MOPSS. II. Extreme Optical Scattering Slope for the Inflated Super-Neptune HATS-8b

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Abstract

We present results for the inflated super-Neptune HATS-8b from the Michigan Optical Planetary Spectra Survey (MOPSS). This program is aimed at creating a database of optical planetary transmission spectra all observed, reduced, and analyzed with a uniform method for the benefit of enabling comparative exoplanet studies. HATS-8b orbits a G dwarf and is a low-density super-Neptune with a radius of 0.873 $R_{\text{Jup}}$, a mass of 0.138 $M_{\text{Jup}}$, and a density of 0.259 g cm$^{-3}$. Two transits of HATS-8b were observed in 2017 July and August with the Inamori-Magellan Areal Camera and Spectrograph (IMACS) instrument on the Magellan Baade 6.5 m telescope. We find an enhanced scattering slope on each night that agree within 2.3$\sigma$. This slope is stronger than one due only to Rayleigh scattering and cannot be fully explained by unocculted starspots. We explore the impact of condensates on the scattering slope and determine that MnS particulates smaller than 10$^{-5}$ $\mu$m can explain up to 80% of our measured slope if the planet is warmer than equilibrium, or 50% of the slope at the equilibrium temperature of the planet for a low mean molecular weight atmosphere. The scattering slope that we observe is thus beyond even the most extreme haze case we consider. We suggest further follow up on this target and host star to determine if the temporal variation of the slope is primarily due to stellar or planetary effects, and to better understand what these effects may be.

Unified Astronomy Thesaurus concepts: Extrasolar gas giants (509); Exoplanet atmospheres (487); Exoplanets (498); Hot Jupiters (753); Hot Neptunes (754)

1. Introduction

Our ability to probe the atmospheres of exoplanets is rapidly advancing, with transmission spectroscopy leading the way as a robust method to constrain the composition of a planet’s atmosphere, for a well-characterized host star. With the number of detected exoplanets increasing rapidly in the past few years, we are no longer forced to study planets as single, unrelated data points, but rather we are moving toward an era of comparative studies (see Sing et al. 2016 for a discussion of the variety of hot-Jupiter atmospheres, Fu et al. 2017 for an updated look at Hubble spectra, and Crossfield & Kreidberg 2017 for a look at Neptune-sized planets). In this new era for exoplanet science, it becomes necessary to have sets of uniformly observed and reduced planetary transmission spectra to better make comparisons between planets. In this work, we present our third data set in our catalog of such observations. Our work makes use of the Inamori-Magellan Areal Camera and Spectrograph (IMACS) instrument on the Magellan Baade telescope at Las Campanas Observatory in Chile.

Transmission spectroscopy relies on detection of stellar light that filters through the planet’s atmosphere as it transits the host star. The transit depth as a function of wavelength is then a combination of the light blocked by the optically thick part of the planet and the scattering/absorption effects on starlight that passes through the atmosphere. When the stellar light is absorbed or scattered, the transit depth becomes larger, due to additional stellar light being removed from our line of sight. By precisely measuring the transit depth as a function of wavelength, we can probe the composition of the atmosphere based on absorption and scattering features; particularly allowing constraints on the mean molecular weight, molecular and atomic atmospheric constituents, and the presence of clouds or other scattering particles. The expected strength of a feature due to absorption and scattering scales with the planet’s atmospheric scale height: a function of the planet’s limb temperature divided by its surface gravity and atmospheric mean molecular weight. For these reasons, a typical good target for transmission spectroscopy is a planet with a high limb temperature, low atmospheric mean molecular weight, and/or a low gravity.

Observations of most exoplanet atmospheres with this method return spectra suggesting either clear atmospheres showing evidence of atomic and/or molecular absorption with the full absorption profile present, or cloudy/hazy atmospheres exhibiting few or diminished absorption features with possible evidence for scattering slopes appearing as deeper transits at shorter wavelengths. At the optical wavelengths we probe in this work, the primary source of scattering is expected to be Rayleigh scattering, which has a wavelength dependence of $\lambda^{-4}$. This corresponds to a stronger effect at shorter, bluer wavelengths resulting in deeper transits as more light is scattered from our line of sight at the blue end of the spectrum. Meanwhile, the primary sources of absorption at optical wavelengths are the alkali metals sodium and potassium. The presence of their absorption profiles, and the exact shape, gives us information on the composition and properties of the planet’s atmosphere.

Observations that only cover optical or infrared wavelengths are not always able to place unambiguous constraints on atmospheric properties alone. Therefore we are best able to characterize a planet when we combine data from multiple observations at a variety of wavelengths. The Hubble Space Telescope (HST) has been a leading force in infrared transit observations from small, Neptune-like planets (e.g., Ehrenreich et al. 2014; Kreidberg et al. 2014) to large, hot Jupiters (e.g., Vidal-Madjar et al. 2003; Sing et al. 2008). More recently, Tsiaras et al. (2018) and Fu et al. (2017) did a reanalysis of the
**HST** observations for 30 exoplanets in order to provide a uniformly reduced and analyzed sample of planets. At optical wavelengths, numerous ground-based observatories are working on surveys, including the Arizona-CfA-Católica Exoplanet Spectroscopy Survey (ACCESS) group, also at the Magellan telescopes at Las Campanas, with results for GJ 1214 b (Rackham et al. 2017) and WASP-19b (Espinoza et al. 2019), the Gran Telescopio Canarias exoplanet transit spectroscopy survey, currently with results for numerous planets (see Sing et al. 2012; Murgas et al. 2014; Nortmann et al. 2016; Pallé et al. 2016; Parviainen et al. 2016, 2018; Chen et al. 2017a, 2017b, 2018; Murgas et al. 2017), the Gemini Multi-Object Spectrographs at Gemini (Huitson et al. 2017), and FORS2 at the Very Large Telescope (VLT: Nikolov et al. 2016). May et al. (2018, hereafter MOPSS1) is the first paper in our survey. Because telescope time is limited, it is important to make use of all resources available to us to study the atmospheres of new planets, as well as ensure reproducibility of results across telescopes, instruments, and reduction methods.

In this work, we present results for the low-density hot-Neptune HATS-8b from the Michigan Optical Planetary Spectra Survey (MOPSS) at the 6.5 m Magellan Baade Telescope. MOPSS is designed with a goal of creating a catalog of uniformly observed and reduced transmission spectra to better enable comparative exoplanet studies. HATS-8b is the third target in the survey and was selected for its expected transmission signal, as well as the schedulability of transits at Magellan Baade.

In Section 2, we discuss our observational setup and target. Section 3 discusses our reduction pipeline in brief, as well as our noise model and generation of light curves. Section 4 discusses our transmission spectra, as well as any impacts unoccluded starspots may have on our results and the impact of particulates in the atmosphere. Finally, Section 5 presents our conclusions for this work.

## 2. Observations

### 2.1. The Inamori-Magellan Areal Camera and Spectrograph (IMACS) Instrument

IMACS is a wide-field imager and optical multi-object spectrograph located on the 6.5 m Magellan Baade Telescope at Las Campanas Observatory. We use the f/2 camera on IMACS and custom-made observing masks to simultaneously observe our target and a number of calibration stars. The IMACS f/2 CCD consists of eight separate rectangular chips in a $4 \times 2$ arrangement. There is a gap of ~57 pixels between the short edges of the chips, and ~92 pixels between the long edges of the chips.

We use the 300 lines/mm grism at a blaze angle of 17.5°, resulting in theoretical wavelength coverage from 3900 to 9000 Å, but practically, from ~4600 to ~8000 Å. The shortened wavelength coverage on the blue end is due to the use of a blocking filter for light below 4550 Å. The throughput at these wavelengths is low, so we choose this addition in order to eliminate spectral contamination from 7800 to 9000 Å from the grism’s second order. On our first night we did not use this filter, so we do not use wavelengths past 7800 Å in our analysis. Further, the gap between chips occurs at ~7800 Å for our target star, with the main O$_2$ absorption in our atmosphere at ~7600 Å. In our analysis, we skip any bins that contain either of these features.

As mentioned above, we use a custom-made observing mask designed to maximize the number of calibration stars, all aligned in a way to allow the full wavelength span to fall across the chips. The main target is placed on a central chip (see Figure 1). Calibrators were selected based on their magnitudes and spectral type if available, or their color in the common case that a spectral type was not determined. We select those stars that are most similar in color and are within ~0.75 mag of the main target when possible. Each calibrator and the main target is centered in a wide slit (15") with large lengths (20") so that we are not concerned with slit losses and to improve background subtraction. With this setup our resolution is limited by the seeing each night (see Section 2.2 for seeing data). Our observational efficiency was limited by the readout time for the CCD (82 s in fast mode and 1 × 1 binning, 29 s in fast mode and 2 × 2 binning).

### 2.2. The Planet HATS-8b

HATS-8b is an ~1300 K hot Neptune orbiting a G-type star with a V mag of 14.03. Discovered in 2015 (Bayliss et al. 2015), HATS-8b was immediately noted to be an ideal target for transmission spectroscopy. However, as of writing, there are no previous transmission spectra observations in the literature.

HATS-8b was observed on the nights of 2017 July 23 in 1 × 1, binning with exposure times of 300 s, and 72 exposures and 2017 August 11 in 2 × 2 binning, with exposure times of 180 s and 92 exposures. This corresponds to an observational efficiency of 78% and 86%, respectively. Seeing was between ~0.5° and ~1.5° throughout the first night, with the seeing improving as the night went on. Our wide slits mean we were not concerned with slit losses, even at the 1.5° seeing. We were not impacted by clouds or wind throughout the night. During
the second night, seeing was around 0.6–0.7 throughout the night with no cloud coverage. In addition to our main target, we observed an additional seven calibrator stars which are listed in Table 1. We reserve one of the calibrators (star #3) to serve as our check star.

### 3. Data Analysis

#### 3.1. Reduction Pipeline

Our reduction pipeline was developed in Python and is described in detail in MOPSS1. It follows the traditional techniques for spectral reduction. We follow the process outlined in Nikolov et al. (2014) for cosmic-ray removal. We use SpectRes (Carnall 2017) for fast flux-conserving binning when down sampling the spectra to lower resolutions.

Wavelength calibration is done using a second mask with small, 1″ square slits at the locations of each object. We use a HeNeAr lamp and take several frames at the beginning of the night. By measuring shifts in the spectral direction as described in MOPSS1, we can shift the spectrum back to the wavelength frame of the first exposure, which should most exactly match the pixel locations of our arc frames. This paper includes improvements to our treatment of biases introduced due to atmospheric and instrumental effects, as described in the following sections.

#### 3.2. Removing Airmass Trend

Because our red-noise model is best applied to normalized data, we first correct for extinction due to airmass. This process requires fitting for extinction as a function of wavelength following the relationship

$$m_{\text{observed}}(\lambda, t) = m_{\text{true}}(\lambda, t) + k(\lambda)Z(t)$$

where $m_{\text{observed}}$ is the observed magnitude at a given time and wavelength, $m_{\text{true}}$ is the true magnitude of the object, $k(\lambda)$ is the wavelength-dependent extinction coefficient, and $Z(t)$ is the airmass as a function of time. We can use the observed magnitude and airmass from our first exposure and the definition of magnitudes to write Equation (1) as

$$F_{\text{observed}}(t) = F_{Z_0}10^{-k(\lambda)Z(t) - Z_0}/2.5$$

where $F_{\text{observed}}(t)$ is the number of counts detected at time $t$, $F_{Z_0}$ is the number of counts at time $t = 0$, $k(\lambda)$ is the wavelength-dependent extinction, $Z(t)$ is the airmass at time $t$, and $Z_0$ is the airmass at $t = 0$.

For the average $k(\lambda)$ across all objects except the target (the transit event) will bias the fit) and then remove the trend described in Equation (2) from all objects. Figure 2 shows an example of the extinction curve for the white light binning of our check star on night one.

Typically, this trend is addressed simply through the division of the target star by the calibrator star(s). However, because we wish to model the correlated noise component in each star independently, we choose to remove the airmass trend in the manner described here. We find that treating each star independently in our noise model provides a greater precision in our final results.

#### 3.3. Correlated Noise Model

We expect the dominate source of correlated noise in our data to be caused by variations in seeing and the spectra shifting on the chips throughout the night. Though IMACS has very stable pointing, our night-long coverage of the object results in the objects shifting on the chips throughout the night at a measurable level of a few pixels. We extract these shifts during our data reduction process so that we can decorrelate the data against these shifts. The seeing is calculated by converting the spatial FWHM measured when flattening the 2D spectra to 1D, multiplied by the detector’s plate scale of 0.2/ pixel.

In addition to the spectral and spatial shifts and seeing, we decorrelate the data against the background counts as well. We use a linear combination of all of the above parameters fit to the out-of-transit times to predict in-transit data. Our model is described as

$$f = X\beta$$

where $f$ is the data, $X$ is a matrix containing the spatial and spectral positions relative to time = 0, seeing, background counts, and a column of unity values to account for a constant offset, and $\beta$ is an array containing the relative importance of each term. By inverting Equation (3),

$$\beta = (X^TX)^{-1}f,$$

Table 1

| Identifier | R.A. | Decl. | V mag. | R mag. | J mag. |
|------------|------|-------|--------|--------|--------|
| HATS-8     | 19:39:46.08 | -24:44:53.90 | 14.03 | ... | 13.10 |
| Cal #1     | 19:40:14.20 | -25:49:23.23 | 14.47 | 14.22 | 13.39 |
| Cal #2     | 19:39:56.82 | -25:48:59.63 | 13.51 | 13.30 | 12.14 |
| Cal #3     | 19:39:59.75 | -25:46:15.68 | 13.71 | 13.50 | 12.33 |
| Cal #4     | 19:39:57.51 | -25:45:16.27 | 13.53 | 13.27 | 11.81 |
| Cal #5     | 19:39:47.79 | -25:43:09.70 | 14.30 | 14.15 | 12.97 |
| Cal #6     | 19:39:31.70 | -25:41:22.72 | 13.56 | 13.29 | 12.14 |
| Cal #7     | 19:39:07.93 | -25:34:29.86 | 14.46 | 14.21 | 13.41 |

Note: Simbad does not list an R magnitude for HATS-8. See Figure 1 for a visual representation of the layout of the calibrator stars. Star #3 serves as our check star.

Figure 2. Here we plot raw, uncorrected white-light data for our check star as well as an extinction curve derived from the mean extinction coefficient for all calibrator stars. This step removes the overall trend in the data, while keeping each object completely separate for our red-noise models.
To generate our light curves, we first create our master calibrator which consists of all reference stars except the one chosen as the check star. The master calibrator allows us to correct for instrumental effects not captured in our noise model. After applying the master calibrator, a small systematic generally remains in the light curve. Though this trend is smaller than in previous work due to our airmass and red-noise corrections, we still find it necessary to include a baseline fit. For night one, we fit this as a third-order polynomial in time, as detailed in MOPSS1. For night two, we use a second-order polynomial in time due to there being relatively few data points before transit to constrain the fit.

### 3.4. Light Curves

3.4.1. White Light Curves

The white light curves for HATS-8b are generated from 4200 to 8000 Å on night one and 4600–9000 Å on night two. The difference is due to a blocking filter we implemented on night two as described in Section 2.2. The white light curves are used to fit for orbital parameters in the same manner as in MOPSS1. We use Batman (Kreidberg 2015) with a quadratic limb-darkening function, as well as emcee (Foreman-Mackey et al. 2013) to fit for center of transit, period/semi-major axis, inclination of orbit, white-light planet radius, and white-light limb darkening. All orbital parameters are fit with a Gaussian prior defined by the values and errors given in Table 2. We find that our Markov Chain Monte Carlo (MCMC) chains do not converge as easily if we have both the period and semi-major axis as free parameters, and so we maintain the relation between period and semi-major axis by only fitting for period while simultaneously calculating a corresponding semi-major axis based on the stellar mass and radius and their errors cited in Table 2.

In all light curve fits we check for convergence by calculating the autocorrelation time (τ) of our chains for each parameter. We use the autocorrelation function suggested by the emcee package from Goodman & Weare (2010). We run our chains long enough that τ approaches a consistent value regardless of chain length. We find that for all bin sizes (white and binned in wavelength space) all parameters converge to τ ~ 100 steps fairly quickly. Our chains are run at least 500× longer than τ.

For all fits we run an initial short chain and use the resulting reduced χ² to rescale the uncertainties on our light curves such that we obtain a reduced χ² of ~1 on our full production runs. This rescaling accounts for any underestimated uncertainties and produces more reliable uncertainties on the fit transit depth.

3.4.2. Binned Light Curves

We bin the data from each night into bins of width 400, 200, 100, 50, 40, and 20 Å in order to capture the overall shape of the transit at high precision, while also searching for absorption...
features that may be averaged over in wider binnings. For each resultant light curve, we use emcee to fit for $R_p/R_S$ and the two quadratic limb-darkening parameters. We do not fit for orbital parameters as a function of wavelength as they should not have a wavelength dependence. We use the orbital parameters we retrieve from our white light emcee runs. Figure 4 shows the 400 Å binned light curves and their fits from our MCMC runs.

Our initial quadratic limb-darkening parameters are interpolated between the Johnson filter values from Claret & Bloemen (2011). While it is understood that these may not be completely accurate, our use of them as a starting value does not affect our results since we use a noninformative flat prior which allows our walkers to fully explore the parameter space without being biased to our initial guess. We confirm this by also starting white light chains at values of 0.0 for both limb-darkening parameters and the planet radius, which return the same results as those that begin at the Claret & Bloemen values. Because the unconstrained runs take longer to converge, we choose to use the starting guesses from Claret & Bloemen and a more informed initial guess for the planet radius. For this planet, we find that our returned limb-darkening values agree well with those from Claret & Bloemen (2011). Figure 5 shows the theoretical quadratic limb-darkening coefficient values and our fit values for both nights.

4. Results

4.1. Transmission Spectrum

We fit our data from each night independently. We present results here for the 400 Å binnings, which demonstrate the overall scattering slope. We find no definitive evidence of sodium or potassium absorption at any of our finer binnings. Figure 6 shows our transmission spectra and scattering slopes. Table 3 lists our results for both nights.

Our data covers only optical wavelengths, which can only constrain combinations of atmospheric properties by itself. Due to the lack of absorption features, we report only measurements of the strength of the scattering slope. The optical slope we detect is typically a signature of scattering, given by

$$\frac{1}{R_S} \frac{dR_p}{d \ln \lambda} = \alpha \frac{k_B T_{\text{limb}}}{\mu g}$$

first described in Lecavelier Des Etangs et al. (2008), where $R_S$ is the stellar radius, $R_p$ is the planetary radius, $\alpha$ is the power of the wavelength dependence in the scattering cross section ($-4$ for Rayleigh scattering), $k_B$ is the Boltzmann constant, $T_{\text{limb}}$ is the temperature at the limb of the planet, $\mu$ is the mean molecular weight of the atmosphere, and $g$ is the planetary gravity. $1/R_S$ is included on both sides of the equation because transmission spectra are typically plotted as the planet radius relative to the stellar radius.

Our main unknowns in Equation (5) are the atmospheric mean molecular weight ($\mu$) and the limb temperature ($T_{\text{limb}}$). Typical values for $\mu$ range from 2.2 for Jupiter to 2.5–2.7 for Neptune. If the atmosphere of the planet is clear, the gas should produce Rayleigh scattering and $\alpha$ will be equal to $-4$ as on Earth. However, if there exist particles in the atmosphere large enough to produce Mie scattering, $\alpha$ can take on a wider range of values.

Our measured transmission slope on night one, 2017 July 23, is $(1/R_S) (dR_p/d \ln \lambda) = -0.142 \pm 0.024$, ~27 times stronger than that expected for Rayleigh scattering.
than nominal Rayleigh scattering, defined as the right-hand side of Equation (5) with $\alpha = -4$, $T_{\text{limb}} = T_{\text{eq}}$, $\mu = 2.3$, and $g = 464.51 \text{ cm s}^{-2}$ (calculated from the planetary parameters given in Table 2). With these parameters, there is no reasonable combination of $\mu$ and limb temperature to explain the slope at $\alpha = -4.0$. At the equilibrium temperature of the planet and a mean molecular weight of 2.3, we can match the slope with an extremely strong wavelength dependence of $\lambda^{-9.5}$ for scattering.

On night two, the measured slope is $(1/R_3)(dR_p/d \ln \lambda) = -0.057 \pm 0.024$, approximately 40% of that from night one. Prior to searching parameter space for a combination of $\mu$, $T_{\text{limb}}$, and $\alpha$ that matches this slope, we first discuss the effect unocculted starspots may have on the measured scattering slopes.

An important consideration is how uncertainties on planetary properties may affect the nominal Rayleigh slope, which in turn affects our expectations. Taking our parameters and uncertainties from Table 2, we note that $R_{\text{planet}}$ has the highest relative uncertainty. When estimating the Rayleigh slope, planet radius matters only for the planet gravity. This results in a factor of $R_{\text{planet}}^2$. If the true planet radius sits at the edge of the upper error bar, so that $R_{\text{planet}} = 0.996 \times R_{\text{Jupiter}}$, the nominal Rayleigh slope will increase by a factor of 1.3. This is not a significant change when compared to the factor of $\sim 27$ we are looking to explain and so we do not explore this option further.

In addition, HATS-8b is a low-density, low gravity exoplanet, with $\rho = 0.259 \text{ g cm}^{-3}$, 2.6× lower than Saturn. It is possible that the extended atmosphere requires a different treatment for atmospheric models. In particular, Exo-Transmit (Kempton et al. 2017) does not account for variations in scale height with altitude, a potentially important factor for these low-density, inflated planets.

As noted above, we also search for the presence of sodium absorption (5890 Å) and potassium absorption (7665 Å) with our narrow bins. We find that the presence or lack of potassium absorption could not be well established due to the deep O₂ telluric line at $\sim 7600$ Å diluting any signal. We do not find strong evidence of sodium absorption.

4.2. Unocculted Starspots

Although the star HATS-8 is known to be an inactive star from exoplanet discovery observations (Bayliss et al. 2015) and we do not detect an occulted spot during either of the observed transit events, we cannot rule out that the host star has some amount of spot coverage. Particularly because unocculted spots can appear as a scattering slope in transmission spectrum, and our results suggest a stronger than expected slope with differences between the two nights. If the rotational period of the host star is approximately twice the time between two nights. The nominal Rayleigh slope has $\alpha = -4$, $T_{\text{limb}} = T_{\text{eq}}$ (1321 K), $\mu = 2.3$, and $g = g_{\text{planet}}$ (464.51 cm s$^{-2}$).

As noted above, we also search for the presence of sodium absorption (5890 Å) and potassium absorption (7665 Å) with our narrow bins. We find that the presence or lack of potassium absorption could not be well established due to the deep O₂ telluric line at $\sim 7600$ Å diluting any signal. We do not find strong evidence of sodium absorption.

![Figure 5](image_url)

**Figure 5.** Limb-darkening parameters from our MCMC fits. For both, the secondary axis presents feature size in relative scale heights calculated with the equilibrium temperature of the planet and $\mu = 2.3$, which we demonstrate is not representative of the data. Top: results from the night of 2017 July 23. Bottom: results from the night of 2017 August 28. For both, the theoretical treatment for atmospheric models. In particular, Exo-Transmit

![Figure 6](image_url)

**Figure 6.** Top: night one (2017 July 23) transmission spectrum. Bottom: night two (2017 August 11) transmission spectrum. The two nights are plotted separately due to differences in the measured scattering slope. On both panels, the vertical green dashed line at 5890 Å is where we would expect sodium absorption, while the orange dashed line at 7665 Å is where we would expect potassium absorption if they were present (though the features would not show up at the wide binning plotted here). The dashed gray line is the nominal Rayleigh slope and the solid gray line is the fit slope. Both panels include the same slopes for varying $\alpha$ parameters in blue for easy comparison of the two nights. The nominal Rayleigh slope has $\alpha = -4$, $T_{\text{limb}} = T_{\text{eq}}$ (1321 K), $\mu = 2.3$, and $g = g_{\text{planet}}$ (464.51 cm s$^{-2}$).
coverage fraction, \( \eta \), and the relative flux from a spot, \( F_\lambda(\text{spot}) \), compared to the stellar photosphere, \( F_\lambda(\text{star}) \).

\[
\delta_\eta(\lambda) = \delta(\lambda) \frac{1}{1 - \eta(1 - F_\lambda(\text{spot})/F_\lambda(\text{star}))},
\]

(6)

The overall dimming of the star due to unocculted spots can be written as

\[
F_\lambda(\text{star, corrected}) = \eta F_\lambda(\text{star}) + (1 - \eta) F_\lambda(\text{star}) = [1 - \eta(1 - F_\lambda(\text{spot})/F_\lambda(\text{star}))] F_\lambda(\text{star})
\]

(7)

with \( F_\lambda(\text{spot}) \) as the spot contrast given as \( F_\lambda(\text{spot})/F_\lambda(\text{star}) \). When the star dims due to unocculted spots, the transit depth looks relatively larger compared to transits with no unocculted spots. Because the spot’s blackbody spectra peaks at longer (redder) wavelengths, while the star peaks at relatively shorter (bluer) wavelengths, the spot contrast level is higher at shorter wavelengths, and lower at red wavelengths. This is therefore a wavelength-dependent effect, with blue wavelengths more heavily affected than red, resulting in a star-induced slope being injected into the data.

Following Equation (6), we calculate the required \( \delta_\eta(\lambda)/\delta(\lambda) \) to match the observed night one slope to both the nominal Rayleigh slope and the observed slope on night two. Figure 7 shows the corrected/expected slopes (where a ratio of 1 can fully explain the slope) at a variety of spot coverage fractions (\( \eta \)) and \( \Delta T = T_{\text{spot}} - T_{\text{star}} \).

The required spot coverage fraction to fully explain our night one slope versus nominal Rayleigh slope at a \( \Delta T \) of 1500 K is ~80%, much higher than one would expect. HATS-8 is a G star with an age of 5.1 ± 1.7 Gyr (Bayliss et al. 2015), comparable to the Sun. On magnetically active low-mass stars, Jackson & Jeffries (2013) suggest that the spot coverage could be as high at 40% with \( T_{\text{spot}}/T_{\text{star}} = 0.7 \) (similar to our value). Further, long term spot-coverage studies by Alekseev & Kozhevnikova (2018) find spot coverages up to 42% for 13 active G and K stars. In agreement with these literature values for G stars, we can explain the difference between our two nights with a spot coverage fraction of 40% and a \( \Delta T \) of 1500 K. We note, however, that HATS-8 is a slowly rotating G dwarf and aside from metallicity is very similar to our Sun (Bayliss et al. 2015). Typical spot coverage fractions for inactive stars such as the Sun range from 0.05% to 0.5% at solar minimum and solar maximum, respectively. (Bogdan et al. 1988; Solanki & Unruh 2004). Further, if HATS-8 had 40% spot coverage on night one, it is rather unlikely that the observed transit did not exhibit a spot crossing event unless the orbit and rotational axis of the star are very well aligned and the spots are strongly bound to latitudes away from the path of the transit. In addition, a 40% spot coverage fraction on night one is even more unlikely because our two observations are only one month apart. Therefore, because our two slopes are consistent within 1.5\%; we instead move forward by computing a weighted average of the slopes of our two nights. Our weighted slope is then \( (1/R_d \Delta R_d/\Delta \ln \lambda) = -0.091 ± 0.017 \).

4.3. A Clear Atmosphere

With this slope, we explore the range of atmospheric parameters that can explain the observed slope in a clear
atmosphere. In Figure 8 we show a range of possible parameters to satisfy the observed combined scattering slope in our data. Based on the unreasonable parameter values shown in Figure 8, we require a strong wavelength dependence of approximately $\lambda^{-50}$ and a low mean molecular weight atmosphere ($\mu \lesssim 2.0$) to explain our slope. This is inconsistent with a clear atmosphere, where $\alpha$ must equal $-4$. Further, because a $\mu < 2.0$ suggests a large fraction of the atmosphere is atomic rather than molecular (unphysical at these temperatures), we choose to exclude solutions for such low mean molecular weight values.

As described below, we prefer an explanation that involves a portion of the slope due to clouds (see Section 4.4), and the remainder resulting from differences between our expected and realized values of mean molecular weight and the limb temperature.

### 4.4. Clouds and the Scattering Slope

Naturally, the next consideration is that the atmosphere of HATS-8b is not clear, and instead contains scattering particulates of some kind. The well-known hot Jupiter HD 189733b is a natural comparison here, due to its strong optical slope and similar equilibrium temperature (1200–1400 K). A detailed analysis of the optical slope for HD 189733b is

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**Figure 7.** Equation (6) applied to our observed slope for a variety of spot contrast and spot coverage fractions. Top: the corrected slope is divided by the nominal Rayleigh slope. Bottom: the corrected slope is divided by the night two slope. In both panels, the black dashed line denotes the level that would correct our data back onto the nominal Rayleigh slope or night two slope, at a ratio of 1. The higher the value, the further the corrected slope is from the goal slope. We also mark with a red “X” a representative typical set of values and a black “X” the maximum spot coverage and $\Delta T$ we consider in this work; these are the same values on both panels. The shaded gray regions result in a positive slope, and so are considered unallowed. Regardless, it is highly unlikely that a star would have such a high spot coverage and $\Delta T$. We are unable to correct the slope back onto the nominal Rayleigh through unocculted spots alone as demonstrated in the top panel, but we can explain the difference between the two nights.

**Figure 8.** For all frames we show the theoretical Rayleigh slopes (see Equation (5)) divided by the combined measured slope, assuming a clear atmosphere. The thick dashed black line denotes the values that can explain the measured slope (if possible). Dark red lines represent the nominal values. The shaded gray region denotes values of $\mu$ which are unphysical for these temperatures. Top: for a constant $\alpha$ and a range of planet limb temperatures and mean molecular weights. For a suitable range of these parameters, we find no combination that can explain our measured slope. Middle: for a constant mean molecular weight of 2.3 (a value typical of Jupiter) and a range of planet limb temperatures and $\alpha$. For $T_{\text{limb}} = T_{\text{eq}} \approx 1325$ K, an $\alpha \approx -35$ would match the data. Bottom: for a constant limb temperature set to the equilibrium temperature and a range of $\alpha$ and $\mu$ values. The slope is not strongly sensitive to the mean molecular weight, but low values of $\mu$ allow for lower $\alpha$ values.
presented in Pont et al. (2013). As demonstrated in Sing et al. (2016), HD 189733b has the strongest scattering slope among hot Jupiters observed with the Space Telescope Imaging Spectrograph (STIS). Of importance, however, is that Pont et al. (2013) state that the optical slope for HD 189733b can be explained by an \( \alpha = -4 \) Rayleigh scattering slope at a temperature of \( \sim 1300 \) K for particle sizes below 0.1 \( \mu \)m. This is not the case for HATS-8b, as the slope is steeper than \( \alpha = -4 \) even after considering the possibility of an extreme level of unocculted starspots. Therefore we note that the optical scattering slope of HATS-8b is the strongest detected scattering slope to date.

Pinhas & Madhusudhan (2017) explore the effects of a variety of species on the wavelength dependence (\( \alpha \)) of the scattering cross section. In their work, Pinhas & Madhusudhan show that in some cases, the presence of cloud particles can result in a slope as strong as \( \alpha = -13 \).

Of the species Pinhas & Madhusudhan discuss, they suggest that transmission spectra, which show strong optical slopes, are likely to contain sulphide clouds—\( \text{Na}_2\text{S} \), \( \text{MnS} \), or \( \text{ZnS} \). These three species have condensation temperatures of 1176 K, 1139 K, and 700 K, respectively, at 10\(^{-3} \) bar (Wakeford & Sing 2015). It is probable that \( \text{Na}_2\text{S} \) and \( \text{MnS} \) could condense out in the nightside atmosphere of HATS-8b, which has an equilibrium temperature of 1321 K for an albedo of 0. If a large amount of scattering particles are present, we would expect a higher albedo, and therefore lower temperature that allows the condensation of these species. Cloud formation along the limbs is an expected (Parmentier et al. 2016; Roman & Rauscher 2019) consequence of atmospheric dynamics.

Specifically, Pinhas & Madhusudhan find that \( \text{MnS} \) produces the steepest slopes at a modal particle size of 10\(^{-2} \) \( \mu \)m for a cloud scale height (\( H_c \)) equal to the gas scale of \( k_B T_{eq}/(\mu g) \). Under these conditions, one can attain a scattering slope with \( \alpha = -13 \) for a hot Jupiter of \( g = 24.79 \) m s\(^{-2} \), \( \mu = 2.3 \), and a solar abundance of \( \text{MnS} \). The slope models in Pinhas & Madhusudhan (2017) depend on the cloud scale height (a smaller \( H_c \) brings the slope closer to the standard Rayleigh slope), the modal particle size based on their assumed distribution (smaller particles cause steeper slopes), the reference pressure (only varies the absolute depth), the grain abundance, and the molecular abundance of the species. Pinhas & Madhusudhan state that the slopes are insensitive to the gas scale height and the cloud scale height.

Additional condensates at these wavelengths and temperatures may include \( \text{SiO}_2 \), \( \text{Al}_2\text{O}_3 \), \( \text{Fe}_2\text{O}_3 \), \( \text{Mg}_2\text{SiO}_4 \), and \( \text{MgSiO}_3 \) with condensation temperatures of 1725 K, 1677 K, 1566 K, 1354 K, and 1316 K, respectively, at 10\(^{-3} \) bar (Wakeford & Sing 2015). Of these, Pinhas & Madhusudhan find that \( \text{MgSiO}_3 \) can result in the strongest scattering slope, with an \( \alpha \sim -5 \) for small grains (a modal particle size of 10\(^{-2} \) \( \mu \)m) if \( H_c = H \). However, this is not much different from a nominal Rayleigh slope of \( \alpha = -4 \), and insufficient for the scenario we explore here. We note that this large slope may also be a result of a yet to be identified photochemical haze.

In Figure 9 we show the values of limb temperature and mean molecular weight which, combined with \( \alpha = -13 \) for \( \text{MnS} \) clouds and small particle sizes, could explain our data. We plot the same levels as Figure 8 for comparison.

We find that we can explain at most 40% of the observed slope through the inclusion of \( \text{MnS} \) clouds, but only for a warm, low mean molecular weight atmosphere. However, because a \( \mu < 2.0 \) suggests a large fraction of the atmosphere is atomic rather than molecular, for reasonable values of \( \mu \approx 2.0 \), we can at most explain \( \sim 20\% \) of the slope at the equilibrium temperature of the planet.

Finally, in the limiting case that nothing is changing on the star itself, there must be a different explanation for the varying scattering slope we measure. Our two slopes differ by a factor of 2.5, which, following the methods of Pinhas & Madhusudhan (2017), suggests that the cloud scale height is up to 2.5 times larger on night 1. In order to get the strongest scattering slope (\( \alpha = -13 \)) we assume \( H_c = H \), which only gets us within a factor of 2 of matching our data. Invoking an increase in the vertical extent of the cloud to enhance the scattering would require vigorous vertical mixing in the atmosphere, but the change between the two observations would require that the mixing also be time variable, which has not been seen in hot-Jupiter atmospheric simulations, to our knowledge. Therefore, if the particulates in the atmosphere of HATS-8b are composed of small MnS particles, it is not likely that we can explain the difference between the two nights as only an increase in cloud coverage on the terminator.

5. Conclusions

We observed the low-density super-Neptune HATS-8b on two nights during 2017 August and 2017 September. Both data sets show stronger-than-Rayleigh scattering, with significant differences between the two nights, which can possibly be explained by unocculted starspots. After applying a correction to account for this possibility, we find the slope in the data from the combined two nights to be 27 times stronger than a nominal Rayleigh slope at the equilibrium temperature of the planet with a mean molecular weight of 2.3. We are unable to explain this slope with reasonable atmospheric parameters and gas scattering alone, so we explore several options to model the strong slope.

1. We have explored the possible condensates that could contribute to the strong scattering slope detected. MnS clouds with particle sizes no greater than 10\(^{-2} \) \( \mu \)m can result in at most \( \alpha = -13 \). This can explain 20% of our observed slope for a reasonable temperature and mean molecular weight, or up to 40% of the slope if the limb temperature is \( \sim 2000 \) K. No other condensates (based on
work by Pinhas & Madhusudhan 2017 and Wakeford & Sing 2015) produce an $|\alpha| \gtrsim 5$.

2. Uncertainties on planet and stellar parameters can at most account for a factor of 1.3 in the slopes. We discard errors in system parameters as an explanation for the measured transmission slope.

While we cannot completely rule out an instrumental or reduction process systematic, we are confident that they cannot explain the entire slope seen in this work. IMACS has not been previously found to have such a strong blue–red systematic. These are the most recent transits with this instrument currently in the literature, but work by Espinoza et al. (2019) includes transits from 2017 April without strong blue–red biases. We are unaware of any significant instrument work done during the three months between these transit observations. Further, our previous work (May et al. 2018) does not show strong blue–red slopes and uses the same reduction pipeline as this work. MOPSSI presents work that is in agreement with the literature, so we do not expect strong blue–red biases to be a result of our reduction process.

Photometric monitoring of HATS-8 would determine the activity level of the star, allowing a more informed correction for unocculted starspots. Future transits of HATS-8b would confirm if this slope is a time-variable phenomenon, and simultaneous with photometric monitoring, would point to if it is primarily a result of stellar or planetary effects. We recommend future follow up from ground- and space-based telescopes to better explain the atmosphere of HATS-8b and compare results from various sources.

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Facility: Magellan:Baade.

Software: Astropy (Astropy Collaboration et al. 2013), batman (Kreidberg 2015), emcee (Foreman-Mackey et al. 2013), IPython (Pérez & Granger 2007), Matplotlib (Hunter 2007), NumPy (van der Walt et al. 2011), SciPy (Jones et al. 2001), SpectRes (Carnall 2017).

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References

Alekseev, I. Y., & Kozhevnikova, A. V. 2018, ARep, 62, 396
Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., et al. 2013, A&A, 558, A33
Bayliss, D., Hartman, J. D., Bakos, G. Á., et al. 2015, AJ, 150, 49
Bogdan, T. J., Gilman, P. A., Lecerc, I., & Howard, R. 1988, ApJ, 327, 451
Carnall, A. C. 2017, arXiv:1705.05165
Chen, G., Guenther, E. W., Pallé, E., et al. 2017a, A&A, 600, A138
Chen, G., Pallé, E., Nortmann, L., et al. 2017b, A&A, 600, L11
Chen, G., Pallé, E., Weltbanks, L., et al. 2018, A&A, 616, A145
Claret, A., & Bloemen, S. 2011, A&A, 529, A75
Crossfield, I. J. M., & Kreidberg, L. 2017, AJ, 154, 261
Ehrenreich, D., Bonfils, X., Lovis, C., et al. 2014, A&A, 570, A89
Espinoza, N., Rackham, B. V., Jordán, A., et al. 2019, MNRAS, 482, 2065
Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306
Fu, G., Deming, D., Knutson, H., et al. 2017, ApJL, 847, L22
Goodman, J., & Weare, J. 2010, CAMCS, 5, 65
Han, E., Wang, S. X., Wright, J. T., et al. 2014, PASP, 126, 827
Huitson, C. M., Désert, J.-M., Bean, J. L., et al. 2017, AJ, 154, 95
Hunter, J. D. 2007, CSE, 9, 90
Jackson, R. L., & Jeffries, R. D. 2013, MNRAS, 431, 1883
Jones, E., Oliphant, T., Peterson, P., et al. 2001, SciPy: Open Source Scientific Tools for Python https://www.scipy.org
Kempton, E. M.-R., Lupu, R., Owusu-Asare, A., Slough, P., & Calé, B. 2017, PASP, 129, 044402
Kreidberg, L. 2015, PASP, 127, 1161
Kreidberg, L., Bean, J. L., Désert, J.-M., et al. 2014, Natur, 505, 69
Leccavelier Des Etangs, A., Pont, F., Vidal-Madjar, A., & Sing, D. 2008, A&A, 481, L83
Louden, T., Wheatley, P. J., Irwin, P. G. J., Kirk, J., & Skillen, I. 2017, MNRAS, 470, 742
May, E. M., Zhao, M., Haidar, M., Rauscher, E., & Monnier, J. D. 2018, AJ, 156, 122
Murgas, F., Pallé, E., Parvainen, H., et al. 2017, A&A, 605, A114
Murgas, F., Pallé, E., Zapatero Osorio, M. R., et al. 2014, A&A, 563, A41
Nikolov, N., Sing, D. K., Gibson, N. P., et al. 2016, ApJ, 832, 191
Nikolov, N., Sing, D. K., Pont, F., et al. 2014, MNRAS, 437, 46
Nortmann, L., Pallé, E., Murgas, F., et al. 2016, A&A, 594, A65
Pallé, E., Chen, G., Alonso, R., et al. 2016, A&A, 589, A62
Parmentier, V., Fortney, J. J., Showman, A. P., Morley, C., & Marley, M. S. 2016, ApJ, 828, 22
Parviainen, H., Pallé, E., Cheng, G., et al. 2018, A&A, 609, A33
Parviainen, H., Pallé, E., Nortmann, L., et al. 2016, A&A, 585, A114
Pérez, F., & Granger, B. E. 2007, CSE, 9, 21
Pinhas, A., & Madhusudhan, N. 2017, MNRAS, 471, 4355
Pont, F., Sing, D. K., Gibson, N. P., et al. 2013, MNRAS, 432, 2917
Rackham, B., Espinoza, N., Apai, D., et al. 2017, ApJ, 834, 151
Roman, M., & Rauscher, E. 2019, ApJ, 872, 1
Sing, D. K., Fortney, J. J., Nikolov, N., et al. 2016, Natur, 529, 59
Sing, D. K., Huitson, C. M., Lopez-Morales, M., et al. 2012, MNRAS, 426, 1663
Sing, D. K., Vidal-Madjar, A., Désert, J.-M., Lecavelier des Etangs, A., & Ballester, G. 2008, ApJ, 686, 658
Solanki, S. K., & Unruh, Y. C. 2004, MNRAS, 348, 307
Tsiaras, A., Waldmann, I. P., Zingales, T., et al. 2018, AJ, 155, 156
van der Walt, S., Colbert, S. C., & Varoquaux, G. 2011, CSE, 13, 22
Vidal-Madjar, A., Lecavelier des Etangs, A., Désert, J.-M., et al. 2003, Natur, 422, 143
Wakeford, H. R., & Sing, D. K. 2015, A&A, 573, A122