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The NIRSPEC Brown Dwarf Spectroscopic Survey

Mavourneen K. Wilcox[a], Ian S. McLean[a], E. E Becklin[a], Donald F. Figer[b], Andrea M. Gilbert[c], James R. Graham[c], James E. Larkin[a], N. A. Levenson[d], Harry I. Teplitz[e], J. Davy Kirkpatrick[f], and Adam J. Burgasser[g]

[a]Dept. Physics & Astronomy, Univ. California/Los Angeles, Los Angeles, CA 90095-1562
[b]Space Telescope Science Institute, 3700 San Martin Dr., Baltimore, MD 21218
[c]Dept. of Astronomy, Univ. California/Berkeley, 601 Campbell Hall, Berkeley, CA, 94720-3411
[d]Johns Hopkins University, Dept. Physics & Astronomy, Baltimore, MD 21218
[e]Lab. for Astronomy & Solar Physics, Code681, Goddard Space Flight Ctr, Greenbelt MD 20771
[f]Infrared Processing & Analysis Center, M/S 100-22, Caltech, Pasadena, CA 91125
[g]Division of Physics, Caltech, Pasadena, CA 91125

ABSTRACT

The NIRSPEC Brown Dwarf Spectroscopic Survey is a project to obtain a consistent set of high-quality near-infrared spectra for each spectral class and sub-class of low-mass and/or sub-stellar objects to provide a new data base for models of the atmospheres of brown dwarfs and extra-solar giant planets. Most of the current targets are L-dwarfs and T-dwarfs discovered by the 2MASS. The survey is being performed with the recently-commissioned near-infrared spectrometer, NIRSPEC, a 1 - 5 μm cryogenic spectrograph at the W. M. Keck Observatory on Mauna Kea, using resolving powers of R = 2,500 - 25,000. Preliminary results for four sources, three L-dwarfs and one T-dwarf, are presented here. Spectra from 1.13 - 2.33 μm at an average resolution of R = 2,500 illustrate the development of deep steam (H_2O) bands and the weakening of FeH through the L-sequence, and the emergence of methane bands in the T-dwarfs. Complex detail in the spectra are the result of blending of numerous unresolved molecular transitions.

Keywords: low-mass stars, brown dwarfs, infrared spectroscopy, NIRSPEC, Keck telescope

1. INTRODUCTION

After many years of eluding detection, numerous sub-stellar objects–Brown Dwarfs–are now known. Some candidates were discovered in small-scale surveys of young nearby clusters such as the Pleiades and Hyades (see Martín[1] *et al.* for an excellent chronology), but the biggest breakthrough in the detection of this class of object has come as a result of large-scale surveys such as the DEep Near-Infrared Sky (DENIS) survey[2], the 2-Micron All-Sky Survey (2MASS)[3] and the Sloan Digital Sky Survey (SDSS)[4]. Over 100 free-floating very low-mass objects are now known, and the first new spectral class in almost a century has been added to the familiar O, B, A, F, G, K, M sequence. This is the L-class[5,6] for objects cooler than 2200 K. In addition, the first brown dwarf binary systems have been discovered[7]. Many of these objects are extremely faint at normal optical wavelengths where spectral classification is done. For example, GD165B (L4) has I>19 but K≈14. This is a significant gain.

Spectroscopy in the infrared is important in understanding the atmospheres of very low-mass stars, brown dwarfs and extra-solar giant planets because the low temperatures lead to the formation of numerous molecules with transitions at infrared wavelengths. Due largely to the detector technology available, earlier infrared spectroscopy of brown dwarf candidates and very low-mass stars was carried out using spectrographs with lower resolving powers of about $R = \lambda/\Delta\lambda \approx 800$. See, for example, the important work of Ruiz, Leggett and Allard[8], Tinney, Delfosse and Forveille[9], and Geballe *et al.*[10]. With the availability of larger format, low noise infrared arrays however, higher resolution spectroscopy is now possible. In this paper we present new results from NIRSPEC, the first high-resolution cryogenic 1-5 micron spectrograph for the Keck II 10-meter telescope using the ALADDIN

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1024 x 1024 InSb array. This work is part of an on-going survey called the NIRSPEC Brown Dwarf Spectroscopic Survey (BDSS) whose goals are (i) to obtain a consistent set of infrared spectra with R > 2,500 for a large sample of very low mass stars and brown dwarfs for classification; (ii) to obtain a set of very high-resolution spectra for detailed comparison with model atmospheres; (iii) to monitor the spectra of selected sources for Doppler shifts due to unresolved binary systems with the ultimate aim of obtaining mass estimates.

The L spectral class is new and the temperature range is still being debated. Kirkpatrick et al.[6] suggest a range from 2000 K for L0 to about 1250 K for L8, whereas Martín *et al.*[5] suggest a range from 2200 - 1600 K; divergence is mainly among the latest spectral classes and the difference is about 0.5 class. In any case, the spectral characteristics of all these stars are significantly different from late M-dwarfs. Titanium oxide (TiO) and vanadium oxide (VO) bands lose their prominence and give way to iron hydride (FeH) and chromium hydride (CrH). Deep steam (H_2O) bands appear and develop as the temperature falls, and eventually, methane (CH_4) is observed in the coolest objects which are tentatively being called T-dwarfs. Interestingly, the alkali metals (Na, K, Rb and Cs) become very prominent, and the pressure-broadened wings of these lines are a major opacity source. An excellent review of model atmospheres in low-mass stars and brown dwarfs is given by Allard et al.[11].

2. OBSERVATIONS

Table 1 lists the objects discussed in this paper and provides a summary of their photometric properties. The spectral class designations are those of Kirkpatrick et al. 1999[6]. One of the sources is a discovery of the DENIS project and the other three are from 2MASS. Near infrared spectra were obtained in 1999 June - August during the commissioning of NIRSPEC on the Keck II 10-meter telescope on Mauna Kea, Hawaii. NIRSPEC was designed and built at the Univ. of California/Los Angeles by a team led by Ian McLean. A detailed description of NIRSPEC is given elsewhere[12,13]. Briefly, the instrument is a cross-dispersed echelle spectrometer for R ≥ 25,000. There is an option to replace the echelle grating by a plane mirror and use only the cross-dispersion grating to obtain a lower-resolution mode. The detector is a 1024 x 1024 InSb array. For the present study, we used the lowest resolution mode of NIRSPEC to obtain a broad wavelength span in the minimum number of grating settings and the shortest time. The total wavelength region covered is 1.10 - 2.35 μm and the average spectral resolution is R=2,500 (5 Å at 1.25μ m) for a slit width of 0.38" (2 pixels). Four separate grating settings were required to cover this wavelength range. Seeing conditions generally gave full-width half maximum values of 0.5" or better.

For each object, a *pair* of integrations of either 300 s or 600 s was taken at two positions along the 42" long-slit separated by about 20". NIRSPEC's infrared slit-viewing camera was used frequently during the spectroscopic exposures to check centering on the slit. Difference images were used at the telescope to eliminate sky background to first order and provide a check on the quality of the spectra. Stars of spectral type A0 V - A2 V were observed at the same airmass to calibrate for absorption due to the Earth's atmosphere and neon and argon arc lamp spectra, together with the spectrum of a flat field lamp, were obtained immediately after the observation of each source.

Table 1. Summary of the photometric properties of the objects observed

OBJECT	SP. TYPE[a]	J	H	K
2MASSW J1507-1627	L5	12.82	11.89	11.30
DENIS-P J0205.4-1159	L7	14.55	13.59	12.99
2MASSW J1523+3014	L8/9	16.32	15.00	14.24
2MASSW J2356-1553	T	15.80	15.64	>15.83?

[a]The spectral type is that of Kirkpatrick et al. 1999[6]

Since the low-resolution spectra are slightly curved and distorted by the three-mirror anastigmat (TMA) camera optics, reduction of the NIRSPEC data proceeded as follows. First, a spatial map was formed using the sum of the standard star spectra on the assumption that the pair of spectra must be exactly a fixed number of pixels apart. Using the arc lamp spectra, the next step was to make a spectral map to warp the raw data onto a uniform grid of wavelength and position along the slit. In general, a second-order polynomial fit was sufficient. The atmospheric A-type standard star was then 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 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 (or "cal") star.

The same steps were then applied to the raw data frames of the target stars at the two slit positions. After flat-field correction and rectification, the low resolution spectrum of the brown dwarf was extracted and divided by the calibration/ standard star. Finally, the two object spectra are shifted, co-added and extracted to give the resultant calibrated spectrum. Hydrogen absorption lines were removed by interpolation from the spectra of the A-stars before division into the object spectra.

The final spectra were flux calibrated using the measured JHK magnitudes by integrating the spectra over NIRSPEC's slit-viewing camera's known cold filter bandpasses. This calibration is provisional because the filter bandpasses are only approximations to the JHK bands and accurate transformations have not yet been derived; the uncertainty may be as much as 15-20%. After flux calibration, the four spectral segments were matched in intensity and wavelength using their region of overlap. The resulting spectra are shown in Figures 1 - 4. The signal-to-noise ratio in these spectra is quite (> 30), high based on counting statistics, and much of the apparent structure in the spectra is real.

3. RESULTS AND ANALYSIS

In general, as shown in Figs. 1 - 4 , the spectra of the three L-dwarfs are characterized by deep steam (H_2O) bands, whereas the T-dwarf shows significant absorption due to methane (CH_4), which significantly modifies the flux in the H and K bands. Numerous unresolved features and blends of molecular transitions result in the very "structured" appearance of the spectra. The strongest resolved spectral features are the pair of neutral potassium (K I) lines at 1.1690, 1.1770 μm and 1.2432, 1.2522 μm respectively. These lines persist into the T-dwarf temperature range, becoming weaker but much broader. Strong bands due to FeH are seen at 1.194, 1.21 and 1.237 μm which weaken from L5 to L7 and then disappear at lower temperatures. The J-band part of the spectrum has been discussed in more detail recently by McLean *et al.*[14] for a wider range of L-dwarf types.

At the longer wavelengths, the CO band head at 2.29 μm is easily detected in all three L-dwarfs, but there is also a slight change of shape to the continuum beyond 2.2 μm in the coolest L-dwarf, 2MASSW J1523, compared to earlier types. We speculate that this continuum shape may be due to the effects of collisionally-induced absorption (CIA) in molecular hydrogen.

Most of the spectral features evident in these cool objects can be understood from consideration of molecular equilibrium calculations such as those of Burrows and Sharp[15]. Below 2400 K, the main absorbers characteristic of M stars (*e.g.* TiO and VO) decline rapidly in importance with decreasing temperature due to the formation of dust grains; the role of condensates is reviewed by Marley[16]. TiO forms perovskite ($CaTiO_3$) around 2400 K. At about 2200 K iron is expected to condense out into droplets which can "rain" out of the atmosphere. Gas phase FeH dominates until it too disappears in the mid-L range. Less refractory elements such as the neutral alkali metals (Na, K, Rb, and Cs) are expected to remain after the true metals are depleted. The column density of potassium and sodium is expected to increase to the point where the lines show significant pressure broadening, as observed in our data. Potassium and sodium should become depleted (into KCl and NaCl) around 1200 K, but settling of refractory species allows them to persist down to T-dwarf temperatures, at which point they should form their sulfides.

Steam is a significant source of opacity in all of these sources. Extending outwards from the deep troughs due to H_2O absorption, the infrared spectra of L- and T-dwarfs show numerous narrow features which have the appearance of noise, but which show consistent, repeatable patterns from object to object. These are essentially all real features resulting from the blending of numerous unresolved molecular transitions. Similarly, the impact of methane absorption in the T-dwarf results in numerous blended features. The coolest 2MASS L-dwarf (2MASS J1523) shows no evidence of methane, at least at these wavelengths. Some features of the NIRSPEC observations are not in the current models. For example, there is a broad absorption at 1.22 μm which has a similar temperature dependence to FeH but which is absent from the FeH opacity tables (Burrows 1999, private communication).

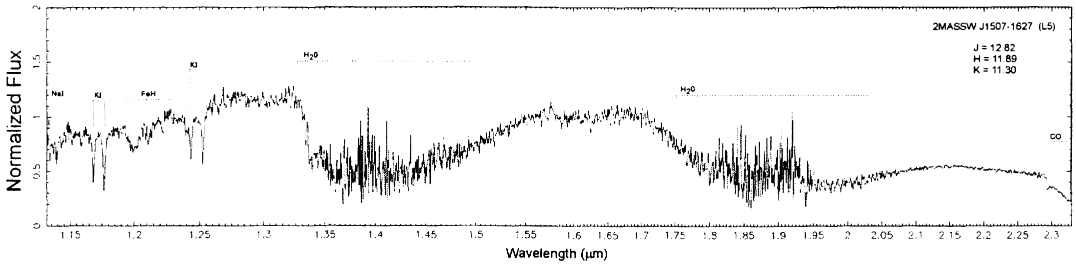

Figure 1. The spectrum of 2MASSW J1507 normalized to its H-band flux of 1.3 x 10^{-18} Wcm^{-2} μm^{-1}. Flux calibration is provisional and subject to revision. Four grating settings were used to provide wavelength overlap. Spectral resolution varies from ~4.5 Å at 1.245 µm to 8.4 Å at 2.115 µm. Major spectral features are indicated. The noisy regions at 1.4 and 1.85 µm are due to poor atmospheric transmission. Other small-scale structure is real. The total exposure time was 40 minutes. The spectral class is that of Kirkpatrick et al.[6] (see text for discussion).

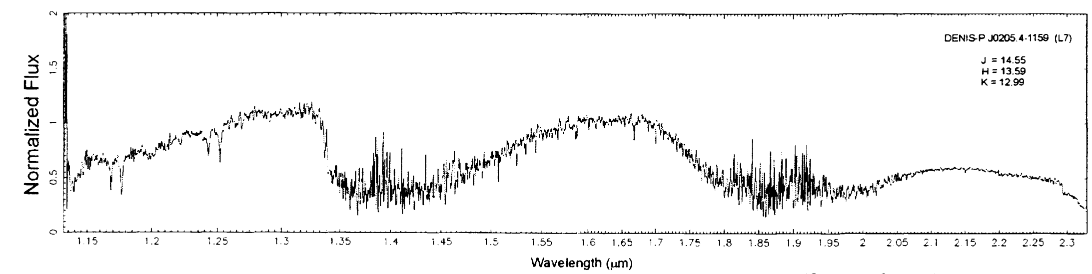

Figure 2. The spectrum of DENIS-P J0205 normalized to its H-band flux of 2.8 x 10^{-19} Wcm^{-2} μm^{-1}. As indicated for Fig. 1, the flux calibration is provisional, but other details are the same. Note that the FeH absorption band at 1.2 µm is much weaker and that the steam band at 1.4 µm is deeper. The total exposure time was 40 minutes.

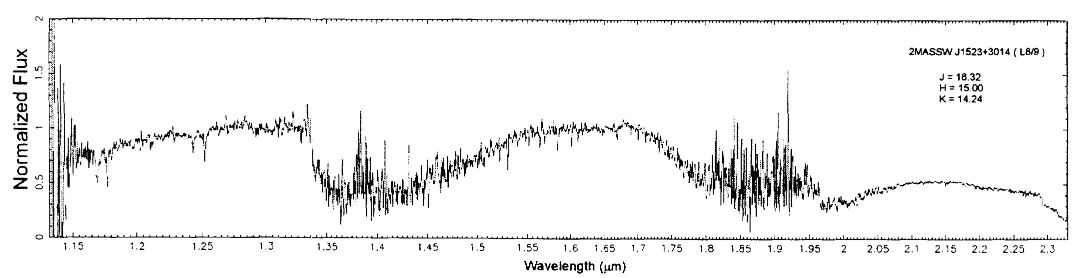

Figure 3. The spectrum of 2MASSW J1523 normalized to its H-band flux of 7.6 x 10^{-20} Wcm^{-2} μm^{-1}. Flux calibration is provisional, and other details are the same as Fig.1. Note that the FeH absorption at 1.2 µm has disappeared, the K I lines are weaker and broader, and the CO band at 2.295 µm is less deep. The total exposure time was 80 minutes.

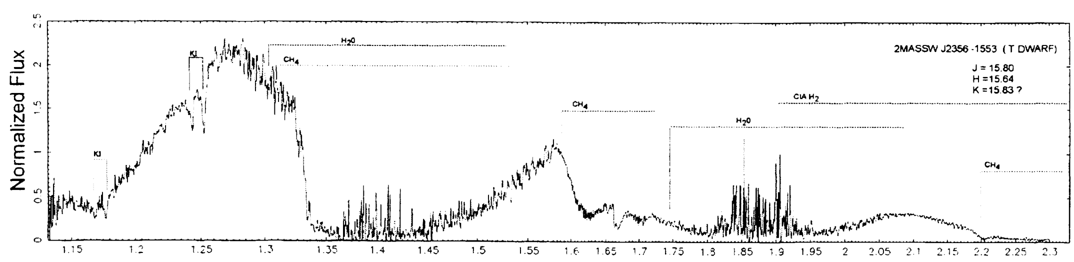

Figure 4. The spectrum of 2MASSW J2356 normalized to its H-band flux of 5.2 x 10^{-20} Wcm^{-2} μm^{-1}. As for Fig. 1, the flux calibration is provisional. Note the dramatic change in the spectral appearance compared to the L-dwarfs caused by the onset of methane (CH_4) absorption. Neutral potassium is still observable. Again, small-scale structure is real and due to blended molecular transitions. The total observing time was 80 minutes.

4. CONCLUSIONS

We have presented the first consistent set of near-infrared spectra, with a resolving power of R ≈ 2,500, for a sample of objects cooler than 2000 K. These data are part of a larger on-going spectroscopic survey. Spectra from 1.13 - 2.33 μm are shown for three L-dwarfs and one T-dwarf. This spectral region is rich in features which, with the exception of strong alkali metal lines, appear to be mainly unresolved blends of molecular species (including H_2O, FeH and CH_4). Higher spectral resolution is required and such measurements are now feasible. The observational data presented here illustrate that the NIRSPEC spectrograph on Keck II is a powerful instrument for the detailed spectral study of such optically-faint, extremely red objects, since the entire set of observations represents only about 4 hours of on-source integration time.

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