precision observations (at a few parts in 104) are achieved ultimately by maximizing photon counts through combinations of large collecting area (Nascimbeni et al. 2013) and/or simultaneous/repeated observations (Mancini et al. 2013; Nikolov et al. 2013). Multicolour broad-band photometry is an efficient means to demonstrate the existence of a measurable exoplanet atmosphere and constrain its gross properties, while providing a prioritized target list for further study.

This paper presents new ground-based multibroadband photometric transit observations of the extrasolar planet HD 189733b, a hot Jupiter well studied with transmission spectroscopy (Sing et al. 2011; Gibson et al. 2012b; Huitson et al. 2012; Lecavelier Des Etangs et al. 2012; Pont et al. 2013; Wytenbach et al. 2015). Our goal is to demonstrate the potential of an observational technique on a 2.3-m telescope through broad-band filters to characterize exoplanet atmospheres. Dedicated access to such a telescope can yield, on its own, a high-quality ‘ultra-low’ resolution transmission spectrum over just a few transits. HD 189733b, a 1.150 ± 0.039 M$_{\text{Jup}}$ exoplanet orbiting a favourably bright V = 7.648 mag host (Koen et al. 2010), was chosen because of the favourable 2.2 d period, transit duration of 1.8 h, and planet-to-star radius ratio of 0.157 (Baluev et al. 2015). Additional characteristics of the exoplanet’s orbit that informed our analysis were the 8.98 ratio of orbital distance to stellar radius, 85.78 deg inclination, and zero eccentricity (Southworth 2010). Section 2 describes the observational procedure; Section 3 outlines the photometric reduction; Section 4 details the analysis employed to obtain the planet-to-star radius ratio as a function of wavelength; Section 5 elaborates on our star-spot corrections, and Section 6 discusses the success of the methodology. Section 7 summarizes our conclusions.

## 2 OBSERVATIONS AT THE WYOMING INFRARED OBSERVATORY

Observations of the HD 189733 system were taken on the UTC dates of 2016 August 2, 2017 June 22, and 2017 August 1 at the Wyoming Infrared Observatory (WIRO). 2.3-meter telescope in the

| Date (UTC) | Filter | $N_{\text{exp}}$ | Exp (s) | Cadence (min) | Airmass |
|------------|--------|-----------------|--------|--------------|--------|
| 2016 Aug 02 | $u$ | 43 | 180 | 6.1 | 1.06–1.93 |
| 2016 Aug 02 | $g$ | 43 | 20 | 6.1 | 1.06–1.91 |
| 2016 Aug 02 | $r$ | 41 | 16 | 6.1 | 1.06–1.92 |
| 2016 Aug 02 | $i$ | 40 | 20 | 6.1 | 1.06–1.98 |
| 2016 Aug 02 | $z$ | 44 | 30 | 6.1 | 1.06–1.97 |
| 2017 June 22 | $u$ | 18 | 320 | 9.5 | 1.05–1.35 |
| 2017 June 22 | $g$ | 18 | 20* | 9.5 | 1.05–1.39 |
| 2017 June 22 | $r$ | 18 | 12 | 9.5 | 1.05–1.36 |
| 2017 June 22 | $i$ | 18 | 16* | 9.5 | 1.05–1.32 |
| 2017 June 22 | $z$ | 18 | 30* | 9.5 | 1.05–1.33 |
| 2017 Aug 01 | $u$ | 45 | 270 | 8.3 | 1.05–1.79 |
| 2017 Aug 01 | $g$ | 61 | 20 | 8.3 | 1.05–1.54 |
| 2017 Aug 01 | $r$ | 60 | 14* | 8.3 | 1.05–1.57 |
| 2017 Aug 01 | $i$ | 53 | 18 | 8.3 | 1.05–1.49 |
| 2017 Aug 01 | $z$ | 54 | 30 | 8.3 | 1.05–1.46 |

Note. *Denotes an exposure duration that changed within the night as a response to total count fluctuations.

These changes were never more than 15% total exposure length and were typically two second corrections.

XO-1b (Deming et al. 2013). In addition, transmission spectroscopy has revealed continuum slopes that indicate Rayleigh scattering in exoplanet atmospheres (e.g. HD 189733b; Lecavelier Des Etangs et al. 2008a) as well as atmospheres large enough to undergo hydrodynamic escape such as HD 209458b (Vidal-Madjar et al. 2003). Sizeable samples of exoplanet transmission spectra demonstrate that their atmospheres range from clear to cloudy (Sing et al. 2015, 2016; Stevenson 2016; Wakeford et al. 2017; Tsiaras et al. 2018).

Clear atmospheres produce strong spectral features dictated by atmospheric composition and temperatures. Completely cloudy atmospheres yield featureless spectra. Most observed atmospheres lie somewhere between these extremes, with transmission spectra exhibiting discrete absorption features and a blue continuum slope. These spectra are best modelled as a mixture of optically thin molecular and atomic species as well as semitransparent hazes and optically thick cloud decks. While the number of known transiting exoplanets has swelled into the thousands, the number with high-quality, broad-coverage, transmission spectra only approaches three dozen. Space-based measurements have been limited by the paucity of suitably instrumented observatories, motivating the need for ground-based efforts.

Though ground-based observations suffer the disadvantages mentioned above, their greater availability has produced significant results (Redfield et al. 2008; Bean, Miller-Ricci Kempton & Homeier 2010; Kirk et al. 2017). By simultaneously observing an ensemble of nearby field stars in addition to the host star, atmospheric effects can be removed to the precision necessary to recover the transit in detail. Typically ground-based spectroscopy employs single-slit differential spectrophotometry with a single comparison star (Sing et al. 2012), but multi-object spectrograph efforts have also been successful (e.g. Bean et al. 2013; Beatty et al. 2017).

Important comparison star considerations include non-variability, similarity in colour, brightness, and angular proximity to the exoplanet host star such that simultaneous spectra can be recorded on the same instrument, allowing telluric variation to be removed from the target spectrum. The first ground-based observations successfully reproduced space-based results, namely the Na I features,
Figure 1. Left: (Top–Middle–Bottom) 2016 Aug 02, 2017 June 22, 2017 Aug 01 raw target flux per second in $u'$ = blue to $z'$ = black with airmass plotted in light blue. Right: Nightly corresponding calculated background flux per second per pixel colour coded $u'$ = blue to $z'$ = black. The dramatic background flux rate rise at the end of the first night and fall at the beginning of the last night come from twilight.

Sloan $u'$, $g'$, $r'$, $i'$, and $z'$ filters. Table 1 provides a listing of exposures on each UTC date, with total exposures per filter, exposure length, the cadence (the time between successive exposures), and the airmass range. Images were acquired with the WIRO DoublePrime prime-focus imager (Findlay et al. 2016) which has a 0.58 arcsec pixel$^{-1}$ pixel scale on 4096 × 4096 sky pixels resulting in a conveniently large 39 × 39 arcmin field of view. The instrument was used in full-field, four-amplifier mode, resulting in a 20 s read-out time.

Sequences of exposures alternating through the five filters were obtained continuously during each night. The telescope was purposely defocused such that the stellar point-spread-function was $\sim 1$ arcmin $\simeq 100$ pixels in diameter to achieve exposure times that maximized photon counts while avoiding pixel saturation, averaging
over interpixel variation noise, smoothing temporal sky variations, and reducing the effect of telescope tracking errors (Winn 2010). Exposure times in all filters were chosen on a nightly basis to achieve ≥10^4 photons in each image for the target star, save for the u’-filter exposures on 2016 August 2 which obtained ≈ few × 10^3 photons per image for the target star. Care was given to ensure the target host’s peak pixel counts remained well within the linear response regime of the detector. Exposure times over all nights ranged from 12 s in r’ to 320 s in u’. A drawback to this approach was the significance of scintillation noise in the uncertainty budget for all but the u’-band observations. For example, using the Osborn et al. (2015) modified Young (1967) scintillation approximation with the shortest exposures gives 0.62 mmag uncertainty at 1 airmass and 1.8 mmag uncertainty at 2 airmasses. This approach allowed us to obtain up to 17 in-transit exposures for each filter on a single night. Corrections to telescope tracking were performed by applying manual offsets between exposures on 2017 June 22 and on 2017 August 21 to maintain absolute image placement on the detector to within 10 pixels after the telescope was found to drift 40 pixels over the entire observation time on 2016 August 2. The target was not placed at the same pixel location between nights, with separations from night to night larger than the 50 pixel defocus radius.

Image reductions involved first overscan-region subtraction, then bias subtraction, and finally flat-fielding with corresponding nightly sky flats in each filter. Bias subtraction and overscan subtraction were applied to remove the bias pattern. Additionally, time transformations to Barycentric Julian Date in Barycentric Dynamical Time (BJDTDB) from JDUTC by mid-exposure time were completed with the Eastman, Siverd & Gaudi (2010) online converter.

Fig. 1 shows the nightly raw target flux (left column) and sky background flux (right column) for each filter versus time. The time evolution of raw flux on the first night suggests somewhat clouded periods around BJDTDB’s 0.86 and beyond 0.89 on 2016 August 2. By comparison, the second and third night do not show evidence of clouded periods by raw flux time evolution. The dramatic rise of the background flux rate at the end of the 2016 August 2 data is due to the approach of twilight. Likewise the dramatic fall of background flux rate on the 2017 August 1 data start is due to the end of twilight. On all nights the total background flux is <10^{-4} of the target flux, meaning the background contributes negligibly to the total noise. The decreased background flux after the first half of the 2017 August 1 observations, notable in u’, g’, and r’, is due to the moon setting.

3 PHOTOMETRIC DATA REDUCTION

We used the ASTROIMAGEJ (AIJ) package (Collins & Kielkopf 2013; Collins et al. 2017), which has been used extensively in exoplanet science in the KELT program (Pepper et al. 2008; Siverd et al. 2012; Gaudi et al. 2017; Johnson et al. 2018) to perform photometry. AIJ performs differential aperture photometry to remove systematic differences between exposures and recover the target transit. Light curve generation was performed with AIJ on a single night, single filter basis, resulting in 15 independent light curves for the HD 189733 system. We adopted a fixed aperture radius of 60 pixels and background annulus of 65 inner and 85 outer pixels that was kept constant between all nights and sources. These photometric parameters were chosen after experimentation over a range of possible values to maximize source signal and robustly measure the background. We selected four nearby field stars of similar apparent magnitude which are listed in Table 2 with their brightness, colour, and angular distance to the target star. We examined light curves of the comparison stars to verify their non-variability at the ≤2 global mmag level over the course of the observations and to remove single images (less than five over the almost 600 total) that were clearly discrepant with the comparison ensemble trend.

The left-hand side of Fig. 2 shows each filter’s AIJ-extracted photometric measurements from UTC 2016 August 2, UTC 2017 June 22, and UTC 2017 August 1 as colour-coded from r’ in blue to z’ in black. Table 3 presents all AIJ-extracted relative photometry for all nights and filters. All measurements are plotted as folded around the best fit, filter-dependent, mid-transit times, and planet-to-star radius ratios as explained in Section 4. The uncertainty budget for each photometric value is dominated by scintillation noise, approximated in the figure by the Osborn et al. (2015) calculation.

4 MCMC AND GP DATA ANALYSIS

We analysed the data through a Markov-Chain Monte Carlo (MCMC) method posterior retrieval using the EMCEE (Foreman-Mackey et al. 2013) PYTHON package to ultimately recover the planet’s most probable radius as a function of wavelength. We utilized the BATMAN (Kreidberg 2015) implementation of the Mandel & Agol (2002) algorithm with a quadratic limb-darkening law to generate transit models in the MCMC process. In generating comparison models, we accounted for photometric smearing in all data points by averaging BATMAN values along the exposure durations. We also utilized the Gaussian process (GP) regression modeller GEORGE (Ambikasaran et al. 2015) to model and remove the noise-induced systematic trends in the data during the MCMC analysis. GP-assisted MCMC analysis has been used to detrend and analyse transmission and emission spectra of exoplanets with success (recent e.g. Beatty et al. 2017; Kirk et al. 2018) and works by non-deterministically modelling the noise-induced correlation between data points in a simple functional way.

The reader is referred to Gibson et al. (2012a) and Gibson (2014) for more information on the application of GP’s to exoplanet transmission data, but here it suffices to give a short explanation of our choices following their methods. Given the variety of structure in the light curves, it was found insufficient to straightforwardly detrend

Table 2. Comparison star description.

| Star | Reference photometry | V (mag) | B−V (mag) | Angular distance (arcsec) | Notes |
|------|----------------------|--------|-----------|---------------------------|-------|
| HD 189733 | Koen et al. (2010) | 7.65   | 0.93      | 0.0                       | Target host for reference |
| HD 345464 | Hog et al. (2000) | 8.93   | 0.57      | 520.34                    | excluded all filters 2016 Aug 2 – not in observed field |
| HD 345459 | Hog et al. (2000) | 8.09   | 1.05      | 523.14                    | |
| HD 345585 | Hog et al. (2000) | 9.47   | 1.10      | 1132.40                   | |
| HD 345442 | Hog et al. (2000) | 8.37   | 0.35      | 1594.96                   | |

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nightly filter series by low-order polynomial fits to auxiliary measurements (in particular airmass). Given the importance of temporal trends blended with changing total noise (itself likely dominated by scintillation noise and cloud interference) in the data set (Fig. 2; the temporal drift of relative target flux in the first night and last night, variability around mean model in all nights), we chose two kernels in our GP effort. To model the temporal trends (likely the result of uncorrected atmospheric transparency and instrumental
The resulting squared exponential kernel amplitudes were of similar order of magnitude with 2016 August observations. At \( \approx 10^{-6} \) d, 2017 August observations especially at \( \approx 10^{-6} \) were made. All orbital parameters necessary for \textsc{batman} other than planet-to-star radius ratio and mid-transit time were fixed to previously published values, as listed in Table 4. These published values were set as fixed after ensuring parameter agreement between our data set and these published values. For each filter data set the MCMC process involved four free physical parameters: a single planet-to-star radius ratio and three mid-transit times. The priors for these four parameters were set broad and flat so as to let the data inform the parameters we were ultimately trying to constrain. The MCMC process was composed of 100 walkers on 100 000 steps each for each five independent filter series. Fig. 2 contains the best-fitting MCMC solutions to each filter by night (left column) as well as a residual to the fit (right column) by filter with 500 randomly drawn corresponding MCMC sample models overplotted to give a sense for the goodness of the fit. Table 5 lists the by night, filter-averaged, mid-transit times in \( \text{BJD}_{\text{TDB}} \). We note these mid-transit times are consistent with the Baluev et al. (2015) mid-transit envelope.

Quadratic limb-darkening coefficients were assigned as fixed values for each filter from those quoted with the closest matching stellar parameters in Claret & Bloemen (2011) (temperature of \( T_{\text{eff}} = 5000 \) K and surface gravity of 4.5 log (cm s\(^{-2}\)) as similar to calculated HD 189733 values from Stassun, Collins & Gaudi (2017), adopted metallicity of solar, and assumed microturbulent velocity of 0 km s\(^{-1}\)). We also explored a small range around the adopted stellar parameters and concluded that the resulting small variations in limb darkening had a negligible effect on the final product as long as the coefficients all came from the same stellar parameter set.

In addition to the four physical parameters, the nine hyperparameters defining the GP kernels (three per night) were given flat and broad priors based on their definitions (see above). After early runs it became apparent that a singly valued description of the data’s nightly white noise amplitude was not always sufficient (as the residual r.m.s. to the best-fitting model changed appreciably on the first and second nights). For each filter’s analysis of the 2016 August 02 data the white noise kernel was increased for the last 10 data points (as motivated by the all-filter flux drop in Fig. 1, top row left) by the ratio of the variance between those data and the pre-transit data. The white noise amplitude for each filter’s in-transit data on 2017 June 22 was increased by the ratio of the variance between those data and the post-transit data. Although no cloudy period could be seen in the raw flux, the differing variance is noticeable in Fig. 2, middle row. These piece-wise changes to the white noise kernel represent only an improvement to the accuracy of the variance for those data points to be used in the diagonal of the covariance matrix. This piece-wise approach could be expanded into a fully realized noise model, but such additional complexity was deemed unwarranted. The resulting white noise amplitudes were \( \approx 10^{-6} \) d, 2017 August observations especially at \( \approx 10^{-6} \). The white noise amplitude for each filter’s in-transit data on 2017 June 22 was increased by the ratio of the variance between those data and the post-transit data. Although no cloudy period could be seen in the raw flux, the differing variance is noticeable in Fig. 2, middle row. These piece-wise changes to the white noise kernel represent only an improvement to the accuracy of the variance for those data points to be used in the diagonal of the covariance matrix. This piece-wise approach could be expanded into a fully realized noise model, but such additional complexity was deemed unwarranted. The resulting white noise amplitudes were \( \approx 10^{-6} \) for all August observations and \( \approx 4 \times 10^{-6} \) for the June observations. The resulting squared exponential kernel amplitudes were of similar order of magnitude with 2016 August observations \( A_\alpha \approx 10^{-6} \), \( L_\alpha \approx 0.14 \) d, 2017 August observations \( A_\alpha \approx 5 \times 10^{-6} \), \( L_\alpha \approx 0.026 \) d and June observations resolving to a negligible kernel. These general estimates are useful to understand the importance of white noise in all nights/filters, the importance of the squared exponential kernel in the 2017 August observations (as can be seen in the data trends in the bottom right-hand panel of Fig. 2) and to a lesser extent...
the 2016 August observations, and the lack of squared exponential kernel importance for the June 22 data (which were dominated by white noise over the relatively shorter observation series). The lack of pre-transit baseline in both 2017 observations requires justification to support inclusion in the multinight analysis. To this end each single-night, single-filter data set was independently run through a version of the above MCMC process adapted for single-night fitting. The resulting nightly planet-to-star radius ratios are shown in Fig. 3. The figure indicates that for the non-u filters the nights are in good agreement. Further there seems to be no systematic trend biasing one night through all five filters. The 2017 June 22 reported u filter ratio does appear to be significant in its offset from the other two nights, but due to the white noise envelope’s relatively larger size (as seen in Fig. 2) on the in-transit data for that night (compared to the other nights) the 2017 June 22 contribution to the derived multinight u ratio is weighted less (effectively the 2017 June 22 u ratio has a larger than quoted uncertainty).

5 STAR SPOT CORRECTIONS

HD 189733 is a chromospherically active star with many years worth of photometric measurements through the Automated Patrol Telescope photometer monitoring (Henry 1999; Henry & Winn 2008). As described in the literature on HD 189733 (Désert et al. 2011; Sing et al. 2011; Pont et al. 2013; McCullough et al. 2014) this necessitates corrections to the observed planet-to-star radius ratios for occulted and unocculted star spots. Given the time resolution, noise budget of our data, and uncorrelated residuals in time and colour during transit we conclude that there were no measured star-spot crossings during our transit observations. Given the discrepancy between efforts utilized within the literature to correct HD 189733b transmission spectra for unocculted star spots, we endeavor to show agreement between our data set and those previous by recreating the Pont et al. (2013) and McCullough et al. (2014) unocculted star-spot corrections to compare our corrected photometry to their results [we follow McCullough et al. (2014, section 5.2) for the limiting case of ‘all of the observed increase in the blue is due to unocculted star spots’]. For both the Pont and McCullough corrections we utilize the aggregate star-spot model, ignoring limb darkening as in McCullough et al. (2014, equation 1),

$$\frac{R_p'}{R_*'} = \frac{R_p}{R_*} \frac{1}{\sqrt{1 - \delta(1 - F_{spot}\lambda/F_{phot}\lambda)}}$$

where ’s denotes the observed radius ratio, δ is the fraction of projected stellar surface covered with spots, $F_{spot}\lambda$ and $F_{phot}\lambda$ denote the star-spot and stellar photosphere radiances, respectively. The first factor on the right is the radius ratio that would be observed in the absence of unocculted star spots. Despite knowledge that the activity level has been measured to vary by as much as 1–2 per cent (Pont et al. 2013), we are forced to approximate every night’s correction by the same average spot corrections. This was due to the varied placement on the CCD for each source between nights prohibiting sufficient absolute characterization of the out-of-transit stellar flux between nights. To our advantage, the spacing between the observations was significantly larger than the ≈12 d rotation period of HD 189733 (Henry & Winn 2008) and, thus, each of the three nights absolute flux was effectively independent.

With this approach, two corrections can be made to our data set to compare to the two literature sources based on simple differences in the spot coverage fraction and spot temperature. To recreate the average Pont et al. (2013) spot covering fraction and spot temperature we utilize a $\delta = 0.01$, 4000 K spot population. To recreate the McCullough et al. (2014) limiting case spot covering fraction and spot temperature we utilize $\delta = 0.043$, 4250 K spot population correction. McCullough et al. (2014) was concerned with an unobserved additional spot population beyond the Pont et al. (2013) population assumed through observed stellar variability. Such a spot population which does not change with time could have a large impact on the observed transit depth, but would require inhomogeneous distribution across the star to be unobserved by planet occultations. McCullough et al. (2014) point to polar regions as a potential physical location.

To generate the spot and photospheric radiances we utilized PHOENIX atmosphere models (Husser et al. 2013) of log (g) = 4.5 and [M/H] = 0.0 [consistent with Stassun et al. (2017) and our earlier limb darkening assumptions]. Table 6 first lists uncorrected planet-to-star radius ratios for our multinight analysis of each filter followed by the resulting spot-corrected values. The top of Fig. 4 shows the uncorrected $R_p/R_e$ (in blue) with both our Pont spot covering fraction and spot temperature (in orange, with slight mid-point offset for clarity) and our McCullough limiting case spot covering fraction and spot temperature (in green) against wavelength of observation, where the filter bandpasses are represented by the horizontal error bars. Overplotted for convenience are the Pont et al. (2013) (in red) and McCullough et al. (2014) limiting case (in purple) data series, both offset by –0.001 $R_p/R_e$ due to their results [we follow McCullough et al. (2014, section 5.2) for the limiting case of ‘all of the observed increase in the blue is due to unocculted star spots’].
to limb-darkening correction differences between our data and the two literature sources.

For the Pont spot covering fraction and spot temperature points, the increasing exoplanet radius towards shorter wavelengths from \(\approx 0.1537\) to \(\approx 0.1565\) indicates that the exoplanet appears bigger at bluer wavelengths, ostensibly the signature of an atmosphere. Given the expectation of a linear relation between exoplanet size and \(\ln(\text{wavelength})\) we ran a 100-walker 10 000-step MCMC linear fit of our data to retrieve the most probable slope. Fig. 5 shows the data points (black) with the quoted fit overlotted denoting the \(\pm 1\sigma\) (dark red-dashed) and \(\pm 2\sigma\) (light red-dashed) slope uncertainties, respectively. The retrieved slope is \(\frac{d\ln R_p}{d\ln \lambda} = -0.0029 \pm 0.0011 \ln(\text{nm})^{-1}\), which argues against a grey atmosphere in the observed range at the 99 per cent (2.6\(\sigma\)) level.

By following the general arguments and equation (4) in Lecavelier Des Etangs et al. (2008a), we can apply,

\[
a T = \frac{\mu g}{k} \frac{dR_p}{d \ln \lambda}
\]

(3)
to relate the slope \(\frac{d\ln R_p}{d\ln \lambda}\) in the observed spectral regime to a temperature \((T)\) of the observed atmosphere where \(\mu\) is the mean molecular weight of the atmospheric particles, \(g\) is the local gravity, and \(k\) is the Boltzmann constant. In calculating the temperature we elect to make the assumption that the \(\frac{d\ln R_p}{d\ln \lambda}\) slope is singly valued across the observed wavelengths. This decision is a simplification made despite knowledge of a break at 600 nm by more detailed, space-based, studies (Lecavelier Des Etangs et al.2008a; Pont et al.2013) because it is appropriate given the quality of the current data set. By multiplying the \(\frac{d\ln R_p}{d\ln \lambda}\) result by the stellar radius of 0.75 R\(_{\odot}\) (Stassun et al. 2017), we find an average slope of \(\frac{d\ln R_p}{d\ln \lambda} = -1513 \pm 574\) km from 320 nm to 1000 nm. Assuming the mean mass of atmospheric particles is 2.3 times the mass of the proton, calculating the exoplanet surface gravity \((21.9 \text{ m s}^{-2})\) (Stassun et al. 2017), and assuming Rayleigh scattering \((\alpha = -4)\), we derive a temperature of \(T = 2401 \pm 911 \text{ K}\) which agrees with the 2000 K 300–600 nm and is \(1.2\sigma\) from the 1300 K 600–1000 nm models adopted in Pont et al. (2013) as well as the \(T = 2300 \pm 900 \text{ K}\) results from DiGloria, Snellen & Albrecht (2015) with precision more similar with our own. The arguments of Lecavelier Des Etangs et al. (2008a, section 4) can be applied to our result as well, implying Rayleigh scattering by well-mixed grains (haze) is preferred over molecular hydrogen as the Rayleigh scatterer. As in Lecavelier Des Etangs et al. (2008a), our preference is driven by the molecular hydrogen Rayleigh-scattering scenario requiring higher pressures that would lead to other abundant species (assuming solar-like abundances) signatures overcoming the Rayleigh signature.

By contrast, a spot correction with a covering fraction of 4.3 per cent and spot temperature of 4250 K in Fig. 4 results in our planet-to-star radius ratio slope consistent with zero slope at 1.5 \(\sigma\). This is in agreement with the McCullough et al. (2014) limiting case analysis and the implication of a grey atmosphere for HD 189733b. This correction leads to a physical interpretation that for the atmosphere that is inconsistent with the conclusions of Pont et al. (2013) and our own conclusions following a \(\delta = 0.01, 4000 \text{ K}\) spot population correction. The bottom of Fig. 4 shows a variety of potential unocculted spot corrections over a magnitude of potential coverage fractions. The initial 5.2 limiting case and final spot correction argued for by McCullough et al. (2014) are also shown. Fig. 4 shows that for preferentially unocculted spot corrections \(R_p/R_s\) is reduced for all filters with a greater relative effect in the bluer filters as coverage fraction increases. At the lowest coverage corrections, the exoplanet is required to have Rayleigh scattering hazes to account for the large spectral slope. McCullough et al. (2014) argues for \(\delta = 0.056, 3700 \text{ K}\) at which the stellar spot correction applied leaves the atmospheric interpretation as clear, without clouds or hazes. Eventually the proposed coverage fraction is large enough that the correction results in a grey atmosphere and beyond that the unphysically motivated situation of larger effective size in the redder optical wavelengths.

The reduction of \(R_p/R_s\) for all filters with any spot correction is particularly important in constraining potential overinterpretation in our by-night uncorrected \(R_p/R_s\). As seen in Fig. 3, each night’s filter ensemble cannot be adjusted uniformly by a single spot correction to account for the low confidence discrepancy between the nights – implying that an uncorrected noise source is the dominant source in the scatter seen. The low coverage fraction corrections (<6 per cent), all of which are eminently reasonable given the limited understanding of the stellar spot population, highlight the complexity of disentangling stellar and planetary signals around active stars.

### 6 DISCUSSION

Our multiple, near-simultaneous, broad-band photometric observations over three transits of HD 189733b were analysed to successfully recover the exoplanet size with a precision necessary to retrieve atmospheric properties. These results demonstrate the capability of 2-m-class ground-based observations over just a few observed transits to explore exoplanet atmospheres. We show that for HD 189733b, interpretation of the observed exoplanet-to-star radius ratio is dominated by stellar spot assumptions inferred from previous literature observations. Outside of stellar activity concerns, a comprehensive list of the supplemental data required to perform this analysis included modestly constrained exoplanet orbital properties and modelled stellar limb-darkening coefficients – values that can be found in the literature for all confirmed exoplanets.

Inclusion of similarly bright comparison stars in the field was an important limiting factor in this analysis, as the \(u\)-filter results can attest, and preconsideration of the best orientation/placement of the field will result in the best use of this methodology. We found that the <60 s exposures suffered non-negligibly from additional r.m.s. variations about the best fit likely due to unaveraged sky variations. We also found that the filter/observation sequencing described in

### Table 6. Single filter \(R_p/R_s\)

| Star spot model | \(u\) | \(g\) | \(r\) | \(i\) | \(z\) |
|-----------------|------|------|------|------|------|
| Uncorrected     | 0.15719 ± 0.00074 | 0.1566 ± 0.0011 | 0.1571 ± 0.0013 | 0.1547 ± 0.0010 | 0.15415 ± 0.00092 |
| \(\delta = 0.01, T = 4000 \text{ K}\)-correction | 0.15648 ± 0.00074 | 0.1560 ± 0.0011 | 0.1566 ± 0.0013 | 0.15422 ± 0.00099 | 0.15372 ± 0.00092 |
| \(\delta = 0.043, T = 4250 \text{ K}\) | 0.15433 ± 0.00073 | 0.1541 ± 0.0011 | 0.1551 ± 0.0013 | 0.15296 ± 0.00098 | 0.15263 ± 0.00095 |
Figure 4. Above: Our multinight, spot uncorrected $R_p/R_*$ versus wavelength (in blue) shown with the $\delta = 0.01$, $T = 4000$ K spot correction (in orange) and the $\delta = 0.043$, $T = 4250$ K spot correction (in green) with small mid-point offsets for clarity. Overplotted are optical Pont et al. (2013) results (in red) and the limiting case created in McCullough et al. (2014, Section 5.2) of a grey atmosphere (in purple). All literature values have been offset by $-0.001$, to approximately correct for a difference in stellar limb-darkening assumptions. We find agreement between our own potential corrections and the corresponding literature. Below: Our multinight, spot uncorrected $R_p/R_*$ versus wavelength (in blue) again, with a variety of potential spot coverage fractions and temperatures applied as colour-coded. Each potential correction is visualized by a line connecting each filter’s $R_p/R_*$ at mid-filter location. The atmospheric interpretation of our data, like literature sources, is highly dependent on the applied stellar spot correction.

Section 2 led to smaller photometric residuals than a similar strategy that employed multiple exposures in each filter before switching to the next due to the more rapid cadence. Unsurprisingly, we found full transits better constraining than partials. Improvement in the ultimate measurements could be made in future efforts by measuring stellar psf’s on the same pixels from night to night to do absolute calibration of the active star flux to $<1$ per cent necessary to constrain the relative stellar activity.
Figure 5. Our $R_p/R_*$ corrected for a spot temperature of 4000 K and coverage factor of 1 per cent in each filter (black points). 10000-step, 100-walker MCMC linear fit is shown (solid red) with 1σ and 2σ slope uncertainties (dashed red).

7 CONCLUSIONS

We have obtained >550 photometric measurements of HD 189733 over the course of three HD 189733b transit events. The measurements were spread approximately equally over the five Sloan filters and enable a characterization of the exoplanet’s atmosphere. We find the existence of a measurable atmospheric response across the visible to near-infrared spectral range indicative of a grey atmosphere for the exoplanet.

We have shown the Wyoming Infrared Observatory is capable of the precision needed to attain exoplanet atmospheric characterization in transiting systems. In particular the 2.3-m observatory would be efficient at characterizing exoplanets hosted by less active stars.

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SUPPORTING INFORMATION

Supplementary data are available at MNRAS online.

Table 3. Extracted Relative Photometry.

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