THE GROUND-BASED H-, K-, AND L-BAND ABSOLUTE EMISSION SPECTRA OF HD 209458b

ROBERT T. ZELLEM1, CAILTIN A. GRIFFITH1, PIETER DEROO2, MARK R. SWAIN2, AND INGO P. WALDMANN3
1 Lunar and Planetary Laboratory, University of Arizona, 1629 East University Boulevard, Tucson, AZ 85721, USA; rzellem@lpl.arizona.edu
2 Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Drive, Pasadena, CA 91109, USA
3 University College London, Department of Physics and Astronomy, Gower Street, London WC1E 6BT, UK
Received 2014 August 11; accepted 2014 September 21; published 2014 November 4

ABSTRACT

Here we explore the capabilities of NASA’s 3.0 m Infrared Telescope Facility (IRTF) and SpeX spectrometer and the 5.08 m Hale telescope with the TripleSpec spectrometer with near-infrared H-, K-, and L-band measurements of HD 209458b’s secondary eclipse. Our IRTF/SpeX data are the first absolute L-band spectroscopic emission measurements of any exoplanet other than the hot Jupiter HD 189733b. Previous measurements of HD 189733b’s L band indicate bright emission hypothesized to result from non-LTE CH4 ν1 fluorescence. We do not detect a similar bright 3.3 μm feature to ~σ, suggesting that fluorescence does not need to be invoked to explain HD 209458b’s L-band measurements. The validity of our observation and reduction techniques, which decrease the flux variance by up to 2.8 orders of magnitude, is reinforced by 1σ agreement with existing Hubble/NICMOS and Spitzer/IRAC1 observations that overlap the H, K, and L bands, suggesting that both IRTF/SpeX and Palomar/TripleSpec can measure an exoplanet’s emission with high precision.

Key words: atmospheric effects – methods: numerical – planets and satellites: general – planets and satellites: individual (HD 209458b) – techniques: spectroscopic

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Space-based telescopes offer the ability to make high-precision measurements of transiting exoplanets (e.g., Knutson et al. 2008; Swain et al. 2008; Crossfield et al. 2012b; Zellem et al. 2014; Diamond-Lowe et al. 2014). However, these platforms have limited time and instrumentation compared to ground-based capabilities. On the other hand, ground-based platforms are plagued by atmospheric attenuation and systematic errors that increase a data set’s variance, making it difficult to extract an exoplanetary signal.

Here we investigate the potential of ground-based measurements with NASA’s 3.0 m Infrared Telescope Facility (IRTF) with the SpeX spectrometer and the 5.08 m Hale telescope with the TripleSpec spectrometer at Palomar Observatory. Our observations of the bright exoplanetary system HD 209458b span the infrared H, K, and L bands and include the first transiting exoplanet observations with Palomar/TripleSpec. These wavelengths have also been explored by the Hubble and Spitzer space telescopes, allowing us to test our own methodologies for treating the extraction of the planetary signal from atmospheric effects and systematic errors. Our ultimate goal is to demonstrate the capability of both platforms for near-IR transiting exoplanet spectroscopy.

This project also includes the first absolute L-band (∼3–4 μm) spectroscopic measurements of an exoplanet other than the hot Jupiter HD 189733b. The four spectra recorded for HD 189733b reveal a bright (Tbright ≈ 2750 K, compared with HD 189733b’s Teff ≈ 1200 K) emission source at 3.3 μm with a wavelength and shape that are consistent with the P, Q, and R branches of the CH4 ν1 vibrational-rotational band (Swain et al. 2010; Waldmann et al. 2012). This feature is also observed in the spectra of Titan (Kim et al. 2000), Jupiter (Drossart et al. 1999; Brown et al. 2003), and Saturn (Drossart et al. 1999), where its large flux is explained by fluorescence. Since HD 209458b (Teff ≈ 1450 K) is hotter than HD 189733b, it has a comparably lower CH4 content, according to thermochemical equilibrium (Moses et al. 2011), and potentially no bright L-band feature. We search here for a similar feature, or lack thereof, in HD 209458b’s L-band spectrum to further investigate the radiative mechanisms of exoplanetary atmospheres.

2. OBSERVATIONS AND DATA REDUCTION

We observed HD 209458b’s emission with the 3.0 m NASA IRTF at the Mauna Kea Observatory and SpeX (Rayner et al. 2003), a near-IR spectrometer with a wavelength coverage of 2.0–4.2 μm (K and L bands) and a resolution of R = 2500, and with the 200 inch (5.08 m) Hale Telescope at the Palomar Observatory and TripleSpec, a near-IR spectrometer with a wavelength coverage of 1.0–2.4 μm (J, H, and K bands) and a resolution of R = 2500–2700. While low-resolution spectroscopic observations are incapable of observing the fine-scale structure of the spectral lines, the SpeX and TripleSpec spectral channels can be binned to increase the signal-to-noise ratio (S/N). Thus IRTF/SpeX and Palomar/TripleSpec can observe the broad spectral behavior of an exoplanet such as HD 209458b, allowing them to complement their high-resolution counterparts (e.g., the R = 100,000 Very Large Telescope/CRHRES). The capability of IRTF/SpeX for exoplanet spectroscopic observations was verified by the observations of Swain et al. (2010), who binned spectral bands unaffected by terrestrial absorption in Fourier space to reduce ground-based systematic errors and reproduce the Hubble K-band spectra of HD 189733b. Their results were confirmed by Thatte et al. (2010) using a method involving a principal component analysis (PCA) and reproduced by Waldmann et al. (2012), despite the variable humidity between their four nights of observations. Others (e.g., Richardson et al. 2003; Crossfield et al. 2012a; Danielski et al. 2014) have also used IRTF/SpeX for additional eclipsing exoplanet observations. The capability of Palomar/TripleSpec for transiting exoplanet spectroscopy has yet to be demonstrated. The wavelengths covered by SpeX and TripleSpec are also partly covered by previous Hubble/NICMOS (Swain et al. 2009) and Spitzer/IRAC1 (Knutson et al. 2008; Diamond-Lowe...
et al. 2014) measurements of HD 209458b’s emission, thereby providing important verification for our difficult ground-based observations.

2.1. IRTF/SpeX

We observed HD 209458b’s 2011 September 9 (UT) secondary eclipse for ~8 hr, resulting in 1210 exposures of 10 s each in an ABBA nodding sequence. Systematic errors can be introduced by telescope jitter caused by, for example, slewing to a comparison to check star or adjusting the telescope’s focus. Therefore, to limit the introduction of additional systematics, we set the focus only once at the beginning of the night and stayed on the target throughout the entire night. Error from seeing- and pointing-induced signal loss is minimized by a 1′/6 wide slit; the seeing was at best 0′:47 and at worst 1′:51. The raw images are dark subtracted, flat fielded, and wavelength calibrated. The spectrum is extracted from each image using the Spextool reduction package for IDL (Cushing et al. 2004; Vacca et al. 2003).

For ground-based observations, typical sources of error include changing airmass as the target rises and sets, telescope jitter, or mirror flexure. Such errors can cause data scatter on the order of ~10%–20% (but sometimes even as large as ~40%–60%), which dwarf HD 209458b’s expected secondary eclipse depth of <0.2% (Figure 1). These non-Gaussian error sources are reflected in the raw flux histogram (Figure 2, top) and must be removed or reduced to detect the small planetary signal. To minimize error propagation from telluric absorption lines, we select wavelength channels that are not close to the band edges: 2–2.38 μm, corresponding to 900 spectral channels in the K band, and 3–3.99 μm, corresponding to 1400 spectral channels in the L band. All observations at comparably higher air mass values (≥1.65; corresponding to a phase ≥0.55 in Figure 1) and just after the telescope flipped the pier (0.5175 ≤ phase ≤ 0.5215) were also removed.

As with previous IRTF/SpeX observations (Swain et al. 2010), the time-varying flux (Figure 1) indicates that the A and B nods are affected differently by systematic errors (e.g., due to varying pixel efficiencies on different parts of the detector). Therefore we separate the two nods, reduce each set independently to eliminate nod-specific systematics, and then merge them at the end. Anomalies such as cosmic rays are removed with a two-dimensional Wiener filter. This filter estimates the mean and variance for each pixel from its eight nearest neighbors and replaces an outlying pixel with the mean of its surrounding pixels.

This reduction is based upon and uses the same assumptions of the “self-coherence” methods of Swain et al. (2010) and Waldmann et al. (2012), which assume that (1) the systematic errors are large with respect to signal, (2) the systematic errors are based either on correlations in wavelength or time, and (3) the difference between eclipse depths in adjacent wavelength channels is small.

Systematics can affect each spectrum differently, causing individual spectra to have unique brightness variations that manifest as intra-spectral variations. To reduce these variations, we divide the data into blocks of 100 spectral channels and then normalize each spectrum’s time-varying flux by the mean of its bin’s time-varying flux:

\[
F_i^j = \frac{S_i^j}{S_{avg,i}}, \tag{1}
\]

where

\[
S_{avg,i} = \frac{\sum_{j=1}^{n} S_i^j}{n}, \tag{2}
\]
and \( i \) is the time index, \( j \) is the wavelength channel, and \( n \) is the number of wavelength channels in the block \((n = 100)\). This normalization divides out wavelength-dependent and time-dependent errors common among the wavelength channels in each bin (referred to as “common-mode” errors in Swain et al. 2010). Since the eclipse signal is too small to be detected at this point, only systematic errors are removed and not the commonly shared eclipse signal.

At this point, air mass variations dominate the data. As seen in Figure 1, the data have a different shape before and after HD 209458 reaches the zenith. This phenomenon is due to the telescope settling throughout the beginning of the night. Therefore, each half of the light curve (pre- and post-zenith) is fit with an exponential air mass correction:

\[
a^j \cdot e^{b^j \cdot \text{air mass}} = F^j_i, \tag{3}
\]

where the air mass is a function of time \( i \) and \( j \) is the wavelength channel index such that each half of the time series (for each wavelength channel) is individually corrected via the equation

\[
I^j_i = \frac{F^j_i}{a^j \cdot e^{b^j \cdot \text{air mass}}}, \tag{4}
\]

where \( I^j_i \) is each individual air mass-corrected channel \( j \) at time \( i \).

While this correction flattens the light curves, some outliers persist. We statistically identify these outliers with Chauvenet’s criterion: if a data point from a population of \( n \) data points has a Gaussian probability less than 1/2\( n \), then this data point is an outlier. We use Chauvenet’s criterion in a running boxcar with a width \( n = 10 \) on each light curve’s time-varying flux and replace any outliers with the mean of the \( n \) data points.

However, at this point, the eclipse signal is still too small to be detected. This low-frequency eclipse signal is enhanced by taking the geometric mean of each block in Fourier space (Swain et al. 2010):

\[
F^j_i = \text{IFT} \left[ \left( \prod_{j=1}^{n} \text{FT} (I^j_i) \right)^\frac{1}{n} \right], \tag{5}
\]

where \( I \) is the channel’s flux, \( i \) is the time index, \( j \) is the wavelength channel index, \( \text{FT} \) is the Fourier transform, \( n \) is the number of channels per bin \((n = 100)\), \( k \) is the new bin index \((k = 1–9 \) for the \( K \) band; \( k = 10–23 \) for the \( L \) band), and \( \text{IFT} \) is the inverse Fourier transform. This method converts the data from time-space to frequency-space, then enhances the eclipse signal by taking the geometric mean of 100 spectral channels to form a new wavelength bin. All modes are kept and then this bin is converted back from frequency–to–time–space with the IFT. The end result is nine new \( K \)-band spectral bins due to binning 900 spectral channels by 100, and 14 new \( L \)-band spectral bins due to binning 1400 spectral channels by 100.

However, some residual systematic errors (e.g., air mass and possibly some curvature introduced by the Fourier transform) remain, as indicated by residual curvature in the light curves. In order to correct for this curvature, we fit various amounts of baseline (out-of-eclipse points) to a second-degree polynomial. Since the amount of pre-eclipse data is limited due to the eclipse ingress being comparatively close to sunset (Figure 1), we vary the pre-eclipse baseline only up to half its length and allow the total number of baseline points to vary as long as their number is always greater than or equal to the number of in-eclipse (second to third contact) points. As a result, 3783 different amounts of baseline per light curve are fit to a second-degree polynomial. The optimal amount of baseline is the one that best minimizes the out-of-eclipse baseline scatter. Its corresponding second-degree polynomial fit is then interpolated to the in-eclipse data to flatten the entire light curve. The eclipse depth is then extracted from the light curve by fitting a Mandel & Agol (2002) model light curve using the physical parameters of \( R_{\text{plan}} = 1.146 \ R_{\odot} \) (Brown et al. 2001), \( R_{\text{plan}} = 1.38 \ R_{\text{Jupiter}} \), orbital inclination of 86.59, semimajor axis of 0.04747 AU (Southworth 2010), orbital period of 3.524746 days (Torres et al. 2008), and period epoch of 2455216.405640 BJd UTC (Zellem et al. 2014).

This baseline fitting routine can potentially introduce additional uncertainty to the derived eclipse depth. We estimate this error with a Monte Carlo simulation of the baseline fitting routine with 3.458 million light curves per original light curve, generating 3.458 million eclipse depths. The standard deviation of all of these simulated eclipse depths reflects the uncertainty of the final light curves’ eclipse depths and, as a result, the calculated planet-to-star flux ratio.

The flux ratios of the planet to the star \((F_{\text{planet}}/F_{\text{star}})\) are calculated from the eclipse depths of the final reduced light curves (Figures 3 and 4) and then used to construct the low-resolution emission spectrum of HD 209458b (Figures 5 and 6). The 1\( \sigma \) error bars for each spectral point are calculated from the root-sum-square of the standard deviations of the in- and out-of-eclipse data points as well as the error introduced from the baseline fit. The uncertainty of the eclipse depth, and therefore the planet-to-star flux ratio \((F_{\text{planet}}/F_{\text{star}})\), is due to not only errors introduced by the baseline fitting routine but also the scatter in the in- and out-of-eclipse data. Therefore, we conservatively estimate the 1\( \sigma \) error bars on our eclipse depths by adding in quadrature the uncertainties from the in-eclipse data, the out-of-eclipse data, and then the error introduced by the baseline fit.

2.2. Palomar/TripleSpec

We recorded HD 209458b’s 2010 September 4 (UT) secondary eclipse in the near-IR \( J, H \), and \( K \) bands with Palomar/TripleSpec. We observed HD 209458 for ~4.5 hr with
an ABBA nodding sequence, taking 396 exposures of 20 or 23 s and coadding two frames. The night was not optimal—the seeing was at best 1.2 and at worst 1.5, causing some (≤22%) of the target to be cut off by the 1" wide slit and induce variance in the data set, as indicated in the raw flux histogram (Figure 7, top) and raw light curves (Figure 8).

Standard methods are adopted to derive the initial light curve (Figure 8). The raw image is first dark subtracted, flat fielded, and normalized to an exposure time of one second. TripleSpec routines (P. Muirhead 2011, private communication) wavelength-calibrate each image and extract each spectral order. A Gaussian is fit across the dispersion axis to determine the average horizontal location of the spectral order on the detector and its associated FWHM. The flux per wavelength channel includes the sum of the pixels in a column along the dispersion axis within 3 × FWHM of the order’s mean horizontal position. The five spectral orders and the two nods are initially kept separate; systematics are eliminated from each nod and order before they are combined together.

To minimize telluric absorption lines from propagating errors throughout the data, we select wavelengths far from the band edges, i.e., 1.55–1.75 μm for the H band and 2.1–2.46 μm for the K band, which correspond to 500 and 400 spectral channels, respectively. Due to high telluric absorption at the band edges,
The eclipse signal of HD 209458b is not immediately discernible because of the variance from systematic errors. To reduce intra-spectral variations, following Swain et al. (2010), each spectrum is normalized by its mean number of counts over all channels (Equations (1) and (2)). Each spectrum indicates a slight wavelength shift on the CCD, which is corrected by identifying a relatively sharp and bright spectral feature, fitting it with a fourth-degree polynomial and moving it to match up with a mode reference position. Anomalies such as cosmic rays are removed with a two-dimensional Wiener filter.

The spectra in each nod are still plagued by separate, distinct errors that prevent their combination. Previous tests of combining the nods and proceeding with the Swain et al. (2010) and Waldmann et al. (2012) reductions (normalizing the spectra, binning in Fourier space, etc.; see Section 2.1) without removing these systematic errors result in error bars three times larger than their current size, preventing the sensitivity necessary to confirm that the Palomar/TripleSpec data agrees with previous Hubble/NICMOS measurements. To reduce these errors, a PCA is conducted to calculate a new set of orthogonal basis vectors that minimize the amount of variance in a data set. Along with PCA, other non-parametric de-trending techniques have been used in the literature, most notably Gaussian processes (GP; e.g., Gibson et al. 2012), and independent component analysis (ICA; e.g., Waldmann 2012). These techniques have been demonstrated for space-based data but not ground-based observations. In the case of our Palomar data, the aim (performed by the PCA analysis) is to reduce the effect of telluric noise, which manifests itself in high variance scatter of the raw light curve. In the case of GP, the large initial variance makes the model convergence over the model’s hyper-parameters difficult. Furthermore, systematic noise not pertaining to the instrument (such as atmospheric seeing and clouds) cannot be captured by a regression of auxiliary optical state vectors as described in Gibson et al. (2012). Similarly, the efficiency of an ICA is significantly reduced in the presence of a significant Gaussian noise component in the data. With PCA being a pre-processing step to ICA, the independent components converge to the more classical principal components in high variance data sets (see Waldmann 2012; Waldmann et al. 2013; Waldmann 2014). We hence opt for the PCA approach that was demonstrated by Thatte et al. (2010) to be a robust non-parametric de-trending approach to ground-based data sets. The PCA analysis produces a new set of components where the first principal component corresponds to a new basis vector containing the most variance, the second principal component contains the second-most variance, and so on. Assuming that the eclipse signal is much smaller than sources of error (typically, systematic errors account for ~10%–20% variance while the eclipse signal is only <0.2%), the first principal component should contain most of the systematic errors. The eclipse signal would then be present in higher-order components. Our PCA differs from that used by Thatte et al. (2010) to recover the secondary eclipse of HD 189733b—where they implement PCA to extract the common eclipse signal from multiple wavelength channels, we use a PCA to find and remove systematic errors common among wavelength channels to clean the data and uncover the underlying eclipse signal.

However, PCAs have two caveats: (1) while errors are likely to be contained in the first principal component, they can leak into higher orders, and (2) it is likely that multiple components contain the eclipse signal. Oftentimes the signal and noise are mixed across components as they can have similar amplitudes. We observe a secondary eclipse of an exoplanet on a night with higher seeing and a passing cloud, resulting in large scatter which dwarfs the much smaller eclipse signal. Therefore, we assume that the principal component contains most of the noise due to systematic errors and none of the eclipse signal. Since the eclipse signal could be mistakenly removed by eliminating too many components in an attempt to remove the systematic error, only the first principal component is removed. However, systematic errors likely leak into the higher (>2) orders, which we keep, requiring further data reduction in order to resolve the eclipse signal.

The time-varying flux data is prepared for the PCA by first grouping each nod’s data into bins of five spectral channels. While other bin sizes were tested, this one best reduces systematic errors as it is large enough to find commonly shared systematic errors but small enough so that the eclipse signal is not resolved and inadvertently removed by the PCA. Thus, a PCA on this bin size will find a first principal component that contains a systematic error common among the spectral channels in the bin rather than a common eclipse signal. We then run a PCA on the time-varying flux of each bin and eliminate the first principal component to get rid of ~80% of the wavelength- and time-correlated systematic errors, such as air mass. The remaining (>second-order) components are mapped back to obtain cleaned light curves. With most of the systematic errors removed, the nods are then combined.

At this point, the stacked spectra indicate large flux variations at the phase of 0.526 (~30 minutes post-eclipse) and the autoguider failing onward of the phase of 0.55 (~2.5 hr post-eclipse). However, these two sections of data likely influence the PCA; therefore, we manually remove both of these sections and re-run the entire analysis to better reduce the variance. Despite

Figure 8. Sample raw, normalized Palomar/TripleSpec light curve extracted from one wavelength channel (1.6 μm) out of 396 total wavelength channels. At this point, systematic errors cause a variance of ~10%–20%, preventing the detection of the smaller (<0.2%) eclipse signal. Nod A (blue circles) and nod B (red squares) are plagued by their own distinct set of systematic errors, preventing their combination. We therefore use a principal component analysis to reduce the systematic errors by 2.8 orders of magnitude (Figure 7), allowing us to then combine the nods. The drop in flux at a phase of 0.55 (~2.5 hr post-eclipse) is due to autoguider failure.

(A color version of this figure is available in the online journal.)
this “pre-filtering” of obvious bad data, the eclipse signal is still not resolved. To enhance the low-frequency eclipse signal over the noise, we bin the data by taking the geometric mean in Fourier space (Equation (5)).

The light curves still indicate some low-order polynomial curvature introduced by the Fourier transform and from residual systematic errors, such as air mass. In order to correct for this curvature, we fit various amounts of baseline (out-of-eclipse points) to a second-degree polynomial. This low-order polynomial is chosen to prevent overfitting the data with higher-order functions. Since the amount of pre-eclipse data was comparably limited, we vary the pre-eclipse baseline up to half its length. The post-eclipse data is then free to vary so that its length. The post-eclipse points are removed with a normalization routine for IRTF/SpeX Measurements of HD 209458b’s Emission

| Wavelength (μm) | $F_{\text{planet}}/F_{\text{star}}$ ($\times 10^3$) | Uncertainty $\sigma$ ($\times 10^3$) | Photon Noise $\sigma_{\text{photon}}$ ($\times 10^3$) | $\sigma/\sigma_{\text{photon}}$ |
|-----------------|-----------------------------------|--------------------------------|------------------------|------------------|
| 2.0401          | 0.2652                             | 0.2522                          | 0.0391                 | 6.4484           |
| 2.0803          | 0.0548                             | 0.1439                          | 0.0354                 | 4.0666           |
| 2.1205          | 0.0921                             | 0.0951                          | 0.0328                 | 2.9012           |
| 2.1607          | 0.1592                             | 0.1038                          | 0.0330                 | 3.1503           |
| 2.2027          | 0.1880                             | 0.1710                          | 0.0349                 | 4.8998           |
| 2.2474          | 0.0688                             | 0.1241                          | 0.0349                 | 3.5533           |
| 2.2921          | 0.0593                             | 0.1547                          | 0.0345                 | 4.4842           |
| 2.3368          | 0.2111                             | 0.1886                          | 0.0350                 | 5.3823           |
| 2.3815          | 0.2688                             | 0.3400                          | 0.0363                 | 9.3771           |
| 3.0287          | 0.9747                             | 0.9976                          | 0.0650                 | 15.3561          |
| 3.0865          | 0.5286                             | 1.0381                          | 0.0641                 | 16.1913          |
| 3.1478          | 1.1756                             | 0.8403                          | 0.0606                 | 13.8753          |
| 3.2150          | 2.5665                             | 1.4820                          | 0.0697                 | 21.2674          |
| 3.2839          | 2.0470                             | 1.8989                          | 0.0673                 | 28.2092          |
| 3.3558          | 1.7134                             | 1.2129                          | 0.0685                 | 17.6953          |
| 3.4228          | 1.9494                             | 1.0108                          | 0.0729                 | 13.8590          |
| 3.4901          | 0.3035                             | 0.3274                          | 0.0785                 | 4.1694           |
| 3.5576          | 0.3257                             | 0.3797                          | 0.0661                 | 5.7405           |
| 3.6258          | 0.4718                             | 0.3734                          | 0.0564                 | 6.6184           |
| 3.7035          | 0.2078                             | 0.8235                          | 0.0602                 | 13.6899          |
| 3.7845          | 0.2703                             | 0.4291                          | 0.0587                 | 7.3109           |
| 3.8652          | 1.4744                             | 1.0290                          | 0.0617                 | 16.6830          |
| 3.9457          | 0.1677                             | 0.5896                          | 0.0647                 | 9.1174           |

3. DISCUSSION

3.1. Results

Here we present the IRTF/SpeX and Palomar/TripleSpec H-, K-, and L-band emission spectra of the hot Jupiter HD 209458b measured from two secondary eclipses. Systematic errors, such as telescope jitter and air mass variations, can cause data scatter on the order of ~10%–20%, which dwarf HD 209458b’s secondary eclipse depth (~0.2%). These common-mode errors are removed with a normalization routine for IRTF/SpeX (Section 2.1) and a PCA for Palomar/TripleSpec (Section 2.2). The low-frequency eclipse signal is enhanced over the remaining noise by binning spectral channels in Fourier space. The IRTF/SpeX reduction decreases the variance by 1.6 orders of magnitude (Figure 2) to get within 2.9 times the photon noise limit (Table 1). Due to high telluric absorption at the band edges, the Palomar/TripleSpec J band lacks a sufficient number of spectral channels to resolve the eclipse signal. Yet for the H and K bands, the Palomar/TripleSpec reduction decreases the variance by 2.8 orders of magnitude (Figure 7) to get within 8.8 times the photon noise limit (Table 2). Both reductions restore a more symmetrical shape in the final flux histograms, suggesting a reduction of non-Gaussian red noise (Figures 2 and 7). Despite the persistence of red noise, as suggested by the non-Gaussian shape of the final flux histograms (Figures 2 and 7), we reduce the IRTF/SpeX K-band mean variance to 175 ppm and the Palomar/TripleSpec binned K-band uncertainty to 208 ppm. For comparison, Swain et al. (2010) found a mean K-band variance of ~150 ppm while observing the secondary eclipse of HD 189733b (V-mag = 7.68, K-mag = 5.54) with IRTF/SpeX. After scaling our IRTF/
Eclipse depths in 3 of the 9 

in Mauna Kea. In the IRTF Palomar likely due to the IRTF’s superior observing conditions smaller than IRTF on the same targets under similar observation the Hale telescope can theoretically achieve a variance of IRTF (3 m) and Palomar (5.08 m), we achieve a similar

HD 209458b and HD 189733b and primary mirror diameters while accounting for the difference in brightnesses between HD 209458b and Palomar

/ SpeX and Palomar

b Scaled from the binned 
a Estimated flux ratio of the planet to the star (see the text).

HAT-P-32 b 9.99000 1.20003 1.13340 1.05878

WASP-33 b 7.46800 1.44271 0.35480 4.06625

Ks 2.2058 0.1088 0.4409 0.0111 39.7775

2.1771 0.0131 0.2626 0.0109 23.9908

2.1182 0.0952 0.6897 0.0111 62.0932

1.6943 0.2053 0.3193 0.0116 27.6098

1.6314 0.0064 0.1023 0.0116 8.8418

1.6106 0.1108 0.1835 0.0119 15.4531

1.7711 0.0202 0.8475 0.0111 76.4640

2.2058 0.1088 0.4409 0.0111 39.7775

Notes.

\( a \) Estimated flux ratio of the planet to the star (see the text).

\( b \) Scaled from the binned K-band uncertainty measured here for HD 209458b (208 ppm) to each system using their respective \( K_s \) magnitudes.

SpeX and Palomar/TripleSpec binned K-band uncertainties while accounting for the difference in brightnesses between HD 209458b and HD 189733b and primary mirror diameters of IRTF (3 m) and Palomar (5.08 m), we achieve a similar variance (123 ppm and 174 ppm, respectively) to Swain et al. (2010). However, due to its larger primary mirror (5.08 m), the Hale telescope can theoretically achieve a variance ~60% smaller than IRTF on the same targets under similar observation conditions. We do not achieve this theoretical precision for Palomar likely due to the IRTF’s superior observing conditions on Mauna Kea. In the IRTF/SpeX data, we detect non-zero eclipse depths in 3 of the 9 K-band light curves (Figure 3) and in 7 of the 14 L-band light curves (Figure 4). All of the Palomar/TripleSpec light curves are consistent with a null detection (Figure 9). Both data sets, despite the different platforms and reduction schemes, agree both with each other and with previous Hubble/NICMOS (Swain et al. 2009) and Spitzer/IRAC1 (Knutson et al. 2008) observations to 1σ and a new Spitzer/IRAC1 measurement (Diamond-Lowe et al. 2014) to 1.5σ (Figures 5, 6, and 10), suggesting the validity of the observation and reduction techniques employed here. In addition, the K- and L-band measurements resemble previous IRTF/SpeX HD 209458b emission contrast spectra (Richardson et al. 2003).

3.2. Palomar/TripleSpec’s Ability to Measure Other Targets

The HD 209458b binned K-band uncertainty (208 ppm) suggests that Palomar/TripleSpec is capable of high-precision exoplanet measurements of both primary transits and secondary eclipses. In particular, the number of secondary eclipse, higher S/N targets for Palomar/TripleSpec is estimated from the host star’s radius \( R_p \) and effective temperature \( T_e \), and the planet’s semimajor axis \( a \). Assuming an albedo of zero and efficient energy transport to the night side, the planet’s equilibrium temperature \( T_p \) is

\[
T_p = T_e \sqrt{\frac{R_p}{2a}}. \tag{6}
\]

Note that this simple estimate underestimates the dayside temperature of hotter planets \( (T_{\text{dayside}} \geq 2000 \text{ K}) \), which are predicted to redistribute energy from the dayside to the nightside less efficiently (e.g., Cowan & Agol 2011; Perna et al. 2012; Perez-Becker & Showman 2013). Therefore, our estimated S/Ns of the hotter exoplanets are very conservative. Assuming that the host star and planet emit as black bodies, we estimate the planet-to-star flux ratio \( F_p/F_s \) at the center of the \( K_s \) band (2.15 \( \mu \)m, Note that while planetary spectra diverge from blackbody emission, this assumption is necessary as we do not know the planet’s composition a priori. To estimate each target’s theoretical uncertainty \( \sigma \), we scale HD 209458b’s binned K-band uncertainty (\( \sigma_{\text{HD 2090}} = 208 \text{ ppm} \)) to each system using their respective \( K_s \) magnitudes \( m \):

\[
\sigma = \sigma_{\text{HD 2090}} \sqrt{\frac{F_{\text{HD 209}}}{F}} \quad \text{or} \quad \sigma_{\text{HD 209}} = \sigma_{\text{HD 2090}} \sqrt{\frac{F}{10^{-0.4(m_{\text{HD 209}} - m)}}}; \tag{7}
\]

where \( F_{\text{HD 209}} \) is the flux of HD 209458, \( F \) is the flux of the system’s host star, \( m_{\text{HD 209}} \) is the \( K_s \) magnitude of HD 209458 \( (K_s = 6.307) \), and \( m \) is the \( K_s \) magnitude of the system’s host star. According to these calculations, for example, Palomar/ TripleSpec can measure WASP-33b’s K-band emission with a S/N \( \approx 4 \) (Table 3). The theoretical Palomar/TripleSpec K-band S/Ns of primary transit measurements are calculated by first estimating the
Table 4  
Potential Exoplanet Targets for Measuring the Primary Transit with Palomar/TripleSpec

| Exoplanet     | $K_s$-mag | $H$ | Absorption$^b$ | Uncertainty$^c$ | S/N$^d$ |
|---------------|-----------|-----|----------------|----------------|---------|
| HD 189733 b   | 5.54100   | 217.994 | 23.5265       | 0.146077       | 161.055 |
| WASP-80 b     | 8.35100   | 214.307 | 28.9982       | 0.532823       | 54.4237 |
| GJ 436 b      | 6.07300   | 203.274 | 7.18361       | 0.186631       | 38.4910 |
| HD 80606 b    | 7.31500   | 17.3602 | 11.1666       | 0.330661       | 33.7707 |
| WASP-43 b     | 9.26700   | 107.398 | 24.8430       | 0.582349       | 26.1318 |
| WASP-77 A b   | 8.40500   | 233.018 | 16.6508       | 0.546240       | 30.4826 |
| WASP-34 b     | 8.79200   | 475.315 | 18.3705       | 0.652805       | 28.1409 |
| HAT-P-20 b    | 8.60100   | 16.0539 | 15.8112       | 0.597838       | 26.4474 |
| HAT-P-22 b    | 7.83700   | 111.412 | 11.0576       | 0.420539       | 26.2954 |
| HAT-P-17 b    | 8.54400   | 240.431 | 15.2178       | 0.582349       | 26.1318 |
| HD 1214 b     | 8.78200   | 251.885 | 14.9799       | 0.652805       | 28.1409 |
| WASP-10 b     | 9.96300   | 223.018 | 16.6508       | 0.546240       | 30.4826 |
| WASP-32 b     | 9.99000   | 1285.69 | 23.8054       | 0.546240       | 30.4826 |
| CoRoT-2 b     | 10.3100   | 161.794 | 27.1131       | 1.31333        | 20.6441 |

Notes.

$^a$ Scale height $H$ calculated by assuming an H$_2$-dominated atmosphere and that the mean atmospheric temperature is equal to the planet’s equilibrium temperature.

$^b$ Estimated light curve depth during primary transit; assuming that the planet’s atmosphere is optically thick at 5 scale heights $H$.

$^c$ Estimated mean atmospheric temperature is equal to the planet’s equilibrium temperature.

$^d$ Estimated mean atmospheric temperature is equal to the planet’s equilibrium temperature.

3.3. HD 209458b’s L-band Emission Spectrum

The L-band data (Figure 6) presented here is the first absolute measurement of any exoplanet other than HD 189733b. The resultant L-band spectrum that we derive for HD 209458b differs significantly from that observed three times for HD 189733b (Figure 11). Unlike HD 189733b, HD 209458b does not exhibit bright emission at 3.3 $\mu$m, suggesting that HD 189733b’s emission is specific to that exoplanet. HD 189733b’s bright L-band emission is attributed to non-LTE CH$_4$ $\nu_3$ fluorescence (Swain et al. 2010; Drossart et al. 2011). HD 209458b does not exhibit similar emission to $\sim$3$\sigma$ at 3.3 $\mu$m, suggesting that fluorescence is not needed (Figure 12).

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

Figure 11. Our final IRTF/SpeX HD 209458b L-band emission spectrum (blue circles) versus IRTF/SpeX L-band emission spectra of HD 189733b binned over three nights (Waldmann et al. 2012, green squares). HD 189733b exhibits bright emission at 3.3 $\mu$m, which is attributed to non-LTE CH$_4$ $\nu_3$ fluorescence (Drossart et al. 2011). HD 209458b does not exhibit similar emission to $\sim$3$\sigma$ at 3.3 $\mu$m, suggesting that fluorescence is not needed (Figure 12).

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

Figure 12. Comparison of existent HD 209458b secondary eclipse data (Swain et al. 2009; Knutson et al. 2008; Zellem et al. 2014; Diamond-Lowe et al. 2014; Swain et al. 2008; Crossfield et al. 2012b) with our IRTF/SpeX K- and L-band data (blue circles). A radiative transfer model (black line), whose inputs are based on the Moses et al. (2011) atmospheric model, fits all of the data nominally well, including our new IRTF/SpeX data. Also included are blackbody emission curves for $T = 1000$ K (dash dot), $T = 1500$ K (dash dot dot dot), and $T = 2000$ K (dash).

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

The resultant L-band spectrum that we derive for HD 209458b differs significantly from that observed three times for HD 189733b (Figure 11). Unlike HD 189733b, HD 209458b does not exhibit bright emission at 3.3 $\mu$m to $\sim$3$\sigma$, suggesting that HD 189733b’s emission is specific to that exoplanet. HD 189733b’s bright L-band emission is attributed to non-LTE CH$_4$ $\nu_3$ fluorescence (Swain et al. 2010; Drossart et al. 2011; Waldmann et al. 2012). Considering thermochemical equilibrium (Moses et al. 2011), the relatively cooler HD 189733b ($T_{\text{eff}} \approx 1200$ K) is predicted to have a higher CH$_4$ abundance than the hotter HD 209458b ($T_{\text{eff}} \approx 1450$ K); thus one might expect for HD 209458b to have weaker CH$_4$ $\nu_3$ emission. The theory that cooler objects have more CH$_4$ is supported by brown dwarf studies (e.g., Burrows et al. 1997; Burgasser 2008) and

scale height $H$ of each planet, assuming a mean atmospheric temperature equal to the planet’s equilibrium temperature and a H$_2$-dominated atmosphere. If the planet’s atmosphere is optically thick at 5 scale heights in the $K_s$ band, then the primary transit depth is

$$\text{transit depth} = \left( \frac{R_p + 5H}{R_s} \right)^2.$$

Since atmospheres can change drastically between different targets, we avoid adding any additional interpretation or assumptions into their composition or structure with a “channel to channel” S/N calculation. We instead calculate a “broadband” S/N across the entire $K_s$ band and avoid giving S/Ns on the atmospheric absorption, as doing so presupposes knowledge of the planet’s atmospheric composition. The typical channel-to-channel signal from a spectrum will be approximately a factor of $10^{-100}$ times smaller than the total photometric $K_s$-band transit depth calculated here.

3.3. HD 209458b’s L-band Emission Spectrum

The L-band data (Figure 6) presented here is the first absolute measurement of any exoplanet other than HD 189733b. The resultant L-band spectrum that we derive for HD 209458b differs significantly from that observed three times for HD 189733b (Figure 11). Unlike HD 189733b, HD 209458b does not exhibit bright emission at 3.3 $\mu$m to $\sim$3$\sigma$, suggesting that HD 189733b’s emission is specific to that exoplanet. HD 189733b’s bright L-band emission is attributed to non-LTE CH$_4$ $\nu_3$ fluorescence (Swain et al. 2010; Drossart et al. 2011; Waldmann et al. 2012). Considering thermochemical equilibrium (Moses et al. 2011), the relatively cooler HD 189733b ($T_{\text{eff}} \approx 1200$ K) is predicted to have a higher CH$_4$ abundance than the hotter HD 209458b ($T_{\text{eff}} \approx 1450$ K); thus one might expect for HD 209458b to have weaker CH$_4$ $\nu_3$ emission. The theory that cooler objects have more CH$_4$ is supported by brown dwarf studies (e.g., Burrows et al. 1997; Burgasser 2008) and
further reinforced by the lack of detection of a bright 3.3 μm feature on HD 209458b. In order to explore the question of whether the HD 209458b L-band measurements require non-LTE emission, we compare these data with a spectrum of a model atmosphere (Figure 12). Radiative transfer analyses of HD 209458b assume solar abundances and the presence of major sources of opacity expected for an extrasolar planet with HD 209458b’s equilibrium temperature, considering thermochemical equilibrium and disequilibrium processes (Moses et al. 2011), i.e., H2O, CH4, CO, and CO2, and using a temperature–pressure profile consistent with current GCM models (Showman et al. 2009). Using k coefficients of Griffith (2014), the emission of the exoplanet is calculated over pressure levels ranging from 10 to 10−5 bar, assuming LTE and the appropriate stellar model from Castelli & Kurucz (2004) for the host star’s flux. Note, however, that the model does not use the hot CH4 lines of Yurchenko & Tennyson (2014)—we leave a full radiative transfer analysis implementing these line lists to a future study. The agreement between the model and the data further suggests that fluorescence is not needed to explain HD 209458b’s emission, unlike HD 189733b (Swain et al. 2010; Waldmann et al. 2012).

4. CONCLUSIONS

IRTF/SpEX, until the launch of the James Webb Space Telescope, is one of the few platforms currently capable of measuring an exoplanet’s low-resolution L-band emission spectrum, which probes the CH4 ν3 band. Combined with Palomar/TripleSpec, with simultaneous J-, H-, and K-band coverage and a large primary mirror, these two platforms have the potential to observe wavelength regions where the major C and O bearing species (H2O, CO, CO2, and CH4) emit. Thus, measurements of these wavelengths coupled with radiative transfer analyses constrain the abundances of these molecules. In addition, these two platforms can help identify targets for future missions, such as the James Webb Space Telescope. IRTF/SpEX and potentially Palomar/TripleSpec, combined with significant data reduction as demonstrated here, are reliable instruments to use for high-precision ground-based eclipsing exoplanet spectroscopy.

R.T.Z. and C.A.G. are supported by the NASA Planetary Atmospheres Program. Part of the research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors thank Ming Zhao for observing HD 209458b with Palomar/ TripleSpec. R.T.Z. thanks Ian J. M. Crossfield and Michael R. Line for their helpful discussions. We also thank the referee for helpful comments and suggestions.

REFERENCES

Brown, R. H., Baines, K. H., Bellucci, G., et al. 2003, Icar, 164, 461
Brown, T. M., Charbonneau, D., Gilliland, R. L., Noyes, R. W., & Burrows, A. 2001, ApJ, 552, 699
Burgasser, A. J. 2008, P&T, 61, 70
Burrows, A., Marley, M., Hubbard, W. B., et al. 1997, ApJ, 491, 856
Castelli, F. & Kurucz, R. L. 2004, e-print (arXiv:pho0405087)
Cowan, N. B. & Agol, E. 2011, ApJ, 729, 54
Crossfield, I. J. M., Hansen, B. M. S., & Barman, T. 2012a, ApJ, 746, 46
Crossfield, I. J. M., Knutson, H., Fortney, J., et al. 2012b, ApJ, 752, 81
Cushing, M. C., Vacca, W. D., & Rayner, J. T. 2008, PASP, 116, 362
Danielski, C., Deroo, P., Waldmann, I. P., et al. 2014, ApJ, 785, 35
Diamond-Lowe, H., Stevenson, K. B., Bean, J. L., Line, M. R., & Fortney, J. J. 2014, e-prints (arXiv:1409.5336)
Drossart, P., Fouchet, T., Crovisier, J., et al. 1999, in ESA Special Publication, Vol. 427, The Universe as Seen by ISO, ed. P. Cox & M. Kessler (Noordwijk: ESA), 169
Drossart, P., Tinetti, G., Waldmann, I., & Swain, M. 2011, in EPSC-DPS Joint Meeting 2011, Model of Molecular Non-LTE Emission in Exoplanetary Atmospheres, 363
Gibson, N. P., Aigrain, S., Roberts, S., et al. 2012, MNRAS, 419, 2683
Griffith, C. A. 2014, Phil. Trans. R. Soc. A., 372, 20130086
Kim, S. J., Geballe, T. R., & Noll, K. S. 2000, Icar, 147, 588
Knutson, H. A., Charbonneau, D., Allen, L. E., Burrows, A., & Megeath, S. T. 2008, ApJ, 673, 526
Mandel, K., & Agol, E. 2002, ApJL, 580, L171
Moses, J. I., Visscher, C., Fortney, J. J., et al. 2011, ApJ, 737, 15
Perez-Becker, D., & Showman, A. P. 2013, ApJ, 776, 134
Perna, R., Heng, K., & Pont, F. 2012, ApJ, 751, 59
Rayner, J. T., Toomey, D. W., Onaka, P. M., et al. 2003, PASP, 115, 362
Richardson, L. J., Deming, D., & Seager, S. 2003, ApJ, 597, 581
Showman, A. P., Fortney, J. J., Lian, Y., et al. 2009, ApJ, 699, 564
Southworth, J. 2010, MNRAS, 408, 1689
Swain, M. R., Bouwman, J., Akeson, R. L., Lawler, S., & Beichman, C. A. 2008, ApJ, 674, 482
Swain, M. R., Deroo, P., Griffith, C. A., et al. 2010, Natur, 463, 637
Swain, M. R., Tinetti, G., Vasisht, G., et al. 2009, ApJ, 704, 1616
Thatte, A., Deroo, P., & Swain, M. R. 2010, A&A, 523, A35
Torres, G., Winn, J. N., & Holman, M. J. 2008, ApJ, 677, 1324
Vacca, W. D., Cushing, M. C., & Rayner, J. T. 2003, PASP, 115, 389
Waldmann, I. P. 2012, ApJ, 747, 12
Waldmann, I. P. 2014, ApJ, 780, 23
Waldmann, I. P., Tinetti, G., Deroo, P., et al. 2013, ApJ, 766, 7
Waldmann, I. P., Tinetti, G., Drossart, P., et al. 2012, ApJ, 744, 35
Yurchenko, S. N., & Tennyson, J. 2014, e-prints (arXiv:1410.2917)
Zellem, R. T., Lewis, N. K., Knutson, H. A., et al. 2014, ApJ, 790, 53