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# FIRST RESULTS FROM THE SPACE TELESCOPE IMAGING SPECTROGRAPH: OPTICAL SPECTRA OF GLIESE 229B

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## ABSTRACT

We report the first *Hubble Space Telescope* Space Telescope Imaging Spectrograph (STIS) CCD spectroscopy of the bona fide brown dwarf Gliese 229B. The optical spectrum shows absorptions of Cs I at 8944 Å and water vapor bands at 9300–9600 Å. Strong CaH, FeH, TiO, and VO bands observed in late M dwarfs are absent from the spectrum of Gliese 229B. The formation of dust grains may explain the absence of strong atomic lines and molecular bands of these refractory elements. The broad spectral coverage obtained helps resolve current speculations about the presence of dust clouds in the atmosphere of cool brown dwarfs. We find the slope of the STIS/CCD spectrum and the lack of flux detected shortward of 8000 Å strongly supports the presence of dust hazes suspended in the photosphere of Gl 229B rather than a complete settling of the grains to regions below the photosphere.

*Subject headings:* binaries: general — stars: individual (Gl 229B) — stars: low-mass, brown dwarfs

## 1. INTRODUCTION

Current theory predicts that, like stars, brown dwarfs form through contraction of a molecular cloud, while planetary bodies are thought to form through accretion of material in a flattened disk. At an early age, brown dwarfs will fuse deuterium but have masses too low to undergo hydrogen fusion. According to theory, a minimum mass of ∼0.08 $M_\odot$ is required to sustain hydrogen fusion (D'Antona & Mazzitelli 1985; Stringfellow 1991; Burrows & Liebert 1993; Baraffe et al. 1995). These models indicate that a brown dwarf still contracting could possibly be misidentified as an older late-type M dwarf. Once a brown dwarf reaches the main sequence, deuterium fusion ends, and the brown dwarf cools below 2000 K, becoming fainter as it radiates energy.

Gliese 229B (0.04–0.055 $M_\odot$; Gunn $R$ magnitude ≥22) is about 7″.5 from Gliese 229A and was discovered in a coronagraphic imaging survey (Nakajima et al. 1995; Oppenheimer et al. 1995). It has been unequivocally identified as a brown dwarf on the basis of spectral features indicative of an extremely low effective temperature (900–1000 K; Allard et al. 1996; Tsuji, Ohnaka, & Aoki 1996a; Marley et al. 1996). Gl 229B provides an important data point in the low-mass regime at the bottom of the mass-luminosity function. The infrared spectrum of Gliese 229B (Geballe et al. 1996) and the recent discovery of giant planets around solar-type stars (Mayor & Queloz 1995; Marcy & Butler 1996; Cochran et al. 1997) have sparked theoretical interest in establishing the physical characteristics of substellar objects, i.e., temperature, mass, and gravity (Allard et al. 1996; Marley et al. 1996; Saumon et al. 1996; Burrows et al. 1997).

One outstanding question is whether photospheric clouds and hazes like those found in lower main sequence objects persist in cooler brown dwarfs (Tsuji et al. 1996b; Allard 1997). These atmospheric dust clouds and hazes may have settled gravitationally below the photosphere, as seems to be the case in yet cooler planetary atmospheres (Marley et al. 1996; Burrows et al. 1997). An optical spectrum of Gliese 229B covering a broad spectral region can therefore help resolve current speculation about the presence of clouds and hazes in the atmosphere of cool brown dwarfs.

The presence of infrared telluric water vapor bands and scattered light from the M1 primary star have until now prevented an accurate estimate of the atmospheric composition of Gliese 229B. As part of the *Hubble Space Telescope* (*HST*) Servicing Mission Orbital Verification (SMOV) program to assess the scientific capabilities of the Space Telescope Imaging Spectrograph (STIS), we report on an Early Release Observation (ERO) program to obtain STIS/CCD spectroscopic observations of Gl 229A and 229B covering the wavelength region 0.53–1.02 $\mu$m.

## 2. OBSERVATIONS AND DATA REDUCTIONS

On 1997 May 3, Gliese 229A and 229B were each observed separately with the *HST* STIS/CCD. Gliese 229A ($m_V = 8.13$) was acquired with an STIS/CCD ACQ using the F28X50OII aperture, but no peak up was performed. Typical centering errors in this situation are ∼0″.02 (∼0.4 pixel). Blind offset pointing was then used to position the brown dwarf companion into the 52″ × 0″.5 aperture. The slit width of 0″.5 corresponds to 10 pixels at the detector. Offsets for the brown dwarf were predetermined from Wide Field Planetary Camera 2 (WFPC2) images retrieved from the *HST* archive. The derived right ascension and declination offsets were 0.1730 s and −7″.425, respectively. The offset slew positioned Gl 229B about 1.7 pixels (∼0″.07) from the center of the slit. This miscentering was determined from a comparison of the fringes between the brown dwarf spectrum and the contemporaneous flat field, after accounting for known offsets. Figure 1 illustrates the Gl 229 system at the time of the observations with the brown dwarf

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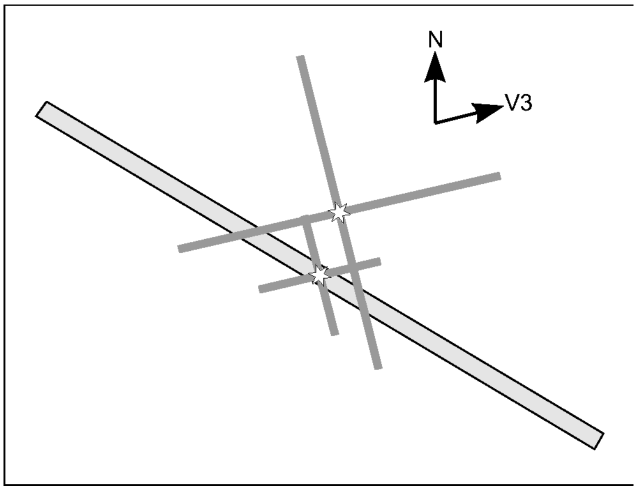


FIG. 1.—Schematic depicting the STIS aperture orientation. The bright star Gliese 229A and the fainter brown dwarf companion Gliese 229B are illustrated as stars and with diffraction spikes. The STIS 52 × 0.5 aperture is overlayed on the brown dwarf. The diffraction spikes from Gl 229A cross the aperture resulting in the spectra of Gl 229A above and below the spectrum of Gl 229B in the CCD image. The width of the slit has been exaggerated by a factor of 4.

in the slit, including the position of the diffraction spikes from the primary star. The STIS/CCD observations were made with the G750L grating, covering the wavelength range 5300–10200 Å at a dispersion of 4.92 Å pixel$^{-1}$. Table 1 summarizes the observations.

The observations were bias and flat-field corrected, and cosmic rays were removed. No appreciable pixel shift was found among the 10 separate images obtained over three orbits. Fringing is significant longward of ~8000 Å, with an uncorrected amplitude of ~20% at 9300 Å. The contemporaneous flat field was not used to remove the fringing due to a 3.7 pixel offset. A library flat field, with a 0.65 pixel offset relative to the spectrum, was shifted and applied to the data. This flat reduced the fringe amplitude in the spectrum to ~5%. The brown dwarf spectrum was extracted from the CCD frame by summing the counts contained in 11 rows centered on the spectrum. The spectrum was calibrated to a flux scale using a sensitivity curve determined from standard star observations. The spectrum of Gliese 229B is presented in Figure 2.

### 3. MOLECULAR BANDS

The STIS/CCD spectrum of Gl 229B shows no detectable flux shortward of 8000 Å. Inspection of the STIS/CCD image indicates that the counts in this region of the spectrum are most probably noise or light scatter from Gl 229A. Longward of 8000 Å, the spectrum of Gl 229B rises sharply, but there is no indication of TiO and VO bands that are present in very cool M dwarfs. The absence of metallic oxides does not necessarily suggest low metallicity, since the spectrum of Gl 229A appears to be normal in metals. The two strongest spectral features in Gl 229B are the absorption lines of cesium (Cs I) at 8944 Å and water vapor bands at 9300 Å. The Cs I line sits on a broad shallow feature that we tentatively identify as methane ($CH_4$) absorption (λ8890). However, because of residual fringe amplitude, the corresponding methane band at 9990 Å cannot be confirmed with the STIS spectrum. A search of the spectrum for the FeH Wing-Ford absorption band (9850–10200 Å) shows no pronounced features (Wing & Ford 1969; Schiavon, Barbuy, & Singh 1997). If present in the spectrum, this band is possibly hidden because of the low resolution.

TABLE 1

*HST* STIS/CCD OBSERVATIONS OF GL 229B

| Start Date (UT) | Observation | Exposure (minutes) |
|---|---|---|
| 1997 May 3 06:16:50 ...... | o3wd01040 | 22.38 |
| 1997 May 3 07:25:40 ...... | o3wd01050 | 44.50 |
| 1997 May 3 09:02:29 ...... | o3wd01060 | 45.63 |

Figure 3 presents the STIS/CCD spectra of Gliese 229A and 229B, the Faint Object Spectrograph (FOS) spectrum of Proxima Centauri, and the albedo spectrum of Jupiter (Karkoschka 1994). The spectra have been binned to similar resolution. These observations provide a small sample for comparison with the optical spectrum of Gl 229B, illustrating the TiO and VO absorptions in M dwarfs and the dominant absorption of methane in the atmosphere of Jupiter.

We find a strong suppression of emergent radiation in the visual to near-infrared STIS spectrum, when compared with earlier-type brown dwarfs and model spectra. The absence of spectral features in the spectrum, except for Cs and $H_2O$, indicates that grain formation has depleted refractory elements such as Ti, V, and Fe. This phenomenon has already been observed in the spectra of dwarfs later than about dM8 and explains the nondetection of TiO, VO, and FeH bands in Gl 229B. If grains have not settled out of the photosphere, but remain suspended, they would give rise to excess optical opacity. Since grains typically have broad absorption profiles, we propose that the observed flux suppression shortward of 8000 Å is due to grain absorption. If confirmed, this will indicate that dust can remain suspended in the photospheres of brown dwarfs and explain why Gl 229B is far redder and fainter in the optical than otherwise expected.

The lithium test is one of the most decisive criteria of substellarity for low-mass brown dwarf candidates. For dwarfs with masses comfortably below the hydrogen fusion limit, i.e., $\leq 0.06\ M_\odot$, the presence of Li I lines in spectra provides an indicator for substellar classification (Rebolo et al. 1992). Low-

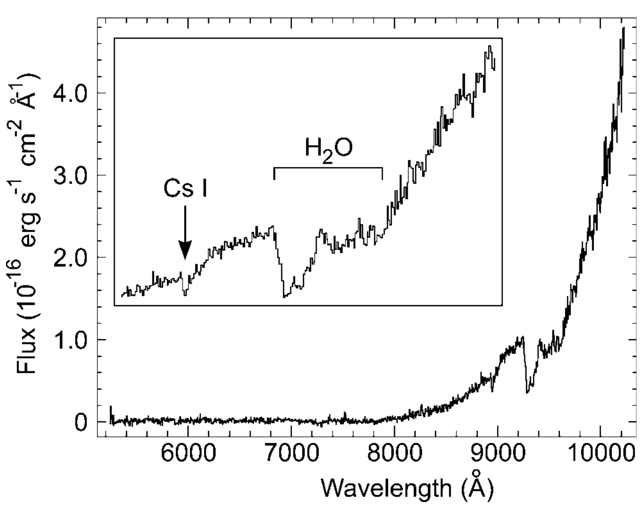


FIG. 2.—STIS/CCD spectrum of the brown dwarf Gliese 229B. The spectrum shows no detectable flux shortward of ~8000 Å, then rises steeply longward of 8000 Å, and matches the detected flux of the IR spectrum at 1.0 $\mu$m. The insert shows part of the spectrum (λλ8800–9900) enlarged. The absorptions of Cs I (λ8944) and water vapor bands (λ9300) are seen.

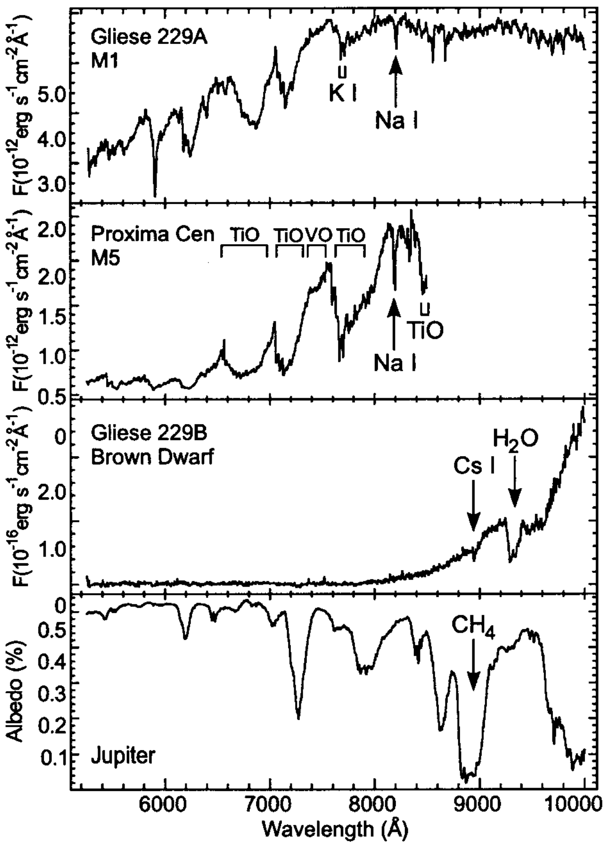


FIG. 3.—Optical spectra of M dwarf stars, Gl 229B, and Jupiter. The Proxima Centauri spectrum was obtained with the FOS. The Jupiter albedo spectrum is from Karkoschka (1994). The spectra were binned to similar resolution. The comparison of the brown dwarf spectrum (5300–10000 Å, i.e., 0.53–1.0 $\mu$m) with the M dwarfs shows an absence of the titanium oxide (TiO) bands. The methane bands ($CH_4$) are stronger in Jupiter than in the spectrum of Gl 229B.

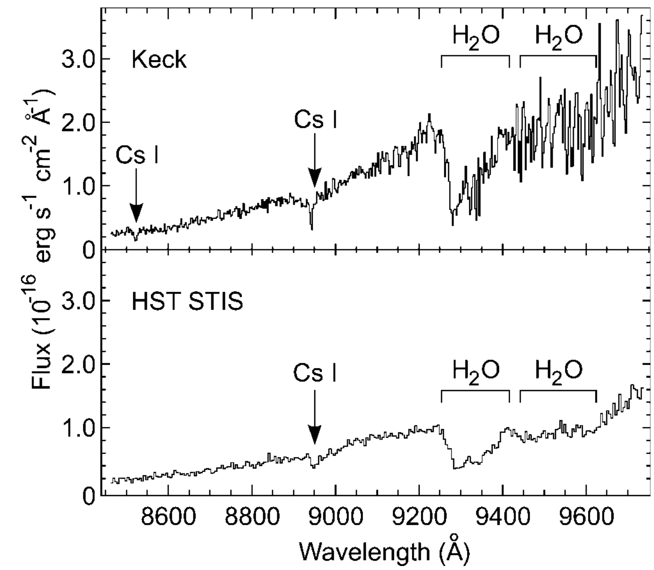


FIG. 4.—Optical spectra of Gliese 229B. The Keck spectrum is courtesy of Oppenheimer (1997). The spectra are compared over a common spectral range. The Keck spectrum reveals the presence of Cs I absorptions (λλ8521, 8944) and water vapor bands (λ9300). The STIS spectrum provides information about broad spectral features.

mass objects cannot reach the Li burning temperature and will retain most of their initial Li abundances (Nelson, Rappaport, & Chiang 1993; Burrows & Liebert 1993; Chabrier, Baraffe, & Plex 1996). This lithium test has led to the confirmation of two young brown dwarfs, Teide 1 and Calar 3, in the Pleiades star cluster (Rebolo et al. 1996) and, recently, to the confirmation of two more single-field brown dwarfs in the galactic disk, Kelu 1 (Ruiz et al. 1997) and DENIS 19 (Bedding et al. 1997). While a brown dwarf like Gl 229B must certainly carry undepleted amounts of Li, the Li I 8126 Å line was not detected in the spectrum, possibly because of the low resolution.

A high-resolution spectrum (~0.85 to ~0.97 $\mu$m) has been obtained of Gl 229B with the Keck telescope (Oppenheimer 1997). We note that the Keck spectrum reveals the presence of Cs I transitions (λλ8521, 8944) in Gliese 229B. The Cs I line λ8944 has also been detected in the STIS spectrum. No other atomic lines were detected or identified in the Keck and STIS spectra. One would expect in addition to the Cs I transition to detect transitions of Li I λ8216, Rb I λλ7800, 7948, and perhaps CrH λλ8611, 8800 in this spectral window (Henry et al. 1997; Kirkpatrick, Beichman, & Skrutskie 1997). These transitions become prominent in the spectra of hotter brown dwarfs such as Kelu 1, GD 165B, and the DENIS objects. This Keck spectrum and the STIS spectrum are presented in Figure 4, displayed to a common spectral range.

Giant planets, like brown dwarfs, radiate energy because of the release of gravitational potential energy. For a Jovian-like atmosphere, it is thought that metals as well as water have condensed and settled to the bottom of the atmosphere. In optical spectra of brown dwarfs, model atmospheres predict the formation of methane bands (Tsuji, Ohnaka, & Aoki 1995; Hauschildt, Allard, & Alexander 1995; Allard & Hauschildt 1995; Allard et al. 1996; Marley et al. 1996). Indeed, strong bands of methane have been confirmed at 1.7 and 2.4 $\mu$m in the infrared spectrum of Gl 229B (Oppenheimer et al. 1995). A broad shallow feature at 8890 Å could be interpreted as due to methane absorption.

Water has condensed in the Jovian atmosphere, while for the brown dwarf, it has not. Water vapor bands at 9300 Å are the strongest features in the Gl 229B spectrum. The temperature of Gl 229B is too high to permit condensation of $H_2O$, and water and CO are the abundant oxygen compounds in its atmosphere. Thus, unlike giant planets but very much like cool stars, water must fully control the atmospheric structure of the brown dwarf.

## 4. DISCUSSION

We have obtained a STIS/CCD optical spectrum of Gliese 229B. The spectrum confirms the presence of cesium (Cs I) and water vapor bands in the optical spectrum of Gl 229B (Oppenheimer 1997). Methane ($CH_4$) absorption bands are not clearly evident in the spectrum. Also, the STIS/CCD spectrum shows an absence of strong absorption lines and molecular bands of refractory elements. The spectrum confirms the trend observed in more massive brown dwarfs that as temperature decreases, molecular absorptions (predominately TiO and VO) and other refractory elements become less dominant in the spectrum. It also demonstrates the increasing importance of dust clouds in these objects. The spectrum of Gliese 229B is quite different in appearance from the published optical spectra of later-type M dwarfs and the young brown dwarfs Teide 1, PPL 15, and Calar 3. However, the STIS spectrum and the spectra of the latest discovered field brown dwarfs Kelu 1 and

DENIS 19 can be used to extrapolate a brown dwarf spectral sequence.

Our preliminary analysis of the Gl 229B STIS/CCD spectrum strongly suggests that (1) refractory elements have condensed to form photospheric grains, (2) some of these grains have remained suspended in the photosphere to suppress the optical flux of the brown dwarf, and (3) Gliese 229B has more similarities to earlier-type brown dwarfs than to Jupiter. The probable persistence of dust grains in the photosphere of the brown dwarf will allow for the first time reliable spectroscopic modeling of intermediate brown dwarfs with masses between 0.02 and 0.06 $M_\odot$.

The STIS/CCD observations of the brown dwarf Gl 229B as reported here clearly demonstrate the capabilities of the spectrograph to obtain spectra of low-luminosity targets in proximity to a much brighter object, an observation that is difficult to perform with ground-based telescopes. In addition, the STIS/CCD observations cover a wavelength range (0.9–1.0 $\mu$m) that is greatly affected by the Earth's atmosphere. The brown dwarf is relatively faint in the optical, and it is doubtful that other fainter spectral features will be detectable with longer exposures using the G750L grating. Future observations with STIS using the G750M grating with a dispersion of 0.56 Å pixel$^{-1}$ and centered at 8311, 8825, and 9338 Å might be able to detect the Li I $\lambda$8126 line and to resolve the Cs I, $CH_4$, and $H_2O$ features.

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