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Optical spectroscopy of DENIS mini-survey brown dwarf candidates*

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Abstract. We present optical (6500-9200Å) spectroscopy of eight cool dwarfs detected in a 231 square degree "Mini-survey" of the Deep NEar Infrared Survey (DENIS) data. We are able to confirm that the spectral types derived from the Mini-survey infrared spectroscopy are meaningful. We provide a spectral sequence which extends beyond the M-dwarf range and into the proposed "L" class of dwarfs. The dominant spectral features in the optical for these L-type dwarfs are resonance lines of Cs I and molecular band heads of CrH and FeH. The other dominant feature in these L-type spectra is a broad 600 Å absorption dip centered on 7700 Å, which we identify with extremely strong (equivalent width $\sim$ several hundred Å) absorption associated with the 7664,7698 Å resonance doublet of K I. We find that model atmospheres which include the effects of molecular condensation without dust opacity (to simulate rapid gravitational settling of dust grains) produce significantly better agreement with observed optical spectra for L-type dwarfs, than models including dust opacity. This suggests gravitational settling of dust grains plays an important role in L-dwarf photospheres. The extreme strength of the K I resonance doublet, and disappearance of TiO and VO, and the consequent dominance of CrH and FeH in L-dwarf spectra offer considerable prospects as sensitive effective temperature diagnostics, even at low spectral resolution.

Key words: stars: low-mass, brown dwarfs – stars: late-type

1. Introduction

The history of the study of very-low mass (VLM) stars and brown dwarfs has shown again and again that when new technologies are implemented, new objects with previously unseen properties are discovered. Examples include the use of wide-field photographic surveys and digital scanning machines to discover the first VLM stars (Luyten 1979; Reid & Gilmore 1981; Probst & Liebert 1983; Bessell 1991; Irwin et al. 1991); the use of infrared spectroscopy to discover the importance of H_2O absorption in VLM stars (Berriman & Reid 1987); and, the use of infrared imaging, adaptive optics and coronography to discover the proto-typical cold brown dwarf Gl 229B, which further confirmed the importance of CH_4 in cold brown dwarfs (Nakajima et al. 1995; Oppenheimer et al. 1995). The next major breakthrough will be the identification of significant numbers of brown dwarfs by the coming generation of infrared all-sky surveys – in particular DENIS (Epchtein 1997) and 2MASS (Skrutskie et al. 1997).

DENIS will be a complete near infrared survey of the southern sky (Epchtein et al. 1994; Epchtein 1997) in the I, J and K′ bands, to approximate 3-σ limits of I=18, J=16, and K=13.5. The products of this survey will be databases of calibrated images, extended sources, and small objects. The survey started in January 1996 and is expected to be completed within five years. We have carried out a "Mini-survey" with infrared spectroscopic follow up on the very low-mass (VLM) star and brown dwarf candidates contained in $\approx$1% of the DENIS survey data (Delfosse et al. 1998, 1997). The image data from the high latitude part ($|b_{II}| > 20$-30°) of 47 survey strips, were processed and used to identify a sample of objects for which infrared H- and K-band spectroscopy was carried out in order to estimate luminosities/temperatures. In this paper we present optical spectroscopy for a sample of cool dwarfs identified in a 231 square degree "Mini-survey" of the data from the DEep Near-Infrared Survey (DENIS), and discuss the significant features these spectra reveal.

2. Optical spectroscopy

Optical spectroscopy of a sample of the Mini-survey sources was obtained with the AAT on 1997 June 7-9 (UT), using the RGO Spectrograph with TEK 1K CCD#2. Observations were made using a 270R grating in blaze-to-camera mode with a 1.7″ slit, providing a resolution of 7 Å and a wavelength coverage of 6425–9800 Å. The observations of both our DENIS Mini-survey targets and several comparison VLM stars are summarised in Table 1. Total exposure times of more than 1800s, were obtained as multiple half-hour exposures. Finding charts for the DENIS objects can be found in Delfosse et al. (1998). The data

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* Based on observations made at the Anglo-Australian Telescope, Siding Spring.

were processed using standard techniques within the FIGARO data reduction package (Shortridge 1993). In particular the data were: bias subtracted; trimmed; flat fielded; straightened; sky-subtracted; cleaned of cosmic rays by hand; optimally extracted; and, flux calibrated using observations of HST standard stars (Turnshek et al. 1990). Photon counting errors were propagated through the reduction, so that as a last step, multiple exposures (after normalising to the same mean level in the wavelength range 8300-8400Å) were combined to produce a final weighted mean spectrum. Seeing ranged from $1''$ to $2''$ over the run.

2.1. The spectra

The resulting spectra are shown in Fig. 1. The spectra were not corrected for the effects of atmospheric absorption, so the locations of significant terrestrial absorption are also indicated. Also shown are the wavelengths of atomic and molecular absorption features commonly seen in very late M-dwarf spectra. These are discussed in more detail by Tinney & Reid (1998). Preliminary versions of the coolest of these spectra were presented by Tinney et al. (1997).

The spectra shown in Fig. 1 clearly fall into two categories: the lower 8 objects are very late M-dwarfs, with prominent TiO, VO, Na and K features; while the upper three objects are also low temperature objects, they show either weak, or totally absent, TiO and VO absorption. Infrared spectroscopy (Delfosse et al. 1998, 1997) indicates that they are all considerably lower in effective temperature than M-type dwarfs. The detection of Li in DENIS-P J1228-1547 (Tinney et al. 1997; Martín et al. 1997), indicates a mass of less than $0.065 M_{\odot}$, and definite brown dwarf status. The weakness of TiO and VO in their spectra is understood to be due to the condensation of dust in their photospheres. This has two main effects: (1) it creates a "greenhouse" effect which warms the upper photosphere, weakening the bands of H_2O, TiO and VO (Tsuji et al. 1996a; Jones & Tsuji 1997) ; and (2) below $T_{\rm eff} \sim 2600\,$K dust condensates – in particular perovskite ($CaTiO_3$) and solid VO, containing Ti and V – will begin to condense out of the photosphere, therefore depleting it of TiO and VO (Allard 1998; Allard et al. 1997; Sharp & Huebner 1990). This has led to the suggestion by Kirkpatrick (1998) that there is a clear need for a new spectral class for these objects. Although a definitive allocation has yet to be made, we adopt here the preliminary "L" designation for these very low temperature dwarfs.

We have therefore ordered the spectra in apparent order of decreasing temperature. In the case of the M-dwarfs this has been done by comparison with the spectra for BRI 0021 and VB 10 (the spectral types for which are due to Kirkpatrick et al. 1997b and Kirkpatrick et al. 1995 respectively) on the typing system of Kirkpatrick et al. (1991) and Kirkpatrick et al. (1995). Our estimated spectral types are shown in italics in Fig. 1. These are not based on the detailed least-squares fitting procedure adopted by Kirkpatrick et al. (1991), but by eyeball comparison of the reference spectra, in particular concentrating on the strength of the VO bands at 7445 and 7850 Å, and the TiO bands at 7050 and 7600 Å. A more quantitative typing was also attempted using the pseudo-continuum ratios of Martín et al. (1996) – in particular their "PC3" index, the values for which are shown in Table 2. This produced exactly the same ordering for the M-dwarfs as the eyeball comparison shown in Fig. 1. However, it produced sub-types for VB10 and BRI 0021-0214 at variance with their standard values by ≈ 0.5 sub-types, and systematically high. Given this we have chosen to only provide estimated spectral types to the nearest unitary sub-type in Fig. 1.

In the case of the L-dwarfs, the ordering has been performed based on the infrared spectroscopy of Delfosse et al. (1998). The absence of a well defined typing scheme for the L-dwarfs leads us to leave the subtypes as undetermined ("?" in the figure), though work on this front is in hand (Kirkpatrick et al. 1998b).

3. Discussion

3.1. The M-dwarf spectra

The latest DENIS M-dwarf (DENIS-P J0021, $\geq$M9V) shows an almost identical spectrum to the very late M-dwarf BRI 0021-0214, which itself shows one of the latest M spectra known for a field dwarf (only 2MASSP J0345 is known to have a later M-type spectrum; Kirkpatrick et al. 1997a). DENIS-P J2146 shows a slightly earlier spectral type of M9V. The remaining DENIS M-dwarfs all show types of M8V. GRH 2208 was discovered by Gilmore et al. (1985), who classified it as a possible VLM star. Its M8V spectral type and large proper motion (Tinney 1996) confirm this.

Of the M-dwarfs observed only a few show evidence for Hα emission: GRH 2208 has emission at an equivalent width of $\approx$5 Å, while VB10, DENIS-P J2052, DENIS-P J0020 and DENIS-P J0020 show evidence for emission at the $\sim$1 Å level.

3.2. The L-dwarf spectra

As discussed above, the most prominent feature of the L-dwarf spectra is weak, or non-existent, TiO and VO absorption. Also obvious is the strong resonance line of Cs I at 8521.4 Å (equivalent widths for which are provided in Table 1) and a pair of strong bandheads at 8610 and 8700 Å. These latter bandheads have recently been identified by Kirkpatrick et al. (1998a) as being due to CrH bandheads at 8611 Å and 8696 Å (Pearse & Gaydon 1976), and an FeH bandhead at 8692 Å (Phillips et al. 1987).

It is interesting to note, however, that once one has identified these bands in the spectra of L-dwarfs, it becomes obvious that they are also present (though somewhat masked by TiO and VO) in the spectra of the latest M-dwarfs. All of the dwarfs of M9V or later show the same CrH/FeH bandheads. It is also interesting to see that the ordering provided by the the infrared spectra for the L-dwarfs in combination with the M spectral types, shows a clear sequence of decreasing TiO and VO band strength with decreasing temperature. In particular, DENIS-P J1058 shows weaker TiO at 8400 and 7600 Å than BRI 0021, while DENIS-P J1228 shows only hints of TiO at 8400 Å and DENIS-P J0205 shows no evidence for TiO or VO at all.

Table 1. Optical spectroscopy.

Object	Position[a] (J2000.0)	Exp. (s)	I	I–J	EW(Å)[b] Cs I	C[c]	Ref[d]
DENIS-P J0020−4414	00:20:59.4 −44:14:43	3600	18.32±0.16	3.35±0.17	-	2.0	1
DENIS-P J0021−4244	00:21:05.7 −42:44:50	1800	16.83±0.05	3.30±0.05	0.9±0.3	3.5	1
DENIS-P J0205−1159	02:05:29.0 −11:59:25	5400	18.30±0.24	3.67±0.25	7.5±1.0	7.0	1
DENIS-P J1058−1548	10:58:46.5 −15:48:00	3600	17.80±0.17	3.72±0.17	2.6±0.5	5.0	1
DENIS-P J1228−1547	12:28:13.8 −15:47:11	1800	18.19±0.27	3.76±0.27	5.8±1.0	6.0	1
DENIS-P J2040−3245	20:40:06.2 −32:45:24	3600	17.86±0.16	2.97±0.17	-	1.0	1
DENIS-P J2052−5512	20:52:55.0 −55:12:03	3600	17.52±0.13	2.70±0.15	-	0.0	1
DENIS-P J2146−2153	21:46:10.6 −21:53:09	3600	18.40±0.27	2.98±0.29	-	3.0	1
BRI 0021-0214	00:24:24.6 −01:58:22	1800	15.07±0.03	3.17±0.05	-	4.0	2
VB 10/LHS 474	19:16:57.9 +05:09:10	600	12.80	2.90	-	1.5	3
GRH 2208	22:10:50.0 −19:52:13	1800	-	-	-	0.5	

Notes :

a - Positions for the DENIS objects are from Delfosse et al. 1998, those for the remainder are from Tinney et al. 1995 and Tinney 1996. The DENIS-P prefix indicates that these are provisional DENIS objects, which have not been produced by the final DENIS catalogue pipeline.

b - Psuedo-continuum defined by polynomial fit to the wavelength range 8430-8560Å. Blank entries imply unmeasurable equivalent widths $\lesssim 0.5$Å.

c - Constant offset applied to the spectrum in Fig. 1.

d - References for photometry: (1) Delfosse et al. 1998, (2) Tinney et al. 1993, (3) Leggett 1992.

If we assume that the temperature ordering we have adopted is reasonable, we can then see that the CrH/FeH bands appear *weaker* in the coolest object (DENIS-P J0205), than in the two earlier type L-dwarfs. This is not necessarily contrary to what one might expect. Molecular equilibrium calculations by Sharp & Huebner (1990), have shown that at plasma temperatures of ≈1420 K solid Fe will begin to condense, and similarly that at plasma temperatures of ≈1250 K Cr_2O_3 will begin to condense, depleting the photosphere of CrH. In other words, we can expect CrH and FeH to become prominent when TiO and VO are depleted by grain formation, but that they themselves will weaken at a somewhat lower effective temperature. Such an interpretation of the observed behavior of these bands is supported by the fact that *no* evidence for CrH or FeH is seen in the optical spectrum of the $T_{\rm eff} \approx 900$ K brown dwarf Gl 229B (Oppenheimer et al. 1998; Schultz et al. 1998), which shows only Cs I, H_2O and possibly CH_4 features in the optical.

This "on-again-off-again" behavior offers tantalising possibilities for future brown dwarf studies. The difficulty of making model atmospheres deal with the complex opacities needed to match observed VLM spectra has severely hampered progress in their understanding (Allard et al. 1997). In particular, it has proved difficult in the extreme to estimate precise and robust effective temperatures below ≈2500 K. However, the appearance and disappearance of bands like CrH over a fairly narrow range of temperatures offers the possibility of a temperature diagnostic which is both easily observed, and which should be accessible to photospheric models including the effects of dust condensation.

Care must be taken however to distinguish between the plasma temperature at which a species will condense, from a dwarf's overall effective temperature. For example, the atmospheric models discussed in Sect. 3.3, show that solid Fe will begin to condense in objects with $T_{\rm eff}$ considerably hotter than 1500 K. However, this does not affect the formation of FeH bands at $T_{\rm eff} = 1500$ K, because FeH opacities lead to band formation deep in the photosphere, where FeH does *not* condense at this effective temperature. Similar behaviour may occur for CrH. At present we can only point out that there does appear to be a considerable change in the observed CrH/FeH band strengths between $T_{\rm eff}$=2000 and 1000 K, and that these offer the prospect of a modellable and robust temperature sensitive indicator.

There is one further obvious feature in the L-dwarf spectra which has not been discussed. This is the pronounced broad dip seen in DENIS-P J1228 and DENIS-P J0205 centered on 7700 Å. Some evidence for this feature is also seen in DENIS-P J1058, though it is masked by the overlying stellar TiO and terrestrial O_3 absorption. Fig. 2a shows an expanded version of Fig. 1 in this wavelength range for the latest six dwarfs observed. We see a clear depression of the L-dwarf "continuum" in the neighbourhood of the K I lines near 7700 Å – in fact over the wavelength range 7600-7750 Å we detect essentially zero flux.

Martín et al. (1997) have discussed the core of this feature, but the limited spectral coverage of their high resolution echelle orders prevented them from appreciating its full extent. They suggested that it is due to an extreme broadening of the 7664,7698 Å K I doublet. At first glance, such an interpretation seems hard to believe, given the huge extent of the absorption seen in our L-dwarf spectra. It requires that the absorption line is not only extremely broad, but that it be totally saturated over a wavelength range of 150Å (or $\lambda/\Delta\lambda \approx 51$), with the line wings extending over almost 600 Å (or $\lambda/\Delta\lambda \approx 13$). The total equivalent width (EW) of such a line in the two latest L dwarfs

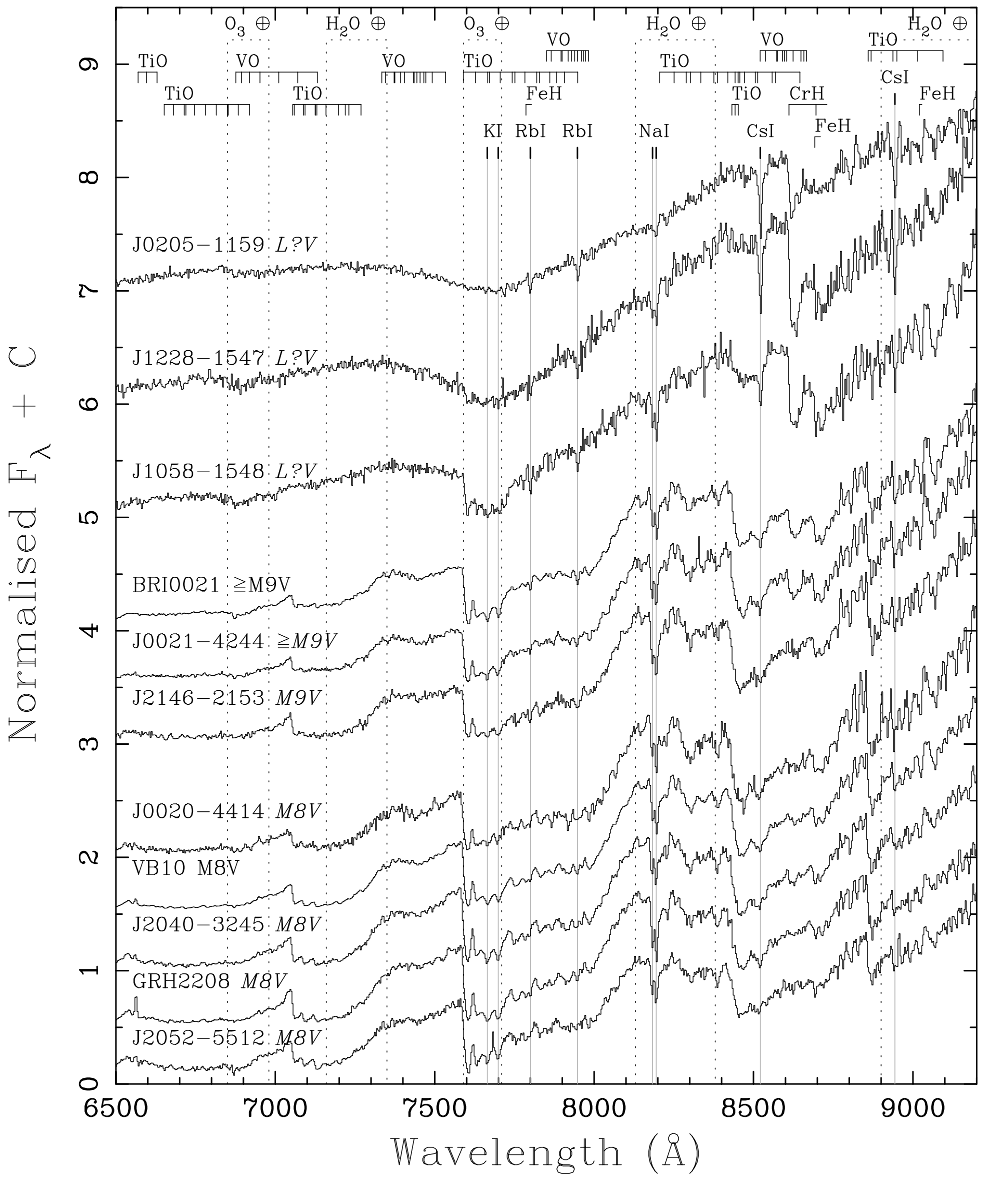

Fig. 1. Optical Spectra of DENIS Mini-survey sources. The spectra shown have been normalised in the range 8700-8800Å, and are offset by the constants (C) provided in Table 1. The spectral types provided and the absorption features marked are discussed in Sect. 2.1 of the text.

presented is ∼300 Å[1]. This is almost without precedent in stellar spectra, even for the extremely strong H or He lines seen in white dwarfs. Moreover, while the spectra of slightly earlier M-dwarfs show K I, these lines represent only EW ∼ 10-20 Å absorptions. If the 7700 Å dip is due to K I then it requires that the photosphere, for a change of only a few hundred degrees in effective temperature, produces a massive change in K I absorption equivalent width.

3.3. Model atmospheres including condensation

In order to investigate the nature of the 7700 Å dip, it is necessary to refer to detailed atmospheric models. The construction of model atmospheres which include the effects of dust on the equation of state and radiative transfer, is a field still in its infancy. We show in Fig. 2b preliminary "NextGen-AMES-Cond" or "NGAMES-Cond" models due to F.Allard and P.Hauschildt for a range of temperatures in the region of the K I line. These models were constructed using the full "Opacity Sampling" (OS) technique of the "NextGen" models of Allard et al. (1997) with the further addition of; the AMES H_2O opacities of Partridge & Schwenke (1997); and molecular condensation equilibria using the thermodynamic equlibrium constants of Sharp & Huebner (1990). They differ from the "NGAMES-Dusty" models of Allard & Hauschildt (Allard 1998; Allard et al. 1998; Kirkpatrick et al. 1998a) in that they do not include the effects of dust opacities on radiative transfer. The "NGAMES-Dusty" models have been used by Kirkpatrick et al. (1998a) to study the optical-infrared spectrum of GD 165B. They found that the inclusion of dust in the radiative transfer dramatically improved the agreement of the models to the observed infrared spectrum. However, they also found that dust opacity resulted in a significant over-prediction of TiO and VO band strengths in the optical,

[1] Measured relative to pseudo-continuum points at 7200 and 8200Å

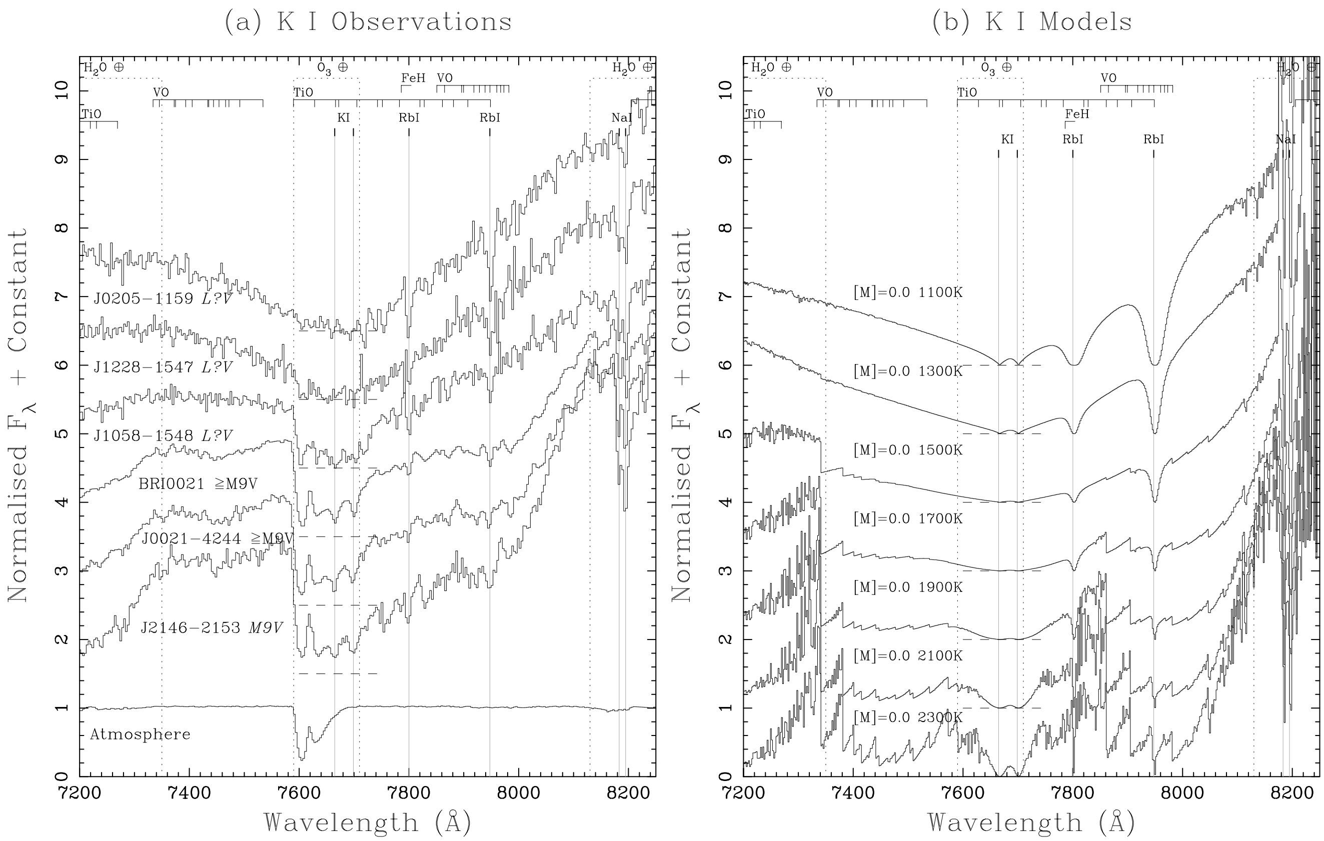

Fig. 2a and b. Region of the K I Doublet. **a** expanded versions of the data for the coolest objects in Fig. 1, in which the spectra have been normalised in the range 7275-7325Å, and offset. The zero-level for each spectrum is indicated by the dashed line between 7600 and 7750 Å. Also shown is a normalised standard star spectrum to indicate the location of terrestrial O_3 and H_2O absorption. **b** "NGAMES-Cond" atmospheric models for solar metallicities, log$g$=5.0 at the indicated temperatures.

Table 2. Comparison of optical and infrared spectral typing

Object	I–J	Infrared Spectrum M_K Estimate[a]	PC3[b]	Spectral Type[c]
DENIS-P J0205−1159	3.67±0.25	12.1±0.5	11.21	L?
DENIS-P J1228−1547	3.76±0.27	12.0±0.5	6.86	L?
DENIS-P J1058−1548	3.72±0.17	11.5±0.5	3.26	L?
DENIS-P J0021−4244	3.30±0.05	11.3±0.5	2.44	≥M9V
DENIS-P J2146−2153	2.98±0.29	11.4±0.6	2.39	M9V
DENIS-P J0020−4414	3.35±0.17	11.0±0.5	2.18	M8V
DENIS-P J2040−3245	2.97±0.17	11.1±0.5	1.66	M8V
DENIS-P J2052−5512	2.70±0.15	10.7±2.8	1.56	M8V

Notes :

a - Estimated absolute K magnitudes based on infrared spectral characteristics due to Delfosse et al. 1998.

b - PC3 index defined for spectral typing Martín et al. 1996. Although Martín et al. do not actually provide the flux scale used to define the index, we have used F_λ.

c - Spectral types from Fig. 1 derived as described in Sect. 2.1.

because of heating of the upper photosphere by the greenhouse effect, which among other things will reduce the rate of grain formation, and so of TiO and VO depletion. The over-prediction of these bands by the models is thought to take place because they do not take into account gravitational settling, which will actually deplete the upper photosphere of dust. As we are most interested in examining optical spectra, we have therefore used the "NGAMES-Cond" models to simulate the effects of gravitational settling, since they essentially make grains "disapear" after they have formed.

Kirkpatrick et al. (1998a) derived an effective temperature of 1900±100 K for GD 165B. Given the similarity of GD 165B's spectrum to the L-dwarfs shown in Fig. 2a (Tinney et al. 1997), we therefore assume that their effective temperatures lie somewhere in the range 2000-1600 K. The NGAMES-Cond models predict that at these effective temperatures, opacity due to TiO/VO does indeed decrease due to the combined effects of condensation and dust settling, and that the lines of the K I doublet become *very* strong. Fig. 2a and b also shows some disagreement between the models and the data – in particular, the models still seem to over-predict absorption due to TiO near 7200 Å and VO at 7340-7560 and 7870-7960 AA, as well as predicting larger equivalent widths for the resonance lines of Rb I than are observed. This is not surprising, given crude assumption of infinitely rapid settling for all grain species. The models also fail to predict features due to CrH, which is not included in the current opacity line list. It would clearly, therefore, be premature to draw detailed conclusions from these models. However, we can clearly see that they produce a much better match to observations than the "NGAMES-Dusty" models presented by Kirkpatrick et al. (1998a – Fig. 4), indicating that gravitational settling is clearly taking place in the upper photospheres of L-dwarfs. Moreover, they show that the effects of dust condensation do produce qualitatively the correct trend for decreasing molecular absorption, and that K I is responsible for the 7700 Å dip in the "molecule-poor" photospheres of L-dwarfs.

The reality of dust settling will clearly lie somewhere in between the rapid settling modelled by the NGAMES-Cond models, and the absence of settling indicated by the NGAMES-Dusty models. The infrared spectrum of Gl 229B shows both no evidence for dust in its infrared spectrum (Oppenheimer et al. 1998, Tsuji et al. 1996b), *and* evidence for dust in its optical spectrum (Schultz et al. 1998). Pavlenko et al. (1998) have produced models which can reproduce L-dwarf spectra, by including an *a postiori* power-law opacity component in the optical. However, such a model does not lead to any immediate physical understanding of the processes which produce such an opacity law. Clearly simple dust models cannot reproduce the complex behaviour seen in L-dwarfs. Real understanding will have to await the coming generation of atmospheric models which include the chemical equilibria of dust formation, an understanding of the grain size distribution, and the physics of gravitational settling.

The relative weakness of other neutral lines in our observed spectra, despite the strength of the K I doublet, is also reasonable. The lines of Na I at 8183 and 8194 Å are not resonance lines like the K I doublet – they would therefore be expected to be significantly weaker in a very cool, dense photosphere. The lines of Rb I at 7800 and 7947 Å and Cs I at 8521 and 8943 Å are resonance lines and have similar line strengths to the K I doublet (Corliss & Buzman 1962), *but* have abundances ~ 3500 and 7000 times (respectively) lower than K (Allen 1976). So again, it is reasonable to expect them to be significantly weaker than the K I doublet. The lines of the Na I doublet at 5890,5896 Å(which lie outside the wavelength coverage of our spectra), on the other hand *are* resonance transitions with similar line strengths to the K I doublet, and indeed the "NGAMES-Cond" models predict these lines to be even stronger than K I. The huge strength of these high abundance resonance lines offers exciting possibilities for the estimation of photospheric properties (in particular effective temperatures) with quite low resolution spectra, once the details of grain growth and settling are understood.

3.4. A comparison of infrared and optical spectral typing

In order to refine the sample produced by pure colour selection on the DENIS survey data, Delfosse et al. (1998) obtained infrared spectra for *all* the DENIS Mini-survey VLM and brown dwarf candidates. These were then used to define H_2O indices which were used to "type" spectra in the infrared. Rather than define infrared spectral types, however, Delfosse et al. made use of the fact that cooling brown dwarfs slide *along* an extension of the main sequence in the H-R diagram (see e.g. D'Antona & Mazzitelli 1985; Burrows, Hubbard & Lunine 1989; Burrows et al. 1997) to classify their spectra directly onto an M_K scale.

The results of this are shown in Table 2 for the Mini-survey dwarfs for which optical spectroscopy has been obtained, alongside the optical spectral types derived in Sect. 2.1. First we can see that the three latest/faintest objects are classified as such by both schemes, and second that the ordering of the spectra produced by both schemes is very similar. This similarity can also be seen in a comparison of the PC3 optical typing index of Martín et al. (1996), with the infrared spectral types.

We conclude that the procedures adopted by Delfosse et al. produce results which are believable and consistent with those produced by optical spectroscopy. At present optical spectroscopy for the complete Mini-survey sample is not available. However, the infrared spectra of Delfosse et al. would suggest that there are several more dwarfs as late, or later, than the latest M-dwarf presented here (DENIS-P J0021). In particular, the infrared spectrum of DENIS-P J1228-2415 suggests it may be an M-dwarf similar to the latest M-dwarf known 2MASSP J0345 (Kirkpatrick et al. 1997a).

4. Conclusion

We have shown that optical spectroscopy confirms the luminosity classifications derived from the infrared spectra of brown dwarf candidates by Delfosse et al. (1998). In particular we confirm the detection of at least two objects which are as late as the latest known field M-dwarfs. The coolest objects studied in this work show prominent features of Cs I, K I, CrH and FeH, and a sequence of decreasing strength in TiO and VO features with decreasing temperature. The coolest object in our sample also shows decreased strength in CrH. The "on-off" behaviour of CrH, which is driven by the equilibria of molecular condensation as effective temperature decreases, implies it may be useful as a temperature diagnostic which can be readily modelled. Lines of the K I doublet become *extremely* strong (∼300 Å equivalent width) in the coolest DENIS objects ($T_{eff} \lesssim 1800$K), and also offer the possibility of being powerful temperature diagnostics. And lastly, the improved match of models assuming rapid gravitational settling of dust grains, over models with no settling of dust grains, would seem to indicate that settling effects play a role in 2000-1000 K photospheres.

It is clear that an entirely new sequence of spectral sub-classes for the "L"-type dwarfs will be required. Assignment of specific sub-classes must await both improvements in atmospheric models to detail the effects of dust condensation and settling on radiative transfer and the equation of state, and an increase in the sample of L-dwarfs with optical spectra. The latter will be achieved by the 2MASS and DENIS surveys within the next two to three years, promising exciting developments in our understanding of the behaviour and properties of brown dwarfs.

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