New ultracool subdwarfs identified in large-scale surveys using Virtual Observatory tools

Part I: UKIDSS LAS DR5 vs SDSS DR7

N. Lodieu\textsuperscript{1,2}, M. Espinoza Contreras\textsuperscript{1}, M. R. Zapatero Osorio\textsuperscript{3}, E. Solano\textsuperscript{4,5}, M. Aberasturi\textsuperscript{4,5}, and E. L. Martín\textsuperscript{3}

\textsuperscript{1} Instituto de Astrofísica de Canarias (IAC), Calle Vía Láctea s/n, E-38200 La Laguna, Tenerife, Spain
e-mail: nlodieu@iac.es, marcela@iac.es
\textsuperscript{2} Departamento de Astrofísica, Universidad de La Laguna (ULL), E-38205 La Laguna, Tenerife, Spain
\textsuperscript{3} Centro de Astrobiología (CSIC-INTA), Ctra. Ajalvir km 4, 28850, Torrejón de Ardoz, Madrid, Spain
e-mail: mosorio.ege@cab.inta-csic.es
\textsuperscript{4} Centro de Astrobiología (INTA-CSIC), Departamento de Astrofísica. P.O. Box 78, E-28691 Villanueva de la Cañada, Madrid, Spain
e-mail: esm.miriam@cab.inta-csic.es
\textsuperscript{5} Spanish Virtual Observatory

May 10, 2014; May 10, 2014

ABSTRACT

\textbf{Aims.} The aim of the project is to improve our knowledge on the low-mass and low-metallicity population to investigate the influence of metallicity on the stellar (and substellar) mass function.

\textbf{Methods.} We present the results of a photometric and proper motion search aimed at unearthing ultracool subdwarfs in large-scale surveys. We employed and combined the Fifth Data Release (DR5) of the UKIRT Infrared Deep Sky Survey (UKIDSS) Large Area Survey (LAS) and the Sloan Digital Sky Survey (SDSS) Data Release 7 complemented with ancillary data from the Two Micron All-Sky Survey (2MASS), the Deep Near-Infrared Survey (DENIS) and the SuperCOSMOS Sky Surveys (SSS).

\textbf{Results.} The SDSS DR7 vs UKIDSS LAS DR5 search returned a total of 32 ultracool subdwarf candidates, only two being recognised as a subdwarf in the literature. Twenty-seven candidates, including the two known ones, were followed-up spectroscopically in the optical between 600 and 1000 nm thus covering strong spectral features indicative of low metallicity (e.g., CaH), 21 with the Very Large Telescope, one with the Nordic Optical Telescope, and five were extracted from the Sloan spectroscopic database to assess (or refute) their low-metal content. We confirmed 20 candidates as subdwarfs, extreme subdwarfs or ultra-subdwarfs with spectral types later than M5; this represents a success rate of 60%. Among those 20 new subdwarfs, we identified two early-L subdwarfs very likely located within 100 pc that we propose as templates for future searches because they are the first examples of their subclass.

Another seven sources are solar-metallicity M dwarfs with spectral types between M4 and M7 without H$_\alpha$ emission, suggesting that they are old M dwarfs. The remaining five candidates do not have spectroscopic follow-up yet; only one remains as a bona-fide ultracool subdwarf after revision of their proper motions. We assigned spectral types based on the current classification schemes and, when possible, we measured their radial velocities. Using the limited number of subdwarfs with trigonometric parallaxes, we estimated distances ranging from $\sim$95 to $\sim$600 pc for the new subdwarfs. We provide mid-infrared photometry extracted from the WISE satellite databases for two subdwarfs and discuss their colours. Finally, we estimate a lower limit of the surface density of ultracool subdwarfs of the order of 5000–5700 times lower than that of solar-metallicity late-M dwarfs.

\textbf{Key words.} Stars: subdwarfs — techniques: photometric — techniques: spectroscopic — Infrared: Stars — surveys — Virtual Observatory tools

1. Introduction

Cool subdwarfs are metal-deficient population II dwarfs which appear less luminous than their solar-metallicity counterparts due to the dearth of metals in their atmospheres (Baraffe et al. 1997). They tend to exhibit halo or thick disk kinematics, in part due to the dearth of metals in their atmospheres (Baraffe et al. 1997). They are very old and represent useful tracers of the Galactic chemical history (Gizis 1997). They are very old and represent useful tracers of the Galactic chemical history (Burgasser et al. 2003). The new classification for M subdwarfs (sdM) and extreme subdwarfs (esdM) has been recently revised by Lepine et al. (2007). A new class of subdwarfs, the ultra-subdwarfs (usdM), has been added to the sdM and esdM classes originally defined by Gizis (1997). The new scheme is based on a parameter, $\gamma_{\text{TiO/CaH}}$, which quantifies the weakening of the strength of the TiO band (in the optical) as a function of metallicity. An alternative classification based on temperature, gravity, and metallicity has been proposed by Jao et al. (2008). The range of metallicity for subdwarfs, extreme subdwarfs, and ultra-subdwarfs span approximately $-0.5$ and $-1.0$, $-1.0$ and $-1.5$, and below $-1.5$, respectively (Gizis 1997, Woolf et al. 2009). M-type subdwarfs have typically effective temperatures below $\sim3500–4000$ K (depending on the metallicity Baraffe et al. 1997, Woolf et al. 2009) and should display high gravity (log $g$$\sim$5.5) although some variations is seen among low-metallicity spectra (Jao et al. 2008).
Subdwarfs were generally identified from optical \((B_J, R, \) and \(I)\) proper motion catalogues on photographic plates at different epochs \((\text{Luyten 1979, 1980; Scholz et al. 2000; Lépine et al. 2003b; Lodieu et al. 2005})\). Several surveys have been conducted to search for subdwarfs over a large temperature range, including hot \((\text{Ryan 1989}),\) intermediate \((\text{Yong & Lambert 2003; Digby et al. 2003}),\) and cool components \((\text{Gizis 1997})\). A growing number of M subdwarfs have been announced over the past years, raising the number of metal-deficient dwarfs with spectral types later than M7 to about ten \((\text{Gizis 1997; Gizis & Reid 1997; Schweitzer et al. 1999; Lépine et al. 2003a; Digby et al. 2003}),\) and cool components \((\text{Gizis 1997})\). This number increased significantly after the discovery of 23 late-type subdwarfs in the Sloan Digital Sky Survey \((\text{SDSS; Adelman-McCarthy et al. 2009})\) spectroscopic database \((\text{Lépine & Scholz 2008})\) and 15 others in the multi-epoch database of the 2MASS survey \((\text{Kirkpatrick et al. 2011})\). Moreover, the hydrogen-burning limit has been crossed with the discovery of the first substellar subdwarf in the 2MASS database \((\text{Burgasser et al. 2003})\). This discovery was quickly followed by the announcement of another L subdwarf \((\text{Burgasser et al. 2004},\) and, more recently, by seven new ones \((\text{Sivaraman et al. 2009; Cushing et al. 2009; Lodieu et al. 2010; Kirkpatrick et al. 2010a; Schmidt et al. 2010a; Bowler et al. 2010})\). This number of ultracool subdwarfs remains however very small and is at odds with the numerous L and T dwarfs reported in the solar neighbourhood within the framework of large-scale optical and infrared surveys, including the Two Micron All Sky Survey \((2\text{MASS; e.g. Kirkpatrick et al. 2000; Burgasser et al. 2002}),\) DEep Near Infrared Survey \((\text{DENIS; e.g. Delfosse et al. 1997, 1999; Martin et al. 1999}),\) SDSS \((\text{e.g. Fan et al. 2003; Leggett et al. 2000; Geballe et al. 2002}),\) the UKIRT Infrared Deep Sky Survey \((\text{UKIDSS; e.g. Lépine et al. 2007; Pinfield et al. 2008; Cunningham et al. 2010}),\) the Canada-France-Hawaii Brown Dwarf survey \((\text{Delorme et al. 2008}; \text{Reylé et al. 2010}; \text{Albert et al. 2011}),\) and WISE \((\text{Kirkpatrick et al. 2011}; \text{Cushing et al. 2011})\).

The aim of our study is to identify a complete census of metal-poor dwarfs to bridge the gap between the coolest M subdwarfs and the recent L subdwarfs identified in various surveys. In this paper we report the outcome of a photometric and proper motion searches using the UKIRT Infrared Deep Sky Survey \((\text{UKIDSS; Lawrence et al. 2007}),\) Large Area Survey \((\text{LAS; Data Release 5 (DR5)}),\) and the Sloan Digital Sky Survey \((\text{SDSS; Data Release 7 (DR7; Abazajian et al. 2009)})\). This catalogue search was complemented by ancillary data from 2MASS \((\text{Cutri et al. 2003; Skrutskie et al. 2006}),\) DENIS \((\text{DENIS Consortium 2003}),\) and SuperCOSMOS \((\text{Hambly et al. 2001c, 2001d}).\) In Sect. 2 we describe the photometric and proper motion criteria designed to identify ultracool subdwarfs in public databases using Virtual Observatory tools. In Sect. 3 we detail the spectroscopic follow-up conducted at optical wavelengths with the visual and near UV Focal Reducer and low dispersion Spectrograph \((\text{FORS2; Appenzeller et al. 1998})\) mounted on the Very Large Telescope \((\text{VLT}),\) the ALFOSC spectrograph on the Nordic Optical Telescope \((\text{NOT})\) and complemented by optical spectra downloaded from the SDSS spectroscopic database. In Sect. 4 we present the results of the spectroscopic analysis and determine the main properties of the newly identified ultracool subdwarfs including colours, spectral types, radial velocities, and distances. Finally, we summarise our work in Sect. 5.

Fig. 1. \((J - K_s, i - J)\) colour-colour diagram showing the positions of our subdwarf candidates identified in the SDSS/UKIDSS search (filled circles) with their respective error bars. Overplotted as filled red triangles are two known ultracool subdwarfs from Lépine & Scholz (2008) with \(J\) and \(K\) photometry from UKIDSS LAS DR5 (error bars are smaller than the symbols) and the solar-metallicity M/L dwarf sequence (line with crosses; spectral types are labelled; \(0\equiv M0, 10\equiv L0\)) from West et al. (2008) and Schmidt et al. (2010b). The photometry shown on this diagram in the MKO photometric system (Hewett et al. 2006).

2. Sample selection

In this section we describe the selection procedure developed to unveil new subdwarfs in the cross-correlation of the SDSS DR7 and UKIDSS LAS DR5 catalogues.

The idea of a generic photometric search for subdwarfs was triggered by the \((I - J, J - K)\) colour-colour diagram presented in Fig. 4 of Scholz et al. (2004b). A similar diagram is shown in Fig. 1. Known ultracool subdwarfs identified by Lépine & Scholz (2008) in the SDSS spectroscopic database are plotted along with the sequence of field M/L dwarfs \((\text{West et al. 2008}; \text{Schmidt et al. 2010b}).\) Subdwarfs tend to be bluer than solar metallicity M/L dwarfs but occupy the same region in the \(i-J\) domain as their solar metallicity counterparts, making their identification difficult in a pure optical-to-infrared search. However, the onset of collision-induced molecular hydrogen \(H_2\) opacity at near-infrared wavelengths generates bluer \(J - H\) and \(J - K_s\) colours \((J - K_s \leq 0.7)\) than observed for solar metallicity M and L dwarfs.

To optimise our photometric selection, we have employed the reduced proper motion \((\mu_r = r \pm 5 \times \log(\mu) + 5)\) as a proxy for metallicity. This parameter is useful to separate solar-metallicity stars from subdwarfs, and white dwarfs (Jones 1972; Evans 1992; Salim & Gould 2002, Lépine & Shara 2005; Burgasser et al. 2007; Lodieu et al. 2009). A reduced proper motion diagram is shown in Fig. 2 with known subdwarfs from Lépine & Scholz (2008) marked as open symbols and our new candidates confirmed as subdwarfs shown as filled symbols.

\[\begin{align*}
J - K_s &\leq 0.7 \\
J - H &\leq 0.7 \\
J - K_s &\leq 0.7
\end{align*}\]
| ID    | Name                        | RA (hh:mm:ss) | Dec (°:′′′′′′) | SDSSr mag | SDSSg mag | SDSSr mag | Epoch (yr) | SDSSr mag | SDSSg mag | Epoch (yr) | Distance (in arcsec) |
|-------|-----------------------------|---------------|----------------|-----------|-----------|-----------|------------|-----------|-----------|------------|----------------------|
| 1     | 2MASS J101613.89-002158.2   | 10:19:40.2    | +00:00:00.0    | 14.05      | 13.24     | 14.05     | 1999.78    | 14.05     | 13.24     | 1999.78    | 100.00                |
| 2     | 2MASS J112445.73+044309.9    | 11:24:45.7    | +04:43:09.9    | 13.36      | 12.90     | 13.18     | 1999.87    | 13.36     | 12.90     | 1999.87    | 150.00                |
| 3     | 2MASS J125635.91+031449.4    | 12:56:36.0    | +03:14:49.4    | 12.46      | 11.96     | 12.46     | 1999.87    | 12.46     | 11.96     | 1999.87    | 150.00                |
| 4     | 2MASS J131705.66+091016.9    | 13:17:06.0    | +09:10:16.9    | 11.70      | 11.29     | 11.70     | 1999.87    | 11.70     | 11.29     | 1999.87    | 150.00                |
| 5     | 2MASS J141806.71+000035.5    | 14:18:07.0    | +00:00:35.5    | 11.31      | 10.86     | 11.31     | 1999.87    | 11.31     | 10.86     | 1999.87    | 150.00                |
| 6     | 2MASS J145441.42+125356.7    | 14:54:41.4    | +12:53:56.7    | 11.80      | 11.33     | 11.80     | 1999.87    | 11.80     | 11.33     | 1999.87    | 150.00                |
| 7     | 2MASS J151211.64+064251.7    | 15:12:12.0    | +06:42:51.7    | 11.65      | 11.20     | 11.65     | 1999.87    | 11.65     | 11.20     | 1999.87    | 150.00                |
| 8     | 2MASS J154331.93+245337.8    | 15:43:32.0    | +24:53:37.8    | 11.78      | 11.32     | 11.78     | 1999.87    | 11.78     | 11.32     | 1999.87    | 150.00                |
| 9     | 2MASS J154540.60+051613.6    | 15:45:41.0    | +05:16:13.6    | 11.96      | 11.50     | 11.96     | 1999.87    | 11.96     | 11.50     | 1999.87    | 150.00                |
| 10    | 2MASS J154855.74+080050.2    | 15:48:56.0    | +08:00:50.2    | 12.46      | 12.00     | 12.46     | 1999.87    | 12.46     | 12.00     | 1999.87    | 150.00                |
| 11    | 2MASS J163359.39+045352.8    | 16:33:59.4    | +04:53:52.8    | 13.29      | 12.83     | 13.29     | 1999.87    | 13.29     | 12.83     | 1999.87    | 150.00                |

Notes:
- LP468.277 = Lepine & Sharpe (2005) West et al. (2006)
- LHS 2045 (ID=9) = Lepine & Sharpe (2005) West et al. (2006)
- SDSS J12041.61+073113.7 (ID=17) classified as M4 by West et al. (2008)
- 2MASS J123659.42-021578.0 (ID=2) classified as M3 by West et al. (2008)
- 2MASS J125639.00-019457.0 (ID=24) classified as M3 by West et al. (2008)
- 2MASS J145441.54+123557.0 (ID=22) = Lepine & Sharpe (2005) West et al. (2006)
- Located at ~42 arcsec from 2MASS J133388.40+050119.6 classified as a L0 dwarf by Zhang et al. (2013)
Our search has been conducted taking advantage of Virtual Observatory (VO) tools, namely STILTS and Aladin (Bonnarel et al. 2000). The detailed photometric and proper motion criteria used for the SDSS DR7 vs UKIDSS LAS DR5 search are given below. The resulting total number of candidates returned by this query is 33 (Table 1) but one was rejected after looking at the images. Those candidates are shown as filled symbols in Figs. 1 and 2. The finding charts created with Aladin are displayed in Figs. 1 and 2 of the Appendix.

- Only SDSS point sources (class=6) were considered
- UKIDSS point sources (mergedClass parameter equal to -1 or -2) and detections in Y, J, and H
- Only sources fainter than Y > 10.5, J > 10.5, and H > 10.2 mag were considered to avoid saturated stars
- For all SDSS sources, we looked for UKIDSS counterparts between 1 and 5 arcsec, implying that we are sensitive to dwarfs with proper motions between 0.125 and ~1.0 arcsec per year depending on the baseline existing between SDSS and UKIDSS (our targets span the 3.11–7.93 year baseline)
- Colour selection were then applied as follows: r – i ≥ 1.0 mag, g – r ≥ 1.8 mag, r – z ≥ 1.6 mag
- Only UKIDSS sources with good quality flags were kept i.e. ppErrBits parameter in each filter less or equal to 256
- Infrared criterion of J – K ≤ 0.7 mag was applied
- Xi and Eta parameters referring to positional matching should be between −0.5 and 0.5
- Only objects satisfying H_r ≥ 20.7 mag were kept

The proper motion of each candidate was computed using the UKIDSS LAS and SDSS positions only but images from 2MASS, DENIS, and SuperCOSMOS were checked by eye for additional epochs to get rid of false positives. A revision of the proper motions is detailed in Section 3.1.

Candidates were visually inspected using the scripting capabilities of Aladin. Sources from DENIS, 2MASS, SDSS, SuperCOSMOS and UKIDSS as well images from UKIDSS, 2MASS and SDSS were used in the analysis. False candidates were rejected due to several reasons, the most likely being the mismatch between the SDSS source and the associated UKIDSS counterpart.

We imposed a lower limit on the proper motion on purpose in order to bias our search towards halo objects (e.g., Scholz et al. 2000) and avoid contamination by “normal” dwarfs and extragalactic sources. Originally, we took 0.5 arcsec (instead of 1 arcsec) as the lower limit for the SDSS-UKIDSS separation but it produced a large number of false candidates. Moreover, imposing a detection in the ~250 M- and L-type subdwarfs, only 11 lie in the common area between UKIDSS LAS DR5 and SDSS DR7: seven do not satisfy either the optical colour constraints because they have spectral types earlier than M5 or are missing near-infrared photometry in at least one of the three bands (YJH); two out of 11 are recovered by our search criteria: LHS 2045 (esdM4.5) and SDSS J020533.75+123824.0 (ID=5; esdM8.5; Lépine & Scholz 2008). However, two are not within our sample: LHS 2096 (esdM5.5; Hr=20.62 mag Lépine & Shara 2005; West et al. 2008) because of the lower limit we imposed on the reduced proper motion, and SDSS J023557.61+010800.5 (esdM7; Lépine & Scholz 2008) because of its separation between the SDSS and UKIDSS coordinates (0.92 arcsec) compared to our lower limit of 1.0 arcsec.

3. Proper motion revision

In this section we discuss the accuracy of the proper motions obtained by the Virtual Observatory tools by comparing the positions in the SDSS and UKIDSS catalogues (no errors considered) and dividing by the epoch difference.

3.1. Method

We computed accurate proper motions by measuring the pixel coordinates (x,y) of the targets and tens of other sources on the Sloan z and UKIDSS LAS J images. We carried out this procedure under the IRAF environment. Firstly, we downloaded the SDSS and UKIDSS LAS images with a size of 6 arcmin aside, centered on each target. Secondly, we identify high-quality point sources with a signal-to-noise higher than 10 in both images, objects selected as reference stars for proper motion measurements. We assumed that these sources (about 30 per target) are not moving, assumption valid because they are centered around (0,0) in Fig. 3.

Then, we transformed the pixel coordinates from one epoch to the other epoch using second-order polynomial transformations for both x and y axes. The dispersion of the transformations was typically 0.16 pixel (or 0.032 arcsec). The resulting x and y shifts were converted into proper motions by taking into account the time baseline of the data and the appropriate pixel scale values. Our measurements along their associated error bars are given in Table 2.

3.2. New proper motions

We find that the revised proper motions agree with the proper motion obtained from the VO for 22 of the 32 candidates (~70%) (Table 2). Below we give details on the 10 sources whose new proper motion differ from the original ones, leading to a different position in the reduced proper motion diagram (Table 2, Fig. 2):

- Sources #30 and #31 should be rejected because no object is detected on the UKIDSS images suggesting that these are false cross-matches. No optical spectra (Section 4) are available for these sources so we reject them from our sample
- Sources #11 and #12 have smaller proper motion because of large offsets between the position of the source on the SDSS image and the position reported by the SDSS catalogue. Their revised Hr is smaller than 20.7 mag, implying that they would not enter our sample. No optical spectra are available for them so we reject them
- Three sources classified as M dwarfs (#8, 28, and 29) are rejected because their revised proper motions are smaller than the one derived by the VO, leading to smaller Hr value and/or a position in the reduced proper motion diagram suggesting that they are solar-metallicity dwarfs

---

1 The Virtual Observatory (http://www.ivoa.net) is an operational research infrastructure designed to facilitate the access and analysis of the information hosted in astronomical archives
2 http://www.star.bris.ac.uk/~mbt/stilts/
3 http://aladin.u-strasbg.fr/
Fig. 2. Reduced proper motion diagram for new ultracool subdwarfs identified in the SDSS DR7 vs UKIDSS LAS DR5 search. The small dots represent all sources in the catalogue published by Lépine & Shara (LS05; 2005) with counterpart in the SDSS DR7 database. Our new subdwarfs, extreme subdwarfs, and ultra-subdwarfs are marked as filled squares, circles, and triangles, respectively. Diamonds represent our candidates classified as solar-metallicity M dwarfs. The five sources without optical spectroscopy are marked with a star symbol. Known subdwarfs from the literature are marked as open symbols (LS08; Lépine & Scholz 2008).

Left: Diagram for the values given by the Virtual Observatory. Right: Diagram using the revised proper motions computed with the method detailed in Section 3.

Fig. 3. Revised proper motions of our candidates. Astrometric reference stars (small open squares) are concentrated around (0,0). Symbols as in Fig. 2. Error bars are smaller than the size of the symbols.

Three M dwarfs (#14, 15, and 19) have smaller revised proper motions but lie in the same region as subdwarfs in the reduced proper motion diagram.

We note that sources #7 and #2 have revised proper motions identical to those from the VO and both objects lie in the subdwarf domain in the reduced proper motion diagram. Source #7 has no optical spectroscopy, it thus remains a reliable ultracool subdwarf candidate. On the contrary, source #2 has optical spectroscopy suggesting it is a solar-metallicity M dwarf contaminating our sample.

To summarise, we conclude that only one of the five sources without optical spectrum remains as a bona-fide subdwarf. Moreover, three of the seven sources spectroscopically classified as M dwarfs (Fig. 5) would be rejected based on the revised proper motion, the remaining ones being photometric contaminants because they lie in the region of the reduced proper motion diagram where ultracool subdwarfs are found (right panel in Fig. 2).

4. Optical spectroscopy

We emphasise that optical spectroscopy was obtained for candidates identified in the preliminary search i.e. with the proper motion derived from the VO and not from the revised proper motions discussed in Section 3.

4.1. NOT spectroscopy

We carried out low-resolution (R\textasciitilde450) optical (500–1025 nm) spectroscopy with the ALFOSC spectrograph on the 2.5-m Nordic Optical Telescope (NOT) at the Observatory of the Roque de Los Muchachos on the island of La Palma, Canary Islands. One candidate, ULAS J145441.41+123556.6 (ID=27), was observed on 3 September 2011 (Table 3). Weather conditions were non photometric with high level clouds and seeing...
around 0.7–0.9 arcsec. The object was observed around UT = 21h at parallactic angle under high airmass, starting at 1.5 and finishing around 1.9 (Table 3).

The ALFOSC spectrograph is equipped with a 2048 × 2052 pixel back-illuminated CCD42-40 charge coupled device. We employed the grism number 5. The total exposure time for ULAS J145441.41+123556.6 was divided into three on-source integrations of 800 seconds with a slit width of 1 arcsec to achieve a resolution of 1.55 nm at 700 nm. An internal flat-field was obtained immediately after the target to remove as much as possible the fringing at long wavelength, the effect being of the order of 18% at 800 nm. Unfortunately fringing is clearly visible beyond 800 nm because the internal flat field was obtained after the last of the three individual exposures taken for the target. Bias frames were observed in the afternoon before the beginning of the night. He, Ne, and Ar arc lamps were also obtained immediately after each exposure to calibrate our target in wavelength.

The data reduction of the NOT/ALFOSC spectra was entirely carried out under the IRAF environment. First, we subtracted the average of all bias frames from the raw science exposures and then divided by the normalised response function of the mean flat field (also bias subtracted). Second, we extracted a one-dimensional spectrum interactively by choosing the appropriate width for the aperture width. Then, we used the arc lamps to calibrate our spectra in wavelength with an accuracy better than 0.2 Å. The flux calibration of the spectrum was conducted using BD+174708 (Latham et al. 2002) as spectrophotometric standard star. The final optical spectrum, covering the 500–900 nm wavelength range and normalised at 750 nm is shown in Fig. 4.2.

### 4.2. FORS2 spectroscopy

We conducted low-resolution (R ~ 350) optical (600–1010 nm) spectroscopy with the visual and near UV FOcal Reducer and low dispersion Spectrograph FORS2 (Appenzeller et al. 1998) on the ESO VLT Antu unit in Paranal, Chile. We observed 22 subdwarf candidates identified in the UKIDSS LAS DR5 and SDSS DR7 cross-match (Table 3). All observations were conducted in service mode under programs 084.C-0928A and 084.C-0928B. The requested conditions, grey time, thin cirrus were often not acceptable, and seeing less than 1.4 and 1.0 arcsec for the bright and faint targets, respectively, were generally satisfied (Table 5). All objects were observed at parallactic angle.

The FORS2 instrument is equipped with two 2048x4096 MIT CCDs with pixels of 15 µm working in the 330–1100 nm range (Appenzeller et al. 1998). We employed the grism 150+27 with the order blocking filter OG590 with the standard resolution of 2.07 nm per pixel and a slit of 1.0 arcsec to achieve a spectral noise of 2.07 nm per pixel and a slit of 1.0 arcsec to achieve a spectral resolution of ~175 at 720 nm due to the 2x2 binning. The exposure time was scaled according to the brightness of the target in the Sloan r and i filter. We then achieved a minimum signal-to-noise ratio of 20. The faintest sources, observed several times along the slit, have lower signal-to-noise because they are faint even for a 8-m class telescope. Some flat fields, bias frames, arc lamps, and spectrophotometric standard stars were observed every night as part of the ESO calibration plan.

As for NOT/ALFOSC, the data reduction of the VLT FORS2 spectra was entirely carried out under the IRAF environment. First, we cut the 2D images to select the interesting part of the spectrum, from ~600 to 1000 nm roughly. Then, we subtracted the average of all bias frames from the raw science exposures and from the median-combined dome flat. Afterwards, we divided the science frame by the normalised flat field using the mean value over the entire dome flat frame. Later, we extracted a one-dimensional spectrum interactively by choosing the appropriate value for the aperture width. Then, we used the arc lamps with Helium, HgCd, and Argon to calibrate our spectra in wavelength with an accuracy of the order of 0.4–0.6 Å rms. Finally, we calibrated the 1D spectra with spectrophotometric standard stars observed on the same night as the target. Spectra have been normalised at 750 nm and are not corrected for the telluric band around 760 nm. The VLT FORS2 spectra of the 11 candidates classified as subdwarfs are displayed in Fig. 5. The sources classified as extreme subdwarfs (7 objects) and ultra-subdwarf (2 objects) are shown in Fig. 5 while the seven sources classified as solar-metallicity M dwarfs are displayed in Fig. 6. The two known subdwarfs previously reported in the literature are included in these figures.

### 4.3. SDSS spectroscopy

The SDSS spectroscopic database represents an invaluable source of good quality spectra for a large number of astrophysicists.
N. Lodieu et al.: Ultracool subdwarfs in large-scale surveys using VO tools

Table 3. Log of the spectroscopic observations

| R.A.          | Dec         | Instr | Date       | # Expt | Airmass | Seeing |
|---------------|-------------|-------|------------|--------|---------|--------|
| hh:mm:ss.ss   | °/′/″       | yyyy-mm-dd | sec     |       |         |        |
| 00:45:39.97   | +13:50:32.7 | FORS  | 2009-11-10 | 3      | 1170    | 1.286  |
| 01:28:30.89   | +14:35:07.4 | FORS  | 2009-11-04/15 | 4    | 2640    | 1.286  |
| 01:50:34.33   | +14:20:02.4 | FORS  | 2009-10-30 | 3      | 1170    | 1.494  |
| 03:33:50.84   | +00:34:06.1 | FORS  | 2009-10-30 | 3      | 870     | 1.546  |
| 08:41:53.89   | +02:06:35.1 | FORS  | 2009-12-21/25 | 4   | 2640    | 1.121  |
| 08:55:00.12   | +00:02:04.1 | FORS  | 2009-12-25 | 1      | 660     | 1.122  |
| 10:01:26.29   | −01:34:26.6 | FORS  | 2010-01-08 | 2      | 1330    | 1.092  |
| 10:07:43.96   | −02:28:30.0 | FORS  | 2009-12-17/24 | 4   | 2644    | 1.150  |
| 10:16:13.89   | +01:13:11.4 | FORS  | 2009-12-24 | 2      | 1320    | 1.161  |
| 11:58:26.62   | +04:47:46.8 | FORS  | 2009-12-21 | 1      | 1320    | 1.468  |
| 12:02:14.62   | +07:31:13.8 | FORS  | 2010-01-23 | 1      | 390     | 1.222  |
| 12:15:08.37   | +04:02:00.5 | FORS  | 2010-02-12 | 3      | 1170    | 1.183  |
| 12:21:45.28   | +08:04:04.4 | FORS  | 2010-01-08/09 | 4   | 2644    | 1.280  |
| 12:42:34.62   | +14:33:06.2 | FORS  | 2010-03-07 | 1      | 390     | 1.306  |
| 12:44:25.90   | +10:24:41.9 | FORS  | 2010-01-23 | 1      | 390     | 1.237  |
| 12:46:21.90   | +04:43:09.9 | FORS  | 2010-03-07 | 1      | 390     | 1.181  |
| 13:17:05.66   | +09:10:16.9 | FORS  | 2010-03-07 | 1      | 390     | 1.239  |
| 14:18:06.71   | +00:00:35.5 | FORS  | 2010-02-13 | 3      | 1170    | 1.119  |
| 15:12:11.64   | +06:42:51.3 | FORS  | 2010-03-07 | 4      | 2640    | 1.510  |
| 15:43:31.93   | +02:45:37.8 | FORS  | 2010-03-07 | 8      | 5280    | 1.333  |
| 23:33:59.39   | +00:49:35.2 | FORS  | 2009-11-10 | 3      | 1170    | 1.130  |
| 13:44:41.42   | +12:35:56.7 | NOT   | 2011-09-03 | 3      | 2400    | 1.700  |
| 01:33:46.25   | +13:28:22.4 | SDSS  | 2000-12-01 | 5      | 5400    | 1.143  |
| 02:05:33.75   | +12:38:24.1 | SDSS  | 2000-12-01 | 5      | 4500    | 1.143  |
| 08:43:58.50   | +06:00:38.6 | SDSS  | 2003-03-10 | 3      | 2400    | 1.161  |
| 12:02:14.62   | +07:31:13.8 | SDSS  | 2004-03-25 | 3      | 3000    | 1.133  |
| 12:36:59.43   | −00:21:58.2 | SDSS  | 2001-02-01 | 4      | 3600    | 1.209  |
| 12:56:35.91   | −00:19:44.9 | SDSS  | 2001-03-26 | 3      | 2702    | 1.214  |
| 13:17:05.66   | +09:10:16.9 | SDSS  | 2006-04-25 | 4      | 4900    | 1.216  |

Fig. 4. Low-resolution optical (600–1000 nm) spectra of confirmed subdwarfs obtained with VLT FORS2. Spectra are ordered by increasing spectral type and offset by a constant value for clarity. Overplotted in red are known template subdwarfs from the SDSS spectroscopic database (600–940 nm) except for the top 3 templates which come from the IRTF/Spex library.

5. New ultracool subdwarfs

In this section, we assign spectral types to the new subdwarfs, measure their radial velocities, estimate their spectroscopic distances, discuss their mid-infrared properties, search for telluric absorption bands, and present a preliminary estimate of their surface density.

5.1. Spectral types

We employed two independent but complementary methods to assign spectral types to our new ultracool subdwarfs.

The adopted classification for M-type subdwarfs and extreme subdwarfs relies on the scheme proposed by Gizis (1997) and extends to spectral types sdM7 and esdM5.5, respectively. This scheme is based on the strength of CaH (temperature index) and TiO (metallicity index) bands. An extension to later spectral types (up to sdM9) has been more recently proposed by Lépine et al. (2003a).

We measured the four spectral indices (TiO5, CaH1, CaH2, and CaH3) defined by Gizis (1997) and later updated by Lépine et al. (2003a) to distinguish ultra-subdwarfs, extreme subdwarfs, and subdwarfs from solar metallicity M dwarfs based on the strength of the CaH and TiO absorption bands (Fig. 4). The spectral indices and their associated spectral types (quoted to the nearest decimal) derived for each of the confirmed subdwarfs are listed in Table 4 and plotted in Fig. 7 and 8.

The SDSS spectroscopic database provides optical spectra over the 600–940 nm wavelength range for a large number of metal-poor dwarfs with spectral types based on two independent classification schemes: the Hammer scheme discussed by Covey et al. (2007), and the updated subdwarf classification proposed by Lépine et al. (2007). The former distinguishes between solar-metallicity M dwarfs and subdwarfs whereas the latter provides an accurate classification for metal-poor dwarfs with subclasses. Therefore, we downloaded from the Sloan spectroscopic database the brightest object of each subclass between 0 and 9 for subdwarfs, extreme subdwarfs, and ultra-subdwarfs. These “templates” were used to assign visually spectral types to our targets with an uncertainty of half a subclass (or better). We should mention that the SDSS templates have been corrected for telluric absorption whereas our spectra were not, resulting in a differ-
Fig. 5. Low-resolution optical (600-1000 nm) spectra of confirmed extreme subdwarfs and ultra-subdwarfs obtained with VLT FORS2. The second spectrum from bottom is from NOT/ALFOSC. Spectra are ordered by increasing spectral type and offset by a constant value for clarity. Overplotted in red are known template extreme subdwarfs and ultra-subdwarfs from the SDSS spectroscopic database (600–940 nm).

Fig. 6. Low-resolution optical (600-1000 nm) spectra of photometric candidates classified as solar-metallicity M dwarfs. Spectra are ordered by increasing spectral type and offset by a constant value for clarity. Overplotted in red are known M dwarf templates downloaded from the SDSS spectroscopic database.

Fig. 9. Comparison of the spectral types obtained from the visual comparison with metal-poor “templates” and spectral types derived from the spectral indices defined by Gizis (1997) and Lépine et al. (2007). Subdwarfs, extreme subdwarfs, and ultra-subdwarfs are marked as squares, circles, and triangles, respectively. Metal-poor dwarfs with a discrepant spectral type derived from both classification methods (comparison with templates vs spectral indices) are displayed with asterisks (e.g. sdM vs esdM or usdM vs esdM, etc). Typical uncertainties on the spectral types derived from both methods are half a subclass.

The comparison between the spectral types inferred from spectral indices and from the direct comparison with “templates” is shown in Fig. 9. We find that the spectral types derived from spectral indices tend to underestimate the spectral type (overestimate the effective temperature). Therefore, we adopted the direct and visual comparison with “templates” to assign spectral types to our targets because it provides a more accurate classification. We note that the spectral indices are not so reliable to classify subdwarfs because they rely on a narrow wavelength range as pointed out by Lépine et al. (2007) and also depend strongly on the resolution of the spectra (Table 4). The differences between both classifications are listed in Table 4 and shown in Fig. 9 where asterisks represent confirmed metal-poor dwarfs with discrepant classes (not only spectral types) derived from the spectral indices and the direct comparison with templates, suggesting some shortcomings in the spectral types derived solely on indices. Our sample of 20 low-mass stars with low-metal content consists of nine subdwarfs, seven extreme subdwarfs, two ultra-subdwarfs, and two L subdwarfs.

The remaining seven sources in our spectroscopic sample are M dwarfs with spectral types ranging from M4 to M7. We believe that the contamination of our sample by these M dwarfs

5 http://web.mit.edu/ajb/www/browndwarfs/spexprism/
come from large error bars on their Sloan positions, leading to spurious proper motions placing them at the bottom of the reduced proper motion diagram mimicking subdwarf candidates. We remark that a revision of proper motions as that outlined in Section 5 likely reduces the contamination level by a factor of 2–3. None of these M dwarfs exhibit $H\alpha$ in emission at the resolution of our spectra (R ~ 150), suggesting that they are older than typical M dwarfs in the solar vicinity. West et al. (2008) reported $H\alpha$ in emission for 50% of the sources or more at spectral types later than M4, with equivalent widths larger than 1 Å. These authors also discussed the decrease in activity with age and scale height, suggesting that the M dwarfs contaminating our sample may be either older than the average low-mass stars in the solar neighbourhood and may be located at a higher scale height. The lack of $H\alpha$ in emission also places a lower limit on the ages of these M dwarfs, 5 and 8 Gyr for M5 and M7 dwarfs, respectively.

5.2. Radial velocities

In this section we tentatively compute the radial velocities of our targets in spite of the low-resolution of our spectra. We used two different methods.

First, we computed the offsets between lines resolved in our FORS2 spectra and the centroids of several atomic lines whose accurate positions can be found on the webpage of the National Institute of Standards and Technology\(^6\). $CaI$ at 6572.18 Å, $TiI$ at 8434.94 Å, $NaI$ doublet at 8183.25 and 8194.79 Å, $CsI$ at 8542.09 and 8943.47 Å, and $CaII$ at 8542.09 Å (see also Table 2 of Burgasser et al. 2009). The uncertainties on these offsets are typically of the order of 1 Å, corresponding to typical uncertainties of 35–50 km s\(^{-1}\). We focused only on the $CaI$, $NaI$ doublet, and $CaII$ lines for the NOT spectrum and the SDSS spectra. We derived the observed radial velocities by multiplying those offsets by the speed of light and dividing by the wavelength ($c/\lambda/\Delta\lambda/I$). Observed velocities were converted into heliocentric velocities by computing the Earth’s rotation, the motion of the Earth’s center about the Earth-Moon barycenter, and the motion of the Earth-Moon barycenter about the center of the Sun using the RV CORRECT routine in IRAF. In the fifth column of Table 5 we provide our heliocentric radial velocities measured with this method.

Independently, we computed radial velocities by cross-correlating our optical spectra with the optical spectrum of the sdM3.5 subdwarf SDSS J125637.13-022452.4 (Burgasser et al. 2009) using the task FXCOR under the IRAF environment. This subdwarf has a well-measured radial velocity of −130 km s\(^{-1}\) and we decided to use it as a template despite having a spectral type later than our confirmed subdwarfs. We transformed the vacuum wavelength published by Burgasser et al. 2009 into air wavelength and degraded its resolution to match our observations. We cross-matched the full spectrum of our sdM9.7 and sdL subdwarfs with Burgasser’s template because of the similarities in the shape of the spectra and spectral types but focused only on the NaI doublet region for the earlier subdwarfs in our sample. We cross-matched the spectra using two different functions: a gaussian fit to the cross-correlation function peak or simply the central value of the peak. Both method led to differences smaller than the uncertainties output by FXCOR. The radial velocities inferred by this method are listed in Table 5 and have typical uncertainties of 40–50 km s\(^{-1}\) measured from the dispersion of the measurements from different part of the spectra. Radial velocities derived from both methods usually agree within the uncertainties, except for ULAS J115826.62+044746.8 (ID=16) and ULAS J12:36:59.43–00:21:58.2. In this case, we favor the radial velocities derived from the direct comparison with SDSS J125637.13-022452.4.

\(^6\) http://physics.nist.gov/asd3

Table 4. Coordinates (in J2000), spectral indices, spectral types determined following the definitions by Gizis (1997) and Lépine et al. (2007) for the new subdwarfs. The last column gives the adopted spectral types derived from direct comparison with spectral templates. If a target appears twice, the first line corresponds to the FORS2 spectrum while the second is the SDSS spectrum.
Fig. 7. Top left: CaH1 vs TiO5 indices for our new ultracool subdwarfs. Top right: CaH2 vs TiO5 indices. Bottom left: CaH3 vs TiO5 indices. Bottom right: Sum of CaH2 and CaH3 vs TiO5 indices. Subdwarfs, extreme subdwarfs, ultra-subdwarfs, old solar-metallicity M dwarfs from our sample are marked as filled squares, circles, triangles, and diamonds, respectively. Numbers denoting our new discoveries follow the order by right ascension from Table 4. Open symbols are known subdwarfs discussed in Gizis (1997). The small coloured dots in the bottom right plot represent sources with SDSS spectroscopy classified as subdwarfs (red), extreme subdwarfs (green), and ultra-subdwarfs (blue). For the subdwarfs with two spectra from FORS2 and SDSS, we plotted only the indices derived from the VLT FORS2 spectra. Typical uncertainties on the spectral indices are of the order of 0.1 (cross at the bottom of each plot). These plots follow the standard figures presented in Figure 1 of Gizis (1997) and Figure 3 of Lépine et al. (2007).

5.3. Spectroscopic distances

In this section, we estimate the spectroscopic distances by comparing our new discoveries with subdwarfs of similar spectral types with known trigonometric parallaxes.

We looked for subdwarfs with parallaxes whose spectral types are sdM5, sdM6, sdM6.5, sdM7, sdM7.5, and sdM9.5. We considered the following sources as subdwarfs with known distances to derive spectroscopic distances for our new ultracool subdwarfs: LP 807-23 (sdM5.0; \( J = 12.92 \) mag; \( d = 28.17 \pm 31.74 \) pc; van Altena et al. 1995), LHS 1074 (sdM6; \( J = 14.68 \) mag; \( d = 85.7 \pm 17.1 \) pc; Salim & Gould 2003, Riaz et al. 2008), LHS 1166 (sdM6.5; \( J = 14.26 \) mag; \( d = 73 \)–89 pc; van Altena et al. 1995), LP 440-52 (sdM7;
Fig. 8. Spectral indices as a function of the adopted spectral types for our new ultracool subdwarfs. Typical uncertainties on the spectral indices are of the order of 0.1 (cross at the bottom of each plot). Uncertainties on the spectral types are 0.5 subclass. Top left: Adopted spectral types vs TiO5 index. Top right: Adopted spectral types vs CaH1 index. Bottom left: Adopted spectral types vs CaH2 index. Bottom right: Adopted spectral types vs CaH3 index.

\( J = 13.19 \) mag; \( d = 34.4–36.1 \) pc; van Altena et al. 1995), LSR J203621.86+505950.3 (sdM7.5; \( J = 13.628 \) mag; \( d = 43.7–49.2 \) pc; Lépine et al. 2003; Schilbach et al. 2009), LSR J142504.81+710210.4 (sdM8; \( J = 14.828 \) mag; \( d = 75.4–89.9 \) pc; Lépine et al. 2003; Burgasser et al. 2008; Schilbach et al. 2009), and SSSPM101307.34−135620.4 (sdM9.5; \( J = 14.637 \) mag; \( d = 45.0–54.6 \) pc; Scholz et al. 2004a; Schilbach et al. 2009). After applying the standard transformations using the \( J \)-band magnitudes of our new discoveries, we assigned mean distances between 88 and 628 pc (see Table 6), assuming that they are single. Typical error bars on the spectroscopic distances are 20–25% taking into account the uncertainties on the trigonometric parallaxes of the templates. For the two L subdwarfs, we used the trigonometric parallax of the sdM9.5 template to place upper limits on their distances. Both objects very likely lie within 100 pc unless they are binaries (Table 6).

In addition to the aforementioned subdwarfs, we were able to assign a spectroscopic distance for our esdM5 extreme subdwarf using LHS 515 as template (esdM5; \( J = 13.64 \) mag; \( d = 42.6–64.5 \) pc; van Altena et al. 1995). Hence, we derive a spectroscopic distance of 257 pc with a probable range of 214–323 pc for ULAS J124621.90+044309.9 (ID=23; Table 6). For the other extreme subdwarfs we are unable to assign spectroscopic
distances because no object with similar spectral types has known trigonometric parallax in the literature. Instead, we used LHS 2096 (esdM5.5; \( J = 13.99 \); d = 56.10 pc) \footnote{Lépine & Shara 2005}, LHS 2023 (esdM6; \( J = 14.91 \); d = 73.9 pc) \footnote{Riaz et al. 2008}, LSR J0822+1700 (esdM6.5; \( J = 15.517 \); d = 106 pc) \footnote{Lépine et al. 2003c}, and APMPM0559 (esdM7; \( J = 14.887 \); d = 70 pc) \footnote{Schweitzer et al. 1999} to infer tentative (mean) distances. We do not quote uncertainties for these sources because of the (already) very uncertain distances of the templates used. We do not provide a distance for the two ultra-subdwarfs in our sample because none has trigonometric parallaxes published in the literature.

5.4. Mid-infrared photometry

We cross-matched our list of new ultracool subdwarfs with the Wide-field Infrared Survey Explorer (WISE) \footnote{Wright et al. 2010} data release which took place in April 2011. We found two subdwarfs with mid-infrared photometry using a matching radius of 6.5 arcsec, the spatial resolution of WISE. However, we ensured that no other source was detected in WISE because of the large proper motions of subdwarfs. The WISE photometry of these two subdwarfs at 3.4 (W1) and 4.6 (W2) microns is reported in Table 5 and plotted in Fig. 10. These two sources are undetected at longer wavelengths.

We compared the infrared colours of our new ultracool subdwarfs to the sample of Kirkpatrick et al. (2011) drawn from the DwarfArchives.org webpage in order to identify any trend that may help future searches for metal-poor brown dwarfs. In the case of ULAS J015034.33+142002.4 (ID=4; esdM6), we find colours similar to normal M6 dwarfs in \( H-W2 = 1.07 \), \( J-W2 = 0.76 \), and \( K-W1 \) although on the red side of the distribution. Other colours, including \( J-W1 = 0.76 \), \( W1-W2 = 0.79 \), \( K-W2 = 0.92 \) mag differ to those of normal M6 dwarfs which span the following ranges 1.0–1.4, 0.2–0.4, and 0.3–0.6 mag, resulting in a deviation of \( -1 \sigma \) (Fig. 10) Table 7. The other subdwarf in our sample, ULAS145441.42+125566.7 (ID=27; esdM5.5), exhibits similar colours to M dwarfs in all combinations of colours at odds with ULAS J015034.33+142002.4 (Fig. 10). We repeated the process with a larger number of known subdwarfs and did not spot any obvious trend with decreasing metallicity, suggesting that ULAS J015034.33+142002.4 may be peculiar, or a multiple source, or more likely the WISE photometry has underestimated uncertainties.

We also checked the Spitzer archive to extract additional information on the mid-infrared properties of some of our candidates but none of them was found from the Spitzer public database.

5.5. Search for wide companions

In this section we looked for wide companions brighter than each of our subdwarfs within a radius of 10 arcmin. The idea is to find potential primaries with distances, metallicities, and (possibly) ages (often referred to as benchmark objects) \footnote{Pinfield et al. 2006} determined with a higher precision than our new subdwarfs. We used large-scale surveys with accurate proper motions: the USNO-B1 \footnote{Monet et al. 2003}, the UCAC3 \footnote{Zacharias et al. 2010}, and the PPMXL \footnote{Roeser et al. 2010} catalogues. We selected only bright sources with \( \mu_{\text{USNO}} \leq 18 \) mag and proper motions in right ascension and declination within 30% of the measured motion of our targets derived from the UKIDSS LAS DR5 vs SDSS DR7 cross-match.

We found one potential wide companion to ULAS J233359.39+004935.2 (ID=32) in USNO-B1 and PPMXL at a distance of about 5 arcmin on the sky. This potential companion, USNO J233350.27+005342.9, has a proper motion in right ascension and declination of (149, -75) and (154, -78)
plying that this object felt out of our sample. At the spectroscopic distance of ULAS J233359.39 +14:20:02.4 (ID = 32) estimated to 400 pc (Table 6), the projected physical separation of the system would be very large, of the order of 120,000 au. Hence, we cannot claim that both objects are gravitationally bound but they might have formed in the same cluster or might belong to the same moving group.

### Table 7. Coordinates (in J2000), spectral type, J-band magnitude, and mid-infrared photometry with the associated error bars (3.4 and 4.6 microns) for the two ultracool subdwarfs covered by the WISE mission. The signal-to-noise ratio of the photometry quoted by the WISE catalogue is indicated in brackets. The photometry in the WISE 12 and 22 micron bands is not included because the signal-to-noise ratios are less than 3.

| ID   | R.A.       | Dec        | SpType | J      | 3.4μm (SNR) mag | 4.6μm (SNR) mag | mag err () | mag err () |
|------|------------|------------|--------|--------|----------------|----------------|------------|------------|
| 4    | 01:50:34.33 | +14:20:02.4 | sdM6.0 | 17.424 | 16.66±0.131 (8.3) | 15.87±0.230 (4.7) |           |            |
| 25   | 14:54:41.42 | +12:35:56.7 | sdM5.5 | 16.121 | 15.13±0.044 (24.4) | 14.83±0.090 (12.1) |           |            |

5.6. Notes on individual objects

In this section we give additional details on a few specific candidates identified in our search for ultracool subdwarfs.

5.6.1. Spectra in the SDSS DR7 spectroscopic database

Some photometric candidates in our sample have spectra publicly available in the SDSS DR7 spectroscopic database (Table 6). As noted in the caption of Table 1 in Appendix, all of them were included in the sample of West et al. (2008) and classified as early-M dwarfs using the Hammer classification (Covey et al. 2007). However, the Sloan spectra clearly look like subdwarf with strong CaH and TiO bands typical of low-metallicity M dwarfs (Figs. 4–5). We should mention that LP 468-277 (01:33:46.25+13:28:22.4) was included in the catalogue of Northern stars of Lépine & Shara (2005) but no spectral type was derived. Finally, we recovered SDSS J020533.75+123824.1 (ID = 5) classified as sdM7.5 by Lépine & Scholz (2008) and reclassified as sdM8 in this paper based on the spectral type provided by the SDSS DR7 spectroscopic database.

5.6.2. ULAS J145441.45+123557.6 (ID = 27)

This source is part of the catalogue of Northern stars of Lépine & Shara (2005) but no spectral type was derived. Our proper motion derived from the LAS and SDSS DR7 epochs (0.31 arcsec/yr) is in good agreement with the value of 0.321 arcsec/yr published by Lépine & Shara (2005). We do not have spectroscopic follow-up for this source yet.

5.6.3. ULAS J233359.39+004935.2 (ID = 32)

This candidate, observed with VLT FORS2, is classified as a sdM6 subdwarf. Its proper motion in right ascension and declination is (93.9, 23.0) and (81.9, 16.6) mas/yr from the 2MASS/UKIDSS and SDSS/UKIDSS cross-match. We discuss the presence of a possible wide companion five arcmin away in Section 5.5.

This subdwarf is located at ~42 arcsec from 2MASS J223538.40+005011.9, a L0 dwarf reported by Zhang et al. (2010) with a proper motion of (139.7, 29.5) mas/yr reported by the PPMXL catalogue (Roeser et al. 2010). The proper motion values in right ascension differ by 50–70%, suggesting that both objects are not physically associated. Nonetheless, we investigated further the SDSS DR7 spectrum of this possible wide companion and compared it to known M9 and M9.5 dwarfs, young L dwarf templates (Cruz et al. 2009), a sdM9.5 subdwarf (Scholz et al. 2004a), and our two possible L subdwarfs (Fig. 11). The best fit is obtained for a field M9 dwarf of solar metallicity, LHS 2065 (Kirkpatrick et al. 1991) downloaded from the PPMXL and USNO-B1, respectively, in agreement with the values of (136, −71) mas/yr quoted by Sloan. The differences in the proper motions in right ascension and in declination between our subdwarf and its potential companion are about 23–27% and 10–15%, respectively. No spectrum is available in the SDSS spectroscopic database. The SDSS of this object is 19.118±0.021 mag, roughly 1 mag brighter than our spectroscopic subdwarf. Its optical colours (g − r = 1.785, r − i = 1.429, r − z = 2.158 mag) and reduced proper motion (H = 21.64 mag) satisfy our original selection criteria and suggests that this potential wide companion may also be metal-poor. However, its J − K infrared are redder than our original cut of 0.7 mag, implying that this object felt out of our sample. The spectroscopic distance of ULAS J233359.39+004935.2 (ID = 32) estimated to 400 pc (Table 6), the projected physical separation of the system would be very large, of the order of 120,000 au. Hence, we cannot claim that both objects are gravitationally bound but they might have formed in the same cluster or might belong to the same moving group.

Fig. 10. WISE colours as a function of spectral type for known M dwarfs (open squares) from the sample published by Kirkpatrick et al. (2011). Our two subdwarf candidates are highlighted with large filled circles.
of the imaging survey is incomplete. For this reason, we considered the photometric sample from Bochanski et al. (2010), their Figure 4) and focus on sources with $i$ brighter than 22 mag, $r - i > 2.5$, $i - z > 0.2$, and $r - i > 0.3$ mag, corresponding to $\geq$ M5 dwarfs and later. We counted a total number of 653,625 photometric $\geq$ M5 dwarfs in 8000 square degrees surveyed by SDSS DR7, implying a density of $\sim$82 $\geq$ M5 dwarfs per square degree. We sent a query with the aforementioned criteria to the WFCAM Science Archive (Hambly et al. 2008) to see how many M5 (and later) dwarfs in UKIDSS LAS DR5 and SDSS DR7 we could recover in order to match those numbers with our search criteria defined in Sect. 2. We imposed a detection in $YJH$ but not in $K$ and requested good quality point sources in addition to the constraints on the optical colours. The query returned 113,393 sources in 1343 square degrees. If we limit the sample to dwarfs with $z - J > 1.4$ (West et al. 2011), the query returns 106,746 sources, implying a number of M5 dwarfs (and later) of the order of 79.5–84.4 per square degree which is highly consistent with the numbers derived from the Sloan sample alone. This density is $\sim$5000–5700 times higher than the number of ultracool subdwarfs found in our photometric and proper motion search which is broadly consistent with the 0.2% contribution from metal-poor stars quoted by Digby et al. (2003) and the upper limit derived from the SDSS M dwarf sample (Covey et al. 2008). We should mention that according to the evolutionary models (Baraffe et al. 1997, 1998), the masses of $\geq$ M5 dwarfs and subdwarfs are similar at ages of Gyr but lower metallicity M dwarfs have high effective temperatures. Finally, we should point out that we found two ultra-subdwarf and seven extreme subdwarfs for 11 subdwarfs, suggesting a fairly quick decrease in the numbers of subdwarfs as a function of metallicity.

6. Summary

We have presented the outcome of a dedicated photometric and proper motion search aimed at finding new ultracool subdwarfs in public databases. We identified 32 ultracool subdwarf candidates, 20 of them being confirmed as metal-poor late-M and early-L dwarfs by low-resolution optical spectroscopy. We discovered two new early-L subdwarfs which we propose as spectroscopic templates for future searches because these are the first of their subclass. We measured radial velocities for most of the new subdwarfs with the cross-match technique. We estimated their spectroscopic distances when templates of similar spectral types with trigonometric parallaxes were available. We uncovered seven old M dwarfs contaminating our sample whose ages are estimated to $> 5$–8 Gyr due to the lack of $H\alpha$ in emission. Of the 32 candidates, five do not have optical spectroscopy. Only one of these five remains a good subdwarf candidate, the others being rejected. We found a contamination of about 30% by solar-metallicity M dwarfs in our photometric and proper motion search, mainly due to large errors on the Sloan positions leading to spurious proper motions affecting the determination of the reduced proper motion. We are able to reduce this level of contamination by a factor 2 to 3 after revision of the proper motion measurements. We also present mid-infrared data from WISE for two subdwarfs as well as a search for bright and wide common proper motions which led to an extremely wide pair $\geq$ M5 dwarfs very likely not gravitationally bound.

We intend to expand our search for subdwarfs with upcoming data releases from UKIDSS to increase the census of low-metallicity dwarfs. Moreover, we plan to update our colour crite-

---

8 http://kellecruz.com/M_standard/

9 Numbers kindly provided by John Bochanski and Andrew West
ria to optimize future searches and discover even cooler ultracool subdwarfs. The main overall scientific goal of this large project is to update and extend the current low-metallicity classification into the L dwarf (and later T dwarf) regime.

Acknowledgements. NL was funded by the Ramón y Cajal fellowship number 08-303-01-02 and the national program AYA2010-19136 funded by the Spanish ministry of science and innovation. NL was partly funded by the RoPACS (Rocky Planets Around Cool Stars) Marie Curie Initial Training Network. This research has made use of the VizieR and the M, L, and T dwarf catalogs maintained at the University of California, Los Angeles, and the Jet Propulsion Laboratory.

This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

This research has been partly funded by the University of Minnesota, 1980 and 1979, 2nd ed.)

References

Abazajian, K. N., Adelman-McCarthy, J. K., Aguirre, M. A., et al. 2009, ApJS, 182, 543

Adelman-McCarthy, J. K. & et al. 2009, VizieR Online Data Catalog, 2294, 0

Albert, L., Artigau, É., Delorme, P., et al. 2011, AJ, 141, 203

Appenzeller, I., Frick, K., Fürttig, W., et al. 1998, The Messenger, 94, 1

Baruffa, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1997, A&A, 327, 1054

Baruffa, I., Chabrier, G., Allard, F., & Hauschildt, P. H. 1998, A&A, 337, 403

Bochanski, J. J., Hawley, S. L., Covey, K. R., et al. 2010, AJ, 139, 2679

Bonnarel, F., Fernique, P., Bienaymé, O., et al. 2000, A&AS, 143, 33

Bowler, B. P., Liu, M. C., & Dupuy, T. J. 2010, ApJ, 710, 45

Burgasser, A. J. 2004, ApJ, 614, 173

Burgasser, A. J., Cruz, K. L., & Kirkpatrick, J. D. 2007, ApJ, 657, 494

Burgasser, A. J., Kirkpatrick, J. D., Brown, M. E., et al. 2002, ApJ, 564, 421

Burgasser, A. J., Kirkpatrick, J. D., Burrows, A., et al. 2003, ApJ, 592, 1186

Burns, A. J., Vrba, F. J., Lépine, S., et al. 2008, ApJ, 672, 1159

Burgasser, A. J., Witte, S., Helling, C., et al. 2009, ApJ, 697, 148

Burningham, B., Pinfield, D. J., Lucas, P. W., et al. 2010, MNras, 406, 1885

Covey, K. R., Hawley, S. L., Bochanski, J. J., et al. 2008, AJ, 136, 1778

Covey, K. R., Ivezić, Ž., Schlegel, D., et al. 2007, AJ, 134, 2398

Cruz, K. L., Kirkpatrick, J. D., & Burgasser, A. J. 2009, AJ, 137, 3345

Cutri, R. M., Skrutskie, M. F., van Dyk, S., et al. 2003, 2MASS All Sky Catalog of point sources, 2246

Delfosse, X., CN, Foxge, T., et al. 1997, A&A, 327, L25

Delfosse, X., CN, Foxge, T., et al. 1999, A&A, 315, 41

Delorme, P., Delfosse, X., Albert, L., et al. 2008, A&A, 482, 961

DENIS Consortium. 2005, VizieR Online Data Catalog, 1, 200

Digby, A. P., Hambly, N. C., Cooke, J. A., Reid, I. N., & Cannon, R. D. 2003, MNras, 344, 583

Evans, N. W. 1992, MNras, 258, 587

Fan, X., Knapp, G. R., Strauss, M. A., et al. 2000, AJ, 119, 928

Geballe, T. R., Knapp, G. R., Leggett, S. K., et al. 2002, ApJ, 564, 466

Gizis, J. E. 1997, AJ, 113, 2366

Gizis, J. E. & Reid, I. N. 1997, PASP, 109, 849

Hambly, N. C., Collins, R. S., Cross, N. J. G., et al. 2008, MNras, 384, 637

Hambly, N. C., Davenhall, A. C., Irwin, M. J., & MacGillivray, H. T. 2001a, MNras, 326, 1311

Hambly, N. C., Irwin, M. J., & MacGillivray, H. T. 2001b, MNras, 326, 1297

Hambly, N. C., MacGillivray, H. T., Reid, M. A., et al. 2001c, MNras, 321, 1279

Hewett, P. C., Warren, S. J., Leggett, S. K., & Hodgkin, S. T. 2006, MNras, 367, 454

Jao, W.-C., Henry, T. J., Beaulieu, T. D., & Subasavage, J. P. 2008, AJ, 136, 840

Jones, E. M. 1972, ApJ, 177, 245

Kirkpatrick, J. D., Cushing, M. C., Gímez, C. M., et al. 2011, ApJS, 197, 19

Kirkpatrick, J. D., Henry, T. J., & McCarthy, D. W. 1991, ApJ, 77, 417

Kirkpatrick, J. D., Looper, D. L., Burgasser, A. J., et al. 2010, ApJS, 190, 100

Kirkpatrick, J. D., Reid, I. N., Liebert, J., et al. 2000, AJ, 120, 447

Lépine, S., Rich, R. M., & Shara, M. M. 2003a, ApJL, 591, L49

Lépine, S., Rich, R. M., & Shara, M. M. 2003b, AJ, 125, 1598

Lépine, S., Shara, M. M., & Rich, R. M. 2002, AJ, 121, 1490

Lépine, S., Shara, M. M., & Rich, R. M. 2003c, AJ, 126, 921

Latham, D. W., Stefanik, R. P., Torres, G., et al. 2002, AJ, 124, 1144

Lawrence, A., Warren, S. J., Almainn, O., et al. 2007, MNras, 379, 1599

Leggett, S. K., Geballe, T. R., Fan, X., et al. 2000, ApJL, 536, L35

Lépine, S., Rich, R. M., & Shara, M. M. 2007, ApJ, 669, 1235

Lépine, S. & Scholz, R.-D. 2008, ApJL, 681, L33

Lépine, S. & Shara, M. M. 2005, AJ, 129, 1483

Lépine, S., Shara, M. M., & Rich, R. M. 2003, ApJL, 585, L69

Lodieu, N., Leggett, S. K., Bergeron, P., & Nitta, A. 2009, ApJ, 692, 1506

Lodieu, N., Pinfield, D. J., Leggett, S. K., et al. 2007, MNras, 379, 1423

Lodieu, N., Scholz, R.-D., Magnier, E. A., et al. 2005, A&A, 440, 1061

Lodieu, N., Zapatero Osorio, M. R., Martin, E. L., Solano, E., & Aberasturi, M. 2010, ApJL, 708, L107

Luyten, W. J. 1979, LHS catalogue. A catalogue of stars with proper motions exceeding 0.5 annually (Minneapolis: University of Minnesota, 1979, 2nd ed.)

Luyten, W. J. 1980, NLTT catalogue. Vol.3: 0. deg. to -10. deg. (Minneapolis: University of Minnesota, 1980)
Riaz, B., Gizis, J. E., & Samaddar, D. 2008, ApJ, 672, 1153
Roesser, S., Demleitner, M., & Schilbach, E. 2010, AJ, 139, 2440
Ryan, S. G. 1989, AJ, 98, 1693
Salim, S. & Gould, A. 2002, ApJL, 575, L83
Salim, S. & Gould, A. 2003, ApJ, 582, 1011
Schilbach, E., Röser, S., & Scholz, R. 2009, A&A, 493, L27
Schmidt, S. J., West, A. A., Burgasser, A. J., Bochanski, J. J., & Hawley, S. L. 2010a, AJ, 139, 1045
Schmidt, S. J., West, A. A., Hawley, S. L., & Pineda, J. S. 2010b, AJ, 139, 1808
Scholz, R., Lehmann, I., Matute, I., & Zinnecker, H. 2004a, A&A, 425, 519
Scholz, R.-D., Irwin, M., Ibata, R., Jaehreiß, H., & Malkov, O. Y. 2000, A&A, 353, 958
Scholz, R.-D., Lodieu, N., & McCaughrean, M. J. 2004b, A&A, 428, L25
Schweitzer, A., Scholz, R.-D., Stauffer, J., Irwin, M., & McCaughrean, M. J. 1999, A&A, 350, L62
Sivarani, T., Lépine, S., Kembhavi, A. K., & Gupchup, J. 2009, ApJL, 694, L140
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
van Altena, W. F., Lee, J. T., & Hoffleit, E. D. 1995, The general catalogue of trigonometric [stellar] parallaxes, ed. van Altena, W. F., Lee, J. T., & Hoffleit, E. D.
West, A. A., Hawley, S. L., Bochanski, J. J., et al. 2008, AJ, 135, 785
West, A. A., Morgan, D. P., Bochanski, J. J., et al. 2011, AJ, 141, 97
Wood, V. M., Lépine, S., & Wallerstein, G. 2009, PASP, 121, 117
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Yong, D. & Lambert, D. L. 2003, PASP, 115, 796
Zacharias, N., Finch, C., Girard, T., et al. 2010, AJ, 139, 2184
Zhang, Z. H., Pinfield, D. J., Day-Jones, A. C., et al. 2010, MNRAS, 404, 1817
Fig. 1. Finding charts for 16 confirmed subdwarfs. Images are in the Sloan $z$-band and approximately $2.64 \times 1.94$ arcmin aside with North up and East left. The ID number of the object is indicated at the top left of the image and the scale at the bottom left.
Fig. 2. The other 16 candidates identified in this work: the remaining four subdwarfs confirmed spectroscopically are shown at the top, the seven solar-metallicity M dwarfs below followed by the five candidates without optical spectra. Images are in the Sloan $z$-band and approximately $2.64\times1.94$ arcmin aside with North up and East left. The ID number of the object is indicated at the top left of the image and the scale at the bottom left.
