Hazy with a Chance of Star Spots: Constraining the Atmosphere of Young Planet K2-33b

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Received 2022 June 21; revised 2022 October 21; accepted 2022 November 3; published 2022 December 20

Abstract

Although all-sky surveys have led to the discovery of dozens of young planets, little is known about their atmospheres. Here, we present multiwavelength transit data for the super-Neptune sized exoplanet, K2-33b—the youngest (~10 Myr) transiting exoplanet to date. We combined photometric observations of K2-33 covering a total of 33 transits spanning >2 yr, taken from K2, MEarth, the Hubble Space Telescope (HST), and Spitzer. The transit photometry spanned from the optical to the near-infrared (0.6–4.5 μm), enabling us to construct a transmission spectrum of the planet. We find that the optical transit depths are nearly a factor of 2 deeper than those from the near-infrared. This difference holds across multiple data sets taken over years, ruling out issues of data analysis and unconstrained systematics. Surface inhomogeneities on the young star can reproduce some of the difference, but required spot coverage fractions (>60%) are ruled out by the observed stellar spectrum (<20%). We find a better fit to the transmission spectrum using photochemical hazes, which were predicted to be strong in young, moderate-temperature, and large-radius planets like K2-33b. A tholin haze with CO as the dominant gaseous carbon carrier in the atmosphere can reasonably reproduce the data with small or no stellar surface inhomogeneities, consistent with the stellar spectrum. The HST data quality is insufficient for the detection of any molecular features. More observations would be required to fully characterize the hazes and spot properties and confirm the presence of CO suggested by current data.

Unified Astronomy Thesaurus concepts: Exoplanet atmospheres (487); Transit photometry (1709); Open star clusters (1160); Exoplanet evolution (491); M dwarf stars (982); Markov chain Monte Carlo (1889); Starspots (1572)

1. Introduction

The study of exoplanet atmospheres has progressed at a tremendous pace in the last decade due to the high-sensitivity spectroscopic observations covering secondary-eclipse spectroscopy, high-resolution Doppler spectroscopy, and direct-imaging spectroscopy. Transmission spectroscopy, a measurement of the planet radius as a function of the wavelength, has enabled the detection of a range of atomic and molecular species (e.g., Seager & Sasselov 2000; Brown 2001; Hubbard et al. 2001; Huitson et al. 2013; Sing et al. 2015, 2016). Detecting such molecules can provide information about the planet’s formation and migration history, although complexities in the planet and disk properties can make such detections difficult to interpret.

For example, planets formed beyond the snow line will have an atmosphere that is carbon-rich (an enhanced C/O) compared to planets formed closer in (Öberg 2011; Booth et al. 2017; Booth & Ilee 2019).

Measurements of young exoplanet atmospheres offer a more direct correlation to the disk, which is unadulterated by later-stage evolution. However, the majority of planets that have had their atmosphere characterized are mature (>1 Gyr), or have unconstrained ages. This is because young planetary systems with precise ages are rare (usually limited to those in young associations, e.g., Mann et al. 2016a; Newton et al. 2019; Bouma et al. 2020; David et al. 2019; Obermeier et al. 2016) and are harder to detect due to stellar variability. Only in the last decade has there been a significant increase in the number of known young planetary systems. This has been driven by improvements in near-infrared radial velocities (e.g., Johns-Krull et al. 2016), mitigation of stellar variability (e.g., Donati et al. 2017; Rizzuto et al. 2017), as well as NASA’s K2 (Howard et al. 2014) and the Transiting Exoplanet Survey Satellite (TESS; Ricker 2014) missions surveying nearby young clusters and associations.

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Only three young (<1 Gyr) exoplanets have had their atmospheres characterized through transmission spectroscopy: K2-25b, Kepler 51b, and Kepler 51d—all of which are adolescent (≈500–700 Myr) and may be in the midst of undergoing thermal contraction. Statistical analyses of Kepler planet candidates suggest that most planets larger than 1.6 R⊕——as is the case for the aforementioned planets——have an extended envelope with a low mean molecular weight (e.g., of H/He; Rogers 2015) and therefore were predicted to have a large scale height, resulting in strong spectral features. However, all three planets showed featureless transmission spectra (Thao et al. 2020; Libby-Roberts et al. 2020), which were interpreted as ongoing atmospheric mass loss (expected in such young systems) leading to dusty atmospheric outflows with small dust grains (Wang & Dai 2019) or high-altitude photochemical hazes (Gao & Zhang 2020). The small particle size leads to a lower opacity (and hence shallower transit) in the near-infrared (NIR) compared to the optical. Grains or hazes also inflate observed radii (Lammer et al. 2016; Cubillos et al. 2017) and weaken the spectral features. Gao & Zhang (2020) showed that this effect is strongest on young, low-mass planets with a moderate or low equilibrium temperature. Additional objects and broader-wavelength coverage could confirm these predictions.

A recurring challenge in interpreting transmission spectra is the contamination by star spots and faculae (Rackham et al. 2017). Spots can change the observed signal, whether or not the planet crosses them. In the case of unocculted spots, the transit chord will be brighter than the stellar average, leading to a deeper transit with increasing spot coverage and contrast even for fixed planet size. As spot contrast depends on the wavelength, such unocculted spots can introduce features and produce haze-like variations in the transmission spectrum that are not present in the planet. Barclay et al. (2021) showed that spots alone can explain the observed H2O features seen in the transmission spectrum of K2-18 b (Benneke et al. 2019; Tsiaras et al. 2019). The imprint of the star on the planet’s spectrum is particularly concerning for young planets, as spot coverage fractions are statistically higher for young stars (Morris 2020; Luger et al. 2021a).

To understand the evolution and formation of planetary atmospheres, a greater sample size of young planets——particularly new-born planets——need their atmospheres to be characterized. To this end, we explore the atmospheric transmission spectrum of the youngest transiting exoplanet to date, K2-33b (David et al. 2016; Mann et al. 2016b). This ≃10 Myr, super-Neptune-sized exoplanet orbits a late-type pre-main-sequence M3.5 dwarf in the Upper Scorpius OB Association every 5.42 days. Its youth, moderate equilibrium temperature (∼770 K), and abnormally large radius (5R⊕ in the optical wavelengths; Figure 1) make it an ideal target for strong haze detection. We combined 14 transits from the discovery K2 data with 7 transits taken from the MEarth survey, 10 transits taken from Spitzer, and a partial transit taken with the Hubble Space Telescope (HST).

The paper is presented as follows. Section 2 describes our observations and data reduction. Using the precise parallax from Gaia, we update K2-33’s stellar parameters in Section 3.

We utilize this information in our fit to the transit light curve, as described in Section 4. Due to the planet’s youth, we discuss the effect of surface inhomogeneities on the transmission spectrum in Section 5. In Section 6, we investigate photochemical hazes inferred from the transmission spectrum of K2-33b. In Section 7, we conclude with a brief summary of our results.

2. Observation and Data Reduction

We collected 33 total transits of K2-33b obtained from 2014 to 2017 taken by K2, the MEarth Project, the Spitzer Space Telescope, and the HST. The combined data sets span from the visible to the near-infrared (0.64–4.5 μm). The details of each data set are summarized in Table 1.

2.1. K2

The K2 light curve covered 14 transits from 2014 August 23 to 2014 November 13 (UT). We used the K2 data with extraction and reduction as described in one of the discovery papers (Mann et al. 2016b). To briefly summarize, following Vanderburg et al. (2016) and Mann et al. (2016a), we derived a correction to the raw light curve using least-square minimization to simultaneously fit for low frequency variations from stellar activity, the Kepler flat field (Vanderburg & Johnson 2014), and the transits of K2-33b. As shown in Grunblatt et al. (2016), this simultaneous fit was required to avoid biasing both the flat-field correction and the resulting transit depth; the bias is larger for highly variable stars like K2-33.

Unlike Mann et al. (2016a), we did not apply our initial least-squares stellar variability fit before passing it to our transit analysis (Section 4). We instead included the final stellar variability fit as part of the Markov chain Monte Carlo (MCMC) analysis in the form of a periodic Gaussian process (GP) kernel (Section 4). While the initial variability fit is consistent with that derived from our transit analysis, the stellar signal is large enough on transit timescales so the earlier fit may yield underestimated errors on the transit parameters.

15 While there are several young planets (β Pic b, 51 Eridani b, HR 8799 b; Chilcote et al. 2017; Samland et al. 2017; Lee et al. 2013) with direct spectroscopy, these are more massive and at wider separations (≫1 au) than the planet transit survey, they likely have a different formation history.
Following reduction, we decided to remove two transits from our analysis, resulting in only seven transits. The two transits were removed because: (1) the data taken on 2016 July 17 (UT) only had 1.5 hr of usable data near ingress; (2) the data taken on 2017 May 22 (UT) showed two sudden changes in flux during the transit, which is likely due to the instrument’s meridian fit and a later halt in data from MEarth-South, or a poorly timed flare. For the latter transit, it was difficult to remove or mitigate these problems because this transit did not contain an egress, and our GP model could not simultaneously fit for such effects.

### 2.3. Spitzer

We obtained 10 full transits of K2-25b, 5 in 3.6 μm (Channel 1) and 5 in 4.5 μm (Channel 2), taken by the InfraRed Array Camera (IRAC; Fazio et al. 2004) on the Spitzer Space Telescope (Werner et al. 2004). Observations were executed over the period 2016 November 08 to 2017 November 29 (Program ID: 13037, PI: A. Mann). Two additional transits were also taken in each band for another program (Program ID: 11026, PI: M. Werner), but were not included in this analysis. All Spitzer data analyzed here used the 32 × 32 pixels subarray mode, with each image taken as a 2 s exposure. Each transit consisted of a ∼24 minute dither, a ∼360 minute stare of the full-transit and out-of-transit baselines, followed by another ∼7 minute dither. The initial dither allows an initial settling time at the new pointing position. For the long stare, we used the peak-up pointing mode, which keeps the star stable on a 0.5 × 0.5 pixel box region of the IRAC CCD with relatively uniform sensitivity (the “sweet spot,” Ingalls et al. 2012, 2016).

We first processed the flat-fielded and dark-subtracted basic calibrate data (BCD) images produced by the Spitzer pipeline using the Photometry for Orbits, Eccentricities, and Transits (POET; Stevenson et al. 2012; Campo et al. 2011)\(^\text{18}\) pipeline to create systematics-corrected light curves. The process includes masking and flagging bad pixels, and calculating the Barycentric Julian Dates for each frame. The center position of the star was fitted using a two-dimensional, elliptical Gaussian in a 15 pixel square window centered on the target’s peak pixel. Simple aperture photometry was performed using a radius of 2.0 to 4.0 pixels, in increments of 0.25 pixels, with an inner sky annulus set to 7 pixels, and an outer sky annulus set to 15 pixels. We selected to set the radius to 2.25 pixels for both channels as it minimizes the standard deviation of the normalized residuals (SDNR). Additional reduction was done simultaneously with fitting the transit and is described in Section 4.

### 2.4. Hubble

HST observed a single transit of K2-33b using the Wide Field Camera 3 (WFC3) on 2017 May 23 (ID: 14887; PI: B. Benneke), spanning six 30 minute spacecraft orbits. Observations used the G141 grating, which provided a wavelength coverage of 1.1–1.7 μm and was taken in the 256 × 256 subarray mode to reduce overhead times with the NSAMP = 7 and SAMP–SEQ = SPARS25 readout settings. In the beginning of the observations, a direct (nondispersed) image of K2-33 was taken in the F139M filter for calibration purposes. Afterwards, a total of 95 spectroscopic images were taken in

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\(^\text{18}\) https://github.com/kevin218/POET

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### Table 1

**Observation Log**

| Telescope     | Filter/Grisn | Transit Number | UT Start Date |
|---------------|--------------|----------------|---------------|
| K2 Campaign 2 | Kepler       | 1-14\(^b\)     | 2014 Aug 03   |
| MEarth-North  | RG715        | 99\(^c\)        | 2016 Feb 16   |
|               |              | 104\(^d\)       | 2016 Mar 14   |
|               |              | 106\(^d\)       | 2016 Mar 25   |
|               |              | 111             | 2016 Apr 21   |
|               |              | 122\(^e\)       | 2016 Jun 20   |
|               |              | 186             | 2017 Jun 02   |
|               |              | 188\(^e\)       | 2017 Jun 13   |
| MEarth-South  | RG715        | 104\(^d\)       | 2016 Mar 14   |
|               |              | 111             | 2016 Apr 21   |
|               |              | 186             | 2017 Jun 02   |
|               |              | 188\(^e\)       | 2017 Jun 13   |
|               |              | 191\(^e\)       | 2017 Jun 29   |
| Spitzer/IRAC | Channel 1    | 148             | 2016 Nov 08   |
|               |              | 150             | 2016 Nov 19   |
|               |              | 188             | 2017 Jun 13   |
|               |              | 190             | 2017 Jun 24   |
|               |              | 217             | 2017 Nov 18   |
| Spitzer/IRAC | Channel 2    | 153             | 2016 Dec 06   |
|               |              | 186             | 2016 Jun 03   |
|               |              | 187             | 2017 Jun 08   |
|               |              | 191             | 2017 Jun 30   |
|               |              | 219             | 2017 Nov 29   |
| HST/WFC3      | G141         | 184             | 2017 May 23   |

**Notes.**

\(a\) There were 14 total consecutive transits taken by K2.
\(b\) Data were already published in the Mann et al. 2016b.
\(c\) Only a partial transit was observed.
the forward direction of the spatial-scanning mode, in which the stellar spectrum is spread along the spatial direction to avoid nonlinearity or saturation. All spectra were taken with a scan rate of $0.037$ s$^{-1}$ for an effective exposure time of $\sim 112$ s to produce a scan $4''38$ in length.

Initial visual inspection of the spectra indicated that the telescope slewed so images from these orbits were discarded.

Figure 2. Left: typical raw HST image from Orbits 1–4. Right: typical raw image from Orbits 5–6. The telescope slewed so images from these orbits were discarded.

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3. Updated Stellar Parameters

Mann et al. (2016b) estimated the effective temperature ($T_{\text{eff}}$), stellar luminosity ($L_*$), stellar radii ($R_*$), and reddening ($A_V$) for K2-33 using the combination of moderate-resolution spectra, magnetic models (Feiden 2016), the transit-fitt stellar density (assuming $e = 0$), and the distance to the Upper Scorpius OB association (de Zeeuw et al. 1999). The more precise distance and photometry from Gaia data release 2 (DR2; Lindegren et al. 2018) enabled us to improve on these parameters.

We followed the methods in Mann et al. (2016b) for estimating the bolometric flux ($F_{\text{bol}}$) and $A_V$ by simultaneously comparing the flux-calibrated spectra of K2-33 to unreddened young templates and observed photometry of K2-33 from Gaia DR2 (Evans et al. 2018), the Two Micron All-Sky Survey (2MASS; Skrutskie et al. 2006), the Wide-field Infrared Survey Explorer (WISE; Cutri et al. 2014), the Sloan Digital Sky Survey (SDSS; Abolfathi et al. 2018), and the AAVSO All-Sky Photometric Survey (APASS; Henden et al. 2012). This yielded $F_{\text{bol}} = 2.40 \pm 0.18 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$ and $A_V = 0.89 \pm 0.13$. Adding the Gaia DR2 distance yielded $L_* = 0.146 \pm 0.012 L_\odot$, and using the $T_{\text{eff}}$ from Mann et al. (2016b) and the Stefan–Boltzmann relation gave $R_* = 1.017 \pm 0.057 R_\odot$. These are broadly consistent but more precise than values derived in Mann et al. (2016b).

To update $M_*$, we compared the above photometry to the magnetic model grid from Feiden (2016) using a Gaussian prior on age of $10 \pm 3$ Myr and $A_V$ from our spectral fit above. This yielded $M_* = 0.571 \pm 0.054 M_\odot$. Other model-based parameters ($R_*$, $L_*$, and $T_{\text{eff}}$) were consistent with our spectral analysis, but we selected the empirical parameters above. Using the $R_*$ above and the model-based mass gave a stellar density ($\rho_*$) of $0.54 \pm 0.12 \rho_\odot$. A summary of our adopted stellar parameters used in our transit analysis are listed in Table 2.

We estimated limb-darkening parameters for all observations using the above stellar parameters and the LDTK toolkit (Parviainen & Aigrain 2015), which uses PHOENIX models (Husser et al. 2013) and propagated uncertainties in stellar parameters onto the output limb-darkening values. Different models give different limb-darkening parameters at the $0.04$–$0.08$ level, so we inflated these errors by those values to account for differences between input stellar models. For MEarth, K2, and both Spitzer bands, we opted for a two-parameter limb-darkening value ($g_1$, $g_2$). For HST, we used the nonlinear (four-parameter) limb-darkening formula detailed in Claret (2000; $a_1$, $a_2$, $a_3$, $a_4$). In each case, we used the relevant filter profile from the instrument documentation. To simulate the HST spectral bands, we multiplied the G141 filter profile

Table 2
Updated Stellar Parameters for K2-33

| Parameters | Value                  | Source                  |
|------------|------------------------|-------------------------|
| $A_V$      | $0.89 \pm 0.13$        | This paper              |
| $F_{\text{bol}}$ ($\times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$) | $2.40 \pm 0.18$        | This paper              |
| $R_*$ ($R_\odot$) | $1.017 \pm 0.057$     | This paper              |
| $M_*$ ($M_\odot$) | $0.571 \pm 0.054$    | This paper              |
| $\rho_*$ ($\rho_\odot$) | $0.54 \pm 0.12$       | This paper              |
| $L_*$ ($L_\odot$) | $0.146 \pm 0.012$     | This paper              |
| $T_{\text{eff}}$ (K) | $3540 \pm 70$         | Mann et al. (2016b)    |

19 https://github.com/acl-exoplanets/Iraclis
20 https://hla.stsci.edu/hlaview.html
21 v1.5, which added support for limb-darkening parameters past 5 $\mu$m.
with top-hat profiles corresponding to the limits of each spectral band. The resulting limb-darkening estimates were fed directly into MISTTBORN (K2, MEarth, and Spitzer) or IRAcIS (HST), as described in the next section. A summary of our adopted limb-darkening coefficients used in our transit analysis are listed in Table 5.

4. Transit Fitting

4.1. K2 and MEarth

We fit both the K2 and MEarth data individually using the MISTTBORN (MCMC Interface for Synthesis of Transits, Tomography, Binaries, and Others of a Relevant Nature) fitting code 22 described in Mann et al. (2016a) and in more detail in Johnson et al. (2018). MISTTBORN uses BATMAN (Kreidberg 2015) to generate model transit curves and uses emcee (Foreman-Mackey et al. 2013) to explore the transit parameter with an MCMC algorithm.

With MISTTBORN, we fit four parameters directly relating to the transiting planet: the time of periastron ($T_0$), the orbital period of the planet ($P$), the ratio of the planet radius to the star radius ($R_p/R_*$), and the impact parameter ($b$). For the K2 data, all of these parameters evolved under uniform priors. For the MEarth data, we placed a weak Gaussian prior on $T_0$ and $P$ ($\pm 0.01$ days) to prevent the solution from wandering away from the data; other parameters evolved under uniform priors. An additional parameter, the stellar density ($\rho_*$), allowed us to replace the more common transit duration and impose a Gaussian prior from our stellar parameters in Section 3. For each of the two wavelengths, we fit two linear and quadratic limb-darkening coefficients ($q_1, q_2$) following the triangular sampling prescription of Kipping (2013). Both evolved under Gaussian priors derived from LDTK (see Section 3). We locked the eccentricity ($e$) to zero because the gas drag and gravitational interactions are expected to dampen out eccentricities and inclinations of extremely young planets like K2-33b (Tanaka & Ward 2004). In the case that eccentricity is nonzero, this does change the overall depth, but it does not change the relative depths because all impact parameters will move together.

An important differences between our analysis here and that of Mann et al. (2016b) was that we fit the stellar variability simultaneously with the transit parameters. This change was driven, in part, by cases where our removal of stellar variability would impact the transit, yielding a systematically smaller transit depth than when fitting simultaneously. For example, the transit depths determined by the two discovery papers differed slightly despite using overlapping data (0.23 versus 0.19%; David et al. 2016; Mann et al. 2016b).

To this end, we used the celerite package (Foreman-Mackey et al. 2017) for GP fitting, which has now been incorporated into MISTTBORN. We first tested the “SHOM” kernel, i.e., a mixture of two stochastically driven damped simple harmonic oscillators (SHO) with periods $P$ and $0.5P$. However, we found that the parameters of the second SHO (at half the period) were poorly constrained, which is likely because the primary rotation signal dominates (Nicholson & Aigrain 2022). Instead, we adopted a single SHO fit, which added three free parameters: the log of period ($\log(P_{GP})$), the log of the variability amplitude ($\ln A$), and the decay timescale ($\ln Q$).

When fitting the K2 data, we evolved all GP parameters under uniform priors. For the MEarth data, there is insufficient out-of-transit data to constrain the GP, so we applied a Gaussian prior on $\ln(P_{GP})$ and $\ln A$ based on the output from the K2 fit. As the two data sets are at slightly different wavelengths (0.6 $\mu$m versus 0.8 $\mu$m) the spot-variability amplitude might not be the same (and hence so might be the GP amplitude). However, changes of a factor of 2 in the amplitude prior in either direction did not change the resulting transit depths, most likely because the GP is able to adjust to each transit between the long data gaps between MEarth observations.

For both data sets, we ran MISTTBORN with 100 walkers for 250,000 steps after a burn-in of 50,000 steps. A comparison with the autocorrelation time suggested this was more than sufficient for convergence (Goodman & Weare 2010). We summarize the MISTTBORN output in Table 3. The fit to the K2 data is shown in Figure 3.

4.2. Spitzer

Spitzer’s large intra-pixel sensitivity and pointing jitter can cause the measured flux of a source to vary up to 8%, depending on where it falls on a pixel (Ingalls et al. 2012). However, years of high-precision observations with Spitzer have provided a number of methods to correct for model variations in the photometric response (Ingalls et al. 2016). We tested multiple methods, which include using a high-resolution pixel variation gain map (PMAP; Ingalls et al. 2012) and nearest neighbors (NBR; Lewis et al. 2013), but found the most consistent results using the BiLinearly Interpolated Subpixel Sensitivity (BLISS; Stevenson et al. 2012) mapping technique, which we briefly summarize below. We note that changing to NBR did not change any of the conclusions, only the overall fit quality.

The BLISS mapping technique is provided as an optional part of the POET pipeline. It corrects for both the position-dependent (intra-pixel effect) and time-dependent (ramp effect) Spitzer systematics. The parameters in the BLISS mapping include the grid size of the subpixel sensitivity map, the astrophysical light-curve model (e.g., transit, secondary eclipse), and the ramp model.

For the Channel 1 data, to avoid overfitting, we followed POET’s recommendation of choosing a grid size in which a nearest-neighbor interpolation would not outperform a BLISS interpolation (Stevenson et al. 2012). We tested various grid sizes and selected 0.007 pixels. For the Channel 2 data, we used the most recent fixed intra-pixel sensitivity map from May & Stevenson (2020).

The transit was modeled using the Mandel & Agol (2002) transit model, and several different ramp parameterizations were tested: linear, quadratic, rising exponential, falling exponential, quartic-log + quadratic polynomial, log + linear ramp, and a no-ramp model. For further information about each individual ramp, see Stevenson et al. 2012. For each light curve, we determine the best ramp model based on three metrics: (1) the difference in the predicted $T_0$ value compared to the expected $T_0$, (2) the difference in the predicted transit duration compared to the expected transit duration, and (3) the overall minimal red noise levels in the fit residual, assessed by considering the rms binned residuals as a function of the different bin sizes with the theoretical uncorrelated white noise.

22 https://github.com/captain-exoplanet/misttborn
A small $T_0$ difference, small duration difference, and low rms were all favored. The time-dependent component of the transit model consisted of the mid-transit time ($T_0$), ratio of the planet radius to the star radius ($R_p/R_*$), orbital inclination ($\cos i$), semimajor axis ratio ($a/R_*$), and system flux ($\mu_f$), as well as parameters associated with the ramps (e.g., ramp phase, ramp amplitude, and ramp constant offset). These parameters were explored with an MCMC process, using four walkers with 200,000 steps and a burn-in region of 30,000 steps. The period was fixed to 5.4248 days, based on our analysis of the K2, MEarth, and an initial reduction in the Spitzer data (which provided a subsecond precision period). As recommended by May & Stevenson (2020), temporal binning was not used for Channel 2. The resulting POET fits for each light curve are summarized in Table 4.

A drawback of the POET results is that we could not fit all transits simultaneously. This is particularly important as several of the Spitzer transits yield discrepant depths (Figure 4). To this end, we refit the output light curves from POET with MISTTBORN, as described in Section 4.1. We fit the two channels separately, including all but one transit in each band. The excluded observations were AOR 60658432 from Channel 1 (which had a strong flare) and AOR 60656128 from Channel 2 (which had extremely poor pointing). These two transits also yielded outlier transit depths from POET (see Figure 4).

Unlike with POET, MISTTBORN cannot simultaneously fit for instrumental effects with the transit, so we attempt to account for that by including the GP. We tried several GP kernels, including Matern-3/2 and a simple white-noise term, but found the SHO we used for stellar variability worked as well or better. As the periodic signal in this case is instrumental, not stellar, we allow all GP parameters to evolve under uniform priors (instead of forcing it to match the rotation period, for example). As above, the only transit parameters we place priors on were the limb darkening and stellar density.

The resulting MISTTBORN fits are summarized in Table 3. Other than the depth, the transit-specific parameters were in broad agreement with those from K2 and MEarth. Excluding the two problematic transits, the transit depths from our MISTTBORN fits are in excellent agreement with those from POET. The MISTTBORN fits gave similar or smaller uncertainties than individual POET fits, but still larger than expected from a simple weighted mean of the individual POET fits. We consider the MISTTBORN fits to be more realistic.

Importantly, both the MISTTBORN and POET fits to the data yielded a transit depth ≈ half that from the optical data. This difference was not explainable through the fitting, as it is clear even in the extracted light curves (Figure 5). Further, as we will show in Section 4.3, the effect is seen in the HST data as well.

### 4.3. HST

#### 4.3.1. White Light-curve Fitting

In order to fit the extracted light curves, we must first correct the time-dependent systematics (ramps) introduced by the WFC: (1) a long-term ramp that occurs throughout the visit and typically has a linear behavior and (2) a short-term ramp that occurs during each orbit and typically has an exponential behavior (Tsiaras et al. 2016).

The light curve is fitted using a transit model from PyLightcurve,23 and with an instrumental systematics function $R(t)$ (Tsiaras et al. 2016):

$$R_w(t) = n_w(1 - r_{01}(t - T_0))(1 - r_{02}e^{-r_{01}^2(t - T_0)})$$

where $n_w$ is a normalization factor, $t$ is the time of the data, $T_0$ is the model mid-transit time, $r_{01}$ is the starting time of each HST orbit, $r_{02}$ is the slope of the linear systematic trend, and $r_{01}$ and $r_{02}$ are the coefficients of the exponential systematic trend. As the first orbit ramp (Orbit 2) is steeper compared to the ramps of the subsequent orbits (Figure 6), a different set of the short-term exponential coefficients ($r_{01}$ and $r_{02}$) was used to fit this ramp. Removing these coefficients will correct the rms of the residuals.

Due to only having half a transit and missing both the egress and out-of-transit baseline, we limit our ability to constrain the orbital parameters. Therefore, we locked the inclination ($i$), the ratio of the semimajor axis to the star radius ($a/R_*$), the period ($P$), the argument of periastron ($\omega$), and the eccentricity ($e$) to the values from a combined fit of data from K2, MEarth, and Spitzer. The limb-darkening coefficients ($c$) were fixed to the model-derived values (Table 5).

The only free parameters were the coefficients for the Hubble systematics, the normalization factor ($n_w$), the ratio of the planet radius to the star radius ($R_p/R_*$), and the mid-transit time ($T_0$). These parameters were explored with an MCMC process, using 200 walkers with 40,000,000 steps and a burn-in

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23 https://github.com/ucl-exoplanets/pylightcurve

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| Description                      | Parameter | K2            | MEarth        | Spitzer [3.6] | Spitzer [4.5] |
|----------------------------------|-----------|---------------|---------------|---------------|---------------|
| First Transit Midpoint           | $T_0$ (KBJD) | 2065.692 $\pm$ 0.0025 | 2065.6923 $\pm$ 0.0045 | 2065.6982 $\pm$ 0.0046 | 2065.6954 $\pm$ 0.0079 |
| Orbital Period                   | $P$ (days) | 5.42503 $\pm$ 0.00034 | 5.424832 $\pm$ 2.5 $\times$ 10^{-5} | 5.424851 $\pm$ 2.5 $\times$ 10^{-5} | 5.424862 $\pm$ 4.1 $\times$ 10^{-5} |
| Planet–Star Radius Ratio         | $R_p/R_*$ | 0.04735 $\pm$ 0.00099 | 0.0489 $\pm$ 0.0019 | 0.03545 $\pm$ 0.00086 | 0.03746 $\pm$ 0.00087 |
| Impact Parameter                 | $b$       | 0.19 $\pm$ 0.13 | 0.27 $\pm$ 0.18 | 0.24 $\pm$ 0.21 | 0.22 $\pm$ 0.25 |
| Stellar Density                  | $\rho_*$  | 0.46 $\pm$ 0.066 | 0.527 $\pm$ 0.096 | 0.483 $\pm$ 0.04 | 0.476 $\pm$ 0.038 |
| Limb-darkening coefficient       | $q_1$     | 0.48 $\pm$ 0.083 | 0.401 $\pm$ 0.079 | 0.072 $\pm$ 0.033 | 0.06 $\pm$ 0.027 |
| Limb-darkening coefficient       | $q_2$     | 0.351 $\pm$ 0.046 | 0.286 $\pm$ 0.048 | 0.209 $\pm$ 0.033 | 0.204 $\pm$ 0.034 |
| Log Period                       | $\ln P$   | 1.838 $\pm$ 0.015 | 1.836 $\pm$ 0.015 | 2.65 $\pm$ 0.57 | 0.99 $\pm$ 0.68 |
| Log Variability Amplitude        | $\ln A$   | $-8.96$ $\pm$ 0.26 | $-10.14$ $\pm$ 0.44 | $-13.84$ $\pm$ 1.04 | $-13.93$ $\pm$ 1.12 |
| Log Decay Timescale              | $\ln Q$   | 0.926 $\pm$ 0.007 | 0.048 $\pm$ 0.01 | 6.2 $\pm$ 0.9 | 4.5 $\pm$ 3.9 |
The optical and NIR transit depths; HST and Spitzer both yielded transit depths almost half as deep as the depths from K2 and MEarth. This rules out that the depth difference is due to unconstrained systematics in the data sets. We explored two possible reasons for this difference: spots on the stellar surface (Section 5) and hazes in the planet’s atmosphere (Section 6).

5. The Effect of Surface Inhomogeneities on the Transmission Spectrum

Unocculted spots on the stellar surface can make a transit appear deeper. If the transit chord has fewer spots, the planet will block a statistically warmer (brighter) region of the star. The effect is reversed for unocculted plages. As surface inhomogeneities vary in intensity with the wavelength, the effect is wavelength-dependent and can mimic or complicate transmission spectroscopy of the planet (e.g., Kreidberg et al. 2015; Rackham et al. 2017). Similarly, occulted spots or plages can make the transit shallower or deeper, respectively. We show below that the large difference between the optical and NIR transit depths could be explained if more than half (>60%) of the stellar surface is covered in cool spots and the transit chord is clear, or if the transit chord is heavily populated by plages while the rest of the star is clear.

5.1. Planet Crossing Over Spots and Plages

If the planet were crossing a significant number of spots or plages during transit, we would expect to see two effects. First, we would see distortions in the light curve during transit (e.g., as seen for HAT-P-11 in Morris et al. 2017). While this would be a challenge to see with long-cadence (cadence = 1765.5 s) data from K2, it should be readily visible in the high-cadence (cadence = 60 s) MEarth data. The second effect should be variations in the transit depth between transits due to differences between the stellar and orbital periods; each transit crosses a slightly different region of the star, changing the properties of the occulted surface. Changes in the underlying spot pattern are also visible in the the K2 light curve (Figure 3), likely due to differential rotation (as noted in David et al. 2016). However, individual transit depths are consistent with each other within measurement errors; the scatter in the light curve during transit is the same as outside of the transit, and there are no clear morphological changes in the MEarth or K2 data during transit. Planet-crossing plages would also need to be long-lived to explain both the K2 and MEarth data, which spans 2.7 yr and has more than 150 full stellar rotations.

Due to the reasons above, we assumed that the transit chord is pristine for the rest of our analysis and focused on the effects of unocculted spots on the rest of the star. We note that...
Table 4
Best-fit Parameters for Spitzer Data Using POET

| AOR       | Transit Num | BIC Value | Best Ramp                | T\(_\text{eff}\) [BJD] | cosi | a/R\(_\text{e}\) | System Flux [\(\mu\)Jy] | R\(_p)/R\(_\text{e}\) |
|-----------|-------------|-----------|--------------------------|------------------------|------|--------------|--------------------------|----------------|
| 3.6 \(\mu\)m |
| 60655360  | 148         | 10773     | quadratic                | 2457701.57             | 0.07 | 8.46         | 31325                    | 0.037 ± 0.004 |
| 60658432  | 150         | 10765     | quadratic                | 2457712.42             | 0.07 | 8.79         | 31172                    | 0.063 ± 0.002 |
| 60661504  | 188         | 14433     | quadratic-log-+quartic polynomial | 2457918.57             | 0.00 | 10.52        | 30291                    | 0.035 ± 0.003 |
| 60664576  | 190         | 14396     | linear                   | 2457929.41             | 0.03 | 10.00        | 29864                    | 0.036 ± 0.002 |
| 60664576  | 217         | 14407     | quadratic                | 2458075.89             | 0.07 | 8.63         | 30618                    | 0.035 ± 0.002 |
| 4.5 \(\mu\)m |
| 60656128  | 153         | 10754     | quadratic                | 2457728.70             | 0.00 | 10.50        | 19369                    | 0.050 ± 0.003 |
| 60659200  | 186         | 14406     | log                      | 2457907.72             | 0.07 | 8.61         | 19550                    | 0.037 ± 0.004 |
| 60662272  | 187         | 14390     | quadratic                | 2457913.15             | 0.00 | 10.27        | 19662                    | 0.038 ± 0.003 |
| 60665344  | 191         | 14390     | rising-exponential       | 2457934.85             | 0.07 | 8.54         | 19677                    | 0.037 ± 0.002 |
| 60668416  | 219         | 14388     | rising-exponential       | 2458086.74             | 0.07 | 8.80         | 19664                    | 0.041 ± 0.001 |

Table 4: Best-fit Parameters for Spitzer Data Using POET

5.2. Unocculted Spots

5.2.1. What Kind of Spot Coverage Can Reproduce the Observed Transit Depths?

Faculae have shown to have less of an effect in the stellar variability in the Kepler light curves, justifying our reasons for not including them in our analysis (Johnson et al. 2021). To estimate what kind of spots are required to reproduce the observed transit depths, we followed a modified procedure from Rackham et al. (2017), Thao et al. (2020), and Libby-Roberts et al. (2022). To summarize, we assumed the surface can be described by a simple two-temperature model of three parameters: the surface temperature (\(T_{\text{surf}}\)), the spot temperature (\(T_{\text{spot}}\)), and the fraction of the star with \(T_{\text{eff}} = T_{\text{spot}}(f_S)\).

As explained by Libby-Roberts et al. (2022), \(f_S\) is actually time variable for these two reasons: (1) it represents the surface seen from Earth, and therefore \(f_S\) changes as the star rotates; and (2) the overall surface spot pattern can change with time. We ignore this effect for now. As we will show in Section 5.2.2, the overall spot coverage needs to be relatively stable over the rotational period, or the light curve would show more significant variability in the K2 data.

We built our synthetic star using surface brightness estimates from PHOENIX/BT-SETTL atmosphere models (Allard et al. 2013, 2012). For both the spots and surface, we assumed solar abundances and adopted a simple linear interpolation between grid points in \(T_{\text{eff}}\). Surface gravity (\(\log(g)\)) has negligible effects on the spectrum at the resolution considered here, so we fixed it to 4.5. We adopted a single transit depth (\(D\)), which we would measure for an unspotted star (i.e., a featureless spectrum), although this can also work as a normalization constant for a model spectrum (as we do in Section 6). We blocked light only from the region described by \(T_{\text{surf}}\), which we then combined with the spotted regions to compute an observed transit depth after normalizing to the combined spectrum with no light blocked (the out-of-transit spectrum). This yielded an observed transit depth at any wavelength, which we convolved with the relevant filter profile (K2, MEarth, HST, and Spitzer) to compare to the observed data. We eliminated one free parameter by fixing \(T_{\text{surf}}\) to the temperature assigned from the optical spectrum (3540 K; Section 3). This assumption was imperfect, as it is possible to reproduce the observed spectrum with significant spot coverage and/or cooler spots while increasing \(T_{\text{surf}}\). However, allowing \(T_{\text{surf}}\) to go to higher values while forcing it to reproduce the observed spectrum did not significantly change the answer, as we explore further in Section 5.2.3.

We compared our model to the observed transit depths data within an MCMC framework using emcee (Foreman-Mackey et al. 2013). Each of the three free parameters evolved under uniform priors, with physical limits \((0 < f_S < 1 \text{ and } 0 < D < 1)\), and those imposed by our model grid (1500 K \(< T_{\text{spot}} < 4000\) K). We ran the chain with 12 walkers for 100,000 steps, following a burn-in of 10,000 steps. This was sufficient for convergence based on the autocorrelation time.

We show the best-fit transmission spectrum in Figure 8, and a subset of the posteriors in Figure 9. The results suggest that we can explain the deeper optical transits if \(71\%_{-6}^{+14}\) of the star is covered in spots with \(T_{\text{spot}} = 2750 \pm 260\) K. Such large spot coverage fractions are rare, even for young stars (Morris 2020), but they have been observed on stars in star-forming regions (e.g., Gully-Santiago et al. 2017) so we could not dismiss this option on statistical grounds alone. We explore constraints provided by the transit light curve and stellar spectrum in the next two sections.

The star is likely to harbor spots with a range of temperatures. However, adding an additional spot with a different temperature and coverage fraction did not alter our conclusions: the preferred solution is (1) to have both spots of similar temperatures, or (2) to have one of the spots be equivalent to the result above, and the other being either too cold or possessing too small a coverage fraction to impact the final result. In either case, the combined effect is not significantly different from the single spot temperature model. The conclusion is still that the spot coverage fraction must be >60% to explain the observed transit depths.

5.2.2. Spots from the Light Curve

Surface inhomogeneities imprint on the stellar light curve as the star rotates, with spots moving into darker regions of the
stellar disk before disappearing from view. All else being equal, larger/more spots and plages will lead to higher-amplitude variation. As discussed in Luger et al. (2021b), it is difficult to use this relation in reverse to infer spot coverage fractions from light curves because many different spot coverage fractions and distributions can produce similar light curves. Rather than trying to use the light curve to constrain the spot coverage fraction, we instead attempted to explore what kind of surface patterns could reproduce both the light curve and the observed transit depths.

To this end, we used Fleck (Morris 2020), which produced light curves from simple limb-darkened spotted stars. We compared the model-generated light curves to the light curve within an MCMC framework using emcee. We restricted our analysis to the K2 curve; the HST and Spitzer curves contain too little out-of-transit data, and the MEarth out-of-transit monitoring is not precise enough to add significant constraints above the K2 data. The K2 data likely...

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25 https://github.com/bmorris3/fleck
have long-term systematics, which we remove by fitting the light curve with a low-order polynomial before comparing it to the Fleck-generated model.

We fixed the rotation period to that from Mann et al. (2016b) and restricted the spot contrast to be consistent with the results from Section 5.2.1. In particular, we convolved the K2 filter profile with BT-SETTL models (described in Section 5.2.1) using the assumed $T_{\text{surf}}$ and posterior $T_{\text{spot}}$ values. This yielded a spot contrast for every value of $f_S$ (also from the posterior), which we included in our likelihood. The result is that the contrast was fixed based on the model $f_S$ value derived from the spot radii. This also effectively limited $f_S$, as values $\lesssim 0.6$ had no corresponding contrast that could reproduce the transmission spectrum. The goal was to determine if the high spot coverage fraction implied by the transmission spectrum could reproduce the light curve (and what would the resulting star look like).

There were three fit parameters for each spot: latitude, longitude, and radius. Each parameter evolved under uniform priors with physical limits (e.g., latitude from $-90$ to $90$ degrees). We tested using three to seven spots; the results did not change in any way relevant to our analysis.

We highlight some representative results in Figure 10. In order to simultaneously reproduce the low variability ($<2\%$) in the light curve and the inferred large spot coverage, highly symmetric polar spots that cover a large portion of the star are required. Previous studies have suggested the presence of polar spots in M dwarfs (Doyle et al. 2018; Roettenbacher & Vida 2018) so we cannot rule this possibility out. Most often the model prefers either a slight asymmetry in the polar spots and/or 1–3 smaller equatorial spots to explain the perturbation offset from the major sinusoidal pattern seen in the light curve (likely spot clusters at different longitudes). This is consistent with earlier findings that large spot coverage fractions can still produce relatively low variability (Johnson et al. 2021).

As expected, it was possible to recreate a star that reproduced the light curve and could explain the transit depths using a featureless planetary spectrum; a single-band light curve was not uniquely constraining. However, the resulting stellar surface had to be finely tuned to contain mostly polar spots. In Section 5.2.2, we assumed that $f_S$ was not a time variable; while this assumption was not totally correct, the light curve results suggested that it is reasonable nonetheless. The only way to reproduce the low photometric variability was with mostly polar and/or symmetric spots (Figure 10), which, by definition, produce small temporal changes in $f_S$. Or, stated in another way, if $f_S$ changed at $\geq 5\%$, this would be evident in the light curve, validating our simplification in Section 5.2.2.

### 5.2.3. Spot Properties from the Observed Stellar Spectrum

Large cool spots change both the spectral shape and the strength of molecular features, as we show in Figure 11. In extreme cases, cool spots can generate molecular features that should otherwise not be present for a homogeneous surface. Numerous earlier studies have taken advantage of this to study the spot properties of young stars (e.g., Petrov et al. 1994; Fang et al. 2016), likely providing more accurate pictures of stellar surfaces than light-curve-based metrics alone (e.g., Gully-Santiago et al. 2017).

As the effect of spots on the observed spectrum is strongly wavelength-dependent (e.g., the cooler region has a smaller overall contribution in the optical), it can be detected in spectra with broad wavelength coverage. The optical data mostly probes $T_{\text{surf}}$ and reddening, while the NIR data are more sensitive to changes in $T_{\text{spot}}$ and $f_S$. We used the moderate-resolution ($R \approx 1000–2000$) spectra from Mann et al. (2016b)
to explore the spot properties for K2-33. The spectra were built from two overlapping data sets, one from the SNIFS spectrograph (0.32–0.95 μm; Lantz et al. 2004) and one from the SpeX spectrograph (0.7–2.4 μm; Rayner et al. 2003). Both spectrographs provide excellent relative flux calibration (2%–4%; Rayner et al. 2009; Mann et al. 2013) ideal for this work. We refer readers to the discovery paper (Mann et al. 2016b) for more details on the observations and reduction of these data.

We fit the spectra with a two-temperature model (e.g., Gully-Santiago et al. 2017; Morris et al. 2019) derived from BT-SETTL atmosphere models. In total, we had 13 free parameters for the fit. The first three, $T_{\text{surf}}$, $T_{\text{spot}}$, and $f_{\text{S}}$, were as described in Section 4, but without any limit on $T_{\text{surf}}$ and an additional requirement that $T_{\text{spot}}$ be at least 50 K less than $T_{\text{surf}}$. Six additional parameters described the normalization and slope of the blue optical, red optical, and NIR data ($a_1$, $a_2$, $b_1$, $b_2$, $c_2$, and $c_2$). These were needed because the SNIFS blue end, SNIFS red end, and SpeX data were calibrated separately (SNIFS arms are separated with a dichroic at 0.54 μm); as a result, the three regions are often offset at the 2–5% level even after calibration (Mann & von Braun 2015). Two additional parameters handle small wavelength offsets between the data and models, one for the optical/SNIFS data ($\lambda_{\text{off, opt}}$) and one for the NIR/SpeX data ($\lambda_{\text{off,NIR}}$). The remaining two parameters were extinction ($A_v$) and a parameter to handle underestimated uncertainties or other systematics in the spectra ($\sigma_f$), which we treated as a fractional error added in quadrature with measurement errors.

Following Mann et al. (2013), we masked specific regions where the models poorly reproduced observed spectra of stars with empirically determined temperatures (from long-baseline interferometry). No other direct constraints were put on the data.

All parameters were fit using emcee. We placed Gaussian priors on the slope parameters ($a_2$, $b_2$, $c_2$) based on estimates of the flux calibration from Mann et al. (2013) and Rayner et al. (2009). All other parameters evolved under uniform priors. We ran the MCMC chain with 100 walkers for 500,000 steps,
which was more than sufficient for convergence based on the autocorrelation time.

We added the resulting \( f_S \) and \( T_{\text{spot}} \) distributions in Figure 9. As expected, the spot temperatures were unconstrained when the spot fraction was low, and the spot fraction was unconstrained when \( T_{\text{spot}} \) was close to \( T_{\text{surf}} \). The general result was that either spots must be relatively warm \( \geq 3000 \) K or cover a small fraction (\(<10\%) of the star.

We performed a similar fit using the high-resolution IGRINS spectra from Mann et al. (2016b). IGRINS covers most of the \( H \) and \( K \) bands with a resolution of \( \approx 45,000 \). Nearly identical data were used effectively in Gully-Santiago et al. (2017) to study the spot properties of a young star. Of the 54 IGRINS orders, we focused on the 4 with the highest \( S/N \), lowest telluric contamination, and highest sensitivity to spots (e.g., right panel of Figure 11). The fit parameters were similar to what we used for the moderate-resolution data, but each order had separate flux calibration terms, a common wavelength offset, and we did not fit for \( \lambda \nu \) which has a minor impact on the NIR data. We add an additional parameter \( (b) \), which accounts for both rotational and instrumental broadening as a single Gaussian width. All parameters were fit under uniform priors, with \texttt{emcee} using 100 walkers and 100,000 steps.

The results from the IGRINS orders were broadly consistent with that from our SNIFS+SpeX data; the fit strongly prefers either \( T_{\text{surf}} \approx T_{\text{spot}} \) or \( f_S < 20\% \). The major differences from our SNIFS+SpeX results were that the IGRINS fit preferred a warmer \( T_{\text{surf}} \) (and hence warmer \( T_{\text{spot}} \)) and that the fit to IGRINS data allowed for lower-temperature (\(<2500 \) K) spots with higher surface coverage fractions (up to \( \approx 20\%) \) than the fit to the SNIFS+SpeX data.

A comparison between the posteriors from the fit to the stellar spectrum and the fit to the transmission spectrum (Figure 9) had no overlap. The fit to the stellar spectrum rules out all possible \( T_{\text{spot}} \) and \( f_S \) combinations that could explain the observed transmission spectrum. This was true regardless of the data set used.

While the SNIFS+SpeX results are more precise, we used the fit from IGRINS for further analysis. The main reason was that tests on similar spectra (same instrument and setup) for other stars suggested that the SNIFS+SpeX spectra were sensitive to the relative flux calibration. While both SNIFS and SpeX have excellent flux calibration (Mann et al. 2015), K2-33 was observed at an air mass of \( >1.4 \), around which the blue end of the (SNIFS) data become less reliable (Buton et al. 2013). Further, IGRINS data were obtained over many epochs (yielding similar results regardless of which IGRINS spectrum we used), and the data were contemporaneous with the MEarth and Spitzer transits. Overall, we consider the IGRINS fit to be both more accurate and more conservative.

We show a fairer comparison of the spectroscopic results to the transit data in Figure 8. For this, we randomly drew \( T_{\text{surf}} \) and \( T_{\text{spot}} \) values from the (stellar spectrum fit) posterior and computed the predicted transit depth as a function of the
wavelength, normalized to the depth at 4.5 \mu m. As can be seen, even the most extreme samplings yielded transit depths inconsistent with the MEarth and K2 data.

For our fit to the transmission spectrum, we had one less free parameter, as we fixed \( T_{\text{surf}} \) to 3540 K; for our fit to the stellar spectrum, both \( T_{\text{surf}} \) and \( T_{\text{spot}} \) were free parameters. Fixing \( T_{\text{surf}} \) in the spectroscopic fit or shifting the posterior on \( T_{\text{surf}} \) (for the IGRINS fit) did not change the conclusion: the spectroscopic fit was still inconsistent with the spot coverage required to explain the observed transit depths.

The uncertainties from both fits were likely underestimated due to imperfect models, but this is also unlikely to impact our results. For example, we tried using the PHOENIX model atmospheres from Husser et al. (2013), which yielded \( T_{\text{surf}} \) and \( T_{\text{spot}} \) values \( \approx 60 \) K cooler and \( A_v \) values 0.1 magnitudes lower. These changes were larger than the errors within a fit and are likely due to differences in the handling of strong molecular lines in the spectra of cool stars (Mann et al. 2013; Passegger et al. 2016). However, the conclusions on \( f_s \) were largely unchanged; \( T_{\text{spot}} \) must either be within \( \approx 150 \) K of \( T_{\text{surf}} \) or \( f_s \) must be below \( \approx 20\% \). This was expected: this model systematics impacts both the surface and spot spectra in similar ways, keeping the difference in temperature similar. We concluded that even in the presence of significant systematics in the model of M dwarfs, the spectrum rules out any spot pattern that can explain the transit depths.

It is likely that the stellar surface contains more than a single spot and hence more than a single spot temperature. However, adding more spots with different \( T_{\text{eff}} \) values did not meaningfully change the conclusion. The additional spot simply followed the output distribution in \( T_{\text{spot}} \) and \( f_s \) of the single spot assumed above, but with larger uncertainties. It is possible that allowing an arbitrary number of spots, each with an unconstrained temperature, can reproduce the observed transmission spectrum. However, our tests suggest that such a reconciliation would come primarily by increasing the uncertainties until the contours had marginal overlap; in this case, the fit does not improve meaningfully with more spots.

6. Photochemical Hazes

In addition to spots, the existence of submicron aerosol particles in K2-33b’s atmosphere could also lead to enhanced optical transit depths. One possible formation pathway for such particles is photochemistry resulting in the breakup of small molecules at low pressures (\( \sim 1 \mu \text{ bar} \)) and the subsequent polymerization of photochemical products, forming high-altitude hazes (e.g., Morley et al. 2015; Kawashima & Ikoma 2019; Gao et al. 2021). The small size of these particles causes a rapid decrease in opacity toward longer wavelengths and thus a decrease in the transit depth. This effect is strengthened in young planets like K2-33b that may be experiencing atmospheric outflows, which are capable of pushing haze particles to greater altitudes and increasing the difference in the transit depth between the optical and the NIR (Wang & Dai 2019; Gao & Zhang 2020; Ohno & Tanaka 2021).

We explore the impact of hazes on K2-33b’s transmission spectra following the method described in Gao & Zhang (2020). Briefly, we construct model atmospheres defined by user-selected core masses and atmospheric mass fractions composed of a convective zone in depth and a radiative region at lower pressures separated by the radiative–convection boundary, where the temperature is set to the equilibrium temperature of the planet assuming zero albedo and full heat redistribution; we use the Rosseland mean opacity from Freedman et al. (2014) to find the radiative–convective boundary and to calculate the temperature–pressure profile in the radiative zone. The core is assumed to have an Earth-like composition, with the mass–radius relationship from Zeng et al. (2019). As an update to Gao & Zhang (2020), we use a planetary evolution model (Tang et al. 2022; Lopez & Fortney 2014) to derive the intrinsic temperature as a function of the core mass, yielding values of \( \sim 100–150 \) K for core masses of \( 3–10M_{\oplus} \), atmospheric mass fractions of \( <10\% \), and model planet ages matching that of K2-33b.

We consider the effect of atmospheric loss pushing haze particles upward. We compute the atmospheric loss rates assuming energy-limited escape with an energy-deposition pressure level of 1 nbar and a mass-loss efficiency of 10\% (e.g., Lopez 2017). We use the saturated stellar X-ray and ultraviolet flux for M dwarfs (Wright et al. 2011, 2018; Pineda et al. 2021) to drive the atmospheric loss.

The elemental composition of the atmosphere is simplified to just H, He, O, and C, with solar abundances of O and C incorporated into water vapor and methane, respectively, and
the rest of the atmosphere composed of H/He. We initially choose methane as the dominant carbon carrier (“CH4 models”) due to the relatively low temperature of K2-33b (Lodders & Fegley 2002), but we also explore the impact of upward mixed CO (“CO models”) on the transmission spectra (see Fortney et al. 2020, and references therein). Given this atmospheric composition and the assumed fully mixed abundance profiles, we equate the haze production rate profile to the methane photolysis rate profile multiplied by a haze production efficiency factor, which is a free parameter. The methane photolysis rate profile is generated using a simplified photochemical scheme where methane is photolyzed by Lyman α radiation from the host star, with an assumed Lyman α flux of a saturated M dwarf (Pineda et al. 2021).

Once produced, haze particles are transported to the deep atmosphere via sedimentation and mixing, the latter of which is parameterized using eddy diffusion. The eddy diffusion coefficient is a free parameter and assumed to be constant with altitude. The haze particles can grow through coagulation during transport, starting from a fixed minimum radius of 10 nm, and we assume that all haze particles are spherical. The haze evolution is simulated using the Community Aerosol and Radiation Model for Atmospheres (CARMA; Turco et al. 1979; Toon et al. 1989; Ackerman et al. 1995; Gao et al. 2018), which has been applied to exoplanet and solar system hazes on numerous occasions (Gao et al. 2017; Adams et al. 2019; Gao & Zhang 2020; Gao et al. 2020). We use Mie scattering to calculate the haze optical properties and consider two haze compositions: soot and tholin, with the corresponding complex refractive indices (Lee & Tien 1981; Khare et al. 1984; Chang & Chalalampopoulos 1990; Morley et al. 2015; Gavilan et al. 2016; Lavvas & Koskinen 2017). Finally, we combine the model atmosphere and haze optical properties to compute the model transmission spectra.

### 6.1. CH4 Models

As the mass of the planet is unknown, we considered several planet core masses. From the planet mass–radius distribution, we calculated a predicted mass for K2-33b of $16.59_{-11.73}^{+7.08} M_\oplus$ using the python package, forecaster (Chen & Kipping 2017). Due to the young age of the planet, we expect the true value to be smaller because younger planets are larger and less dense than their evolved counterparts (Owen 2020). As such, we tested core masses of 3, 5, and $8 M_\oplus$. We also examined eddy diffusion coefficients of $10^9$ and $10^{11} \text{cm}^2 \text{s}^{-1}$ and haze production efficiencies of 1, 2, 4, and 8% (Lavvas & Koskinen 2017). For each core mass, we varied the atmospheric mass fraction to roughly match the observed planet radius, resulting in values of 1–2.5%.

To compare our models to the data, we convolved the model spectra with the relevant filter profiles to create synthetic transit depths corresponding to each effective wavelength (photon-weighted mean wavelength). The effective wavelength factors in the widths of the broadband filters were calculated using K2-33b’s spectrum and each filter’s bandpass. The results of this calculation yielded effective wavelengths of 0.72 \( \mu \text{m} \) (K2), 0.84 \( \mu \text{m} \) (MEarth), 3.46 \( \mu \text{m} \) (Channel 1), and 4.43 \( \mu \text{m} \) (Channel 2). We added a free parameter, a normalization constant, to allow each model spectrum to shift in median depth, and varied it to minimize the $\chi^2$ when compared to our data. Although the Gao & Zhang (2020) model computes the radius of the model planets, we allow this normalization factor to shift the planet radius to account for model uncertainties in the intrinsic temperature, atmospheric composition, etc.

Our results disfavored a featureless model and all haze models where the carbon carrier in the background atmosphere is CH4 (>4σ confidence) regardless of the haze composition, core mass, atmospheric mass fraction, eddy diffusion coefficient, and haze production efficiency. The lowest $\chi^2$ for these models that had a normalization factor within 20% was $\chi^2 = 58$ for tholin hazes and $\chi^2 = 79$ for soot hazes. These high values are driven by the disagreement between the models and the Spitzer points. The normalization parameters and the corresponding $\chi^2$ values are listed in Table 6. Only the top three lowest $\chi^2$ values are listed for each haze composition.

### 6.2. CO Models

Under the assumption of thermochemical equilibrium and solar metallicity, methane should be the dominant carbon carrier in the atmospheres of planets with K2-33b’s equilibrium...
Table 6
Normalization Factor for Atmospheric Models

| Haze Composition | Planet Core Mass [M⊕] | Atmospheric Mass Fraction | Eddy Diffusion Coefficient [cm² s⁻¹] | Haze Production Efficiency [%] | Normalization Factor | χ² |
|------------------|------------------------|----------------------------|--------------------------------------|-----------------------------|----------------------|-----|
| **Haze Fit with No Spots** | | | | | |
| CH₄ Tholin       | 5.0                    | 0.024                      | 10¹¹                                 | 4.0                         | 0.87                 | 58  |
| CH₄ Soot         | 3.0                    | 0.013                      | 10⁹                                 | 1.0                         | 0.84                 | 79  |
| CO Tholin        | 5.0                    | 0.021                      | 10¹¹                                 | 4.0                         | 1.00                 | 29  |
| CO Soot          | 5.0                    | 0.023                      | 10¹¹                                 | 4.0                         | 0.93                 | 59  |
| Flat Line        | ...                    | ...                        | ...                                  | ...                         | ...                  | 122 |
| **Haze Fit with Spots** | | | | | |
| CO Tholin        | 5.0                    | 0.020                      | 10¹¹                                 | 4.0                         | 1.01                 | 28  |
| CO Soot          | 5.0                    | 0.019                      | 10¹¹                                 | 4.0                         | 1.04                 | 28  |
| Flat Line        | ...                    | ...                        | ...                                  | ...                         | ...                  | 122 |

Notes. Only the top three (lowest χ² values) for each haze composition are listed here. In addition to this, for the combined haze and spots fits, the fit also needed to yield spot properties consistent with the fit to the stellar spectrum.

The spot-free haze fit has dof = 16, and the combined haze and spot fit has dof = 14.

Table 6 lists the top three lowest χ² and normalization factors for each haze composition. Our results disfavor hazes composed of soot to >5σ confidence, as they are unable to fit the optical data. In contrast, tholin hazes (χ² = 29, dof = 16) give reasonable fits to our measured transmission spectrum (>2σ confidence).

To summarize, consideration of photochemical hazes allowed us to put the following constraints on our model parameters:

1. planet core mass: Lower values (3 or 5M⊕) preferred.
2. atmospheric mass fraction: 1–2.5% preferred.
3. eddy diffusion coefficient: Higher values (10¹¹ cm² s⁻¹) preferred for tholin hazes, while lower values (10⁹ cm² s⁻¹) preferred for soot hazes.
4. haze efficiencies: Soot models prefer lower values (1%), while tholin models preferred higher values (4%) preferred.
5. haze composition: Tholin strongly preferred over soot.
6. primary carbon carrier: CO strongly preferred over CH4.

The best-fit model from our grid has a 5M⊕ core and an atmospheric mass fraction of 2.2–2.3%. The model atmosphere possesses a high (10¹¹ cm² s⁻¹) eddy diffusion coefficient, a haze production efficiency of 4% (about midway between that of Jupiter and Titan; Lavvas & Koskinen 2017), and tholin hazes, with CO as the dominant gaseous carbon carrier.

6.3. Combining Spots and Hazes

As we showed in Figure 8, spots alone did a relatively poor job fitting the overall transit depths, and the best fits required spot properties inconsistent with the stellar spectrum. Photochemical hazes provided a better fit to the data, but there is still some tension. Here, we endeavored to improve the fit by combining hazes and spots.

Our methodology was the same as described in Section 5.2.1, except we replaced the flat model with the theoretical haze models from Section 6, and D was changed to a dimensionless scale factor applied to the models (denoted Dmod). The scale factor can be an arbitrary number, but
changing the planet size >20% invalidates the model assumption, so we limited the scale factor to $0.8 < D_{\text{mod}} < 1.2$; more extreme scaling would imply a different surface gravity and hence invalidate the model atmosphere. The two other parameters ($T_{\text{spot}}$ and $f_S$) evolved under uniform priors. For each model, we ran with 50 walkers and as many steps as required to pass 50 times the autocorrelation time (checking every 1000 steps). The number of steps required varied from 4,000 to more than 15,000, depending on the model.

As with the fits ignoring the effects from stellar spots, the models with CO as the primary carbon carrier and tholin hazes gave the best fit. This is because the CO models are able to match the shallower transit at 3.6 $\mu$m compared to that at 4.5 $\mu$m. Spots alone cannot explain this difference, as their effect is weak past 3 $\mu$m and even strong spots tend to predict a deeper transit at 3.6 $\mu$m instead of a shallower one.

Overall, adding spots provided only marginal improvement when fitting the transmission spectrum. For example, the best-fit haze model (both with and without spots) was the CO model with a tholin haze (which we show in Figure 12), with an improvement of $\Delta \chi^2 \approx 1$ over a spot-free haze model. Given that there were two additional free parameters in the spot and haze fit (compared to haze-only), this improvement was not significant for most of the tholin models (see Table 6 for a summary of the best fits). However, it is worth highlighting that the joint fit of the spots and CO Tholin model makes everything consistent: the fit to the stellar spectrum, the fit to the light curve, and the fit to the transmission spectrum. The required small spot coverage fractions and spot properties were consistent with the stellar spectrum (Figure 13).

Including the effect of spots had a larger improvement for fits using the soot models, with the best cases going from $\chi^2 \approx 65$ to $\chi^2 \approx 35$. However, these generally required spot coverage fractions and temperatures inconsistent with those inferred from the stellar spectrum. If we consider just cases where the required spot properties were consistent with the stellar spectroscopic data, the best-fit soot haze and spot combination did a poor job reproducing the full transmission spectrum ($\chi^2 = 56$).

Figure 12. Transmission spectrum of K2-33b from our data (gray circles) compared to haze models composed of (1) CO tholin (green), (2) CO soot (pink), (3) a combined spot model with CO tholin (purple), and (4) a combined spot model with CO soot (orange). Only the models that produced the lowest chi-square values are shown. All models were normalized to give the best fit to the data. The combined haze and spot models gave a lower chi-square value. All calculations were done with high-resolution models.

Figure 13. Posteriors of spot properties from the stellar spectrum (black/gray), a fit to the transmission spectrum using CO tholin models (purple), and a fit to the transmission spectrum using CO soot models (orange). The two transmission spectrum fits shown here are those using the tholin or soot model with the lowest $\chi^2$ that also yielded spot properties consistent with the fit to the stellar spectrum.

7. Summary and Discussion

To explore the transmission spectrum of the $\approx$10 Myr, K2-33b, we combined 33 transit observations taken by K2, MEarth, HST, and Spitzer spanning over $>2.5$ yr. We also updated the stellar parameters based on the parallax from Gaia.

The most striking result from the multiwavelength data was that the optical transits from K2 and MEarth are almost a factor of 2 deeper than the NIR transits from HST and Spitzer (0.24% versus 0.13%). We explore whether this depth difference is due to unconstrained systematics in the data sets or if it is astrophysical in nature. We rule out the first scenario primarily because the difference holds across multiple data sets, with roughly consistent (but shallower) depths from Spitzer and HST and consistent (but deeper) depths from K2 and MEarth.
Agreement between instruments rules out issues related to the data source, data quality, or analysis method. The Spitzer, MEarth, and K2 data each cover at least five transits and span numerous rotational cycles, ruling out single events like data source, data quality, or analysis method. The Spitzer, Agreements between instruments rules out issues related to the overlapping data. Light curves from MEarth and Spitzer for the three transits with the largest at the optical wavelengths because the contrast ratio of photochemical transits and span is not significant, and for soot hazes, the spot fraction required is inconsistent with the stellar spectrum and the fit to the transmission spectrum is still poor (high $\chi^2$) compared to the tholin-only fit. It is, however, encouraging that the resulting spot properties when using the tholin model are consistent with the two-temperature fit to the stellar spectrum. Adding spots does not change any of our conclusions with respect to the CO versus CH4 models or low planet mass.

The complication to our current analysis is that spot coverage fractions may change with time. The K2 and spectroscopy data were used to constrain the spots, but K2 data predate the other sets of data by ~1.5 yr. However, removing the Kepler data did not change the conclusions, and the improvement to the fit was marginal. The IGRINS spectra were taken contemporaneously with the MEarth data, and multiple spectra taken over several months (2016 Jan 25 to 2016 Mar 28) yield consistent results. There is also no evidence of extreme spot evolution in the long-term MEarth monitoring. Thus, these kinds of long-term effects are unlikely to change our findings but may explain some of the tension in the tholin-haze fit.

A possibility we did not explore was a transiting ringed system (Mamajek et al. 2012). Ohno & Fortney (2022) highlight that even close-in planets can retain thick rings at young (<100 Myr) ages, and rings would help explain the large radii observed for young planets. Rings on K2-33b would need to be dominated by micron-sized dust and extend to at least twice the planetary radius to explain the deeper optical transits. Depending on the orientation and size distribution, rings would dominate over any signal from the planet’s atmosphere (Alam et al. 2022), which would explain the lack of spectral features seen here. A companion paper led by Ohno et al. (2022b) investigates this possibility further.

We conclude from our analysis that K2-33b likely hosts tholin-like hazes, with modest (<10%) spot coverage for its host star. This scenario can explain all the data, including the light curve, stellar spectrum, and planetary transmission spectrum. More detailed information, including better constraints on the spot properties and haze production rate, will require more data. The current HST data are particularly limiting, as it was only half a transit. A full transit of HST/WFC3 combined with contemporaneous ground-based transit and spectroscopic monitoring would let us fully disentangle the effects of spot surface inhomogeneities from haze properties in soot hazes, the spot fraction required is inconsistent with the stellar spectrum and the fit to the transmission spectrum is still poor (high $\chi^2$) compared to the tholin-only fit. It is, however, encouraging that the resulting spot properties when using the tholin model are consistent with the two-temperature fit to the stellar spectrum. Adding spots does not change any of our conclusions with respect to the CO versus CH4 models or low planet mass.

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the observed transmission spectrum. These observations will break this degeneracy because stellar spots generally increase the strength of the NIR H₂O feature, while hazes generally weaken it. Further, the former changes the observed out-of-transit spectrum while the latter does not, and each scenario will have a significantly different impact on the transit depths at bluer wavelengths depending on the spot and haze properties. Contemporaneous data would also resolve issues of spot properties changing with time and enable us to do a simultaneous fit of all constraints instead of the one-at-a-time fit we did here.

Our haze results are in line with those of Ohno & Kawashima (2020), which suggested that moderate haze production rates combined with high values of the eddy diffusion coefficient lead to super-Rayleigh optical slopes in transmission spectra. While both of these parameters are loosely constrained in exoplanet atmospheres, the high eddy diffusion coefficient may be reasonable given the young age and therefore high luminosity of K2-33b, and potentially tying into the significant upwelling of CO-rich gas suggested by the Spitzer data. Our results also fit those of Gao & Zhang (2020), which predicted significant enlargement of young planet transit radii due to high-altitude hazes entrained in atmospheric outflows, though here the effect seems to impact the optical wavelengths much more than the NIR. Both the core mass and atmospheric mass fraction implied by our results are similar to those of typical sub-Neptunes (Owen & Wu 2017), suggesting that K2-33b will eventually join that population after thermal evolution and contraction.

The need for CO to be the carbon carrier in our best-fit models (regardless of spot levels) is extremely compelling, but it relies entirely on the Spitzer bands. While the difference in depth holds even when we try different analysis methods, the significance of the difference changes depending on how we handle combining multiple transits (the difference is not significant with a single transit).

Upward mixing of CO is only one way in which it can supersede CH₄ as the dominant carbon carrier in an atmosphere at the temperature of K2-33b. Alternatively, K2-33b’s atmosphere can possess a low C/O and an enhanced metallicity, which would provide clues to its formation and early evolution (e.g., Öberg 2011; Madhusudhan 2012). Due to the large scale heights required to match the observed transmission spectrum, the metallicity cannot be too high (e.g., >100 times the solar metallicity). Detecting a water and/or CO₂ feature would help differentiate between these scenarios. We eagerly await confirmation of this detection with HST and/or JWST, which would enable a more precise measurement of the carbon-to-oxygen ratio.

We thank the anonymous referee for their careful reading and thoughtful comments on the manuscript. The authors would like to thank Laura Kreidberg and Alex Teachey for helpful conversations regarding the HST reduction.

The authors also wish to acknowledge Wally, Penny, and Bandit for their input, sound counsel, and their constant quest to discover the unknown.

P.C.T was supported by NSF Graduate Research Fellowship (DGE-1650116), the NC Space Grant Graduate Research Fellowship, the Zonta International Amelia Earhart Fellowship, and the Jack Kent Cooke Foundation Graduate Scholarship. This work was made possible by grants to A.W.M. from the K2 Guest Observer Program (80NSSC19K0097) and NASA’s Astrophysics Data Analysis Program (80NSSC19K0583). M.J. F was supported by the NC Space Grant Graduate Research program and a grant from NASA’s Exoplanet Research Program (80NSSC21K0393). This paper includes data collected by the K2 mission. Funding for the K2 mission is provided by the NASA Science Mission directorate.

This work is based on observations made with the Spitzer Space Telescope, which is operated by the Jet Propulsion Laboratory, California Institute of Technology under a contract with NASA. Support for this work was provided by NASA through an award issued by JPL/Caltech.

This research is based on observations made with the NASA/ESA Hubble Space Telescope obtained from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. These observations are associated with program ID: 14887 (PI: Benneke).

The MEarth Team gratefully acknowledges funding from the David and Lucile Packard Fellowship for Science and Engineering (awarded to D.C.). This material is based upon work supported by the National Science Foundation under grant AST-1616624, and work supported by the National Aeronautics and Space Administration under Grant No. 80NSSC18K0476 issued through the XRP Program.

Facilities: Spitzer (IRAC), K2, MEarth, Hubble (WFC3).

Software: LDTK (Parviainen & Aigrain 2015), IRACLIS, POET + BLISS (Stevenson et al. 2012), MIST/TBORN, emcee (Foreman-Mackey et al. 2013), corner.py (Foreman-Mackey 2016), celerite (Foreman-Mackey et al. 2017), matplotlib (Hunter 2007), batman (Kreidberg 2015), Fleck (Morris 2020), Astropy (Astropy Collaboration et al. 2013, 2018), numpy (Harris et al. 2020).

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Acknowledgments
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