K-BAND SPECTRA AND NARROWBAND PHOTOMETRY OF DENIS FIELD BROWN DWARFS

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ABSTRACT

Infrared spectra at 1.9–2.5 \( \mu \)m and narrowband photometry of three low-mass objects, DENIS-P J0205.4–1159, J1058.7–1548, and J1228.2–1547, are presented. As shown previously by Delfosse et al., DENIS-P J0205.4–1159 shows an absorption feature at 2.2 \( \mu \)m. We attribute this absorption to H\(_2\). A simple two-parameter analysis of the K-band spectrum of low-mass objects is presented in which the relative strength of the H\(_2\)O and H\(_2\) absorption bands is found to be correlated with the effective temperature of the objects. The analysis confirms that DENIS-P J0205.4–1159 is the lowest temperature object of the three. We present narrowband photometry of these objects that provides the continuum flux level in between the deep H\(_2\)O absorption bands. These data show the continuum level accurately for the first time, and they will provide tight constraints for spectral models of these interesting objects.

Key words: stars: low-mass, brown dwarfs

1. INTRODUCTION

The discovery of brown dwarfs in the field by infrared surveys as well as by a proper-motion survey has demonstrated both the existence and the abundance of such objects. Three brown dwarf candidates, DENIS-P J0205.4–1159, J1058.7–1548, and J1228.2–1547, were reported by Delfosse et al. (1997). For simplicity we refer to these objects as D02–11, D10–15, and D12–15. The detection of lithium in D12–15 suggests that it is a brown dwarf (Martin et al. 1997; Tinney, Delfosse, & Forveille 1997); however, D10–15 did not show any lithium in its spectrum. There were no observations searching for lithium in D02–11 reported at the time this paper was written, although the spectrum of D02–11 shows that it is the coolest object of the three, and therefore it most likely is a brown dwarf (Delfosse et al. 1997; Tinney et al. 1997). Another field brown dwarf, Kelu-1, was discovered in a proper-motion survey (Ruiz, Leggett, & Allard 1997). The presence of lithium in this object, its estimated effective temperature, and its absolute magnitude all indicate that it is a brown dwarf.

In this paper, we report on new K-band spectra of D02–11, D10–15, and D12–15, as well as narrowband photometry at 1.28–3.8 \( \mu \)m.

2. OBSERVATIONS

Spectra at 1.9–2.5 \( \mu \)m were obtained with the CGS-4 infrared spectrograph at the UKIRT on 1997 December 23–24. The 40 line mm\(^{-1}\) grating used provides a spectral resolution of 900 at 2.2 \( \mu \)m with a 0.6 slit. For the removal of the telluric absorption lines, we observed the bright stars HR 692 (F0 V), HR 831 (F6 III–IV), and HR 1978 (F0 III). The spectra were obtained by oversampling by a factor of 3. This was achieved by moving the detector array one-third of a resolution element between exposures. During the observations, every fourth column of the array was unusable owing to an electronic problem. We were able to recover the spectrum because each resolution element was sampled with three grating positions. However, a ripple that was caused by the rejection of every fourth column remained in the spectrum. This ripple was eliminated by applying a Fourier transform to the spectrum, removing the frequencies corresponding to the ripple, and then applying the inverse Fourier transform. The ripple was not evident after this processing, and the division by a standard star spectrum showed no artifacts from the bad columns of the array. At the final stage of reduction, the spectra were smoothed with a 3 pixel boxcar function that matched the spectral resolution of the spectrograph. The spectra are shown in Figure 1.

Narrowband filter photometry at 1.28, 1.68, and 2.18 \( \mu \)m and at \( L’ \) (3.76 \( \mu \)m) were obtained with the NSFCam infrared camera at the IRTF on 1997 December 28–29 UT. The observations at 1.28 \( \mu \)m were obtained with a narrowband 1% filter and at 1.68 and 2.18 \( \mu \)m using a 1% circular variable filter. Photometric standard stars HD 106965 and HD 18881 were used (Elias et al. 1982). The results are summarized in Table 1. The uncertainty in the observations is about 2%.

For D10–15 and D12–15, the flux density was consistent with that determined from the spectral standard (HR 1978) and by using a \( V–K \) color appropriate for the spectral type of the standard. For D02–11, there was a 22% discrepancy between the narrowband photometry and the spectral standard star. This discrepancy may have arisen from the \( K \) magnitude uncertainty of the spectral standard stars (HR 692 and HR 831) or from loss of light at the slit. Therefore, we renormalized the spec-
Delfosse et al. (1997) suggest that the order of warmer to cooler is this order in Figure 1. Strong absorption at 2.0 \( \mu m \) and CO absorption at 2.3 \( \mu m \) are evident. The overall spectral shapes of D10 and D02 are different:

1. There is a steeper rise of the spectrum from 2.0 to 2.1 \( \mu m \).
2. There is a “dip” at 2.1–2.3 \( \mu m \) compared with D10 – 15 and D12 – 15 (more easily seen in Fig. 2). The dip is also seen in the spectrum of D02 – 11 presented by Delfosse et al. (1997).

Closer inspection of the spectra shows additional spectral differences:

1. There is an absorption feature at 2.01 \( \mu m \) in D02 – 11 that is not seen in D10 – 15 and D12 – 15.
2. There is a difference in the slope of the spectrum at 1.95–2.0 \( \mu m \). D02 – 11 is flat, but D10 – 15 and D12 – 15 are both rising toward shorter wavelengths. This appears to be a result of deeper H\(_2\)O absorption in D02 – 11.
3. There is a marginally significant absorption feature at 2.200 ± 0.002 \( \mu m \) in the spectrum of D02 – 11 that is slightly offset from the Na I doublet at 2.206 and 2.209 \( \mu m \). This absorption feature was also observed by Delfosse et al. (1997). A detailed spectral model is needed to confirm the identity of this absorption feature. There are no atomic lines listed by Jones et al. (1994) that are clearly seen in our spectra.
4. There are perhaps many weak absorption features throughout the spectrum. The reality of these features requires both modeling and additional spectra for confirmation. We cannot rely on standard signal-to-noise ratio arguments in assessing the reality of these weak features because of the detector array problem mentioned in § 2.

### Table 1

| Object   | [1.28]  | [1.68]  | [2.18]  | [L']   |
|----------|---------|---------|---------|--------|
| D02 – 11 | 14.22   | 13.36   | 12.88   | 12.05  |
| D10 – 15 | 13.88   | 13.08   | 12.47   | 12.00  |
| D12 – 15 | 14.01   | 13.16   | 12.60   | 11.76  |

### Figure 1

Spectra of the DENIS objects in order of warmer to colder. For clarity, the spectrum of D12 – 15 was multiplied by 2.0 and that of D10 – 15 was multiplied by 4.0. The possible Na I absorption feature is marked.

### Figure 2

Comparison of D02 – 11 to Kelu-1 and GD 165B. Note the similarity of Kelu-1 (Ruiz et al. 1997) and GD 165B (Jones et al. 1994). Also, there is a pronounced dip in the spectrum of D02 – 11 at 2.15–2.30 \( \mu m \) compared to the other two objects. The spectra were normalized at 2.07 \( \mu m \).

### Figure 3

Comparison of D02 – 11 to D10 – 15 and GL 229B. The spectra shown in Figure 3 seem to imply a progression of deeper H\(_2\) and CH\(_4\) absorption, with the spectrum of D02 – 11 being intermediate between that of D10 – 15 and GL 229B. This suggests that the effective temperature of D02 – 11 is less than D10 – 15, a result consistent with that of Tinney et al. (1997). We note that the 1.9–2.5 \( \mu m \) spectrum of D10 – 15 is very similar to that of VB 10, an M8 V spectral type star, at 1.9–2.5 \( \mu m \). However, these objects are known to have significant spectral differ-
ences at 0.65–0.90 \( \mu \text{m} \) (Tinney et al. 1997). Therefore, the 1.9–2.5 \( \mu \text{m} \) spectrum alone is not sufficient to classify objects precisely. Nonetheless, we show in the next section that the 1.9–2.5 \( \mu \text{m} \) spectrum may be sufficient to enable a rough classification of objects and to identify brown dwarfs.

Compared to the other objects, the spectrum D02–11 exhibits a broad and shallow dip at 2.2 \( \mu \text{m} \) (see the comparison in Fig. 3). We believe this broad absorption is caused by \( \text{H}_2 \) absorption based on a comparison of our spectra to atmospheric models of low-mass objects calculated by T. Tsuji (1998, private communication). These models show that \( \text{H}_2 \) is the major absorber in this spectral region and that \( \text{CH}_4 \) is a minor absorber for an effective temperature of about 1800 K. This is consistent with Ruiz et al. (1997), who indicate that \( \text{H}_2 \) is the main cause of the absorption at 2.2 \( \mu \text{m} \) in the brown dwarf Kelu-1 (see their Fig. 3). Additional modeling is needed to determine the best fitting parameters for D02–11, but this is beyond the scope of this paper. Note that Delfosse et al. (1997) attribute the dip at 2.2 \( \mu \text{m} \) to \( \text{CH}_4 \), and as a result they estimate the effective temperature to be about 1500 K. However, no support for this interpretation was presented, and we assume our effective temperature estimate in this paper.

3.1.2. Classification by Means of a “Slope” Analysis

The comparison of D02–11 to various objects leads to the question of whether a crude type of classification of objects might be possible using the shape of the spectrum. We define two parameters as follows:

\[
K_1 = \frac{\langle F_{2.10-2.18} \rangle - \langle F_{1.96-2.04} \rangle}{0.5(\langle F_{2.10-2.18} \rangle + \langle F_{1.96-2.04} \rangle)}
\]

\[
K_2 = \frac{\langle F_{2.20-2.28} \rangle - \langle F_{2.10-2.18} \rangle}{0.5(\langle F_{2.20-2.28} \rangle + \langle F_{2.10-2.18} \rangle)}
\]

where \( \langle F_{w1-w2} \rangle \) is the average flux density in the wavelength range \( w1 \) to \( w2 \). The label “\( K \)” is used because the spectra used are in the photometric \( K \)-band.

These definitions are similar to those of Steele et al. (1998) for the 2.1 \( \mu \text{m} \) slope with the exception that we base our definition based on \( F_k \) versus wavelength in microns instead of \( F_v \) versus wavelength. We also define the denominator to be the average instead of the sum.

\( K_1 \) measures the rise of the spectrum from 2.0 to 2.14 \( \mu \text{m} \), and this is primarily affected by the amount of \( \text{H}_2\text{O} \) absorption. \( K_2 \) measures the amount of absorption between 2.14 and 2.24 \( \mu \text{m} \) that is caused by \( \text{H}_2 \). For extremely low effective temperature objects, \( K_2 \) will be sensitive to the amount of \( \text{CH}_4 \) as well. In D02–11, D10–15, and D12–15, the \( K_2 \) index is influenced primarily by the amount of \( \text{H}_2 \) absorption, while in an extremely cool object such as GL 229B, it is affected primarily by \( \text{CH}_4 \). This results from the overlapping absorption of \( \text{H}_2 \) and \( \text{CH}_4 \) absorption bands at about 2.2 \( \mu \text{m} \). As a result, there should be a gradual transition in the index as one goes from objects with an effective temperature of about 1800 K to cooler temperatures. Therefore the \( K_1-K_2 \) plot should be a good indicator of the temperature of the object.

Values of \( K_1 \) and \( K_2 \) for various low-mass objects are shown in Table 2 and in Figure 4. We can see that cooler objects tend to be located toward the lower right-hand part of Figure 4. Kelu-1 and D12–15 have strong Li absorption at 670.8 nm and are therefore considered to be confirmed brown dwarfs. D02–11 and GD 165B are considered to be likely brown dwarfs and are located at \( K1 \geq 0.11 \). The status of D10–15, whether a brown dwarf or not is unclear.

Several trends can be noted in Table 2 and Figure 4. First, from warmest to coolest, the DENIS objects have been previously ranked as D10–15, D12–15, and D02–11 by Tinney et al. (1997). This is consistent with the trend seen in the \( K \) index plot where these objects progress to larger \( K1 \) index and smaller \( K2 \) index with lower effective temperature (see Fig. 4). This is easily seen as the result of deeper \( \text{H}_2\text{O} \) and \( \text{H}_2 \) absorption with lower effective temperature. Second, GL 229B is characterized by an extremely negative \( K2 \) index but with a \( K1 \) index that is typical of much warmer objects. We therefore expect that the \( K2 \) index to be more important in distinguishing objects cooler than D02–11.

With more objects, it may be possible to establish a relationship between the effective temperature of the object and the position on the \( K1-K2 \) plot. At the present time the effective temperatures for D10–15, D12–15, and D02–11 imply that these values are based on conjecture rather than observations or atmospheric models. The solid circles indicate objects that have Li absorption.
TABLE 2
K INDEX FOR SELECTED LOW-MASS OBJECTS

| Object     | K1  | K2  | Teff (K) |
|------------|-----|-----|----------|
| GL 406     | 0.0257 | -0.0244 | 2580*    |
| LHS 2924   | 0.0880 | -0.0313 | 2080*    |
| VB 10      | 0.100 | -0.00957 | 2330*    |
| D10–15     | 0.226 | -0.0264 | 1800*    |
| BRI 0021–0214 | 0.225 | 0.0331 | 1980*    |
| D12–15     | 0.299 | -0.0694 | 1600*    |
| Kelu 1     | 0.255 | -0.00662 | 1900*    |
| GD 165B    | 0.309 | -0.00426 | 1860*    |
| GL 229B    | 0.320 | -1.172 | 1000*    |
| D02–11     | 0.384 | -0.153 | 1800*    |

* Jones, H. R. A., & Tsuji, T. 1997, ApJ, 480, L39

Effective temperature is estimated to be about 1800 K but not as cool as 1500 K. Note that atmospheric models of brown dwarfs have effective temperature uncertainties of 100–200 K (Ruz et al. 1997; Tsuji et al. 1996). It is also important to keep in mind that dust formation is an important factor in these atmospheric models (Jones & Tsuji 1997; Tsuji et al. 1996). This adds further complication in seeking a straightforward interpretation using the K index.

3.2. Photometry

Our narrowband photometry provides the more precise information on the continuum level of these objects compared to that presented by Delfosse et al. (1997). Compared to broadband photometry, the narrowband data are largely unaffected by the H₂O absorption because it is centered on the continuum and it is insensitive to color transformation uncertainties that exist in broadband photometric observations.

Figure 5 shows the photometry and a comparison to blackbody curves and to broadband photometry. Because of the strong H₂O absorption bands, the broadband magnitudes are 0.1–0.4 mag lower than the narrowband magnitudes. Although a single color temperature can fit the 1–3.8 μm photometry, there is little physical significance to the color temperature because these objects do not radiate like blackbodies. Models by Tsuji et al. (1996) show the extremely nonblackbody emission of low-temperature objects. In addition one can see in Figure 5 that a single blackbody fails to match the 0.79 μm point.

4. CONCLUSIONS

From our 1.9–2.5 μm spectra and narrowband photometry, we conclude the following:

1. A simple two-parameter spectral slope analysis shows promise as a means of estimating the effective temperature of low-mass objects (see Fig. 4). Brown dwarfs are likely to have K1 ≥ 0.25.

2. D02–11 is the coolest of the objects reported by Delfosse et al. (1977), and its spectral shape appears to be intermediate between that of D10–15 and GL 229B.

3. We present accurate narrowband photometry in the continuum for the first time. This will provide better constraints on models of very low mass objects, especially in providing an estimate of the effective temperature.

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