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THE NEAR-INFRARED SPECTRUM OF THE BROWN DWARF GLIESE 229B

T. R. GEBALLE
Joint Astronomy Centre, 660 North A'ohoku Place, Hilo, HI 96720

S. R. KULKARNI
Palomar Observatory 105-24, California Institute of Technology, Pasadena, CA 91125

CHARLES E. WOODWARD[1, 2]
University of Wyoming, Department of Physics and Astronomy, Laramie, WY 82071-3905

AND

G. C. SLOAN[1]
NASA Ames Research Center, MS 245-6, Moffett Field, CA 94035-1000
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ABSTRACT

A medium-resolution 1.0–2.5 μm spectrum of the brown dwarf Gliese 229B has been obtained using the facility spectrometer CGS4 on the United Kingdom Infrared Telescope. In addition to the broad spectral structure seen in earlier low-resolution observations, the new spectrum reveals a large number of absorption lines, many of which can be identified with water vapor. Water and methane are both shown to be strong absorbers in the near-infrared spectrum of the object. Several spectral features in Gl 229B that are attributable to methane match ones seen in reflection in the giant outer planets and, in particular, Titan.

Subject headings: infrared: general — infrared: stars — infrared: lines and bands — stars: individual (Gliese 229B) — stars: low-mass, brown dwarfs

1. INTRODUCTION

Recently, Nakajima et al. (1995) reported the first detection of a cool brown dwarf, Gliese 229B (hereafter Gl 229B), a proper-motion companion of Gliese 229A. Oppenheimer et al. (1995) obtained a low-resolution ($\lambda/\Delta\lambda \approx 150$) near-infrared (1–2.5 μm) spectrum of Gl 229B and found a number of strong absorption bands. Similar absorption bands are seen in the spectrum of Jupiter and are attributed to methane. Methane is not seen in stars. Tsuji, Ohnaka, & Aoki (1995) conclude that methane will be seen only in objects cooler than about 1800 K, lower than the effective temperatures of even the least massive stars (Burrows & Liebert 1993). From the measured broad-band spectrum of Gl 229B and assuming a radius equal to that of Jupiter, Matthews et al. (1996a, 1996b) infer $T_{\rm eff} = 900$ K and a bolometric luminosity of 6.4×10^{-6} $L_\odot$. The low luminosity and the presence of methane in the photosphere require that Gl 229B is a cool brown dwarf.

Here we present a new 1.0–2.5 μm spectrum of Gl 229B with significantly higher resolution and signal-to-noise ratio than the original spectrum presented by Oppenheimer et al. (1995). The new data provide a considerably more detailed view of Gl 229B. We compare our spectrum to spectra of the Jovian planets and Titan that are known to show strong absorption features due to methane in the near-infrared.

2. OBSERVATIONS AND DATA REDUCTION

We obtained spectra of Gl 229B in the 0.99–2.52 μm interval at the United Kingdom 3.8 m Infrared Telescope (UKIRT) on 1995 October 28–29 UT and December 12–13 UT, using the facility spectrometer CGS4 (Mountain et al. 1990). The 75 line mm^{-1} grating and the 150 mm focal length camera optics in CGS4 imaged a slit 90″ long onto a 256 × 256 InSb array. Each pixel spanned 1″.23, and the slit was 1 pixel wide. Table 1 provides details of the observations. The resolution of CGS4 was approximately 390 × λ (μm) in first order and 780 × λ (μm) in second order. To calibrate the spectra, we observed HR 1849 (A0 V, V = 5.55) each night just before observing Gl 229B.

Gl 229B is about 8″ from Gl 229A. In the J, H, and K bands, Gl 229A outshines Gl 229B by approximately 10 mag. At UKIRT, the halo of diffracted and scattered light from Gl 229A contributed a large amount of radiation to the array rows containing the Gl 229B spectrum. In order to minimize the difficulties of removing this background, we observed with the slit of CGS4 perpendicular to the line joining the two sources on the sky and obtained alternate spectra of Gl 229B by nodding the telescope 10 rows along the slit. Subtracting these alternate spectral images removed much of the halo, which allowed Gl 229B to be detected clearly at nearly all wavelengths, typically at greater strength than the residual halo from the primary. We extracted the spectrum of Gl 229B using standard infrared reduction procedures to correct for curvature of the spectra and to remove residual background. Spectra of HR 1849 were utilized to correct for atmospheric and instrumental absorption, after editing them to remove atomic hydrogen absorption lines (with the exception of Paα at 1.875 μm).

Figure 1 presents the complete spectrum of Gl 229B from 0.99 to 2.52 μm (a numerical file of this spectrum is available from the authors upon request). A more expanded version of the spectrum is provided in Figure 2. To produce the spectrum, we slightly smoothed and rebinned the observed spectra in steps of 0.0005 μm for the second-order segments and 0.0010 μm for the first-order segments. The smoothing lowers

[1] Visiting Astronomer, United Kingdom Infrared Telescope.
[2] NSF Presidential Faculty Fellow.

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TABLE 1

Observation Log

Date (1995 UT)	Grating Order	λ (μm)	Integration Time (minutes)	Conditions
Dec 12	Second	0.99–1.33	18	Photometric
Dec 12	Second	1.27–1.61	24	Photometric
Oct 29	First	1.48–2.15	24	Photometric
Oct 28	First	1.85–2.52	30	Partly cloudy
Dec 13	First	1.85–2.52	36	Photometric

the spectral resolving power by ≈10% from the actual instrumental resolution cited above. In the region of overlap between the two orders, we chose to use the first-order spectrum beyond 1.585 μm. We scaled the individual segments (by factors ranging from 0.7 to 1.2) to match the spectra in overlapping sections and at 1.585 μm. The average scaling factor was unity, but we scaled the final spectrum by a factor of 0.76 to match more accurately (to within about 0.1 mag) the recent Palomar photometry of Gl 229B ($J = 14.2$, $H = 14.3$, $Ks = 14.3$, and $K = 14.4$) as reported by Matthews et al. (1996a).

The noise in the CGS4 spectrum varies considerably with wavelength, as illustrated in Figure 2, because of large variations in atmospheric transmission and in the background (caused by both thermal and OH emissions). In particular, in the spectral regions dominated by strong telluric absorption bands (1.12–1.14, 1.36–1.42, 1.81–1.93, and 2.48–2.52 μm), apparent spectral features may not be real. In these spectral regions, the data probably are only useful for estimating the average flux level.

3. DESCRIPTION OF THE INFRARED SPECTRUM

The new spectrum of Gl 229B is consistent with the lower resolution spectrum of Oppenheimer et al. (1995). However, the latter spectrum was incorrectly normalized, as noted by Matthews et al. (1996a). Matthews et al. (1996b) present a revised spectrum with the proper normalization, with which the CGS4 spectrum agrees well.

Two new results are immediately apparent from the new spectrum. First, emission is seen across the entire IR band from 1.0 to 2.5 μm. Specifically, emission is detected through the wavelength intervals of strong telluric H_2O absorption (see discussion above) and in the range 2.2–2.5 μm including a notable rise in flux at wavelengths longward of 2.4 μm. The data of Oppenheimer et al. (1995) were restricted to the usual near-infrared windows (Z, J, H, K) and furthermore were noisy in the range 2.2–2.5 μm. We emphasize that, with the possible exception of the wavelength interval 1.36–1.40 μm, where the detection is marginal, the emission detected is from Gl 229B and is not contamination by Gl 229A; crosscuts through the differenced spectral images in these wavelength intervals show local maxima in the rows of the array corresponding to the location of Gl 229B. Second, numerous narrow lines are seen (see Fig. 2). These appear in regions of high emission and on all of the absorption edges with the exception of the very steep edge at 1.6 μm. Broader features occur in the 1.6–1.9 μm absorption trough at about 1.63, 1.67, 1.71, and 1.80 μm and at 2.17 and 2.20 μm. Most of the broad features were seen in the spectrum of Oppenheimer et al. (1995), albeit at lower resolution.

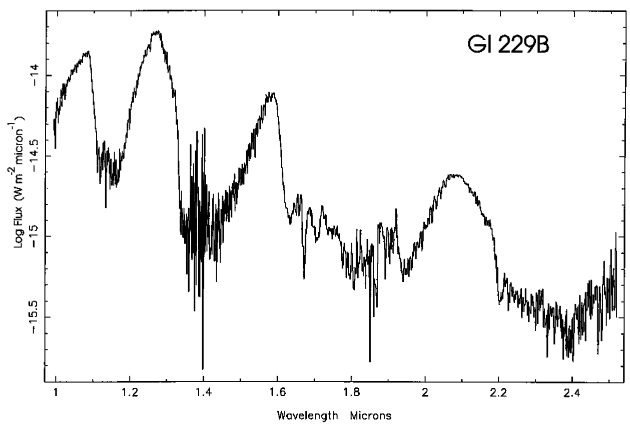

Fig. 1.—Combined 1.0–2.5 μm spectrum of Gl 229B. The intensity scale is logarithmic; negative values near 1.4 μm were removed prior to plotting.

4. DISCUSSION

4.1. *Methane: Comparison with Solar System Objects*

We have compared the new spectrum of Gl 229B to the solar reflectance spectra of three of the giant gaseous planets (Jupiter, Saturn, and Uranus) and Titan, using the data of Fink & Larson (1979), and recent CGS4 spectra of Titan (T. Owen, unpublished) and Saturn (T. R. Geballe, unpublished). Methane dominates the 1.0–2.5 μm spectra of all of the above outer planets and Titan, but the degree of domination varies, increasing in the sequence Jupiter, Saturn, Titan, and Uranus.

The spectrum of Titan provides the best overall spectral match to that of Gl 229B, and the spectra of the two exhibit several similar details. Most remarkably, their very sharp cutoffs at 1.61 μm are essentially identical (see Fig. 3). The matches with the spectra of the other solar system objects do not appear as precise; for example, the cutoff in Saturn is shifted by 0.01 μm to longer wavelength. Between 1.62 and 1.72 μm, the wavelengths of some of the absorption maxima in Titan and Gl 229B agree. Both Titan and Gl 229B show absorption bands at ∼2.17 μm and 2.20 μm (as do Jupiter and Saturn). In Titan, each of these features arises from CH_4 (Fink & Larson 1979; C. Griffith, private communication). Thus, despite the considerably different physical conditions of the CH_4 in Gl 229B compared to those in the atmospheres of the giant gaseous planets and Titan, detailed comparison provides clear confirmation of the strong influence of methane on the spectrum of Gl 229B.

4.2. H_2O *in Gl 229B*

Theoretical model spectra of brown dwarfs with effective temperatures similar to that of Gl 229B show considerable absorption due to steam (Marley et al. 1996; Allard et al. 1996). We note, however, that these model spectra include only low-resolution methane opacities shortward of 1.6 μm (R. S. Freedman, private communication). Jones et al. (1994) have compiled low-resolution spectra of the coolest stars and attribute a broad absorption centered at about 1.4 μm and its sharp absorption edge, whose wavelength they report as 1.34 μm, to H_2O. The 1.4 μm water band also appears strongly in the above model brown dwarf spectra. Following Jones et al. (1994), Oppenheimer et al. (1995) identified the absorption edge seen in Gl 229B at about this wavelength as being due to H_2O.

In the present spectrum, the absorption edge in Gl 229B is

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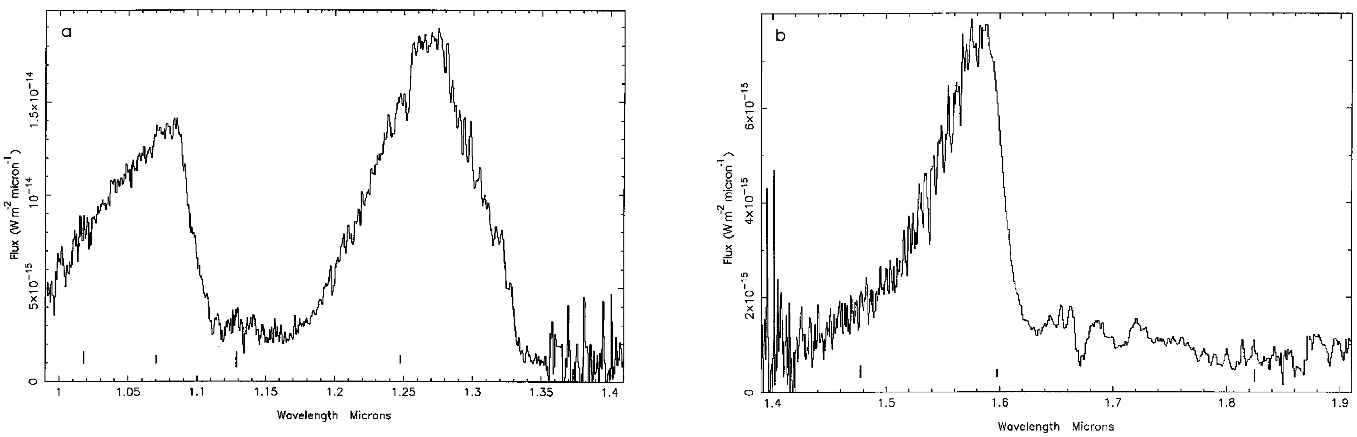

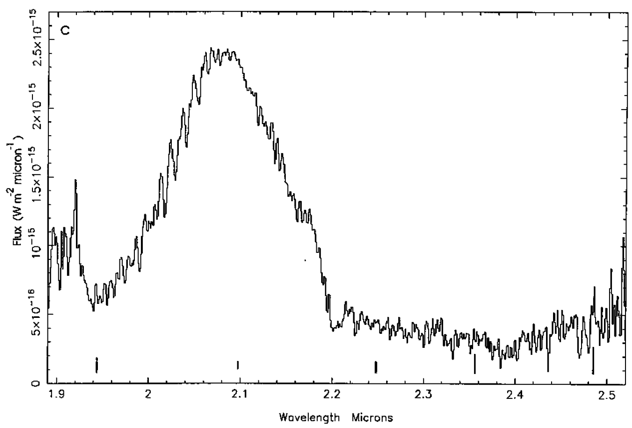

FIG. 2.—Spectral segments for Gl 229B, covering 0.99–2.52 μm. Representative noise levels are shown as vertical lines along the bottom of each panel. (*a*) 0.99–1.41 μm; (*b*) 1.39–1.91 μm; (*c*) 1.89–2.52 μm.

seen to be centered at about 1.31 μm. The H_2O absorption edge in late-M stars actually occurs at 1.33 μm (Walker et al. 1996) and is much steeper than the absorption edge in Gl 229B; indeed, it is expected to strengthen and steepen with decreasing temperature. The methane absorption edges of Titan and Saturn are centered at 1.30 and 1.31 μm, respectively. The work of Jones et al. (1994) is restricted to stars that are cool but certainly not cool enough to have strong photospheric methane bands. Thus, confusion between CH_4 and H_2O does not arise in the interpretation of stellar spectra. We conclude on the basis of the low-resolution spectra alone that the absorption edge and trough longward of 1.3 μm in Gl 229B cannot be attributed unambiguously to water alone and that methane could contribute significantly. However, when compared to the spectra of all of the giant outer planets and Titan, the emission bump at 1.5–1.6 μm is badly eaten away on its short-wavelength side (Fig. 3). Absorption by H_2O in Gl 229B can explain this systematic difference between Gl 229B and the giant planets and Titan. The sharpest portion of the 1.3 μm absorption edge of Gl 229B, at 1.33 μm, would then be due to H_2O.

Although the low-resolution spectra are ambiguous as to the presence of water vapor, comparison of the new higher resolution spectrum of Gl 229B with plots of H_2O opacity at similar resolution (kindly supplied by D. Saumon, R. S. Freedman, and D. Schwenke) demonstrate its presence clearly. An illustration of this is provided in Figure 4. Almost every absorption line in the spectrum of Gl 229B in the intervals 1.30–1.34, 1.53–1.58, and 1.95–2.07 μm has a counterpart in the water opacity spectrum. Moreover, there is good overall correlation between observed and modeled line strengths. The opacities of the lines in the above wavelength intervals are relatively low, implying that the depressions in

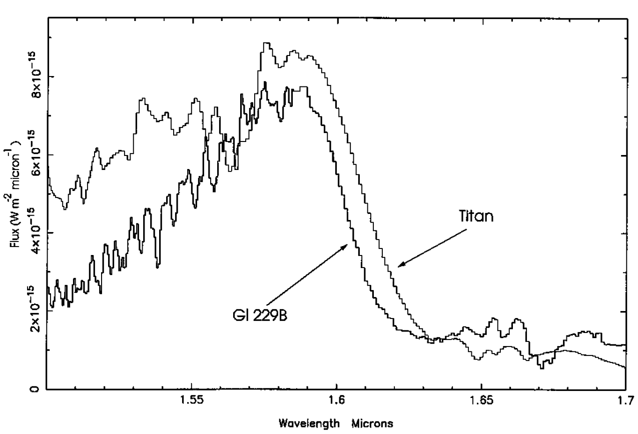

FIG. 3.—Spectra of Gl 229B (*heavy line*) and Titan (scaled by a factor of ~0.003) near the 1.6 μm methane absorption edge.

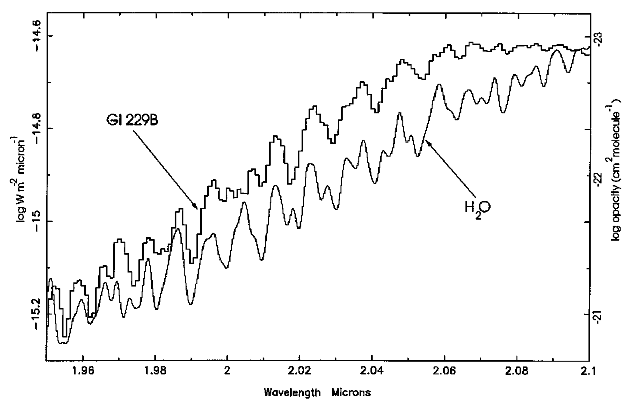

FIG. 4.—Spectrum of Gl 229B and the opacity of water vapor in the 1.95–2.10 μm region. The opacity is for P = 1 bar and T = 700 K, convolved to a resolving power of 1000, and is courtesy of R. S. Freedman, D. Schwenke, and D. Saumon.

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Gl 229B at about 1.4 and 1.9 μm are indeed due to absorption by H_2O, which has much higher opacity at those wavelengths.

Thus, the new spectrum allows a firm identification of water vapor in the photosphere of Gl 229B. It is clear that, as predicted in the models, both H_2O and CH_4 produce strong absorptions in the near-infrared spectrum of Gl 229B. However, until the line parameters of methane are better known, it will be difficult both to disentangle the relative contributions of methane and water and to search for other absorbers at near-infrared wavelengths.

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