Resolved Hubble Space spectroscopy of ultracool binary systems

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Abstract. Using the low-resolution mode of the Space Telescope Imaging Spectrograph (STIS) aboard the Hubble Space Telescope (HST), we have obtained spatially resolved spectra of 20 ultracool dwarfs. 18 of them belong to 9 known very low-mass binary systems with angular separations in the range 0′′.37-0′′.098. We have derived spectral types in the range dM7.5 to dL6 from the PC3 index, and by comparing our STIS spectra with ground-based spectra of similar spectral resolution from Martín et al. (1999). We have searched for Hα emission in each object but it was clearly detected in only 2 of them. We find that the distribution of Hα emission in our sample is statistically different from that of single field dwarfs, suggesting an intriguing anticorrelation between chromospheric activity and binarity for M7–M9.5 dwarfs. We provide measurements of the strength of the main photospheric features and the PC3 index, and we derive calibrations of spectral subclasses versus F814W and K-band absolute magnitudes for a subset of 10 dwarfs in 5 binaries that have known trigonometric parallaxes.

Key words. - stars: very low-mass, brown dwarfs

1. Introduction

Late-type nearby spatially resolved binaries (usually referred to as visual binaries) have been patiently followed up for many decades to obtain orbital parameters (e.g., van de Kamp 1938; Couteau 1957; Chang 1972; Abt & Levy 1973). The dynamical masses obtained from the studies of resolved binaries have been used to calibrate the mass-luminosity relationship for low-mass stars (e.g., Delfosse et al. 2000). A number of recent surveys have extended the search for resolved binaries to very low-mass (VLM) stars and brown dwarfs (BDs). Hubble Space Telescope imaging has been used to search for VLM binaries1 in young associations and open clusters (Martín et al. 2000b, 2003; Kraus et al. 2005) and in the solar neighborhood (Martín et al. 1998, 1999; Reid et al. 2001; Bouy et al. 2003; Burgasser et al. 2003; Gizis et al. 2003; Golimowski et al. 2004). Near infrared-imaging on large ground-based telescopes, usually assisted by adaptive optics, has also been effective in finding VLM binaries (e.g., Koerner et al. 1999; Martín et al. 2000a; Close et al. 2003; Potter et al. 2002; Siegler et al. 2005). These studies have determined that the binary frequency among field VLM stars and BDs in the separation range 1-15 AU is about 15%, and that there is a sharp drop in the binary frequency for separations larger than 15 AU. Nevertheless, a few examples of wider field ultracool binaries are known (Martín et al. 1998, 2000b; Billères et al. 2005; Phan Bao et al. 2005; Burgasser & McElwain 2006). On the other hand, it is not clear what the VLM binary frequency is within 1 AU because of the lack of long-term spectroscopic binary surveys for VLM stars and BDs. The statistical properties of VLM binaries will continue to be investigated because they provide a fundamental constraint for models of VLM star formation (Kroupa et al. 2003; Umbreit et al. 2005).

The increasing number of VLM binaries can be used for follow-up studies of their properties. Astrometric monitoring of three VLM binaries have yielded the first estimates of the orbital parameters and dynamical masses (Lane et al. 2001; Bouy et al. 2004; Brandner et al. 2004). Spatially-resolved low-resolution spectroscopic follow-up has been made in a few cases and spectral types have been obtained (Lane et al. 2001; Goto et al. 2002; Potter et al. 2002; Bouy et al. 2004; Chauvin et al. 2004; Luhman 2004, Koerner et al. 1999; Martín et al. 2000a; Close et al. 2003; Potter et al. 2002; Siegler et al. 2005). These studies have determined that the binary frequency among field VLM stars and BDs in the separation range 1-15 AU is about 15%, and that there is a sharp drop in the binary frequency for separations larger than 15 AU. Nevertheless, a few examples of wider field ultracool binaries are known (Martín et al. 1998, 2000b; Billères et al. 2005; Phan Bao et al. 2005; Burgasser & McElwain 2006). On the other hand, it is not clear what the VLM binary frequency is within 1 AU because of the lack of long-term spectroscopic binary surveys for VLM stars and BDs. The statistical properties of VLM binaries will continue to be investigated because they provide a fundamental constraint for models of VLM star formation (Kroupa et al. 2003; Umbreit et al. 2005).

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2. Observations and data processing

Our sample was selected from known VLM binaries with separations in the range 0′′098 and I-band magnitude brighter than I=19, so that resolved optical low-resolution spectroscopy of each component could be obtained with STIS. Table 1 provides the STIS observing log. The observations of 2MASSW J07464256+2000321 have already been presented in Bouy et al. (2004) but we also include them in our analysis for completeness.

Our goal was to obtain spatially resolved spectra of each component of the binary systems. However, scheduling constraints of HST made it impossible to perfectly align the slit along the axis of each binary. In one case, namely DENIS-P J144137.3-094559, we could not get any spectrum of the secondary because the slit was not oriented along the binary semimajor axis. Another case, namely 2MASSW J0920122+351742, turned out not to be resolved at the epoch of observations. It is possible that this object may not be a binary because it has been resolved in only one epoch (Bouy et al. 2006, in preparation). For the other binaries we obtained resolved 2-D spectra and performed the extraction of the two spectra as explained in detail in Bouy et al. (2004). An example of the de-blending of spectra in two of our binary systems (including one of the tightest) is shown in Figure 1. We used the bias, flat field and wavelength calibrations provided by the STIS pipeline.

The grating used was the G750L centered at 775.1 nm, and the aperture was 52′′0 long by 0′′2 wide. The total wavelength range of each spectrum is 525–1100 nm, but the usable range depends on the brightness and the spectral type of each object. Residual fringing is clearly present at wavelengths longer than about 900 nm. The nominal dispersion is 4.92 Å/pixel and according to the STIS handbook, our slit width is expected to project onto 4 pixels (FWHM = 20 Å). For comparison the resolution quoted by Kirkpatrick et al. (1999) was 9 Å, and the resolution of the spectra presented in Martín et al. (1999) (hereafter M99) was 12 Å. Thus, our STIS data have a resolution somewhat lower than those papers. In Figure 2 we display final spectra for three of our targets spanning the whole range of spectral subclasses in our sample.

3. Spectral classification

Our resolved STIS spectra of VLM binaries allowed us to determine the spectral type of each component. Only two of our program binaries have previous determinations of spectral type for each component: Lane et al. (2001) gave spectral types of M8.5 and M9 for GJ 569 Ba and Bb, respectively, using low-resolution near-infrared (J-band) spectra. Bouy et al. (2004) obtained spectral types of dL0 and dL1.5 for 2MASSW J0746425+200032 A and B, respectively, using the same STIS data as this work. They compared the STIS spectra with ground-based low-resolution spectra from M99.

In this work we have estimated the spectral subclasses using two methods: (a) we measured the PC3 index defined by M99 and used their PC3-spectral type relationship for M and L dwarfs, and (b) we compared our spectra with those of M99 and chose the best match. The spectral subclasses obtained from both approaches are given in Table 2. When the subclasses from the two methods agreed with 1 subclass, we computed the average and we rounded in steps of 0.5 subclass. When there was a disagreement, we favored the subclass derived from method (b). This happened only for the latest L dwarfs of our sample.

3.1. Description of the spectra of each binary

In this subsection the STIS spectra of each target are displayed and they are compared with the best matching M99 spectra:

- DENIS-P J020529.0-115925 A (dL5): The K i resonance doublet is slightly broader, and the CrH and FeH bands are weaker than in the M99 spectrum of DENIS-P J1228-2415 (Figure 3). The M99 spectrum of DENIS-P J0205-1159 is the best match to our STIS spectrum of DENIS-P J020529.0-115925 A, indicating, as expected, that the primary dominates the composite ground-based spectrum. We note that the PC3 index gives a slightly earlier subclass of dL4.1 than the spectrum matching technique.

- DENIS-P J020529.0-115925 B (dL6): The CrH and FeH bands have almost vanished. The M99 spectrum of DENIS-P J0255-4700 is the best match except for the steam band at 930 nm, which is stronger in the ground-based spectrum (Figure 3). This could be due to the contribution of telluric absorption in the M99 spectrum. We also note that the STIS spectra are noisy
in this region due to low quantum efficiency of the detector and the presence of a strong interference pattern at these red wavelengths. The PC3 index gives a spectral type 2 subclasses earlier than the spectrum match, suggesting that this index is not reliable for the latest L dwarfs.

- **DENIS-P J035726.9-441730 A (dM9):** As shown in Figure 4, the best match spectrum from M99 is that of DENIS-P J1441-1953 (dM9). In the ground-based spectrum the region from 740 nm to 770 nm is affected by telluric absorption. The PC3 index also gives a subclass of dM9 in perfect agreement with the spectrum match.

- **DENIS-P J035726.9-441730 B (dL1.5):** As shown in Figure 4, the best match spectrum from M99 is that of DENIS-P J1441-0945 (dL1). In the ground-based spectrum the region from 740 nm to 770 nm is affected by telluric absorption so it is not surprising the mismatch between the STIS data and the M99 data over this wavelength coverage. A similar discrepancy is seen in the spectra of all our late-M and early-L dwarfs. The PC3 index gives a slightly later subclass of dL1.6. We averaged the two methods and rounded our adopted subclass to dL1.5.

- **DENIS-P J100428.3-114648 A (dM9.5):** Both the PC3 index and the best match spectrum (DENIS-P J122821.6-241541) give a spectral subclass of dM9.5 (Figure 5).

- **DENIS-P J100428.3-114648 B (dL0.5):** The PC3 index gives dM9.9 but the STIS spectrum appears to intermediate between a dL0 (DENIS-P 0909-0658) and a dL1 (DENIS-P 1441-0945) as illustrated in Figure 5. We adopt a subclass of dL0.5 by interpolating between dL0 and dL1.

- **DENIS-P J122821.6-241541 A (dL4):** The PC3 index gives dL3.9 and the M99 spectrum of LHS 102 B (dL4) is the best spectral match (Figure 6). The Li i resonance doublet is not detected even though it has been clearly seen from the ground (Martín et al. 1997; Tinney et al. 1997). This non detection is due to the low signal to noise ratio and low resolution of our STIS data.

- **DENIS-P J122821.6-241541 B (dL4.5):** The PC3 index gives dL4.2 and the M99 spectrum of DENIS-P J1228-2415 (bdL4.5) is the best spectral match (Figure 6). The Li i resonance doublet is not detected because of the low signal to noise ratio of our data at 670.8 nm.

- **DENIS-P J144137.3-094559 A (dL1):** The PC3 index gives dL1.3, and the best M99 match is DENIS-P J1441-0945 itself (Figure 7). We note that DENIS-P J144137.3-094559 is a common proper motion companion of the star G124-62 (dm4.5, Seifahrt, Guenther & Neuhau
er 2005), which is a member of the Hyades supercluster.

- **GJ 569 Ba (dM9):** The PC3 index gives a subtype of dM9.2 and the best spectral match is DENIS-P J1431-1953 (dm9) so there is good agreement between the two methods.

- **GJ 569 Bb (dM9):** The PC3 index gives a subtype of dM8.6, but the best match is also DENIS-P 1431-1953 (Figure 8). This example underlines the benefits of using several criteria to determine accurate spectral subclasses among ultracool dwarfs. If the spectral class were assigned using only the PC3 index, we would give a slightly earlier subclass to GJ 569 Bb than to GJ 569 Ba, which is not consistent with the properties of this binary.

- **2MASSW J0746425+200032 A (dL0):** The PC3 index gives a subclass of dM9.5 but the best match is DENIS-P 0909-0658 (dL0) as shown in Bouy et al. (2004). The CrH and FeH bands are stronger than in M dwarfs. However, the CrH and FeH bands are stronger than in the A component.

- **2MASSW J0746425+200032 B (dL1.5):** The PC3 index gives a subclass of dM9.6 but the best match is intermediate between DENIS-P 1441-0945 (dL1) and Kelu 1 (dL2), as shown in Bouy et al. (2004). The TiO and VO bands are weaker, and the CrH and FeH bands are stronger than in the A component.

- **2MASSW J0920122+351742 (dL5):** The PC3 index gives a subclass of dL5.2 and the best match is DENIS-P J0205-1159 (dL5) as shown in Figure 9, so there is good agreement between the two methods.

- **2MASSW J1146344+223052 A (dL2):** The PC3 index gives a subclass of dM9.6 but the best match is intermediate between DENIS-P 1441-0945 (dL1) and Kelu 1 (dL2) as shown in Bouy et al. (2004). The K i resonance lines become so broad that the doublet is blended. They are clearly broader than for the dL1. The CrH and FeH bands are stronger than for the dL1 and the TiO bands are weaker.

- **2MASSW J1146344+223052 B (dL2):** The PC3 index gives a subclass of dL1.7 and the best spectral match is Kelu 1 (bdL2) as shown in Figure 10. The K i resonance lines become so broad that the doublet is blended. They are clearly broader than for the dL1. The CrH and FeH bands are stronger than for the dL1 and the TiO bands are weaker.

- **2MASSW J1146344+223052 B (dL2):** The PC3 index gives a subclass of dL1.7 and the best spectral match is Kelu 1 (bdL2) as shown in Figure 10. Bouy et al. (2003) reported a magnitude difference in the F814W filter of 0.75 mag., which is confirmed by new ACS images (H. Bouy 2006, private communication). The similar spectral types but different brightness of these two dwarfs suggests that 2MASSW J1146344+223052 A could be an unresolved binary with nearly equal components. Thus, 2MASSW J1146344+223052 may be a triple system. Very low-mass triple systems may not be rare as indicated by the recent observations of GJ 900 (Martín 2003) and DENIS-P J020529.0-115925 (Bouy et al. 2005). Confirmation of the suspected unresolved binary of 2MASSW J1146344+223052 A requires high angular resolution observations or radial velocity monitoring.

- **2MASSW J1311391+803222 A,B (dM7.5, dM8):** As shown in Figure 11, the STIS spectra of both components are nearly identical. The spectral type inferred from the PC3 index are dM7.3 for A and dM7.6 for B. The best spectral match for the A component is LHS2243 (dM7.5) and for the B component is VB10 (dM8). The two lines of the K i resonance doublet can be distinguished with our spectral resolution. The
4. Discussion

4.1. Chromospheric activity and binarity

$\lambda_\alpha$ emission is an indicator of chromospheric activity due to nonthermal heating by magnetic fields. We have detected $\lambda_\alpha$ emission in only 2 of our objects. We give the equivalent widths measurements or upper limits in Table 3. We did not see any flares, which usually display a variety of strong emission lines in late-M and L dwarfs (Liebert et al. 1999; Martín 1999; Martín & Ardila 2001).

In Figure 13, we display a zoom of the $\lambda_\alpha$ region for most of our targets. Our three coolest L dwarfs ($dL5$–$dL6$) are missing from the plot because they do not have enough continuum for equivalent width determination at these wavelengths. We have compared the distribution of $\lambda_\alpha$ emission equivalent width with respect to spectral subclass in our sample with the measurements obtained by Gizis et al. (2000) for field dwarfs. We performed a Kolmogorov-Smirnov test to check whether the two distributions of $\lambda_\alpha$ emission equivalent width values are statistically different or similar. We binned the data in steps of 0.5 subclasses, so there were 6 spectral bins in the range $dM7$–$dM9.5$. We found that the two distributions of $\lambda_\alpha$ emission equivalent width with respect to spectral subclass in our sample may not be the same. Our results indicate that there could be an anticorrelation between chromospheric activity and resolved binarity for the latest dMs. This connection may be due to different angular momentum histories in the binary components, although this is not very likely because there is not a good connection between activity and rotation for these late dwarfs (Mohanty & Basri 2003). On the other hand, chromospheric activity has been suggested to be enhanced in some late-type dwarfs after impact of asteroids or comets (e.g. AB Dor, Gómez de Castro 2002). A “planetesimal-impact” hypothesis to explain flares in cool stars has also been discussed in the literature (Hertzsprung 1924; Andrews 1991). Our results may lend support to this hypothesis because in the binaries of our sample there may be less debris material due to disk clearing by the components of the binary system. In single very-late dMs, debris material may last over periods of time longer than for solar-type stars because of the reduced effect of disk dissipation processes such as the Poynting-Robertson drag.

4.2. Alkali lines

We searched for the Li $i$ resonance line in our spectra. This line is a useful diagnostic of the age and mass of ultracool dwarfs (Magazzù et al. 1993; Martín et al. 1994) and it has been detected in the unresolved spectra of one of our program binaries with equivalent widths in the range 2-4 Å (DENIS-P J122821.6-241541 A; Martín et al. 1997; Tinney, Delfosse & Forveille 1997). However, we could not detect it in our spectrum of DENIS-P J122821.6-241541 A.

We conclude that the resolution and limited signal to noise ratio of our STIS spectra do not allow us to detect Li $i$ resonance lines with equivalent widths smaller than about 5 Å, implying that we cannot set useful constrains of the lithium abundance of our program dwarfs.

We measured the K $i$ resonance doublet at 766.5 and 769.9 nm. For the dwarfs where we could distinguish the two lines, we used the gaussian deblending option in the IRAF package splot. The equivalent widths obtained are given in Table 3 and their dependence with spectral class is illustrated in Figure 14. At subclass $dL2$ and later the doublet becomes extremely broad and the two lines are blended (Martín et al. 1997, 1999; Burrows & Sharp 1999; Kirkpatrick et al. 1999). For those dLs we provide the equivalent width of the blended pair. The Na $i$ subordinate doublet at 818.4 and 819.5 nm could not be measured because of a bad column in the array. The Cs $i$ at 852.1 and 894.3 nm were strong enough in the coolest objects to measure the equivalent width (Table 3).

The scatter in the equivalent widths of the K $i$ resonance doublet as a function of spectral class that is seen in Figure 14 is likely due to its well-known sensitivity to surface gravity (M99). For example, we note that GJ 569 Ba and Bb ($dM9$) have weaker K $i$ equivalent width than 2MASSW J1426316+155701 A ($dM8$) and DENIS-P J100428.3-114648 A ($dM9.5$). Weaker K $i$ is an indication of lower surface gravity, and consequently a younger age and lower mass for a given spectral subclass. The age of GJ 569 B has been estimated to be young ($\sim 300$ Myr) by Zapatero Osorio et al. (2004) using evolutionary tracks. It is likely that the ages of DENIS-P J100428.3-114648 and 2MASSW J1426316+155701 are older than that of GJ 569 B. With more observations and detailed modelling, the K $i$ resonance doublet may yield a useful age calibration for very low-mass stars and brown dwarfs.

4.3. Molecular bands

The main molecular bands in our spectra are labeled in Figure 2. We measured their strengths using the indices defined in M99, and we give the values in Table 4. As already discussed in Kirkpatrick et al. 1999 and M99, the TiO bands diminish in strength from the late-M to the
L dwarfs, and eventually become undetectable in mid-L dwarfs. Their dependence on spectral type is shown in Figure 15. This effect is understood in terms of the settling of Ti onto dust grains such as CaTiO₃, which condenses at temperatures below 2500 K (Allard et al. 2001). The VO molecule behaves in a similar way to the TiO but it disappears at slightly cooler temperature (Figure 15). The chromium and iron hydrides become prominent in mid-L dwarfs, and tend to fade away in the late-L dwarfs (Figure 15).

The values of the two TiO indices are lower in GJ 569 Ba than in our dM7.5-dM8 targets, but the VO indices are more similar. This may be another spectroscopic manifestation of low surface gravity. The weakening of TiO bands may be shifted to later spectral subclass in low gravity objects because of less efficient dust formation. It has been noted that dM7-dM9 members of the young Pleiades cluster have stronger TiO bands than their older counterparts in the field (Martín et al. 1996).

### 4.4. Comparison of spectral subclasses

In Table 5 we show a comparison of the spectral subclasses adopted by us in the M99 system with those reported in the literature. The spectral types given in the literature correspond to the unresolved systems, and thus are dominated by the primary. There is a fairly good agreement. No discrepancies larger than 2 subclasses are noted. The near-infrared spectral types from Geballe et al. (2002) for two of our binaries also agree within 2 subclasses. The near-infrared spectral types of Gl 569 Ba and b reported by Lane et al. (2001) are consistent with our optical spectral types within the uncertainties (half a subclass).

### 4.5. Absolute magnitude versus spectral type relationships

Among our sample, only 5 binaries have known parallaxes. Their properties are summarized in Table 6. In Figure 16 we plot the spectral types of their resolved components versus the absolute magnitudes in the photometric bands $F_{814W}$ and $K_s$. As expected later type objects are cooler and have fainter magnitudes. Using second order polynomials, we find that the following equations provide a good fit to our data in the spectral class range dM9 – dL6:

$$M_{F_{814W}} = -2.2167 + 2.3284 \times SpT - 0.0682 \times SpT^2 \quad (1)$$
$$M_{K_s} = 10.502 - 0.2311 \times SpT + 0.0226 \times SpT^2 \quad (2)$$

where we used the numerical code of SpT=9 for M9 through SpT=16 for L6. These fits are shown as dotted lines in Figure 16. The scatter (1 $\sigma$) in relations 1 and 2 over the sample of objects that we fit these relations to is 0.43 mag. and 0.27 mag., respectively. The good correlation between our adopted spectral types and the absolute magnitudes indicates that the late-M and L dwarf spectral classification scale depends primarily on effective temperature. The observed scatter around these relations is likely due to the added contributions of unresolved binarity (higher order multiple systems), observational errors, gravity effects and metallicity differences in the sample.

Our results are consistent with those reported by other authors such as Kirkpatrick et al. (2000), Dahn et al. (2002) and Vrba et al. (2004) within the observational error bars. A comparison of our $SpT - M_{K_s}$ relationship with that of Vrba et al. (2004) is shown in Figure 16.

### 5. Summary

We have presented low resolution (R=470) optical spectroscopy of 20 ultracool dwarfs in resolved binary systems. 18 targets are members of 9 resolved binaries with angular separations in the range 0.′′37-0.′′098.

We derived spectral types for our targets using the PC3 index and direct comparison with the M99 ground-based spectra. We report that the $H_\alpha$ emission in our targets is statistically weaker than that of field dwarfs for the range of spectral class dM7–dM9.5. We did not detect any flare. We did not detect the Li $i$ resonance doublet in our targets because of the poor quality and low resolution of our STIS spectra. We provide pseudo-equivalent widths of the Cs $i$ and K $i$ resonance doublets for the targets where those lines could be measured. These lines tend to increase in breath and strength toward later spectral types, as already reported by Kirkpatrick et al. (1999) and M99, but there is significant dispersion which may be due to gravity effects. This doublet may serve as a useful age indicator for field ultracool dwarfs.

For a subset of 10 targets in 5 binaries with known trigonometric parallaxes, we show that there is a good correlation between our spectral types and the absolute magnitudes of the targets in the $F_{814W}$ and $K_s$ bands. We provide second order polynomial fits to the data, which could be used to derive spectrophotometric parallaxes of late-M and L field dwarfs.

After publication of this paper, we plan to make the spectra available online via the IAC catalog of ultracool dwarfs. The address of this catalog is: [http://www.iac.es/galeria/ege/catalogo_spectral/](http://www.iac.es/galeria/ege/catalogo_spectral/). The description of the catalog can be found in Martín, Cabrera & Cenizo (2005).

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**References**
| Object | Exp. Time [s] | Date Obs. DD/MM/YYYY | Program | Ref. Object | Ref. Binarity |
|--------|--------------|-----------------------|---------|-------------|---------------|
| DENIS-P J144137.3-094559 A | 4695 | 29/03/2002 | GO9157 | Martín et al. (1999) | Bouy et al. (2003) |
| DENIS-P J122821.6-241541 A,B | 4693 | 25/04/2002 | GO9157 | Delfosse et al. (1998) | Martín et al. (1999b) |
| GJ 569 Ba,Bb | 3873 | 26/06/2002 | GO9499 | Forrest et al. (1988) | Martín et al. (2000a) |
| DENIS-P J020529.0-115925 A,B | 4695 | 25/09/2002 | GO9157 | Delfosse et al. (1997) | Koerner et al. (1999) |
| DENIS-P J035726.9-441730 A,B | 4895 | 08/01/2003 | GO9451 | Bouy et al (2003) | Bouy et al. (2003) |
| 2MASSW J1146344+223052 A,B | 4702 | 10/02/2003 | GO9157 | Kirkpatrick et al. (1999) | Koerner et al. (1999) |
| 2MASSW J1311391+803222 A,B | 4183 | 27/02/2003 | GO9451 | Gizis et al. (2000) | Close et al. (2003) |
| 2MASSW J0920122+351742 | 4774 | 10/03/2003 | GO9451 | Kirkpatrick et al. (2000) | Bouy et al. (2003) |
| DENIS-P J100428.3-114648 A,B | 4324 | 14/03/2003 | GO9451 | Bouy et al (2003) | Bouy et al. (2003) |
| 2MASSW J1426316+155701 A,B | 1980 | 28/04/2003 | GO9451 | Gizis et al. (2000) | Close et al. (2003) |
| 2MASSW J0746425+200032 A,B | 1980 | 09/01/2004 | GO9451 | Kirkpatrick et al. (2000) | Reid et al. (2001) |
### Table 2. PC3 index and spectral subclasses

| Name of Object | PC3 | SpT (PC3) | SpT (best match) | SpT (adopted) |
|----------------|-----|-----------|-----------------|---------------|
| DENIS-P J020529.0-115925 A | 6.21 | dL4.1 | dL5 | dL5 |
| DENIS-P J020529.0-115925 B | 5.48 | dL3.6 | dL6 | dL6 |
| DENIS-P J035726.9-441730 A | 2.15 | dM9.1 | dM9 | dM9 |
| DENIS-P J035726.9-441730 B | 2.94 | dL1.6 | dL1 | dL1.5 |
| DENIS-P J100428.3-114648 A | 2.33 | dM9.6 | dM9–dM9.5 | dM9.5 |
| DENIS-P J100428.3-114648 B | 2.49 | dM9.9 | dL0–dL1 | dL0.5 |
| DENIS-P J122821.6-241541 A | 5.92 | dL3.9 | dL4 | dL4 |
| DENIS-P J122821.6-241541 B | 6.39 | dL4.2 | dL4.5 | dL4.5 |
| DENIS-P J144137.3-094559 A | 2.56 | dL1.3 | dL1 | dL1 |
| GJ 569 Ba | 2.17 | dM9.2 | dM9 | dM9 |
| GJ 569 Bb | 1.99 | dM8.6 | dM9 | dM9 |
| 2MASSW J0746425+200032 A | 2.29 | dM9.5 | dL0 | dL0 |
| 2MASSW J0746425+200032 B | 2.34 | dM9.6 | dL1.5 | dL1.5 |
| 2MASSW J0920122+351742 A | 8.58 | dL5.2 | dL5 | dL5 |
| 2MASSW J1146344+223052 A | 2.69 | dL1.4 | dL2 | dL2 |
| 2MASSW J1146344+223052 B | 3.07 | dL1.7 | dL2 | dL2 |
| 2MASSW J1311391+803222 A | 1.68 | dM7.3 | dM7.5 | dM7.5 |
| 2MASSW J1311391+803222 B | 1.75 | dM7.6 | dM8 | dM8 |
| 2MASSW J1426316+155701 A | 1.78 | dM7.7 | dM8 | dM8 |
| 2MASSW J1426316+155701 B | 2.75 | dL1.4 | dL1–dL2 | dL1.5 |
Table 3. Atomic line data

| Name of Object | Hα   | K 1  | K 1  | Cs 1 | Cs 1 |
|----------------|------|------|------|------|------|
| DENIS-P J020529.0-115925 A | ...  | 242  | ...  | 4.2  | 3.9  |
| DENIS-P J020529.0-115925 B | ...  | 247  | ...  | 7.5  | 5.1  |
| DENIS-P J035726.9-441730 A | < 3  | 17.4 | 12.6 | ...  | 2.9  |
| DENIS-P J035726.9-441730 B | < 6  | 12.4 | 10.9 | ...  | ...  |
| DENIS-P J100428.3-114648 A | < 3  | 26.1 | 48.4 | ...  | ...  |
| DENIS-P J100428.3-114648 B | < 3  | 10.9 | 26.6 | ...  | ...  |
| DENIS-P J122821.6-241541 A | < 5  | 258  | ...  | 12.4  | 4.5  |
| DENIS-P J122821.6-241541 B | < 5  | 255  | ...  | 6.6  | 2.2  |
| DENIS-P J144137.3-094559 A | < 3  | 53.6 | 17.5 | 4.3  | ...  |
| GJ 569 Ba | < 3  | 13.8 | 16.6 | ...  | ...  |
| GJ 569 Bb | < 3  | 22.1 | 19.3 | ...  | ...  |
| 2MASSW J0746425+200032 A | -18.8| 27.1 | 17.4 | ...  | ...  |
| 2MASSW J0746425+200032 B | -19.1| 37.4 | 17.6 | ...  | ...  |
| 2MASSW J0920122+351742 A | ...  | 363  | ...  | ...  | 4.3  |
| 2MASSW J1146344+223052 A | < 6  | 160  | ...  | 3.5  | 2.4  |
| 2MASSW J1146344+223052 B | < 7  | 168  | ...  | 4.6  | 4.1  |
| 2MASSW J1311391+803222 A | < 3  | 36.0 | 18.9 | ...  | ...  |
| 2MASSW J1311391+803222 B | < 3  | 22.7 | 18.4 | ...  | ...  |
| 2MASSW J1426316+155701 A | < 3  | 37.5 | 11.8 | ...  | ...  |
| 2MASSW J1426316+155701 B | < 3  | 51.9 | 21.4 | ...  | ...  |

Note.— Equivalent width values are in given angstroms and wavelengths are given in nanometers. 1-σ uncertainties typically are ~15 % of the equivalent width.

1 Corresponds to the blend of the 7665 and 7699 Å doublet. Integration limits 734.0-787.0 nm.
2 Uncertain measurement due to blending or noise.
Table 4. Molecular band and pseudocontinuum slope data

| Object              | CrH1 | FeH1 | H2O | TiO1 | TiO2 | VO1 | VO2 |
|---------------------|------|------|-----|------|------|-----|-----|
| DENIS-P J020529.0-115925 A | 1.64 | 1.43 | 1.20 | 1.06 | 0.98 | 0.84 | 1.42 |
| DENIS-P J020529.0-115925 B | 1.07 | 0.97 | 1.22 | 1.14 | 0.86 | 0.88 | 1.37 |
| DENIS-P J035726.9-441730 A | 1.03 | 0.85 | 1.33 | 1.32 | 1.80 | 1.51 | 1.23 |
| DENIS-P J035726.9-441730 B | 1.10 | 1.33 | 1.23 | 0.97 | 1.09 | 1.05 | 1.29 |
| DENIS-P J100428.3-114648 A | 1.02 | 1.04 | 1.21 | 1.50 | 1.63 | 1.28 | 1.04 |
| DENIS-P J100428.3-114648 B | 0.97 | 0.98 | 1.15 | 1.55 | 1.41 | 1.23 | 1.44 |
| DENIS-P J122821.6-241541 A | 2.19 | 1.91 | 1.17 | 0.74 | 1.03 | 0.55 | 1.30 |
| DENIS-P J122821.6-241541 B | 1.73 | 1.66 | 1.06 | 0.66 | 0.98 | 0.65 | 1.50 |
| DENIS-P J144137.3-094559 A | 1.24 | 1.23 | 1.14 | 1.27 | 1.42 | 1.13 | 1.15 |
| GJ 569 Ba            | 1.05 | 0.99 | 1.24 | 1.55 | 1.57 | 1.25 | 1.25 |
| GJ 569 Bb            | 0.98 | 0.99 | 1.19 | 2.10 | 1.67 | 1.33 | 1.11 |
| 2MASSW J0746425+200032 A | 1.20 | 1.19 | 1.24 | 1.25 | 1.44 | 1.12 | 1.22 |
| 2MASSW J0746425+200032 B | 1.39 | 1.40 | 1.18 | 1.04 | 1.22 | 1.01 | 1.25 |
| 2MASSW J0920122+351742 | 1.63 | 1.41 | 1.21 | 0.40 | 0.83 | 0.68 | 1.31 |
| 2MASSW J1146344+223052 A | 1.52 | 1.53 | 1.17 | 0.80 | 1.12 | 0.90 | 1.31 |
| 2MASSW J1146344+223052 B | 1.37 | 1.38 | 1.11 | 0.84 | 1.04 | 0.90 | 1.26 |
| 2MASSW J1311391+803222 A | 1.06 | 1.03 | 1.22 | 2.35 | 1.71 | 1.26 | 1.35 |
| 2MASSW J1311391+803222 B | 1.03 | 0.97 | 1.20 | 2.37 | 1.68 | 1.39 | 1.27 |
| 2MASSW J1426316+155701 A | 1.11 | 1.09 | 1.23 | 2.07 | 1.90 | 1.28 | 1.17 |
| 2MASSW J1426316+155701 B | 1.38 | 1.49 | 1.14 | 0.95 | 1.26 | 1.16 | 1.08 |

Note.— Integration limits for these spectral indices are given in M99.
Table 5. Comparison of optical spectral types

| Object | This work | M99 | K99,00 |
|--------|-----------|-----|--------|
| DENIS-P J020529.0-115925 A | dL5 | dL5 | L7 |
| DENIS-P J020529.0-115925 B | dL6 | | |
| DENIS-P J122821.6-241541 A | dL4 | dL4.5 | L5 |
| DENIS-P J122821.6-241541 B | dL4.5 | | |
| DENIS-P J144137.3-094559 A | dL1 | dL1 | |
| GJ 569 Ba | dM9 | | dM8.5 |
| GJ 569 Bb | dM9 | | |
| 2MASSW J0746425+200032 A | dL0 | dL0.5 | |
| 2MASSW J0746425+200032 B | dL1.5 | | |
| 2MASSW J0920122+351742 A | dL5 | | |
| 2MASSW J1146344+223052 A | dL2 | | L3 |
| 2MASSW J1146344+223052 B | dL2 | | |
| 2MASSW J1311391+803222 A | dM7.5 | | |
| 2MASSW J1311391+803222 B | dM8 | | |
| 2MASSW J1426316+155701 A | dM8 | | |
| 2MASSW J1426316+155701 B | dL1.5 | | |

References: K99: Kirkpatrick et al. 1999; K00: Kirkpatrick et al. 2000; M99: Martín et al. 1999.
### Table 6. Spectral types and photometric magnitudes for binaries with known parallaxes.

| Object (abridged name) | Sp.T. | \( m-M \) | \( M_{FS14W} \) | \( M_J \) | \( M_{K_s} \) | Refs. |
|------------------------|-------|-----------|----------------|-------|-------------|-------|
| DENIS J0205-1159 A     | dL5   | 1.48±0.06 | 17.10±0.12     | 12.3±0.1 | Bo03,Ko99   |
| DENIS J0205-1159 B\(^2\) | dL6   | 18.18±0.12 | 12.3±0.1       | Bo05,Ko99 |
| DENIS J1228-2415 A     | dL4   | 1.53±0.01 | 16.62±0.04     | 13.56±0.08 | Br04,Ko99,MBB99,V04 |
| DENIS J1228-2415 B     | dL4.5 | 16.71±0.04 | 13.76±0.08     | 12.0±0.1 | Ko99,MBB99 |
| GJ 569 Ba              | dL9   | -0.04±0.02 | 12.54±0.16     | 11.18±0.08 | 10.06±0.09 | L01   |
| GJ 569 Bb              | dL9   | 13.24±0.16 | 11.69±0.08     | 10.47±0.09 |
| 2MASS J0746+2000A      | dL0   | 0.43±0.01  | 14.98±0.16     | 11.76±0.08 | 10.60±0.03 | Bo04  |
| 2MASS J0746+2000B      | dL1.5 | 15.98±0.21 | 12.36±0.22     | 11.12±0.05 | Bo04  |
| 2MASS J1146+2230 A     | dL2   | 2.83±0.05  | 15.34±0.17     | 10.4±0.1  | Ko99,Bo03,V04 |
| 2MASS J1146+2230 B\(^2\) | dL2   | 16.09±0.22 | 10.6±0.1       | Bo03, Ko99 |

References: Br04=Brandner et al. 2004, Bo03=Bouy et al. 2003, Bo04=Bouy et al. 2004, Bo05=Bouy et al. 2005, G02=Geballe et al. 2002, K99=Kirkpatrick et al. 1999, Ko99=Koerner et al. 1999, L01=Lane et al. 2001, MBB99=Martín, Brandner & Basri 1999, V04=Vrba et al. 2004.

\(^1\) \( M_J \) deduced from F110M data from Martín et al. 2000.

\(^2\) DENIS-P J0205-1159 B is itself likely double (Bouy et al. 2005). Our STIS spectrum and the \( K_s \) magnitude of Koerner et al. 1999 include the sum of the two components.
Fig. 1. This figure shows the PSF fitting to the 2-dimensional STIS spectrum at 743.8 nm for two binary systems, namely 2MASSW J1311391+803222 (separation = 0.263′′) and GJ 569 B (separation = 0.090′′). The black lines show the observed profiles, the red lines indicate the best PSF fits for the components of these systems, the light blue line denotes the sum of the best PSF fits, and the green line shows the residuals obtained by subtracting the sum of the PSF fits to the observed profile. The integrated flux of the residuals is about 3% of the integrated flux of the total PSF.
Fig. 2. Final STIS spectra of three resolved ultracool dwarf binaries covering a representative range of spectral subclasses. The main spectral features identified in these spectra are labelled.
Fig. 3. Final STIS spectra of the components of the binary DENIS J0205-1159 A (top) and B (bottom). The following ground-based spectra of M99 are shown for comparison: DENIS J0205-1159 (dL5, red dotted line), DENIS J1228-1547 (bdL4.5, green short dashed line), and DENIS J0255-4700 (dL6, blue long-dashed line).
Fig. 4. Final STIS spectra of the components of the binary DENIS J0357-4417 A (top) and B (bottom). The following M99 spectra are shown for comparison: DENIS-P 1431-1953 (dM9, dotted) and DENIS J1441-0945 (dL1, dashed).
Fig. 5. Final STIS spectra of the components of the binary DENIS J1004-1146 A (top) and B (bottom). The following M99 spectra are shown for comparison: DENIS-P 1208+0149 (dM9.5, green long-dashed line), DENIS-P 0909-0658 (dL0, red short-dashed line), and DENIS J1441-0945 (dL1, blue dotted line).
Fig. 6. Final STIS spectra of the components of the binary DENIS J1228-1547 A (top) and B (bottom). The following ground-based spectra of M99 are shown for comparison: LHS 102 B (dL4, red dot-short dash line on top part of the plot), DENIS J1228-1547 (bdL4.5, blue dotted line on top and red long-dashed line at the bottom), and DENIS J0205-1159 (dL5, green short-dashed line).
Fig. 7. Final STIS spectrum of DENIS J1441-0945 A compared with the M99 spectrum of DENIS J1441-0945 (dL1, blue dotted line).
Fig. 8. Final STIS spectra of the components of the binary Gl 569 Ba (top) and Bb (bottom), which are both matched with the M99 spectrum of DENIS-P 1431-1953 (dM9, red dotted line).
Fig. 9. Final STIS spectrum of 2MASS J0920+3517 A compared with the M99 spectra of DENIS J0205-1159 (dL5, red dotted line), and DENIS J1228-1547 (bdL4.5, dashed blue line).
Fig. 10. Final STIS spectrum of 2MASS J1146+2230 A (top) and B (bottom) compared with the M99 spectra of Kelu 1 (bdL2, red dotted line), and DENIS J1441-0945 (dL1, dashed green line).
Fig. 11. Final STIS spectrum of 2MASS J1311+8032 A (top) and B (bottom) compared with the M99 spectra of VB10 (dM8, red dotted line), and LHS2243 (dM7.5, dashed blue line).
Fig. 12. Final STIS spectrum of 2MASS J1426+1557 A (top) and B (bottom) compared with the M99 spectra of VB10 (dM8, green dotted line), DENIS-P 1431-1953 (dM9, blue dotted line), DENIS J1441-0945 (dL1, dashed red line) and Kelu 1 (bdL2, yellow dotted line).
Fig. 13. A zoom of the STIS spectral region around the H$\alpha$ emission line. In order of increasingly late spectral subclass from bottom to top: 2MASS J1311+8032 A and B, 2MASS J1146+2230 A, DENIS-P 0357-4417 A, Gl 569 Ba and Bb, DENIS J1004-1146 A, 2MASS J0746+2000 A, DENIS J1004-1146 B, DENIS-P 1441-0945 A, 2MASS J0746+2000 B, 2MASS J1146+2230 B, DENIS J1228-1547 A and B.
Fig. 14. Equivalent widths of the K I resonance doublet at 766.5 and 769.9 nm versus spectral type for program ultracool dwarfs.
Fig. 15. Molecular absorption indices versus spectral type for program ultracool dwarfs.
Fig. 16. Absolute magnitude in the HST F814W filter (top panel) and K-band (bottom panel) versus spectral type for program ultracool dwarfs. A second order polynomial fit to the data is shown with a dotted line. The dashed straight line represents the linear relationship reported by Vrba et al. (2004).