THE ALTITUDE OF AN INFRARED-BRIGHT CLOUD FEATURE ON NEPTUNE FROM NEAR-INFRARED SPECTROSCOPY

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ABSTRACT

We present 2.03–2.30 μm near-infrared spectroscopy of Neptune taken 1999 June 2 (UT) with the W. M. Keck Observatory’s near-infrared spectrometer (NIRSPEC) during the commissioning of the instrument. The spectrum is dominated by a bright cloud feature, possibly a storm or upwelling, in the southern hemisphere at approximately 50° south latitude. The spectrum also includes light from a dimmer northern feature at approximately 30° north latitude. We compare our spectra (λ/Δλ ~ 2000) of these two features with a simple model of Neptune’s atmosphere. Given our model assumption that the clouds are flat reflecting layers, we find that the top of the bright southern cloud feature sat at a pressure level of 0.14 ± 0.05 bars, and thus this cloud did not extend into the stratosphere (P < 0.1 bars). A similar analysis of the dimmer northern feature yields a cloud-top pressure of 0.084 ± 0.026 bars. This suggests that the features we observed efficiently transport methane to the base of the stratosphere but do not directly transport methane to the upper stratosphere (P < 10−2 to 10−3 bars), where photolysis occurs. Our observations do not constrain how far these clouds penetrate down into the troposphere. We find that our model fits the data restrict the fraction of H2 in ortho-para thermodynamic equilibrium to greater than 0.8.

Key words: infrared radiation — planets and satellites: individual (Neptune)

1. INTRODUCTION

The first hint of Neptune’s atmospheric complexity and variability came when Joyce et al. (1977) observed significant changes in Neptune’s brightness at 1–4 μm over the course of approximately an Earth year. Pilcher (1977) interpreted this as the formation and slow dissipation of an extensive high-altitude cloud. The 1989 flyby of the Voyager 2 spacecraft revealed a host of time-varying atmospheric features (Smith et al. 1989). Even before the Voyager 2 flyby, the development of the charge-coupled device (CCD) allowed imaging of Neptune at wavelengths up to ~1 μm. Several observers looking in the 0.62 and 0.89 μm methane absorption bands regularly found midlatitude features that were extremely bright relative to Neptune’s disk (Smith 1984, 1985; Hammad & Buie 1987; Hammad 1989; Hammad, Baines, & Bergstralh 1989; Hammad 1990). These features are presumably clouds and may be storms or large upwellings of material from the troposphere. When present, the reflected sunlight from these features dominates images of Neptune at methane-absorbing wavelengths between 0.6 and 2.5 μm, as shown by many observers. The Hubble Space Telescope regularly observed such features at wavelengths less than 1 μm (Sromovsky, Limaye, & Fry 1995; Hammad et al. 1995; Hammad & Lockwood 1997), while ground-based observers using conventional infrared techniques have seen these features at 1–2.5 μm (Sromovsky et al. 2001a, 2001b, 2001c). More recently, high-resolution techniques such as speckle imaging and adaptive optics have been used to observe Neptune and these bright features at 1–2.5 μm (Rodder et al. 1997, 1998; Gibbard et al. 1999; Max et al. 2000; Roe et al. 2001).

Speculation about the nature and origin of these phenomena has primarily focused on the idea of large upwellings punching through the tropopause, resulting in a high column density of condensed methane particles. Thus, these features could in part be responsible for transporting methane through the cold trap of the tropopause and loading the stratosphere with methane gas, where it is then photolyzed and converted to a variety of heavier hydrocarbons, eventually forming hazes (Baines et al. 1995a; Romani et al. 1993; Moses, Rages, & Pollack 1995). It is crucial for our understanding of the dynamics and chemistry of Neptune’s atmosphere to know the altitude range to which these cloud features reach.

Hammad et al. (1989) estimated from their CCD photometry that the bright features they observed were due to increases in the number density of high stratospheric haze particles. Rodder et al. (1998) observed Neptune with adaptive optics techniques. They used two narrowband filters centered on 1.56 μm and 1.72 μm, such that one filter was centered on a strong methane absorption feature, while the other filter was outside the strong methane absorption. These authors estimated that the bright features are located near the tropopause at pressures on the order of 0.1 bars or, possibly, at even higher altitudes. More recently, Sromovsky et al. (2001c), using photometry from the Infrared
Telescope Facility, found the altitudes of a number of discrete cloud features to be between 0.060 and 0.230 bars. In this paper, we present spectra of two of these cloud features. Through comparison with a simple radiative transfer model, we use these spectra to precisely determine the altitude of the cloud features. Our best-fit model places the top of the bright southern cloud feature that we observed at a pressure level of 0.14 bars within an uncertainty range of 0.11–0.19 bars, while the best fit for the dimmer northern feature puts it at 0.084 ± 0.026 bars.

2. OBSERVATIONS AND DATA REDUCTION

We observed Neptune on 1999 June 2 (UT) using NIRSPEC, the W. M. Keck Observatory's new near-infrared spectrometer, on the Keck II Telescope during the commissioning of the instrument (McLean et al. 1998). This spectrometer operates over a wavelength range of 0.95–5.5 μm in either a low-resolution (R ~ 2000) mode or a cross-dispersed high-resolution (R ~ 25,000) mode. NIRSPEC is equipped with a 1024 × 1024 InSb ALADDIN array for spectroscopy, and also a slit-viewing camera ("SCAM") containing a 256 × 256 HgCdTe PICNIC array with 0.18 pixels. The data presented here are from a single low-resolution setting using the NIRSPEC-6 blocking filter, and they cover roughly 2.03–2.30 μm. In low-resolution mode the pixel size in the spatial direction of the ALADDIN spectral array is 0.144 pixel⁻¹.

We acquired a series of SCAM images both before and during our spectral exposures, giving us images of Neptune with the spectrometer’s slit offset from the disk of Neptune and overlapping the disk of Neptune. SCAM images were taken in pairs, and after the first exposure of each pair the pointing of the telescope was offset by 10°. In the current work we did not attempt precise photometry, and therefore our processing of the SCAM images is simplistic: We subtracted one image of each pair from the other for background and bias subtraction. We then shifted and coadded the images using the Gaussian centroids of Triton and an unidentified star for offset determination. From Triton (apparent diameter 0'126) and the unidentified star, the FWHM of the point-spread function was 0'43 ± 0'07.

Figure 1a shows a SCAM image of Neptune taken simultaneously with the spectra presented in this work in which the disk is bisected by the slit. Figure 1b shows an unobstructed image taken 25 minutes earlier. The SCAM image shown in Figure 1a was taken with the NIRSPEC-6 filter F1.-(a) SCAM image of Neptune with spectrometer slit overlying Neptune. This image was taken in the NIRSPEC-6 filter (1.558–2.31 μm) at 1406 UT during the first Neptune spectral exposure. (b) SCAM image of Neptune unobstructed by slit. This image was taken in the NIRSPEC-7 filter (1.839–2.630 μm) at 1345 UT. No unobstructed images of Neptune were taken in the NIRSPEC-6 filter. (c) Schematic showing the scale and orientation of Neptune in (a) and (b). North is up, and Neptune appears as it would look on the sky. The scale of the schematic is shown at lower left and is the same as in (a) and (b). The vertical lines show the approximate location of the slit in (a). (d) Brightness of Neptune along the slit, averaged over all the wavelengths shown in the spectral image in Fig. 2b. For comparison with atmospheric seeing, the profile of the star HD 201941, averaged over the same wavelength range, is also shown. The profile of HD 201941 gives a seeing FWHM of ~0'5–0'6. The FWHM of the unidentified star in the the SCAM images taken simultaneously with the Neptune spectra was 0'4. The narrowness of the FWHM compared with the separation of Neptune's northern and southern features, along with the clear local minimum between the features, leads us to conclude that we have separated the light from these two features relatively well.
(1.56–2.32 μm), while the unobstructed SCAM image in Figure 1b was taken with the NIRSPEC-7 filter (1.84–2.63 μm). We did not take an unobstructed SCAM image in the NIRSPEC-6 filter, and therefore we present the NIRSPEC-7 filter image to show Neptune unobstructed by the spectrometer slit. Neptune’s apparent diameter (at the 1 bar level) was 2:30, Earth’s planetographic sublatitude on Neptune was −28:08, and the solar phase angle was 1:54. Figure 1c shows the orientation and scale of Neptune on the images in Figures 1a–1b. Neptune’s brightness along the slit is shown in Figure 1d. Comparison of Neptune’s brightness as a function of position on the slit with that of HD 201941 (Fig. 1d) shows that the projected size of the storm is only marginally resolved. The local minimum between the features on Neptune indicates that we can extract spectra of the two separate features relatively cleanly without much cross contamination.

The spectra presented here come from two 60 s exposures taken with a 42° × 0:380 slit starting at 1406 UT on 1999 June 2. The slit was aligned parallel with Neptune’s north-south axis and centered on the bright feature in the southern hemisphere. This feature was by far the brightest that we observed on Neptune on 1999 June 2 (UT). The slit also captured light from a dimmer feature in Neptune’s northern hemisphere. Between the two exposures, the pointing of the telescope was moved ~ 10” along the direction of the slit, so that Neptune fit easily on the slit for both exposures. In order to correct for Earth’s atmospheric absorption, we observed an A2 spectral type star (HD 201941) in two 10 s exposures, with an offset of the telescope pointing between exposures in order to move the star along the slit.

The reduction sequence consisted simply of subtraction of one stellar spectral frame from the other for bias and background subtraction. In these images, the spatial and spectral coordinates are distorted with respect to the rows and columns of the detector array. The OH sky emission lines in unsubtracted frames are distorted with respect to the rows and columns of the detector array. The OH sky emission lines are distorted with respect to the rows and columns of the detector array.

![Diagram](image.png)

**Fig. 2.** (a) Observed spectrum of the A2 star HD 201941 divided by the reference spectrum of the A0 V star Vega, providing an estimate of the atmospheric and instrumental transmission functions. (b) Rectified spectral image of Neptune. The spectral region of 2.03–2.05 μm is omitted to show an intensity bar and the spatial size of Neptune’s diameter along the slit. (c) Extracted spectrum of the dimmer northern feature. (d) Extracted spectrum of the brighter southern feature. Note the short vertical tick marks that show methane absorption lines identified from the laboratory spectrum of McKellar (1989).

The vertical scale in (c) is exaggerated by a factor of 11 with respect to the vertical scale in (d).

\[ Y(x) = A_0(\lambda) + A_1(\lambda)x, \]

where \( A_0 \) and \( A_1 \) are functions of wavelength. Meanwhile, the arc of a stellar spectrum traces out a line of constant position along the slit and is well fitted by the function

\[ X(y) = B_0(s) + B_1(s)y + B_2(s)y^2, \]

where \( B_0 \), \( B_1 \), and \( B_2 \) are all functions of slit position \( s \). The \((x, y)\)-position on the array for a given slit position and wavelength \((s, \lambda)\) can then be found by interpolating \( A_0 \) and \( A_1 \) from the numerous OH lines that we fitted, interpolating \( B_0 \), \( B_1 \), and \( B_2 \) from the several stellar spectra fitted, and finally finding the \((x, y)\) intersection of equations (1) and (2). By doing this for a grid of wavelengths and positions along the slit, the data in a spectral image are interpolated from \((x, y)\) to \((s, \lambda)\). The final step in this rectification process is to apply a Jacobian correction for the geometric distortion. We extracted the stellar spectrum from the rectified spectral image using an optimal weighted extraction technique that includes a median-filter rejection algorithm to remove the effects of bad pixels and cosmic-ray hits. Finally, we divided the extracted stellar spectrum by that of Vega (spectral type A0 V; Colina, Bohlin, & Castelli 1996a) to produce an estimate of the combined atmospheric and instrumental transfer function, shown in Figure 2a.

We processed the spectrum of Neptune in a manner similar to that applied to the calibration star; however, after rectification, but before extraction, we inserted the addi-

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8 See the NASA/JPL Horizons ephemeris program, at http://ssd.jpl.nasa.gov/horizons.html.
The free parameters in our model are the mole fraction of temperature and pressure for each layer from Lindal (1992). Calibration for the observed spectrum, case to minimize the overall sum. The introduction of the \( \sim 4 \) spaced in from 5.0 to 10 \( \mu \)m.

The near infrared spectrum is extremely sensitive to the distribution of methane and helium. Light from the cloud dominates over all other features; however, the presence of Triton in the SCAM images makes this problem significantly easier. By centroiding a Gaussian on the cloud feature, we estimate the cloud to be located \( 0^\circ 065 \pm 0^\circ 025 \) from the center of Neptune’s disk at a Neptune latitude of \( -48^\circ 6 \pm 6^\circ \). Thus, the cloud lay at a viewing angle \( \Theta \) of \( 34^\circ \pm 17^\circ \), where \( \Theta \) is the angle between the normal on Neptune’s “surface” and our line of sight. By a similar procedure we estimate the observed northern feature to be at a latitude of \( 30^\circ \pm 13^\circ \) and a viewing angle of \( 55^\circ \pm 9^\circ \) deg.

3. ATMOSPHERIC MODEL

Our aim in this work is to measure the altitude or pressure level at the top of an infrared-bright cloud on Neptune. Toward this end we have taken spectra, presented in the previous section, over a wavelength range where the opacity of Neptune’s atmosphere varies significantly as a function of wavelength because of \( \text{H}_2 \) collision-induced absorption and methane absorption. In model, we calculate the predicted spectrum as a function of the altitude of the top of the cloud and several other parameters described below. We judge the goodness of fit for each model spectrum using the metric \( \sum (I_{\text{obs}}(\lambda) - A I_{\text{model}}(\lambda))^2 \), where \( A \) is chosen in each case to minimize the overall sum. The introduction of the factor \( A \) is necessary because of the lack of an absolute flux calibration for the observed spectrum, \( I_{\text{obs}}(\lambda) \).

Our model atmosphere consists of 120 layers evenly spaced in \( \log P_{\text{bar}} \) from 5.0 to \( 10^{-4} \) bars. We interpolate the temperature and pressure for each layer from Lindal (1992). The free parameters in our model are the mole fraction of helium, \( F_{\text{He}} \); the mole fraction of methane in the stratosphere, \( F_{\text{CH}_4, s} \); the mole fraction of methane in the troposphere, \( F_{\text{CH}_4, t} \); the fraction of \( \text{H}_2 \) in ortho-para thermodynamic equilibrium, \( F_{\text{eq}} \); the viewing angle \( \Theta \); and the pressure altitude of the top of the cloud in bars, \( P_{\text{bar}} \).

Around the tropopause the fractional methane abundance follows the saturation vapor curve, so the methane abundance is never supersaturated. Wavelengths of 2.03–2.30 \( \mu \)m do not probe significantly into the troposphere, and therefore our model fit is insensitive to changes in \( F_{\text{CH}_4, t} \). In each layer a fraction of the \( \text{H}_2, F_{\text{eq}} \), is distributed between ortho and para states according to thermodynamic equilibrium, with the remaining \( \text{H}_2 \) distributed according to an ortho-to-para ratio of 3:1. We calculated the model-predicted spectrum for each point on a grid of these free parameters. The grid points for each parameter are listed in Table 1.

To model collision-induced absorption by hydrogen for \( \text{H}_2-\text{H}_2 \) and \( \text{H}_2-\text{He} \) collisions, we use the FORTRAN routines of A. Borysow (Borysow 1991; Zheng & Borysow 1995; Borysow & Frommhold 1989; Borysow, Frommhold, & Moraldi 1989). Although both 0–1 and 0–2 transitions are included in our model, for wavelengths of 2.1–2.3 \( \mu \)m, only the 0–1 transition is relevant.

Accurate modeling of methane absorption across the near-infrared spectrum is extremely difficult as a consequence of the enormous number of individual lines and huge variation in line strength. We apply the correlated \( k \)-distribution method as described by Lacy & Oinas (1991) and Goody & Yung (1989, p. 230). We use the \( \text{H}_2 \)-broadened methane \( k \)-coefficients of Irwin et al. (1996), since Neptune’s atmosphere is primarily \( \text{H}_2 \). These coefficients are for bins \( 5 \text{ cm}^{-1} \) wide, and this places a limit on the spectral resolution of the model.

Although significant at shorter wavelengths, Rayleigh scattering is negligible at wavelengths of 2.0–2.3 \( \mu \)m. Light reflected from the top of the cloud dominates all other sources that might contribute to our cloud spectrum, such as scattered light from stratospheric hydrocarbon hazes. Therefore, the only scattering process that we include is reflection from the top of the cloud, which we model as a flat reflecting layer. The reflectivity of the top of the cloud or, alternatively, the combined optical depth, scattering phase function, and single-scattering albedo are irrelevant given that we fit the shape of the spectrum, not the absolute flux level. Further, we assume that the optical depth, scat-

| Parameter | Values Used in Model |
|-----------|---------------------|
| \( F_{\text{He}} \) | \( 0.08, 0.10, 0.12, 0.14, 0.16, 0.18, 0.20, 0.22 \) |
| \( F_{\text{CH}_4, s} \) | \( 2 \times 10^{-4}, 8 \times 10^{-5}, 1.8 \times 10^{-5}, 3.5 \times 10^{-4}, 7.0 \times 10^{-4}, 1.05 \times 10^{-3}, 1.7 \times 10^{-3} \) |
| \( F_{\text{CH}_4, t} \) | \( 0.022 \) |
| \( F_{\text{eq}} \) | \( 0.0, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0 \) |
| \( \Theta (\text{deg}) \) | \( 17, 34, 51 \) |
| \( P_{\text{bar}} \) | 120 layers evenly spaced in \( \log P_{\text{bar}} \) from 5.0 to \( 10^{-4} \) bars |

\(^a\) Conrath et al. 1993 found \( F_{\text{He}} = 0.15 \).

\(^b\) Baines & Hammel 1994 found \( F_{\text{CH}_4, s} = 3.5 \times 10^{-4} \) with a maximum uncertainty range of \( 2.5 \times 10^{-4} \) to \( 1.7 \times 10^{-3} \).

\(^c\) Baines et al. 1995b found \( F_{\text{CH}_4, t} = 0.022 \). The fit of our model to data is not sensitive to \( F_{\text{CH}_4, t} \).

\(^d\) Baines & Smith 1990 found \( F_{\text{eq}} = 1.0 \), with a minimum allowed value of 0.85.

\(^9\) Available at http://www.astro.ku.dk/~aborysow/programs/index.html.
FIG. 3.—Constraint on cloud-top pressure. (a) Binned observed spectrum (dark line) and best-fit model spectra (gray lines) for the bright southern feature: (1) The overall best-fit model is for $P_{\text{bar}} = 0.144$ bars, $F_{\text{CH}_4s} = 1.7 \times 10^{-3}$, $F_{\text{He}} = 0.22$, $F_{\text{eq}} = 1.0$, and $\Theta = 34^\circ$. (2) When the cloud top is raised to 0.092 bars, the best fit is poor and requires $F_{\text{He}} = 0.08$. (3) Similarly, when the cloud top is lowered to 0.227 bars, the best fit is poor. In this case, $F_{\text{CH}_4s} = 2 \times 10^{-5}$ is required. (b) Same as (a), but for the dimmer northern feature: (1) The overall best-fit model is for $P_{\text{bar}} = 0.084$ bars, $F_{\text{CH}_4s} = 1.7 \times 10^{-3}$, $F_{\text{He}} = 0.22$, $F_{\text{eq}} = 1.0$, and $\Theta = 55^\circ$. (2) When the cloud top is raised to 0.053 bars, the best fit is poor and requires $F_{\text{He}} = 0.08$. (3) When the cloud top is lowered to 0.132 bars, the best fit is poor and requires $F_{\text{CH}_4s} = 1.05 \times 10^{-3}$. 

The temperature-pressure profile of Lindal (1992). Also plotted are the cloud-top pressures of the model spectra in (a) and (b). The short vertical lines show the narrow range of pressures to which our observations restrict the tops of each cloud.

FIG. 4.—Constraint on the fraction of $H_2$ in ortho-para equilibrium ($F_{\text{eq}}$). (a) Binned observed spectrum (dark line) and best model fits (gray lines) for the bright southern feature. The fits are for $F_{\text{eq}}$ fixed at 0.6, 0.8, and 1.0. In all three cases, the best fit included $P_{\text{bar}} = 0.144$ bars and $F_{\text{CH}_4s} = 1.7 \times 10^{-3}$. In cases 1 and 3 $F_{\text{He}} = 0.22$, while in case 2 $F_{\text{He}} = 0.20$, which is not a significant difference. (b) Same as (a), but for the dimmer northern feature. In all three cases the best fit was $P_{\text{bar}} = 0.144$ bars, $F_{\text{CH}_4s} = 1.7 \times 10^{-3}$, and $F_{\text{He}} = 0.22$.
spectra. Therefore, we binned the observed spectra in wavelength to achieve a resolution as nearly identical as possible to the model spectra. We restricted the model fitting to the wavelength range 2.08–2.25 μm in order to avoid a large telluric CO₂ band shortward of 2.08 μm and a series of sharp methane features at longward of 2.25 μm that are poorly represented by the methane coefficients in the model.

For the bright southern feature at a viewing angle of Θ = 34°, we obtain our best fit for a cloud top at 0.14 bars, \( F_{\text{CH₄,s}} = 0.0017, F_{\text{He}} = 0.22, \) and \( F_{\text{eq}} = 1.0. \) For the dimmer northern feature at a viewing angle of \( \Theta = 55.0\,\text{°}, \) the best fit is for a cloud-top pressure of 0.084 bars, \( F_{\text{CH₄,s}} = 0.0017, \) \( F_{\text{He}} = 0.22, \) and \( F_{\text{eq}} = 1.0. \) These best-fit model spectra are superposed on the observed spectra in spectrum 1 of Figures 3a and 3b, respectively. The two parameters that we can best constrain are \( P_{\text{eq}} \) at the top of cloud and the fractional equilibrium of H₂ in ortho-para equilibrium, \( F_{\text{eq}}. \)

The model spectra do not fit the observations for cloud-top pressures outside the range 0.11–0.19 bars for the bright southern feature (see spectra 2 and 3 of Fig. 3a), or outside the range 0.058–0.110 bars for the dimmer northern feature (spectra 2 and 3 of Fig. 3b). As shown in Figure 4, reasonable model fits to both the northern and southern spectra require \( F_{\text{eq}} \gtrsim 0.8. \) We find that our data do not significantly constrain \( F_{\text{He}} \) and \( F_{\text{CH₄,s}}. \)

Because of the low spatial resolution of our data, there is significant uncertainty in the viewing angle for both features, \( \Theta = 34° \pm 17° \) for the bright southern feature and \( \Theta = 55° \pm 5° \) deg for the dimmer northern feature. Decreasing \( \Theta \) to 17° for the bright southern feature pushes the best-fit cloud-top pressure to 0.16 bars, while increasing \( \Theta \) to 51° changes the best-fit cloud-top pressure to 0.12 bars. Similarly, for the northern feature decreasing \( \Theta \) to 51° moves the best-fit cloud-top pressure to 0.092 bars, while increasing \( \Theta \) to 64° shifts the best-fit cloud-top pressure to 0.076 bars. In all these cases the best-fit parameters include \( F_{\text{eq}} = 1.0 \) and \( F_{\text{CH₄,s}} = 0.0017. \)

5. ERRORS AND UNCERTAINTIES

At this point, it is worthwhile to briefly discuss how the errors and uncertainties in our observations and model fitting could affect our results with respect to cloud-top pressure and \( F_{\text{eq}}. \)

On the observing side, we are much more concerned with systematic errors, for instance, artificial slopes across the entire spectrum, than with random errors in the spectra of HD 201941 and Neptune. Since we are fitting the model to 73 wavelength bins, random errors from bin to bin will tend to cancel out and not bias the model fit. There are several possible sources of systematic errors on the observing side; the three of greatest concern relate to alignment on the slit and the method of atmospheric correction. Misalignment of the slit on the star would redden the spectrum and possibly introduce a bias in the final model fitting. This is less of an issue on an extended source such as the clouds on Neptune. By looking at multiple stellar spectra, we estimate that this source of error introduces at most a 1% to 2% slope from 2.08 to 2.25 μm.

In applying the atmospheric and instrumental transmission correction with HD 201941, there are two more potential sources of systematic error. The first is that to find the atmospheric transmission function we divided HD 201941 by a spectrum of Vega, and the second is that HD 201941 was not observed at exactly the same air mass and time as Neptune. While Vega is an A0 V star, HD 201941 is listed as an A2 star in the SIMBAD database. In order to estimate the maximum slope bias that this stellar mismatch could introduce, we compared blackbody curves. Drilling & Landolt (2000) give the \( T_{\text{eff}} \) for an A0 V star as 9790 K and for that an A2 V star as 9000 K. This difference suggests a slope error of 0.29% from 2.08 to 2.25 μm.

While we did not examine transparency spectra for our exact air masses, the slope difference introduced by observing at air mass 1.0 versus 1.5 across our spectral range of interest would be 1.6%.

Each of these possible slope errors is less than 2%. To show that even a fortuitous addition of all these errors in one direction would not change our primary results, we artificially introduced slope errors of ±10% to our final observed spectra and refitted the model. This had no effect on results concerning \( F_{\text{eq}} \) and at most shifted the best-fit pressure level of the cloud top by one level in our model, to 0.12 bars in the −10% case for the bright southern feature, and to 0.09 bars in the +10% case for the dimmer northern feature.

While there are numerous small ways in which the model may be inaccurate, for instance, if the temperature-pressure curve is not exactly correct for the location of the cloud features, the two major sources of uncertainty in the model are the methane \( k \)-coefficients of Irwin et al. (1996) and the assumption of a flat reflecting cloud layer. For Neptune’s atmosphere, we are forced to extrapolate the methane \( k \)-coefficients to much colder temperatures than the temperatures of the laboratory measurements on which they are based. While the accuracy or inaccuracy of this extrapolation is difficult to judge, the independence of best-fit cloud-top pressure and \( F_{\text{eq}} \) from methane concentrations \( F_{\text{CH₄,s}} \) gives us confidence in our results.

For ease we assume in our model that the cloud top is a flat reflecting layer; however, as a result of particle scattering properties the reflectivity of the cloud may vary with wavelength, and the “top” of the cloud is almost certainly somewhat extended. Our best-fit model for the bright southern feature (see spectrum 1 of Fig. 3a) is systematically slightly off from the observed spectrum. This is most easily seen at wavelengths shortward of ~2.16 μm, where H₂ absorption dominates. This is suggestive that while a flat reflecting layer at 0.144 bars does not fit perfectly, a combination of reflectance from pressures slightly higher to slightly lower than 0.144 bars might result in a better fit, which is exactly what one would expect if the cloud-top were somewhat extended. In fact, a more detailed method of modeling would be to view the computed model spectra for all the pressure levels in the model as a basis set and to construct the best-fit model spectrum from a linear combination of all the spectra from different levels. However,

10 Available at http://simbad.u-strasbg.fr.
11 See http://www.gemini.edu/sciops/telescope/telIndex.html.
one shortfall to this approach is that it implicitly assumes single scattering, ignoring multiple scattering between layers. A more complete modeling approach must include the multiple scattering between layers as well, which is beyond the scope of the current paper. Variation in reflectivity as a function of wavelength may also play a role in these slight discrepancies between model and data.

6. CONCLUSIONS

By comparing a near-infrared spectrum with the predictions of a simple transmission model, we determined the pressure level at the top of an infrared-bright tropospheric cloud on Neptune. We find a best fit of model to data for a cloud-top pressure level of 0.14 bars within a maximum allowed range of 0.011–0.19 bars for the bright southern feature that we observed. We found the dimmer northern feature to sit slightly higher in the atmosphere at 0.084 bars, within a maximum allowed range of 0.058–0.11 bars. Our work places no limit on the pressure at the bottom of the cloud. Our results further restrict the fraction of H$_2$ in ortho-para equilibrium to greater than 0.8, and our best fits consistently put this fraction at 1.0. This is in agreement with the work of Baines & Smith (1990), who found the same results, but from a different technique, measuring the equivalent widths of the 4–0 $\Sigma$(0) and $\Sigma$(1) transitions between 0.6 and 0.7 μm. Our results do not constrain the fractional abundance of methane in the stratosphere or the fractional abundance of helium.

Our primary result is the tight constraint we place on the pressure at the top of the cloud. By constraining the cloud top to pressures around the tropopause, we show that the cloud, possibly a storm or upwelling, does not extend significantly into the stratosphere. If the cloud is made up of condensed methane particles brought up from below, then the mechanism by which this cloud was formed appears to be efficient at bringing methane to near the top of the troposphere, but at least at the time we observed, the mechanism was not acting as an efficient method of transporting methane to the upper stratospheric levels where ultraviolet photolysis occurs ($P > 10^{-2}$ to $10^{-3}$ bars).

In the current paper, we presented a measurement of the altitude of two cloud features at a single time. We expect that longer term observations of multiple infrared-bright features will find that most reach only to approximately the tropopause, as in the case presented here, but occasional features may reach far into the stratosphere ($P > 0.01$ bars) and thus would provide an extremely efficient method of transporting methane to the upper stratosphere for photolysis. We are currently undertaking such a program of observations using NIRSPEC coupled to the Keck adaptive optics system (Wizinowich et al. 2000) to achieve simultaneous high spatial and high spectral resolution.

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