GROUND-BASED NEAR-INFRARED EMISSION SPECTROSCOPY OF HD 189733B

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ABSTRACT

We investigate the K- and L-band dayside emission of the hot-Jupiter HD 189733b with three nights of secondary eclipse data obtained with the SpeX instrument on the NASA Infrared Telescope Facility. The observations for each of these three nights use equivalent instrument settings and the data from one of the nights have previously been reported by Swain et al. We describe an improved data analysis method that, in conjunction with the multi-night data set, allows increased spectral resolution ($R \approx 175$) leading to high-confidence identification of spectral features. We confirm the previously reported strong emission at $\sim 3.3 \mu m$ and, by assuming a 5% vibrational temperature excess for methane, we show that non-LTE emission from the methane $v_3$ branch is a physically plausible source of this emission. We consider two possible energy sources that could power non-LTE emission and additional modeling is needed to obtain a detailed understanding of the physics of the emission mechanism. The validity of the data analysis method and the presence of strong $3.3 \mu m$ emission are independently confirmed by simultaneous, long-slit, L-band spectroscopy of HD 189733b and a comparison star.

Key words: methods: data analysis – planets and satellites: atmospheres – planets and satellites: individual (HD 189733b) – techniques: spectroscopic

Online-only material: color figures

1. INTRODUCTION

The field of extrasolar planets is rapidly evolving, both in terms of the number of planets discovered and the techniques employed in the characterization of these distant worlds. In recent years, increasing attention has been directed to the detection and interpretation of spectroscopic signatures of exoplanetary atmospheres and this was mainly pioneered using Spitzer and Hubble Space Telescope (HST) instruments (e.g., Agol et al. 2010; Beaulieu et al. 2008, 2010; Charbonneau et al. 2002, 2005, 2008; Grillmair et al. 2008; Harrington et al. 2006; Knutson et al. 2007; Snellen et al. 2010b; Swain et al. 2008, 2009a, 2009b; Tinetti et al. 2007, 2010). With the removal of spectroscopic capabilities for Spitzer at the end of the Spitzer cold-phase, increased efforts need to be undertaken to ensure spectroscopic capabilities using ground-based observatories. As inarguably difficult as this is, various groups have succeeded in the detection of metal lines and complex molecules (Bean et al. 2010; Redfield et al. 2008; Snellen et al. 2008, 2010a; Swain et al. 2010). In order to obtain the desired observations, different groups have developed different techniques. These can be divided into three main categories.

1. Time-unresolved techniques: here usually one or more high signal-to-noise ratio (S/N) spectra are taken in-transit and out-of-transit, and both in-transit and out-of-transit spectra are differenced with the additional use of a telluric model. Care needs to be taken to not overcorrect and remove the exoplanetary signal.

2. Time-resolved high resolution: this is sensitive to very thin and strong emission lines where the exoplanet eclipse is followed with many consecutive exposures and the emission line is identified by the varying doppler shift of the planet as it transits (Snellen et al. 2010a).

3. Time-resolved mid-resolution: as above, the exoplanetary eclipse is followed by many consecutive exposures with a mid-resolution spectrograph making this method sensitive to broad roto-vibrational transitions. The use of telluric corrections with a synthetic model is not necessary since we obtain a normalized light curve per spectral channel of which the transit depths constitute the spectral signatures.

Here, we re-analyze the original Swain et al. (2010) data as well as three additional planetary eclipses observed with the Infrared Telescope Facility (IRTF)/SpeX instrument. One eclipse, in particular, was obtained with a reference star in the slit. We used the time-resolved mid-resolution method pioneered by Swain et al. (2010) with an improved methodology and data-preprocessing routine. The additional data in conjunction with the more advanced techniques adopted, secured results at higher spectral resolution and smaller error bars. Furthermore, we thoroughly tested our data to eliminate/quantify the residual telluric contamination.

2. OBSERVATIONS AND DATA REDUCTION

Secondary eclipse data of the hot-Jupiter HD 189733b were obtained on the nights of 2007 August 11 (previously analyzed by Swain et al. 2010), 2009 June 22, and 2009 July 12 using the SpeX instrument (Rayner et al. 2003) on the NASA IRTF. The observations were timed to start approximately one to two hours before the secondary eclipse event, until one to two hours post-eclipse. The instrumental setup was not changed for these three nights. The raw detector frames were reduced using the standard SpeX data reduction package, SpeXTool, available for IDL (Cushing et al. 2004), resulting in sets of 439, 489, and 557 individual stellar spectra for each secondary eclipse event, respectively. The extraction was done using the aperture photometry setting with a two arcsecond aperture.

In addition, we have analyzed a fourth secondary eclipse of HD 189733b observed on 2010 July 3 using the same instrument. As opposed to the other three nights, we observed HD 189733b in the L-band only, with a single-order, long-slit setting. The 1 arcmin slit allowed us to simultaneously observe...
our target and a reference star with a $K$-band magnitude of 8.05 (2MASS 20003818+2242065). For not saturating the target star, we kept the exposure time at 8 s and employed the standard ABBA nodding sequence throughout the night. Each AB set was differenced to remove the background and the final spectra were extracted using both a custom built routine and standard IRAF routines. We found both extractions to yield the same results but the custom built routine performs better in terms of the final scatter observed. The flux received from the reference star is on average 27 times less than that of the target.

The secondary eclipses in the obtained raw spectra (from here onward, “raw” refers to the flat fielded, background corrected, wavelength calibrated, and extracted spectra) are dominated with systematic (telluric and instrumental) noise. Consequently, the spectral reduction step is followed by data de-noising and signal amplification steps as described in the following sections.

3. EXTRACTION OF THE EXOPLANETARY SPECTRUM

We describe in the following subsections how the planetary signal was extracted from the raw spectra. With the nature of the observations being a combined light (planet and stellar flux) measurement, we employ time-differential spectrophotometry during the time of the secondary eclipse. Standard photometric calibration routines typically achieve a ∼1% level of photometric accuracy, hence further de-noising is necessary to reach the required precision. We first removed the instrument systematics in the data (data cleaning) and then extracted the planetary signal in the cleaned data (spectral analysis).

3.1. Data Cleaning

To achieve the accuracy we need, a robust cleaning of the data is required. The cleaning process comprises three main steps: (1) normalizing the spectra, getting rid of flux offsets in the times series, and correcting for airmass variations. (2) Correcting wavelength shifts between spectra by re-aligning all spectra with respect to one reference spectrum. This step removes ∼80% of outliers. (3) Filtering the time series of each spectral channel with adaptive wavelets. This step removes white and pink noise contributions at multiple passbands without damaging the underlying data structure (Persival & Walden 2000).

3.1.1. Normalization

First, we discarded the spectral information outside the intervals of 2.1–2.45 μm and 2.9–4.0 μm to avoid the edges of the $K$ and $L$ photometric bands, respectively. Then, we corrected for airmass and instrumental effects. This was achieved in a two-step process. We first calculated a theoretical airmass function, $AF = \exp(-b \times \text{airmass}(t))$, for each night and divided the data by this function. However, we found this procedure insufficient since the baseline curvature is caused not only by the airmass but by other instrumental effects (e.g., changing gravity vectors of the instrument). We hence additionally fitted a second-order polynomial to the pre- and post-eclipse baseline of each time series and divided each single time series by the polynomial. Furthermore, we normalized each observed spectrum by its mean calculated in a given wavelength band (Equation (1)):

$$
\hat{F}_n(\lambda) = \frac{F_n(\lambda)}{\tilde{F}_n} \begin{cases} \frac{\lambda = 2.1–2.45 \mu m}{K \text{ band}} \\
\frac{\lambda = 2.9–4.0 \mu m}{L \text{ band}} 
\end{cases}
$$

where $F(\lambda)$ is the flux expressed as a function of wavelength, $\lambda$, for each spectrum obtained, $n$. $\tilde{F}_n$ and $\hat{F}_n(\lambda)$ are the normalized spectra. In the case of an idealized instrument and constant airmass, the normalization would be superfluous. However, due to pixel sensitivity variations and bias offsets on the detector, the individual spectra need to be normalized to avoid frequent “jumps” in the individual time series. In the domain of the high-interference limit (Pagiatakis et al. 2007; Swain et al. 2010), the astrophysical signal is preserved. We investigated the effects of normalizing the spectrum over a whole wavelength band or smaller subsections of the spectrum and various combinations of both, but found the differences to be negligible.

3.1.2. Spectra Re-alignment and Filtering

After the normalization, we constructed two-dimensional images with rows representing spectra of the planet–star system at a specific time, and columns representing time series for specific wavelengths (see Figure 1(A)). In Figure 1(A), the main sources of outliers in individual time series are miss-alignments by up to 4 pixels along the wavelength axis. We corrected this effect by fitting Gaussians to thin (FWHM ∼ 5 pixels) emission and absorption lines to estimate the line centers to the closest pixel. When the shift occurred for all the lines, the spectrum was corrected with respect to a reference spectrum, i.e., the first spectrum in the series. Then cosmic rays were removed by a two-dimensional median filter replacing 5σ outliers with the median of its surrounding 8 pixels.

3.1.3. Wavelet De-noising

Due to variations in detector efficiency, the cumulative flux of each spectrum depends on the exact position of the spectrum on the detector (horizontal bands in Figure 1(A)), resulting in high-frequency scatter in each individual time series. This effect was already attenuated by the normalization step but further removal of systematic and white noise is required. Based on the de-noising approach proposed by Thatte et al. (2010), we have opted for a wavelet filtering of the individual time series using the “Wavelet Toolbox” in MATLAB. There are clear advantages to wavelet de-noising compared to simple smoothing algorithms. With wavelets we can specifically filter the data for high-frequency “spikes” and low-frequency trends without affecting the astrophysical signal or losing temporal phase information. This allows for an efficient reduction of white and pink noise in the individual time series. By contrast, smoothing algorithms, such as kernel regression, will impact the desired signal since these algorithms smooth over the entire frequency spectrum (Donoho 1995; Persival & Walden 2000). For a more detailed discussion see Appendix A and Thatte et al. (2010), Donoho (1995), Persival & Walden (2000), Stein (1981), and Sardy (2000). The use of the wavelet filtering to each individual time series yielded a factor of two improvement on the final error bars. The final results were generated with and without wavelet de-noising and found to be consistent within the respective error bars. An example of the final de-noised data can be seen in Figure 1(B).

3.2. Measuring the Exoplanetary Spectrum

After the data were de-noised as described in the previous subsection, we focused on the extraction of the planetary signal. We based our analysis on the approach described in Swain et al. (2010). The spectral emission features of a secondary eclipse event are too small to be statistically significant for
of a convolution is equivalent to the dot product of the Fourier transforms

\[ \mathcal{F}(X_i * X_{i+1}) = k \otimes \mathcal{F}(X_i) \otimes \mathcal{F}(X_{i+1}), \]  

(4)

where \( \otimes \) signifies multiplication in the Fourier space and \( k \) is a normalization constant. This process is the base of our analysis.

### 3.2.1. Time-domain Analysis

Having calculated the Fourier product, \( \mathcal{F}(\tilde{X}(t)) \), for \( i \) spectral channels, we can take the inverse of the Fourier transform to obtain the filtered light curve signal

\[ \tilde{X}(t) = \mathcal{F}^{-1}(\mathcal{F}(\tilde{X}(t))). \]  

(5)

The light curves were then re-normalized by fitting a second-order polynomial to the out-of-transit (oot) baseline. We modeled the final light curves with Equation (8) of Mandel & Agol (2002), using the system parameters reported in Bakos et al. (2006), with the transit depth as the only free parameter left.

As clear from the light curves presented in Section 5, the systematic noise in the data is higher in areas of low transmissivity. Systematic noise increases the scatter of the obtained light curves as well as the error bars of the final spectra and places a lower limit of \( m = 50 \) channels (\( \sim 2.88 \) nm) on the currently achievable spectral bin size. This is a noticeable improvement compared to the original Swain et al. (2010) analysis which reported a lower limit of \( m = 100 \) and 150 spectral channels for the \( K \) and \( L \) bands, respectively.

### 3.2.2. Frequency-domain Analysis

The generated light curves are of high quality and ready for accurate spectroscopic measurements. However, as previously mentioned, a certain amount of periodic and systematic noise is still present in the time series. The noise residuals are in part generated during the conversion of the data from the frequency domain to the time domain, in part are due to systematics. We can remove some of these residuals, by measuring the eclipse...
The Fourier series of such a symmetric square wave is given by to be a box-shaped function or square wave of which the Fourier signal. depth directly in the frequency domain, assuming that most power spectrum of a Mandel & Agol (2002) model light curve of The Astrophysical Journal, time + overheads, Figure 2) decreases by \(2^{k-1}\) for a box-shape function and is an even faster converging series for real light curve shapes which are used in the analysis (see Appendix B). Following from Equation (7) we see that for the first Fourier coefficient, \(k = 1\), the relationship between the transit depth, \(\delta\), and the Fourier coefficient amplitude, \(|A|\), is simply given by \(|A_{k=1}| = (\tau/2)\delta\). From the analytical arguments presented above, we know that \(\tau\) is the transit duration (in units of number of observed spectra). We checked the consistency of the theory with the data, by calculating the value of \(\tau\) numerically. To calculate \(\tau\) we produced secondary eclipse curves with the transit duration and sampling rate of the original IRTF data sets (Mandel & Agol 2002, Equation (8)). We generated 300 curves with transit depths \((\tau)\) ranging from 0.0001 to 1 and measured the corresponding amplitude \(|A_{k=1}|\). Here, the derivative, \(d(|2A|)/d\delta\) gives us the value of \(\tau\). We find \(\tau = 116\) in-eclipse measurements, which agrees with the number of in-transit spectra obtained for the real IRTF data sets.

\(N\) spectra were obtained at a constant sampling interval of \(t_s\), giving us a sampling rate of \(R = 1/t_s\), in the frequency domain. For a complete representation of the data, the sampling rate is equal to the Nyquist rate, \(R = 2B\), where \(B\) is the spectral bandwidth of the Fourier transform. The total number of Fourier coefficients, \(K\), is then given by \(K = 2BN\). It follows that the resolution in the frequency domain is determined by \(\Delta f = 1/N\). In other words, the more measurements are available the more Fourier coefficients can be extracted to describe the data and consequently the frequency range covered by each coefficient is smaller for a fixed sampling rate.

The fact that \(\Delta f\) is finite (\(\Delta f \rightarrow 0\) for infinitely sampled data sets) means that the first Fourier coefficient can be contaminated by remaining noise signals very similar in frequency. To estimate the error bar on this contamination, we varied the oot length \(N_{oot}\) by 50% and calculated the resulting spectrum for each \(\Delta f\). The error is then estimated as the standard deviation to the mean of all computed spectra.

### 3.3. Application to Data

We have applied the same procedure described in Sections 3.1 and 3.2 to the four data sets. In addition to the individual analysis, we also combined in the frequency domain the three data sets recorded with the same observational technique. Given that the low-frequency systematics—such as residual airmass function, telluric water vapor content, seeing, etc.—are significantly different for each individual night, by combining multiple data sets, we can amplify the light curve signal and reduce the systematic noise.

To generate the final \(K\) - and \(L\)-band spectra, we chose in Equation (2) \(m = 100\) spectral channels. From \(R_{spectra} = \lambda_{center}/\Delta\lambda\), we get a final spectral resolution of \(R \sim 50\). Combining all three data sets together (~33 spectral channels taken from each observed planetary eclipse) we obtain a spectral resolution of ~170 and ~185 for the \(K\) and \(L\) bands, respectively. We note that the spectral resolving power for the SpeX instrument, considering the seeing, is \(R \sim 800\).

### 4. MODEL

We have simulated planetary emission spectra using line-by-line radiative transfer models as described in Tinetti et al. (2005, 2006) with updated line lists at the hot temperatures from UCL-ExoMol and new HITEMP (Barber et al. 2006; Yurchenko et al. 2011; Rothman et al. 2009). Unfortunately accurate line lists of methane at high temperatures covering

![Figure 2. Power spectrum of a Mandel & Agol (2002) model light curve of HD 189733b (inset). It can clearly be seen that most power of the light curve signal is contained in the first Fourier coefficient.](image-url)
the needed spectral range are not yet available. We combined HITRAN 2008 (Rothman et al. 2009), and the high temperature measurements from Thiévin et al. (2008). These LTE models were fitted to the spectra presented in Section 5.

In addition to the standard LTE model, we considered possible non-LTE models to fit the presented data. Upper atmospheres of planetary atmospheres are subject to non-LTE emissions; although negligible in most part of the near-infrared spectrum, these emissions become dominant in the strongly absorbing vibration bands of molecular constituents, such as CO₂ in telluric planets and CH₄ in giant planets (and Titan). A synthetic model of the spectrum in the L band has been adapted from a model of giant planets fluorescence of CH₄ developed for Infrared Space Observatory-Short Wavelength Spectrometer (ISO-SWS) (Drossart et al. 1999). The main steps involved in the radiative transfer with redistribution of frequency in non-LTE regime can be summarized as follows.

1. We first calculate the solar (stellar) flux absorbed from all bands of CH₄. Although classical, this part of the model can be cumbersome as all the main absorption bands corresponding to the stellar flux have to be (in principle) taken into account. Limitations come from the knowledge of the spectroscopy of the hot bands. In this model, the following bands are taken into account: Pentad (3.3 μm), Octad (2.3 μm), and Tetradecad (1.8 μm). An estimate of the accuracy of the approximation in neglecting hotter bands will be given below. Following an approach given by Doyennette et al. (1998), the spectroscopy of CH₄ is simplified by dividing the vibrational levels in stretching and bending modes: therefore x superlevels (instead of the 29 potential sublevels of the molecule). It is also assumed that for each superlevel belonging to a polyad, thermal equilibrium is achieved within the population. This assumption comes from the observation that intra-vibrational transitions within polyads have a higher transition rate than inter-vibrational transitions.

2. The population of the vibrational levels is then calculated within each “superlevel” of CH₄. The vibrational de-excitation is assumed to follow the bending mode de-excitation scheme (Appley 1990).

3. From the population of each superlevel, the radiative rate of each level can be calculated to determine the emission within each of the bands (fundamental, octad-dyad, and tetradecad-pentad) that contribute to the 3.3 μm domain.

4. If hot band emission can be proven to remain optically thin down to deep levels of the atmosphere, the resonant fluorescence is not the same, as self-absorption is an essential ingredient of the fluorescence. Evidently, photons absorbed, on average, at a τ = 1 level have the same probability to be re-absorbed as re-emitted upward. The optically thick fluorescence, including absorption and re-emission, is therefore applied to the resonant band.

5. RESULTS

5.1. Validation of the Method Used

As described in previous sections, we analyzed four nights of observations: three in multi-order mode, with only HD 189733b in the slit (referred to as “short-slit night”) and one night in L band with single-order, long-slit setup, observing HD 189733b and a fainter reference star simultaneously. While the long-slit observation covers a narrower spectral interval compared to the other eclipse observations, it is a critical test of the methodology with its simultaneous observations of the target and the reference star. In Figure 11 we present two light curves: HD 189733 and the reference star. Both are centered at 3.31 μm with a binning width of 50 channels (~2.88 nm). As expected the HD 189733 time series (top) shows the distinctive light curve shape while the reference star (bottom) time series shows a null result. We have fitted a Mandel & Agol (2002) secondary eclipse light curve to both and found the HD 189733b transit depth to be δ₁ = 0.0078 ± 0.0003 and δREF = 0.0 ± 0.0007, respectively. These results are in good agreement with the spectra presented below.

5.2. K- and L-band Spectra

The same analysis was undertaken for the three short-slit nights: illustrative light curves are presented in Figures 3 and 4. In Figure 3, plotted are the light curves of the “three-night-combined” analysis for the K and L bands centered at 2.32, 3.20, 3.31, 3.4, and 3.6 μm, with 50 channel (~2.88 nm) bins. The residual systematic noise is most pronounced in the areas of low atmospheric transmissivity, which is reflected in the error.
bars of the light curves and of the retrieved spectra. We also show the light curves centered on the methane $\nu_3$ branch at $\sim 3.31 \mu m$ for all individual nights, Figure 4.

Having verified the detection of HD 189733b eclipse in all data sets, we have generated $K$- and $L$-band spectra for each individual night as well as for all the three nights combined. The three individual nights are plotted in Figures 5 and 7 for $K$ and $L$ bands, respectively. All spectra are consistent with each other and are within the error bars of the initial Swain et al. (2010) results. This said, we find the nights of 2007 August 11 and 2009 July 12 of higher quality and in better agreement. The single-night analysis supports the assumption that intra-night variations are negligible which allowed us to average the data sets and hence increase the signal to noise of the final spectra. We could hence push the resolution to $R \sim 170$–180 for the final combined spectra. Figures 8 and 9 are the three-night-combined $K$- and $L$-band spectra, respectively. We include in these figures the comparison with black body emission curves and LTE models. It is clear from the figures that the strong features observed in the $L$ band cannot be explained by standard LTE processes.

### 5.3. Comparison of the Observations with Atmospheric LTE and Non-LTE Models

Even if many uncertainties subsist on the thermal vertical profile of HD 189733b, the thermal methane emission needed to reproduce the observed spectrum would lead to brightness temperatures of $\sim 3000$ K, which not only are unlikely given the star–planet configuration, but would also appear in other bands—e.g., in the $\nu_4$ band at 7.8 $\mu m$—hypothesis ruled out from Spitzer observations. While LTE models cannot explain such temperatures, non-LTE models with only stellar photons as pumping mechanism do not supply enough excess flux. This result is not unexpected since the contribution of stellar reflection from the planet is smaller in $L$ band than the thermal emission, and fluorescence is only a redistribution of the stellar flux (even if a small enhancement comes from the redistribution of frequency in the fluorescence cascade). However, a good fit

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**Figure 5.** $K$-band planetary signal for the three separate nights: 2007 August 11, 2009 June 22, and 2009 July 12 in blue, red, and green, respectively. The night of 2009 June 22 had poor observing conditions and the data were significantly noisier and planetary emissions retrieved are systematically lower for this night in both $K$ and $L$ band. Results from Swain et al. (2010) are shown in black.

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

**Figure 6.** Combined $K$-band planetary signal for the nights of 2007 August 11 and 2009 July 12 only (red), excluding the poor data quality of the 2009 June 22 night. For comparison the spectrum of all three nights combined (green) is overplotted. The difference between both spectra is small and indicates the night of 2009 June 22 having a small effect on the overall result. Ground-based results from Swain et al. (2010) and HST/NICMOS data (Swain et al. 2008) are shown in black and purple, respectively.

(A color version of this figure is available in the online journal.)
3.1 L-band planetary signal for the three separate nights: 2007 August 11, 2009 June 22, and 2009 July 12 in blue, red, and green, respectively. Same as Figure 5, the night of 2009 June 22 shows a systematic lower emission. As described previously, this may be a result of the poor data quality of this night. Results from Swain et al. (2010) are shown in black.

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

Figure 7.

3.2 Three-night-combined K-band spectrum compared with three black body curves at 1000, 1500, and 2000 K. Furthermore two LTE models of CH₄ in emission (turquoise) and CH₄ plus CO₂ in absorption (orange).

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

Figure 8.

3.3 Three-night-combined L-band spectrum. The blue discontinuous line shows a comparison of the observations with the "enhanced fluorescent" model; non-thermal population enhancement in the octad level with a 5% increase of vibrational temperature of CH₄. Overlaid are black body curves at 1000, 1500, 2000, and 3000 K.

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

Figure 9.

6. DISCUSSION

In Figure 5, we present the K-band spectra of the three separate nights. This plot shows a slight discrepancy between the night of the 2009 June 22 compared to the other two nights analyzed. We can observe a systematic offset in both the can be obtained by assuming a vibrational temperature excess for methane by 5% due to an enhancement of the octad level population in methane which is higher than expected by stellar flux pumping (Figure 9). This increase is currently an ad hoc hypothesis and simply describes the amount of vibrational temperature increase required to explain the observed feature.

In the case of the K-band spectrum, it is less obvious whether LTE or non-LTE processes are prevalent. We show in Figure 8 a comparison with two LTE simulations, one including CH₄ plus CO₂ in absorption as suggested by other data sets. Another model was obtained with LTE emission of methane. However, neither of the two simulations perfectly capture the spectrum observed. Given the stronger non-LTE emission features detected at ∼3.3 μm, one can expect to find non-LTE effects in the K band as well. Further observations are required in order to build up the required spectral resolution to decisively constrain the excitation mechanisms at work.

(A color version of this figure is available in the online journal.)
K and L bands (Figure 7) with this night giving consistently lower emission results. We associate this effect to the poorer observing conditions and a degraded quality of the data compared to the data obtained in the other two nights: a very high intrinsic scatter of the data may in fact reduce the eclipse depth retrieved. We estimated the average spectra excluding the night of 2009 June 22 (Figure 6) and found the results to be in good agreement with the three-night-combined spectrum. This test demonstrates the robustness of the final retrieved spectrum. It should be noted that this issue is less severe in the L band, since the overall signal strength is higher than in the K band.

While the K-band spectra could be explained with LTE models, we encounter a quite different picture in the L band. The observed emission around \( \nu_3 \) branch exhibits a very poor match with the predicted LTE scenario. By contrast, non-LTE emission of methane can capture the behavior of the \( \nu_3 \) branch. Similar fluorescence effects have been observed in our own solar system, mainly CO2 in telluric and CH4 in giant solar system planets (Barthélémy et al. 2005). In Section 4, we outline a plausible model for the creation of such a prominent feature. As previously mentioned, the increase in CH4 vibrational temperature of 5% is presently an ad hoc hypothesis: it simply describes the amount of non-LTE population required to fit the observations, pure LTE populations being insufficient. The source of this population increase can come from a variety of sources: high-energy ultraviolet radiation from the star, electron precipitations, etc., which are presently not constrained at all. Such effects are nonetheless known in planetary physics, such as on Jupiter, where H2 vibrational temperatures in the upper atmosphere have been demonstrated to be out of equilibrium through Lyα observations (Barthélémy et al. 2005), with a 1.4–1.5-fold increase in vibrational temperature.

6.1. Validation of Observations

The results presented here are found to be consistent with the results initially presented by Swain et al. (2010), HST/NICMOS data in the K band (Swain et al. 2008) and verified in the L band by the Spitzer/IRAC 3.6 \( \mu \)m broadband photometry (Charbonneau et al. 2008), see Figures 6 and 7. However, Mandell et al. (2011), from here M11, have recently published a critique of the original Swain et al. (2010), from here S10, result reporting a non-detection of any exoplanetary features in their analysis. Since the results of this publication are in good accord with Swain et al. (2010), the fundamental discrepancy between the findings presented here and those by M11 need to be addressed.

M11 argue that the L-band features reported by S11 were likely due to unaccounted for telluric water emissions rather than exoplanetary methane. This hypothesis poses four main questions which will be addressed below: (1) do the L-band features look like water emissions? (2) Are the results repeatable? (3) Do or do we not see similar light curve features in the reference star? (4) Can we quantify the amount of residual telluric contamination in the data?

6.1.1. Do the L-band Features Look Like Water?

Here the simple answer is no. As discussed in Section 5 and shown in Figures 7 and 9, the improved spectral resolution of these results shows that we are clearly dealing with methane signatures. As M11 pointed out, a temporary change in telluric opacity due to atmospheric water (or methane) could mimic a secondary eclipse event. However, for temporal atmospheric variations to mimic an eclipse signal in the combined result of all three nights, the opacity variations, as well as the airmass function, would need to be identical or at least very similar in all data sets. The likelihood of such a hypothesis is very small.

In addition, we have retrieved weather recordings from nearby weather stations. These include periodic temperature, relative humidity, and pressure readings from the Canada–France–Hawaii Telescope (CFHT) as well as atmospheric opacity (\( \tau \)) readings at 225 \( \mu \)m obtained by the CSO6 (see Figure 12). Spread over all three eclipsing events, we found no significant correlations between these parameters and the secondary transit shape expected.

6.1.2. Are the Results Repeatable?

A main focus throughout this publication is to demonstrate the repeatability of the observations. In Section 5 we present spectra retrieved for each individual observing run of the three “short-slit” nights and found them consistent with each other within the error bars. For the methane \( \nu_3 \) branch which is the most difficult to achieve measurement we present light curves for all three observing runs considered, Figure 4. These do vary in quality from night to night but are found to be consistent with one another over a measured timescale ranging from 2007 August 11 to 2009 July 12. This test of repeatability is of paramount importance in asserting the validity of the analysis as a whole.

6.1.3. Do We or Do We Not See Similar Light curve Features in the Reference Star?

We do not see any light curve features in the reference star’s time series. As described in previous sections, we have obtained a fourth night in addition to the three main nights analyzed here. This fourth night was taken in the single-order, L-band only mode with a 1 arcmin long slit. This allowed us to simultaneously observe the target HD 189733b and a fainter reference star, 2MASS 20003818+2242065, over the course of a secondary eclipse on 2010 July 3. We have equally applied the same routines outlined in Section 3 to both the target and the reference. In Figure 10 we plot the resulting light curves of HD 189733b and the simultaneously observed fainter reference star beneath, centered at 3.31 \( \mu \)m with the standard 50 channel binning. Overplotted are two fitted Mandel & Agol (2002) curves for the secondary eclipse. The HD 189733b light curve is in good agreement with the other results of this paper while the reference star’s time series is noticeably flat.

(A color version of this figure is available in the online journal.)
Figure 11. Top: the observed light curve of HD 189733b, beneath the simultaneously observed flat time series of the fainter reference star. At the bottom in red is the simulated reference star light curve expected to be observed under the assumption that the observed signal in HD 189733b is due to an imperfect background subtraction. The flat nature of the observed reference star light curve is a strong indication that the background subtraction was treated adequately.

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

both stars centered at 3.31 μm using the standard 50 channel bin. We find the transit depth for HD 189733b to be within the error bars of the other nights analyzed, while the reference star time series is flat. Hence, the routines used produce a null result where a null detection is expected.

Furthermore, it is important to note that a faulty background subtraction would have much stronger effects on the fainter reference star than on the target, as any residual background is a proportionally larger fraction of the stellar signal. We find the mean observed flux for a single exposure to be \( F_{HD189} \sim 24300e^- \) and \( F_{REF} \sim 900e^- \) for the target and the reference stars, respectively. We can now state that the observed flux is a sum of the stellar flux and a background contribution:

\[
F_{\text{observed}} = F_{\text{star}} + F_{\text{back}}.
\]

We also assume that the background flux, \( F_{\text{back}} \), is the same for both stars as they were observed simultaneously on the same detector. Whatever the value of \( F_{\text{back}} \) may be, its relative contribution on the overall flux would be \( \sim 27 \) times higher for \( F_{REF} \) than for \( F_{HD189} \). Following this argument, if we now assume the light curve feature to be due to an inadequate background correction (as postulated by M11), we would expect a \( \sim 27 \) times deeper light curve signal in the reference star time series than in HD 189733b. To illustrate the severity of this effect, we re-plotted the time series presented in Figure 10 with an additional 27 times deeper transit than that of HD 189733b underneath. Given the flat nature of the reference star’s time series though, we can confidently confirm an adequate treatment of telluric and other backgrounds.

6.1.4. Can We Quantify the Residual Telluric Contamination in the Data?

Using the Fourier based techniques described in this paper, we can quantify the remaining contribution of systematic noise and the residual telluric components in the spectra shown in Section 5. As described in Section 3.2, we are mapping individual Fourier coefficients of the light curve signal in the

![Figure 12](image-url)

Figure 12. Top to bottom: temperature (°C, CFHT Weather station), rel. humidity (%), CFHT), pressure (mb, CFHT), and optical depth, \( \tau \) (225 μm, CSO) for the 2007 Aug 12 (blue), June 22 (green), and 2009 July 12 (red). The discontinuous vertical lines mark the secondary transit duration.

(A color version of this figure is available in the online journal.)
frequency domain. Any systematic noise or telluric contamination can therefore only contribute to this one frequency bin. The degree of residual contamination by systematics on that frequency bin can hence be estimated by running the routine described in Section 3.2.2 on only out-of-transit and only in-transit data, i.e., removing the eclipse signal. Figures 13 and 14 show the planet signal (black) and out-of-transit and in-transit measurements of the contamination in red and green, respectively. We conclude that the amplitude of the systematic noise and the residual telluric component is within the error bars of the planetary signal.

7. CONCLUSION

In this paper, we present new data on the secondary eclipse of HD 189733b recorded with the SpeX instrument on the IRTF. Our data analysis algorithm for time-resolved, ground-based spectroscopic data is based on a thorough pre-cleaning of the raw data and subsequent spectral analysis using Fourier based techniques. By combining three nights of observations, with identical settings, and a further development of the data analysis methodology presented in Swain et al. (2010), we could increase the spectral resolution to $R \sim 175$.

We confirm the existence of a strong feature at $\sim 3.3 \mu m$, corresponding to the methane $\nu_3$ branch, which cannot be explained by LTE models. Non-LTE processes are most likely the origin of such emission and we propose a plausible scheme to explain it.

The possibility of telluric contamination of the data is thoroughly tested but we demonstrate that the residual due to atmospheric leakage is well within the error bars, both by using Fourier based techniques and additional observations with a reference star in the slit. This critical test demonstrates the robustness of our calibration method and its broad applicability in the future to other space and ground exoplanet data.

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APPENDIX A
ADDITIONAL NOTES ON WAVELETS

As mentioned in Section 3.1.3, wavelet de-noising of times series data has several advantages: (1) wavelet de-composition is a non-parametric algorithm and hence does not assume prior information on the signal or noise properties, making it an easy to use and objective de-noising routine; (2) contrary to smoothing algorithms (e.g., kernel regression) high- and low-signal frequencies are retained; (3) temporal phase information of the signal is preserved during the de- and re-construction of the signal. This allows for an optimal white and systematic noise reduction at varying frequency passbands. For our purposes we use a nonlinear wavelet shrinkage by soft-thresholding of the obtained coefficients for each decomposition step using an heuristic form of the Stein’s Unbiased Risk Estimate (SURE) for soft-thresholding (Stein 1981). This is a non-parametric algorithm and hence does not assume prior information on the signal or noise properties, making it an easy to use and objective de-noising routine; (2) contrary to smoothing algorithms (e.g., kernel regression) high- and low-signal frequencies are retained; (3) temporal phase information of the signal is preserved during the de- and re-construction of the signal. For our purposes we use a nonlinear wavelet shrinkage by soft-thresholding of the obtained coefficients and iterative reconstruction of the data. The intrinsics of such an approach were extensively discussed by Donoho (1995) and Persival & Walden (2000). Using the “Wavelet Toolbox” in MATLAB, each individual time series underwent a four-level wavelet shrinkage using “Daubechies 4” wavelets. The wavelet coefficients were estimated for each decomposition step using an heuristic form of the Stein’s Unbiased Risk Estimate (SURE) for soft-thresholding (Stein 1981). This allows for a MINMAX coefficient estimation (Sardy 2000) in cases of too low S/N for the SURE algorithm. After thresholding, the time series were reconstructed based on the obtained coefficients for each time series.

APPENDIX B
FOURIER ANALYSIS

In Section 3.2.2, we discuss the properties of box-shaped light curves in the frequency domain. It is needless to say that this is a gross oversimplification and that the actual secondary eclipse light curve is more akin to a trapezoid (Equations (B1)) rather than a square-box. In the case of a trapezoid, we can calculate the power to decrease by 1/k² for Fourier coefficients above k = 1. Hence, the Fourier series for a trapezoidal shape converges faster (Equation (B2)):

\[ f_{\text{trap}}(t) = 8\sqrt{2}\delta \left( \frac{\sin(1/\tau)}{9} + \frac{\sin(3/\tau)}{25} - \cdots \right) \]

\[ = 8\sqrt{2}\delta \sum_{k=1,3,5\ldots}^{\infty} \left( \frac{\sin(k/4\tau) + \sin(3k/4\tau)}{k^2} \right) \]  \hspace{1cm} (B1)\]

\[ |A|_{\text{trapez}} = \frac{\tau \delta}{2} \sum_{k=1,3,5\ldots}^{\infty} \frac{1}{k^2}. \]  \hspace{1cm} (B2)\]

The difference between the boxcar and trapezoidal shape does not affect the linear relationship between spectral amplitude and transit depth. We furthermore extend the argument to limb-darkened light curves that exhibit a markedly rounder morphology. These are a natural extension to the trapezoidal case and it is generally true that the “rounder” the eclipse shape, the less power is contained in Fourier coefficients above k = 1, and hence the series are converging even faster.

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