A 0.8–2.4 μm TRANSMISSION SPECTRUM OF THE HOT JUPITER CoRoT-1b

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ABSTRACT

Hot Jupiters with brightness temperatures \( T_b \geq 2000 \) K can have TiO and VO molecules as gaseous species in their atmospheres. The TiO and VO molecules can potentially induce temperature inversions in hot Jupiter atmospheres and also have an observable signature of large optical to infrared transit depth ratios. Previous transmission spectra of very hot Jupiters have shown a lack of TiO and VO, but only in planets that also appear to lack temperature inversions. We measure the transmission spectrum of CoRoT-1b, a hot Jupiter that was predicted to have a temperature inversion potentially due to significant TiO and VO in its atmosphere. We employ the multi-object spectroscopy method using the SpeX and MORIS instruments on the Infrared Telescope Facility (IRTF) and the Gaussian process method to model red noise. By using a simultaneous reference star on the slit for calibration and a wide slit to minimize slit losses, we achieve transit depth precision of 0.03%–0.09%, comparable to the atmospheric scale height but detect no statistically significant molecular features. We combine our IRTF data with optical CoRoT transmission measurements to search for differences in the optical and near-infrared absorption that would arise from TiO/VO. Our IRTF spectrum and the CoRoT photometry disfavor a TiO/VO-rich spectrum for CoRoT-1b, suggesting that the atmosphere has another absorber that could create a temperature inversion or that the blackbody-like emission from the planet is due to a spectroscopically flat cloud, dust, or haze layer that smooths out molecular features in both CoRoT-1b’s emission and transmission spectra. This system represents the faintest planet hosting star \(( K = 12.2 )\) with a measured planetary transmission spectrum.

Key words: infrared: planetary systems – planets and satellites: gaseous planets – planets and satellites: individual (CoRoT-1b) – stars: individual (CoRoT-1) – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

Transiting hot Jupiters are among the most observationally favorable sources for measuring atmospheric composition, global winds, temperature inversions, and disequilibrium chemistry (e.g., Pont et al. 2013; Snellen et al. 2010; Rogers et al. 2009; Moses et al. 2011). Their large physical radii, frequent transits, high temperatures, and large radial velocity amplitudes permit both the measurement of physical parameters (mass, radius, orbital elements) and the ability to test atmospheric models. The primary transit, when the planet goes in front of its host star, and the secondary eclipse, when the planet goes behind, are valuable opportunities to spectroscopically characterize the atmosphere. These spectra can be compared with models to determine mixing ratios of atmospheric gases, clouds, scatterers, and/or aerosols. Furthermore, high-quality spectra can be used to constrain the formation of exoplanets (e.g., Spiegel & Burrows 2012), the extent of equilibrium/disequilibrium chemistry (e.g., Moses et al. 2011), vertical mixing (e.g., Visscher & Moses 2011), and put the solar system in context.

Transmission spectra and emission spectra of hot Jupiter atmospheres have already been used to detect Na (Charbonneau et al. 2002), K (Sing et al. 2011), Ca (Astitudillo-Defru & Rojo 2013), H (Vidal-Madjar et al. 2003), H₂O (e.g., Deming et al. 2013; Birkby et al. 2013), CO (e.g., Snellen et al. 2010), and possibly CH₄ (Swain et al. 2008; though see Gibson et al. 2012a). Furthermore, emission and transmission spectra have been used to constrain the mixing ratios of these atoms and molecules. Of considerable interest is the relative abundances such as the C/O ratio (Teske et al. 2013; Madhusudhan 2012; Madhusudhan et al. 2011a), which gives clues as to the formation of planets such as circumstellar disk composition and location within the disk (e.g., Öberg et al. 2011; Moses et al. 2013).

Infrared (IR) observations of prominent molecular bands in hot Jupiters during secondary eclipse are used to infer an atmospheric temperature profile (e.g., Line et al. 2013b). The level of emission by gases of upper layers as compared to lower levels indicates their relative temperatures. For example, the brightness temperature of the 4.5 μm Spitzer band is expected to be higher than the 3.6 μm band for temperature-inverted planets because it encompasses several molecular bands that are high in opacity (and high in altitude), whereas the 3.6 μm band sees deeper in the atmosphere (Knutson et al. 2010).

Broadly, hot Jupiter atmospheres have been classified into (1) planets that have temperatures that decrease with altitude for observable pressures and (2) planets that contain a temperature inversion or stratosphere at observable pressures. We include an isothermal (constant temperature with altitude) in the later case. One possible explanation for the bifurcation into these profiles is that TiO and VO absorption of stellar flux creates temperature inversions in some planets and not others (Hubeny et al. 2003; Fortney et al. 2008a). An alternative explanation is that the observational techniques to infer temperature inversions (like the 4.5 μm to 3.6 μm brightness ratio) are actually sensing the difference between clear atmospheres and dusty atmospheres, such as has been observed in HD 189733b (Pont et al. 2013; Evans et al. 2013). Recently, spectro-photometry of HAT-P-32b
reference star close in brightness and color (within 0.7 mag in the J, H, and K bands) that permits characterization with the multi-object spectroscopy (MOS) method (Bean et al. 2010, 2013; Sing et al. 2012; Gibson et al. 2013a).

The MOS method is to divide a target star spectrum by one (or an average of several) reference stars to correct for variability in telluric (Earth’s) transmission and the response of the instrument. Close proximity of a reference star to the target provides an advantage for calibration, as their atmospheric turbulence and telluric fluctuations are highly correlated. The reference stars’ spectra are obtained simultaneously either with multiple slits or, as in our observations, a long slit that includes both the planet hosting star and the reference star.

One observational challenge with the CoRoT-1 system is its faintness at $K = 12.2$. This makes it difficult to obtain sufficient signal-to-noise ratio (S/N) for high-resolution measurements but we demonstrate that the Infrared Telescope Facility (IRTF) with SpeX and MORIS instruments in a low-resolution prism mode (with no diffraction grating) can achieve high precision characterization down to this faint magnitude. We present a 0.8–2.4 μm transmission spectrum to constrain the presence of IR absorbing molecules and measure the optical/near-IR radius slope as compared to TiO/VO absorption.

2. OBSERVATIONS

We observed CoRoT-1b with the SpeX instrument (Rayner et al. 2003) on the Infrared Space Telescope Facility in a low-resolution prism mode. When the large $3'' \times 60''$ slit is placed on CoRoT-1, the actual resolution for the target star is set by the point-spread function at $R \approx 80$. A reference star—2MASS 06482020–0306339—was placed simultaneously on the slit to correct for telluric transmission variations as well as correlated (common mode) instrumental variations. The 3'' × 60'' slit was selected to minimize slit losses but it still serves to reduce the background levels as compared to a completely slitless instrument. The reference star with $J = 11.72$, $H = 11.54$, $K = 11.50$ is slightly brighter than CoRoT-1 J = 12.46, $H = 12.22$, $K = 12.15$ as determined from the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) so that the photon noise of the planet host star dominates the photon noise of the measurement. We kept the exposure times short to keep the counts of the two objects well within the linear regime of the detector. At the same time, their fluxes are close enough so that flux-dependent non-linearity is negligible.

We observed CoRoT-1 for three nights on the UT dates of 2011 December 23 (full transit), 2011 December 29 (half-transit), and 2012 January 4 (full transit). The first half of 2011 December 29 was lost due to high wind (>45 MPH) and closure of the telescope. The remainder of the 2011 December 29 night was affected by large seeing fluctuations from 0.9'' to 1.5''. For the full transits, the 2.5 hr transit duration was straddled by 30–120 minutes of out-of-transit observations to establish a baseline flux level. Table 1 lists the exposure times and number of exposures obtained for the three transits.

We also used MORIS, a high-speed, high-efficiency optical camera (Gulbis et al. 2011) simultaneously with SpeX to obtain photometry at the Sloan $\gamma$ band for CoRoT-1. We used a 0.9 μm dichroic to split visible light shortward of 0.9 μm into the MORIS beam path. The field of view of MORIS is similar to the guide camera of SpeX (1' × 1'), permitting us to include two reference stars in addition to CoRoT-1 on the MORIS detector. We used short exposures of 5 s and 10 s
1.5
2.0
2.5

Hmissions show that guiding using the slit were also evaluated for centroid motions. The centroid reference star. The stars are visible as reflections off the slit, guider on SpeX to ensure good alignment of the target and camera. The observing log of MORIS is also included to ensure the fluxes were well within the linear regime of the camera. The observing log of MORIS is also included in Table 1. Photometric data reduction was carried out following the pipeline and steps of Zhao et al. (2012). The total flux of the two reference stars (2MASS 06482101−0306103 and 2MASS 06482020−0306339) was used for flux calibration. We determined that an aperture size of 36 pixels (corresponding to 4′1 for a pixel scale of 0.′141 pixel−1) and a 35-pixel wide background annulus provided the best light-curve precision for all three nights, although aperture sizes with ±5 pixels gave essentially the same results.

The spectral images were reduced with standard IRAF ccdproc procedures with four to eight flat frames, dark subtraction from identical exposure time frames, and one to two wavelength calibration frames. Wavelength calibrations were performed with a narrower (0′.3 × 60′′) slit to better centralize the argon emission lines. Additionally, we rectify all science images using the argon lamp spectrum as a guide to make sure all vertical columns in the image correspond to individual wavelengths.

Simultaneous H+K band exposures were made with the IR guider on SpeX to ensure good alignment of the target and reference star. The stars are visible as reflections off the slit, permitting a simultaneous check that the stars are centered during spectrograph science exposures. In addition to the reflections from the slit, nearby additional reference stars off the slit were also evaluated for centroid motions. The centroid motions show that guiding using the H+K guider was accurate to within 0′.3, minimizing slit loss errors in the spectrograph. No correlations are visible between telescope shifts (measured from H+K images) and the individual target and reference stars’ fluxes or ratio spectrum between the planet host and reference star.

We extracted all of the spectra with the twodspec procedures in IRAF (Tody 1993, 1986). We used a centered aperture of 15 pixels (2′.3) with optimal extraction (spatial pixels weighted by S/N ratio) on the planet host star and reference star (FWHM ≈5−9 pixel or 0′.8−1′.4) with a third-order Legendre polynomial background subtraction from 89 pixels on each side of the spectrum. These extraction and background sizes were chosen experimentally so as to produce the smallest standard deviation of out-of-transit flux in the final time series. The fact that the highest precision was obtained with a 2′.3 aperture size shows that the 3′ slit width is sufficiently wide to make slit losses negligible.

For each exposure, the CoRoT-1 system’s spectrum was divided by the reference star to correct for variable transmission and response of the instrument. This is the same long-slit/multi-object method applied by Sing et al. (2012), Bean et al. (2010, 2013), and Gibson et al. (2013a). Figure 1 shows a dynamic spectrum from the night of 2012 January 4 using the reference star division and then re-normalizing each time series by a linear out-of-transit baseline. The linear baseline division is only used for illustrative purposes in this figure and not the parameter extraction described in Section 3.2. Each of the 475 wavelength channels clearly shows the transit except for the ends of the spectrograph due to low response and high thermal background at the larger wavelength end. The telluric transmission above IRTF at Mauna Kea is high enough that transit measurement is still possible between the J, H, and K telluric windows.

2.1. Noise Measurements

The most critical part of measuring a planet’s spectrum is achieving high S/Ns. Measurement errors are closely approximated by “minimum noise” at the highest time resolution and spectral resolution but are considerably larger when the data is binned. For this paper, “minimum noise” includes constant read noise per pixel of the detector, shot noise of the source, and shot noise of the background. Minimum noise decreases as 1/√N for independent measurements, but we find that the measured noise falls off more slowly, as expected for high precision measurements dominated by systematics. These additional error sources are also known as time-correlated or wavelength-correlated red noise (e.g., Pont et al. 2006; Carter & Winn 2009). Figures 2 and 3 show the measured out-of-transit error as a function of bin size and also shows the minimum noise for comparison.

### Table 1
Summary of the 2.5 Transits Observed for CoRoT-1b

| UT Date     | \( t_{\text{spec}} \) (s) | \( D_{\text{spec}} \) | \( N_{\text{spec}} \) | \( t_{\text{phot}} \) (s) | \( N_{\text{phot}} \) |
|-------------|----------------|----------------|----------------|----------------|----------------|
| 2011 Dec 23 | 10.0            | 49%            | 813            | 5              | 2636           |
| 2011 Dec 29 | 15.0            | 51%            | 233            | 10             | 691            |
| 2012 Jan 4  | 15.0            | 51%            | 600            | 5              | 3319           |

Notes. Columns 2–6 list the exposure time for SpeX Spectra \( t_{\text{spec}} \), number of spectral exposures \( N_{\text{spec}} \), spectral duty cycle \( D_{\text{spec}} \), MORIS photometric exposure time \( t_{\text{phot}} \), and number of photometric frames \( N_{\text{phot}} \), respectively. The non-redundant reads were increased at longer spectrograph exposure times, thus maintaining almost the same duty cycle.
3. LIGHT-CURVE FITTING

As described in Section 2.1, all $R = 80$ spectral data were binned into nine equally spaced wavelength bins and they are analyzed independently. Figure 4 shows the time series for each wavelength bin and it can be seen that the baseline is non-linear. Figures 5 and 6 also show that the shape of the baseline changes from night to night. It is possible to model the baseline as a slowly varying function like a polynomial (e.g., Bean et al. 2013)

For the data analysis, we used nine equally spaced wavelength bins which minimize the out-of-transit noise while still maintaining sufficient spectral resolution to resolve molecular bands. As expected for high precision flux measurements, the measured noise has components that do not scale as minimum noise decreases. We bin the time data slightly to $\sim 3$ minute long time bins for computational efficiency when doing MCMC/Gaussian process fitting. This is still far from the noise floor seen in Figure 3 and shorter than the planet’s transit ingress duration of 22 minutes and the typical systematics $\sim$10–60 minutes.

(A color version of this figure is available in the online journal.)
against complex models to mitigate overfitting. The process method uses Bayesian model selection so that it weights the shape of the baseline can vary from realization to realization. The process assumes the baseline and mid-transit follow a correlated model red noise and the flux baseline. The advantage of the model is the inverse timescale hyper-parameter, \( p \) is the index of the Matérn kernel, \( \delta_{nm} \) is the Kronecker delta function, and \( \sigma_n \) is the white-noise component of an individual point’s error. This is a generalized form of the \( p = 1 \) Matérn kernel used on WASP-29b transit data (Gibson et al. 2013a). We let the \( p \) parameter be another hyper-parameter with the possible values of 0, 1, 2, or infinity. A squared exponential kernel \( C_{nm} = \Theta_0^2 e^{-\Theta_1(x_n-x_m)^2/2} \) because higher values of \( p \) are essentially indistinguishable from the infinity case (Rasmussen & Williams 2006). The four different kernels are parameterized by \( \Theta_2 \) with values of 0, 1, 2, and 3 for the respective values of \( p \). All forms of the above kernel have correlations that decrease with separation in time. In other words, points that are close together are highly correlated but far away are less correlated. For the data series in this work, \( x_n \) and \( x_m \) are orbital phase and \( y_n \) and \( y_m \) are normalized flux. The choice of kernel does not affect the individual white noise errors which are assumed to be independent and Gaussian distributed with a standard deviation \( \sigma_n \).

The need for a covariance kernel is justified by the fact that the time series are not well fit by a flat baseline. If we do fit the time series to a flat, white noise baseline model—with fixed semimajor axis, impact parameter and orbital period from literature values (Bean 2009), and free planet-to-star radius ratio \( \text{R}_p/\text{R}_* \) and linear limb darkening—the resulting residuals show correlations, as visible in the autocovariance estimator. If the autocovariance has a spike at zero lag and then is flat for all lags greater than zero, the noise is independent and identically distributed—white noise. On the other hand, if there is structure to the autocovariance, then there are correlation between flux measurements. Figure 7 shows a few examples of the autocovariance estimator of the residuals and the autocovariance estimator of the best-fit Gaussian process model. The autocovariance estimator is a biased estimator (Wei 2006) so it can be different from the covariance kernel. The Appendix shows the kernel, individual realizations, and the ensemble average of the autocovariance of the same best-fit hyper-parameters used in Figure 7.

The inclusion of correlated noise requires that the full likelihood function must be used in evaluating a model instead of a plain \( \chi^2 \) statistic. The full likelihood function is
\[
\mathcal{L} = \frac{1}{(2\pi)^{n/2}|\mathbf{C}|^{1/2}} \exp\left(-\frac{1}{2} \mathbf{r}^T \mathbf{C}^{-1} \mathbf{r}\right),
\]
where \( \mathcal{L} \) is the likelihood function when evaluating a model for covariance matrix \( \mathbf{C} \) and residual vectors \( \mathbf{r} = \mathbf{y} - \mathbf{f} \) for data value \( \mathbf{y} \) and model value \( \mathbf{f} \), and \( \mathbf{r}^T \) is the transpose (Gibson et al. 2012b). In the case of statistically independent non-correlated data \( \Theta_0 = 0 \) and \( \mathcal{L} \propto \exp^{-\chi^2} \), where \( \chi^2 = \sum_n (y_n - f_n)^2/\sigma_n^2 \) is the standard chi-squared statistic. However, we find that \( \Theta_0 \neq 0 \) and that correlated noise is present in the data.

3.1. Gaussian Process Model

We use a Gaussian process (Gibson et al. 2012b, 2013a) to model red noise and the flux baseline. The advantage of the Gaussian process framework is that it does not assume that the baseline follows a pre-defined function like a polynomial where the coefficients are fitted parameters. Instead, the Gaussian process assumes the baseline and mid-transit follow a correlated normal distribution described by a covariance kernel. For repeated experiments following a Gaussian process, the actual shape of the baseline can vary from realization to realization while maintaining the same covariance kernel. The Gaussian process method uses Bayesian model selection so that it weights against complex models to mitigate overfitting.

We use the integer form of the Matérn covariance kernel (Rasmussen & Williams 2006),
\[
C_{nm} = \Theta_0^2 \exp\left(-\Theta_1 \sqrt{2 \left(\frac{p + 1}{2}\right)} |x_n - x_m|\right) \frac{\Gamma(p + 1)}{\Gamma(2p + 1)}
\times \left(\sum_{i=0}^{p} \frac{(p + i)!}{i!(p - i)!} \left(\Theta_1 |x_n - x_m| \sqrt{8 \left(\frac{p + 1}{2}\right)}\right)^{p-i}\right) + \delta_{nm} \sigma_n^2,
\]
where \( C_{nm} \) is the covariance between data points \((x_n, y_n)\) and \((x_m, y_m)\), \( \Theta_0 \) is a hyper-parameter describing the strength of the correlation between data points, \( \Theta_1 \) is the inverse timescale hyper-parameter, \( p \) is the index of the Matérn kernel, \( \delta_{nm} \) is the Kronecker delta function, and \( \sigma_n \) is the white-noise component of an individual point’s error. This is a generalized form of the \( p = 1 \) Matérn kernel used on WASP-29b transit data (Gibson et al. 2013a). We let the \( p \) parameter be another hyper-parameter with the possible values of 0, 1, 2, or infinity. A squared exponential kernel \( C_{nm} = \Theta_0^2 e^{-\Theta_1(x_n-x_m)^2/2} \) because higher values of \( p \) are essentially indistinguishable from the infinity case (Rasmussen & Williams 2006). The four different kernels are parameterized by \( \Theta_2 \) with values of 0, 1, 2, and 3 for the respective values of \( p \). All forms of the above kernel have correlations that decrease with separation in time. In other words, points that are close together are highly correlated but far away are less correlated. For the data series in this work, \( x_n \) and \( x_m \) are orbital phase and \( y_n \) and \( y_m \) are normalized flux. The choice of kernel does not affect the individual white noise errors which are assumed to be independent and Gaussian distributed with a standard deviation \( \sigma_n \).

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The inclusion of correlated noise requires that the full likelihood function must be used in evaluating a model instead of a plain \( \chi^2 \) statistic. The full likelihood function is
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\mathcal{L} = \frac{1}{(2\pi)^{n/2}|\mathbf{C}|^{1/2}} \exp\left(-\frac{1}{2} \mathbf{r}^T \mathbf{C}^{-1} \mathbf{r}\right),
\]
where \( \mathcal{L} \) is the likelihood function when evaluating a model for covariance matrix \( \mathbf{C} \) and residual vectors \( \mathbf{r} = \mathbf{y} - \mathbf{f} \) for data value \( \mathbf{y} \) and model value \( \mathbf{f} \), and \( \mathbf{r}^T \) is the transpose (Gibson et al. 2012b). In the case of statistically independent non-correlated data \( \Theta_0 = 0 \) and \( \mathcal{L} \propto \exp^{-\chi^2} \), where \( \chi^2 = \sum_n (y_n - f_n)^2/\sigma_n^2 \) is the standard chi-squared statistic. However, we find that \( \Theta_0 \neq 0 \) and that correlated noise is present in the data.

3.2. Extracted Parameters

We fit all time series with the transit function from Mandel & Agol (2002) and use a series of MCMC chains to explore the parameter uncertainty distributions. The out-of-transit flux, planet-to-star radius ratio \( \text{R}_p/\text{R}_* \), linear limb darkening \( u_1 \), and hyper-parameters \( \Theta_0 \), \( \Theta_1 \), and \( \Theta_2 \) are fitted to the data while all other transit parameters—impact parameter, semimajor axis, and orbital period—are fixed at the literature values from Bean (2009). For all parameters and hyper-parameters we use flat priors. All parameters and hyper-parameters are constrained by
the example parameter correlation plot for the fit to the $z'$ light curve of 2012 January 4 in Figure 8 shows how the fitted planet radius $R_p/R_*$ can correlate to the other fitted parameters. This particular light curve showed the strongest dependence of $R_p/R_*$ on the flux offset $A_0$ and hyper-parameters $\Theta_0$, $\Theta_1$, and $\Theta_2$. For the remaining curves, the $R_p/R_*$ posterior is nearly orthogonal to the other hyper-parameters.
Figure 8. Posterior density distribution for the fitted parameters for the night of 2012 January 4 for the MORIS z′ time series from the MCMC chain. The star-to-planet radius ratio \( R_p/R_\star \) parameter correlates with the flux offset \( A_0 \), the hyper-parameters of the Gaussian process model \( \Theta_0 \) (strength of correlations), and \( \Theta_1 \) (inverse timescale of hyper-parameters) and \( \Theta_2 \) (the Matérn type) but not \( u_1 \) (the linear limb darkening parameter) because \( R_p/R_\star \) and \( u_1 \) have nearly orthogonal distributions. The \( \Theta_2 \) parameter is a parameterization of the Matérn index \( p \) and is discrete—see Section 3.1—so there is an apparent discontinuity in phase space. 95% and 68% confidence regions for each projected distribution are shown in red. The correlation between parameters is smaller for the rest of the other SpeX and MORIS light curves. (A color version of this figure is available in the online journal.)

Figure 9. Fitted radius ratio parameter as a function of wavelength for the three independent nights of observations with horizontal error bars as the bandwidths for spectral wavelength bins and vertical error bars with 68% uncertainty. Points with bold lines are the simultaneous z′ photometry with the MORIS camera with a filter transmission curve (normalized to unity and scaled to one-tenth the plot size) shown in green. At a given wavelength, all points are within 2.1σ of the weighted average, though there is a slight systematic shift downward for the night of January 4 (purple). The horizontal red line shows the CoRoT spacecraft radius (Bean 2009) and the dashed red lines indicate three scale heights above and below this value. (A color version of this figure is available in the online journal.)

The same IRAF data analysis pipeline and MCMC light-curve fitting is applied to all three nights of observation and the fitted radius ratio and uncertainties are shown in Figure 9. The three nights are consistent within errors for a given wavelength. However, there is a slight decrease in radius fit for the night of 2012 January 4.

The three sets of observations in Figure 9 are combined with a weighted average to produce a final transmission spectrum of the planet to be used in comparison to models. The weights are the inverse squared error in each wavelength bin for each night. We make the assumption that weather-related variability on the hot Jupiter itself has a negligible effect on the transmission spectrum. We also assume that the errors in radius from night to night are independent.

It is worth noting that the Gaussian process method achieved higher precision than a polynomial baseline on the half-transit observation for 2011 December 29. Figure 10 shows a comparison between the best-fit radius when using a third-order Legendre baseline fit as compared to the Gaussian correlated process. Both the scatter and error bars are larger when imposing a specific baseline shape. There was one particular light curve, the MORIS z′ photometry for 2012 January 4, that showed a very strong dependence on the type of treatment of systematic errors. As seen in the time series, Figure 4, the flux bends downward after egress. When the light curve is fit with a third-order Legendre polynomial, this drop in flux is extrapolated to a higher flux during transit and thus the planet-to-star radius ratio estimate \( R_p/R_\star \) is large. When the light curve is fit with the Gaussian process method, the deviations from a flat baseline are best fit with shorter timescale correlations and an essentially flat baseline. Our Gaussian process kernel (Section 3.1) incorporates different shapes through the Matérn index, but does not increase the upper limit to the same value as the polynomial baseline. We adopt the Gaussian process model fits, but given the dependence of \( R_p/R_\star \) on the method, we also evaluate our science results with the polynomial model fits.

The average spectrum, listed in Table 2, has \( R_p/R_\star \) uncertainties ranging from 0.7% to 2% of the mean value (\( R_{p,\text{mean}}/R_\star = 0.144 \)) across the near-IR coverage. This uncertainty is comparable to the scale height of the atmosphere (~0.8% for a 2400 K atmosphere), whereas strong spectral features are expected to be three to five scale heights in planet radius variation (Burrows & Orton 2009). Figure 9 shows no immediate statistically significant (5σ) molecular features.
Figure 10. Comparison between a polynomial baseline Levenberg–Marquardt fit and a Gaussian process method for the baseline and flux variations. Photometry points (ε' band) are shown with bold lines, and the corresponding ε' bandpass is shown in green. The results are largely consistent for the SpeX data on the full transits of 2011 December 23 and 2012 January 4, but differ on the half-transit of 2011 December 29 and the MORIS photometry for 2012 January 4. The MORIS photometry light curve for 2012 January 4 shows particularly large sensitivity to the fitting method because the flux bends down after egress—see Figure 4. For the half-transits of 2011 December 29, the third-order polynomial (due to the shorter time baseline) produces much larger scatter for the half-transit than the Gaussian process method because it is fitting a specific shape to the light curve in the presence of red noise.

(A color version of this figure is available in the online journal.)

Table 2

| Wavelength (μm) | Rp/R*   |
|-----------------|---------|
| ε' (0.86)       | 0.1389 ± 0.0012 |
| 0.908           | 0.1450 ± 0.0027  |
| 1.083           | 0.1448 ± 0.0013  |
| 1.259           | 0.1440 ± 0.0014  |
| 1.434           | 0.1474 ± 0.0016  |
| 1.610           | 0.1415 ± 0.0010  |
| 1.786           | 0.1426 ± 0.0026  |
| 1.961           | 0.1431 ± 0.0029  |
| 2.137           | 0.1440 ± 0.0022  |
| 2.312           | 0.1470 ± 0.0020  |

Notes. Quoted error bars are calculated by propagating the individual MCMC uncertainties in quadrature. The central wavelength for each 0.1755 μm bin is given in the first column except for the photometry where the first moment is given in parentheses.

4. COMPARISON WITH MODELS

The error-weighted average transmission spectrum for the three nights is compared against a representative model for hot Jupiter atmospheres from Fortney et al. (2008b, 2010). We select this model as a starting point because it has a published IR spectrum, solar abundances, and equilibrium chemistry. The blackbody temperatures fit to IR data of ≈2400 K (Tbb = 2380 K, Tbb = 2460 K; Zhao et al. 2012; Deming et al. 2011), and short orbital period P = 1.509 days (Barge et al. 2008) indicate that it is comparable to the Tkinetic = 2500 K isothermal model from Fortney et al. (2010).

The equilibrium model from Fortney et al. (2008b, 2010) shows substantial opacity in the optical as compared to the IR due to mainly TiO and VO absorption, so we compare the CoRoT derived radius (Bean 2009) to our transmission spectrum, as seen in Figure 11. The Bean (2009) radius is larger than the original discovery (Barge et al. 2008), but we adopt the Bean (2009) value because it was found with a newer data processing pipeline. The combined CoRoT data and IRTF data show no evidence for an optical to IR slope. Fitting a flat spectrum to the data gives a reduced chi-squared (χ^2) of 2.9 for 10 degrees of freedom whereas the model with TiO/VO gives χ^2 of 4.6 for 10 degrees of freedom. The same model with TiO and VO artificially removed, gives χ^2 of 2.4 for 10 degrees of freedom. As mentioned in Section 3.2, the MORIS results were particularly sensitive to the choice of model to fit the time series. If we use a polynomial baseline fit to the time series, the TiO/VO rich model is again disfavored with a χ^2 of 2.9 as compared to the TiO-removed model with χ^2 of 1.6 and a flat line of χ^2 of 1.3.

The hot Jupiter WASP-19b also shows no evidence for TiO/VO absorption (Huitson et al. 2013; Mancini et al. 2013). For this planet, TiO/VO depletion is expected since WASP-19b has no observed temperature inversion (stratosphere; Anderson et al. 2013). WASP-12b similarly has no stratosphere, but does have a larger optical to IR transit depth ratio. Models for WASP-12b that included either TiO/VO or TiH were consistent with initial data (Swain et al. 2013; Stevenson et al. 2013) but adding optical data and including models with aerosols together
suggest that WASP-12b has low levels of TiO/VO (Sing et al. 2013).

CoRoT-1b, by contrast, is better matched by models with a stratosphere or isothermal temperature profile. Rogers et al. (2009) compare a suite of equilibrium abundance models with multi-color photometric secondary eclipses on CoRoT-1b. The molecular features in these models appear in absorption or emission depending on the temperature structure of a planet’s atmosphere and Rogers et al. (2009)’s models with no temperature inversion fail to produce the $K_s$ and narrowband 2.1 μm brightness temperatures for the planet. The only models that come close to matching the observations include an extra optical absorber at the 0.01–0.1 bar level. Deming et al. (2011) also find that the secondary eclipse fluxes are better fit with models that include a temperature inversion than models without. Still, Deming et al. (2011) find consistency with a blackbody spectrum, which could be due to an isothermal profile or a thick layer of high altitude dust.

Plausible absorbers that could create a stratosphere in CoRoT-1b are TiO and VO (Fortney et al. 2008a), which should also increase the optical radius as compared to the IR. However, since our IRTF-CoRoT combined spectrum is disfavored by models with TiO/VO absorption, we expect another species is responsible for the temperature inversion, as has been suggested for HD 209458b (Burrows et al. 2007). Sulfur compounds are one possibility (Zahnle et al. 2009) and there is some doubt that TiO can survive in upper atmospheres due to gravitational settling (Spiegel et al. 2009). Alternatively, a high-altitude haze or dust (e.g., Pont et al. 2013) could explain the blackbody-like emission from CoRoT-1b and also flatten out molecular features in the transmission spectrum.

Many other atmospheric scattering and absorbing processes may occur in hot Jupiter atmospheres including (a list from Sing et al. 2013) Raleigh scattering off molecules, Mie and Raleigh scattering off dust, tholin hazes and gray-absorbing clouds. The majority of these processes increase planetary radii at short wavelengths as compared to long wavelengths. Our observations, by contrast, show that the optical radius is not significantly larger than the IR radius based on the CoRoT photometry. Gray-absorbing clouds are the one item on the above list that could equalize the optical and IR transit depths. Recent observations of HAT-P-32b (Gibson et al. 2013b), HAT-P-12b (Line et al. 2013a), and Kepler-7b (Demory et al. 2013) indicate that high altitude clouds may be pervasive in exoplanet atmospheres. In HAT-P-32b, gray-absorbing clouds may obscure TiO/VO features (or the TiO and VO may be present at very low abundances; Gibson et al. 2013b). Analysis of the above a processes is limited with only CoRoT photometry, but additional optical spectroscopy would be useful in constraining the strength of these scattering and absorbing phenomena.

We observe a 2σ peak at 1.4 μm in the spectrum, close to a 1.4 μm water feature seen in all temperature classes of Fortney et al. (2010)’s equilibrium models. This same feature was used to detect water vapor in WASP-19b with HST (Huitson et al. 2013). However, if water vapor in CoRoT-1b caused the 2σ feature at 1.4 μm, the 1.8 μm radius should also be elevated, which is not seen in our spectrum. One possible explanation is that the 1.4 μm peak is due to H$_2$C$_2$ or HCN, which are both predicted to be abundant in hot Jupiter atmospheres (Moses et al. 2013). Unfortunately, the significance level of this peak is too low to distinguish between these molecules or rule out the possibility of a statistical deviation or un-removed telluric absorption signature.

5. CONCLUSION

We present a 0.8–2.4 μm transmission spectrum for the hot Jupiter CoRoT-1b, the faintest ($K = 12.2$) host star for which the planet has been spectroscopically characterized to date. With the MOS method and a single nearby simultaneous reference star, we achieve 0.03%–0.09% precision of the transit depth $R_p^2/R_∗^2$ when combining all three nights of data, comparable to one atmospheric scale height for this hot Jupiter’s temperature. We conclude the following items from our analysis.

1. The IRTF spectrum, when combined with the optical planet-to-star radius ratio derived from observations by the CoRoT spacecraft (Bean 2009), disfavors a model that includes TiO/VO as compared to a model that is spectrally flat or has TiO removed. This goes against the prediction that CoRoT-1b’s thermal inversion is due to TiO/VO absorption. Other recently characterized hot Jupiters with similarly high temperatures, WASP-19b and WASP-12b, also lack strong TiO/VO (Anderson et al. 2013; Sing et al. 2013) features, but TiO/VO is expected to be depleted in these planets because they have no observed temperature inversions.

2. No statistically significant molecular features are seen in the 0.8–2.4 μm transmission spectrum, although there is a small 2σ peak at 1.4 μm, possibly due to H$_2$C$_2$ or HCN. Our precision is not high enough to constrain the detailed composition of H$_2$O, CO, and other gases due to the systematics and faintness of the host star.

3. The Gaussian process method for determining systematics and the baseline achieves better precision in extracted parameters and more robustness when applied to the half-transit on 2011 December 29 as compared to a deterministic polynomial baseline. For data sets with strong out-of-transit curvature, the Gaussian Process model can
give significantly different results from a polynomial baseline.

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APPENDIX

SIMULATED SERIES

In order to compare an autocovariance of residuals to an input kernel, it is illustrative to show the autocovariance of some simulated time series. Figure 12 shows simulations for the best-fit hyper-parameters from the 1.79 μm, 1.43 μm, and z′ light curves on the night of 2012 January 4. The two autocovariance plots of the residuals are shown in Figure 7.

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