J-BAND INFRARED SPECTROSCOPY OF A SAMPLE OF BROWN DWARFS USING NIRSPEC ON KECK II

IAN S. McLEAN, MAUVOREEEN K. WILCOX, E. E. BECKLIN, DONALD F. FIGER, ANDREA M. GILBERT, JAMES R. GRAHAM, JAMES E. LARKIN, N. A. LEVENSON, HARRY I. TEPLITZ, AND J. DAVY KIRKPATRICK

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ABSTRACT

Near-infrared spectroscopic observations of a sample of very cool, low-mass objects are presented with higher spectral resolution than in any previous studies. Six of the objects are L dwarfs, ranging in spectral class from L2 to L8/9, and the seventh is a methane or T dwarf. These new observations were obtained during commissioning of the near-infrared spectrometer (NIRSPEC), the first high-resolution near-infrared cryogenic spectrograph for the Keck II 10 m telescope on Mauna Kea, Hawaii. Spectra with a resolving power of $R \approx 2500$ from 1.135 to 1.360 $\mu$m (approximately J band) are presented for each source. At this resolution, a rich spectral structure is revealed, much of which is due to blending of unresolved molecular transitions. Strong lines due to neutral potassium (K i) and bands due to iron hydride (FeH) and steam (H$_2$O) change significantly throughout the L sequence. Iron hydride disappears between L5 and L8, the steam bands deepen, and the K i lines gradually become weaker but wider because of pressure broadening. An unidentified feature occurs at 1.22 $\mu$m that has a temperature dependence like FeH but has no counterpart in the available FeH opacity data. Because these objects are 3–6 mag brighter in the near-infrared compared with the I band, spectral classification is efficient. One of the objects studied (2MASS J1523+3014) is the coolest L dwarf discovered so far by the 2 Micron All-Sky Survey (2MASS), but its spectrum is still significantly different from the methane-dominated objects such as Gl 229B or SDSS 1624+0029.

Subject headings: infrared: stars — stars: atmospheres — stars: low-mass, brown dwarfs

1. INTRODUCTION

After eluding undisputed detection for many years, numerous brown dwarfs—objects with substellar mass—are now known. While some candidates were discovered in small-scale surveys of young nearby clusters, such as the Pleiades and Hyades, or as companions to low-mass stars, the biggest breakthrough has come as a result of large-scale surveys such as the Deep Near-Infrared Sky (DENIS) survey (Delfosse et al. 1997), the 2 Micron All-Sky Survey (2MASS; Skrutskie et al. 1997; Kirkpatrick et al. 1999), and the Sloan Digital Sky Survey (SDSS; Strauss et al. 1999). Recently, using optical (CCD) spectroscopy, Kirkpatrick et al. (1999) have defined a new spectral class, L dwarfs, in which the metallic oxides (such as TiO and VO) found in M stars lose their dominance to metallic hydrides (such as FeH and CrH). The temperature range for the L class is given by Kirkpatrick et al. (2000) from about 2000 K for L0 to about 1250 K for L8, whereas Martin et al. (1999) suggest a range from 2200 to 1600 K. Depending on age and model calculations, Kirkpatrick et al. (1999) argue that at least one-third of the L dwarf objects must be brown dwarfs, and perhaps all are.

Spectral classification is based on spectroscopy between 6500 and 10000 Å at a resolution of 9 Å ($R \approx 1000$). While use of this spectral region provides many important spectral diagnostics, it suffers from the fact that L and T dwarfs are extremely faint at these wavelengths, and therefore long exposures on very large aperture telescopes are required to obtain spectra with good signal-to-noise ratios. Typical I-band magnitudes are about 19 or fainter (e.g., GD 165B), but a gain of 3–6 mag can be obtained by going to the near-infrared.

Using earlier generations of infrared instruments, previous observations of individual brown dwarf candidates have yielded a typical resolving power of about $R = 500–1000$ (see the observations of Geha et al. 1996, Ruiz, Leggett, & Allard 1997, Tinney, Delfosse, & Forveille 1997, Kirkpatrick et al. 1999, and Strauss et al. 1999). These pioneering efforts were accomplished with instruments using an earlier generation of IR detector arrays, with at most 256 × 256 pixels. This resolution is sufficient to reveal the major differences that set apart the L dwarfs and T dwarfs from warmer stars, e.g., the presence of deep steam bands and strong methane bands in the L and T dwarfs, respectively. Kirkpatrick et al. (1993) modeled a spectral sequence of M dwarfs using spectroscopy from 0.6 to 1.5 $\mu$m and identified the major bands and atomic features. Jones et al. (1996) performed a similar analysis from 1.16 to 1.22 $\mu$m with a sample of M dwarfs that also included GD 165B. An excellent review of model atmospheres of very low mass stars and brown dwarfs is given by Allard et al. (1997).

In this Letter, we report observations using the near-infrared spectrometer (NIRSPEC), a new cryogenic infrared spectrograph on the Keck II telescope employing a 1024 × 1024 InSb array. A consistent set of J-band spectra with $R \approx 2500$ is presented that, for the first time, allows a detailed comparison of the near-infrared features of the spectral sequence from early
L dwarfs to T dwarfs. Our targets were selected from the list of L dwarfs published by Kirkpatrick et al. (1999) and supplemented with new sources discovered more recently by the 2MASS (Kirkpatrick et al. 2000). One of these objects is reported as being the closest known L dwarf to date, and another is likely the coolest L dwarf discovered thus far.

2. OBSERVATIONS

Table 1 lists the objects observed and provides a summary of their photometric properties and spectral classification based on the far-optical spectroscopy by Kirkpatrick et al. (1999). As part of the “first light” scientific commissioning of the NIRSPEC at the W. M. Keck Observatory on Mauna Kea, Hawaii, near-infrared spectra of this sample were obtained. Kelu-1 (Ruiz et al. 1997) was observed on 1999 April 29, but all of the other sources were observed on 1999 June 2. Since detailed descriptions of the design and performance of NIRSPEC are given elsewhere (McLean et al. 1998, 2000), only a short summary is included here. Briefly, this cryogenic instrument is the world’s first facility-class infrared spectrograph employing the state-of-the-art 1024 × 1024 InSb array. For the highest spectral resolution work, a cross-dispersed echelle grating is used that yields $R = 25,000$ for a $0.43$-wide slit, corresponding to 3 pixels along the dispersion direction. A much lower resolution mode can be obtained simply by replacing the echelle grating with a flat mirror and using the cross-dispersion grating alone. The spectral resolution in this mode is $R \sim 2500$ for a 2 pixel–wide slit (corresponding to $0.38$ in this case).

For the present study, the lower resolution mode was selected for speed and efficiency. The goal was to obtain a spectral sequence of L dwarfs with good signal-to-noise ratios from about 1 to 2.5 $\mu m$. Only the $J$-band results, covering the interesting range from 1.135 to 1.362 $\mu m$, are discussed here.

As shown in Table 1, the $J$ magnitudes of the sample range from 12.8 to 16.3. All objects received the same total exposure time of 600 s. The observing strategy employed was to obtain a 300 s integration at each of two positions along the entrance slit separated by about 20”, referred to as a nodded pair. Seeing conditions were generally very good for these measurements ($0.3^\prime\prime$–$0.5^\prime\prime$), and a slit width of $0.38^\prime\prime$ was used in all cases. To calibrate for absorption due to the Earth’s atmosphere, stars of spectral type A0 V–A2 V were observed as close to the same air mass as possible (typically within 0.05 air masses, except for 2MASS W1632+1904 for which the difference was 0.28) and also close in time. The $J$ band is sensitive to atmospheric extinction due mainly to water vapor absorption. A-type stars are essentially featureless in this region except for the Paβ line at 1.2816 $\mu m$, which can be interpolated out. Immediately after the observation of each source, both neon and argon arc lamp spectra were obtained for wavelength calibration, and a white-light spectrum was recorded for flat-fielding.

Reduction of the data followed the steps set out below. The first requirement is to place the raw data on a uniform grid of wavelength and position along the slit. Using custom software developed by one of us (J. E. L.), the spatial distortions were corrected first. A spatial map was formed by using the sum of the nodded pair of standard star spectra, with the assumption that the pair of spectra must be exactly a fixed number of pixels apart. Next, the arc lamp spectra were used to construct a spectral map to warp the raw data onto a uniform wavelength scale using a second-order polynomial fit. Next, the A-type calibration star was reduced by forming the difference image, warping it with the spatial and spectral mapping routines, dividing by the normalized flat-field lamp, shifting and co-adding the pair of spectra at the two slit positions, and then extracting the resultant spectrum. Division with a blackbody spectrum for the temperature corresponding to the star’s published spectral class completed the reduction of the standard star. Finally, the Paβ absorption line at 1.2816 $\mu m$ was removed by interpolation from the reduced spectra before it was used for division into the corresponding object spectra.

Similar steps were applied to the raw data frames of the target sources. After rectification and flat-field correction, each spectrum was extracted and divided by the fully reduced spectrum of its associated calibration star. Finally, the nodded pair of reduced spectra were shifted, co-added together, and extracted to give the resultant calibrated spectrum of each source. The results are shown in Figure 1. Note that this entire set of new infrared spectra for a sample of seven optically faint, low-mass objects represents a total of only 70 minutes of on-source observing time, comparable to the exposure time per object needed with other instruments or at shorter wavelengths.

3. RESULTS

Clearly, the strongest atomic line transitions in this wavelength region are the pair of neutral potassium (K i) lines at 1.6960, 1.7770 $\mu m$ and 1.2432, 1.2522 $\mu m$, respectively. The first pair corresponds to the multiplet designation $4p^2 P^o \rightarrow 3d^2 D$, and the second pair corresponds to the $4p^2 P^o \rightarrow 5s^2 S$ multiplet. The dominant molecular species in the L dwarfs in this band are $H_2O$ and iron hydride (FeH), with methane (CH₄) appearing in the T dwarf. The strongest FeH bands are expected at 1.194, 1.21, and 1.237 $\mu m$ approximately. A pair of sodium lines, the $3p^2 P \rightarrow 4S$ $4S$ multiplet, can just be detected buried in the water absorption at 1.138 and 1.141 $\mu m$, and we
Fig. 1.—NIRSPEC spectra with a resolving power of $R = 2500$ (5 Å) and a dispersion of 2.5 Å pixel$^{-1}$ from 1.135 to 1.357 μm for a sample of six L dwarfs and one T dwarf. Each spectrum has been normalized to unity using the average flux near 1.28 μm and then displaced by 0.6 units along the y-axis for clarity of presentation. For the fainter sources, the first few and last few data points are too noisy to plot. Prominent features are identified, but much of the structure is due to blending of molecular transitions.

Fig. 2.—An example of a model spectrum with a final (smoothed) resolution of $R = 2000$ (6 Å) from 1.135 to 1.357 μm for qualitative comparison with the NIRSPEC data. The model parameters are $T = 2000$ eff, solar metallicity. Lines identified in the model spectrum are not necessarily the same as those seen in the NIRSPEC observations (see text).

Table 2

| Object   | Spectral Type | 1.169 μm | 1.177 μm | 1.244 μm | 1.253 μm | 1.33 μm/1.27 μm |
|----------|---------------|----------|----------|----------|----------|-----------------|
| Kelu-1   | L2            | 6.18     | 6.86     | 6.64     | 6.32     | 0.55            |
| GD 165B  | L4            | 6.79     | 9.34     | 8.64     | 7.52     | 0.56            |
| DENIS-P J1228−1547 | L5        | 7.26     | 9.94     | 7.88     | 7.06     | 0.52            |
| 2MASSW J1507−1627 | L5         | 8.98     | 10.82    | 7.68     | 7.84     | 0.46            |
| 2MASSW J1632+1904 | L8          | 7.75     | 8.35     | 6.02     | 7.33     | 0.38            |
| 2MASSW J1523+3014 | L8/9       | 8.83     | 9.18     | 6.17     | 6.56     | 0.41            |
| SDSS 1624+0029 | T           | 8.93     | 14.75    | 9.09     | 11.38    | 0.04            |

Of about 7 Å across the L dwarfs to about 12 Å in the T dwarf SDSS 1624, although the line depth decreases significantly. This behavior is due to line broadening. The full width at the base of these lines increases from about 40 Å in the L dwarfs to over 80 Å in the T dwarf. The water index slowly strengthens from about 0.6 to 0.4 through the L dwarfs as the absorption at 1.33 μm becomes deeper and then drops markedly to about 0.04 in the T dwarf.

4. DISCUSSION

The variation in the J-band spectra of this sample of objects is quite remarkable, and it is relatively easy to place the objects in a temperature sequence. The water band strengthens as the temperature decreases. FeH weakens and then disappears, the K lines weaken and broaden, and the continuum at around 1.15 μm slowly drops relative to the continuum at 1.26 μm. As expected, the DENIS L5 source and the 2MASS L5 object exhibit almost identical spectral characteristics. By ordering the spectra according to the classifications given by Kirkpatrick et al. (1999, 2000), with the earliest spectral type (L2) at the top, the following trends are apparent in the J-band spectra.

L2 (Kelu-1)—Strong K and FeH lines are superposed on a larger depression across the region, which is perhaps the result of residual oxide (either TiO and/or VO) absorption; VO is expected at around 1.19 μm.

L4 (GD 165B)—Any residual oxide absorption has gone, effectively raising the continuum to produce a flatter spectrum,
and making the K\textsc{i} and FeH features appear stronger, although they are expected to decrease with decreasing temperature. The water absorption (steam) band at 1.30 $\mu$m is increasing in strength. Numerous small features from 1.25 to 1.30 $\mu$m closely match those in Kelu-1.

$L5$ (2MASS J1507$-$1627).—All features present in the L4 class remain. The K\textsc{i} and FeH features are slightly weaker, while the water band at 1.30 $\mu$m is deeper than before and there is a slight slope of the continuum toward the blue end. $L5$ (DENIS-P J1228$-$1547).—This spectrum is almost the same as the previous one, confirming that they are indeed the same spectral class.

$L8$ (2MASS J1623$+$1904).—At L8, the FeH features have disappeared, and the depth of the K\textsc{i} lines are significantly weaker, but there is evidence of broadening in their wings. There is a slight downward slope of the continuum toward the red. The steam band is relatively stronger.

$L8/9$ (2MASS J1523$+$3014).—This spectral type is very similar to the previous L8, but the K\textsc{i} lines appear slightly broader and the water band is slightly deeper. The slope to the blue is a little stronger than in L8. Consequently, this object may be cooler than 2MASSW J1623$+$1904, as its designation suggests, but the difference is small.

$T$ (SDSS 1624$+$0029).—A dramatic slope toward the blue appears because of the onset of methane absorption in this wavelength region, and there is also a slope or “break” toward the red from about 1.26 to 1.31 $\mu$m before a deep water band sets in. The K\textsc{i} lines are still present but are now very broad.

As an illustration of the density of molecular features and the problem of line blending, Figure 2 shows a model spectrum that was kindly provided by P. Hauschildt (1999, private communication).

Another useful framework for understanding these spectra is the molecular equilibrium calculations by Burrows & Sharp (1999). As their analysis shows, the main absorbers that are characteristic of M stars (e.g., TiO and VO) decline rapidly in importance with decreasing effective temperature. These molecules are expected to condense onto dust grains; TiO, for instance, forms perovskite (CaTiO$_3$). The abundance of gaseous TiO begins to decrease at around 2400 K, and similarly VO will become depleted near 1800 K. For iron, the first condensate to form is the metal itself, at about 2200 K, which can then form droplets and rain out of the atmosphere. We have carefully compared our spectra with the solar atlas and cannot make any conclusive identifications with iron lines or any other metal lines (such as Mn and Al) among the dense forest of H$_2$O transitions. Interestingly, Jones et al. (1996) noted the presence of Fe in earlier spectral types, such as the M6 dwarf GL 406, at a comparable resolution. A significant amount of iron may have rained out.

Since they are less refractory and survive in monatomic form for a greater temperature range, the neutral alkali metals (Na, K, Rb, and Cs) are expected to remain after the true metals become depleted. In effect, as the temperature falls, the atmospheres of cool substellar objects become more transparent. The column density of potassium and sodium, for instance, is expected to increase to the point where the wings of the absorption lines become damped. This result explains the strength, broadening, and temperature dependence of the K\textsc{i} lines seen in our spectra. According to Burrows & Sharp (1999), sodium and potassium should become depleted at around 1500–1200 K, with sodium disappearing first and potassium forming into KC\textsubscript{i} below about 1200 K. If there is settling of refractory species at higher, deeper temperatures, however, then both atomic sodium and potassium are expected to persist to lower temperatures, at which point they should form their sulfides, not chlorides (see Burrows, Marley, & Sharp 2000 and Lodders 1999). Figure 1 shows that the very strong K\textsc{i} lines persist, albeit with broad wings, well into the T dwarf temperature range.

Some features that are apparent in the new data are not yet explained by the existing models. For example, a broad, relatively strong feature is seen in our spectra at 1.22 $\mu$m. This feature remains through L5 but is gone in the L8 spectra. Although this is the same pattern as followed by FeH, this broad feature does not appear in the opacity plot of FeH kindly supplied by A. Burrows (1999, private communication), nor does it appear in the model spectrum provided by P. Hauschildt. Finally, our results imply that any L or T dwarf object meeting the discovery parameters of the 2MASS and/or the SDSS can be observed spectroscopically with NIRSPEC on Keck at medium to high spectral resolution.

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