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

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Abstract. Subdwarfs are metal-poor low-mass stars located in the halo or thick disk of our Galaxy. They appear less luminous than their solar counterparts, show high proper motions, and strong metal-hydride absorption bands and metal lines in their optical spectra. We conducted a photometric and astrometric search for subdwarfs with Virtual Observatory tools. We obtained low-resolution optical spectra for 77 of 100 candidates and classified them using two methods: spectral indices and templates. We report 72 new ultracool subdwarfs, including 2 new L subdwarfs. We checked WISE photometry of known and new subdwarfs and present some preliminary results.

Key words. Stars: subdwarfs – Stars: – Stars: Population II – Galaxy: halo – technique: spectroscopic – surveys – virtual observatory tools

1. Introduction

Subdwarfs are Population II stars located mainly in the halo of our Galaxy, but also in the thick disk. They appear less luminous than the dwarfs of solar-type due to the lack of metals in their atmospheres (Saumon et al. 1995; Baraffe et al. 1997). They show halo or thick disk kinematics, have high proper motions, and large heliocentric velocities (Gizis 1997). They likely have ages between 10 and 15 Gyr, so they belong to the first generations of stars and are considered chemical tracers of the Milky Way history (Burgasser et al. 2003). They lie below the main sequence in the Hertzsprung-Russell diagram and have luminosity VI in the Yerkes classification. Typically M subdwarfs have $T_{\rm eff}$ ~2500-4000 K (it also depends on the metallicity, see Woolf et al. 2009). The current spectral classification for subdwarfs was presented by Lépine et al. (2007) considering indices presented by Gizis (1997) and it is based on the strength of the TiO and CaH absorp-

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tion bands at optical wavelengths. They are divided in 3 classes: subdwarfs, extreme subdwarfs, and ultra subdwarfs, with metallicities of ~ -0.5, -1.0, and -2.0 respectively (Lépine et al. 2007).

We searched for subdwarfs with spectral types equal or later than M5 in large-scale surveys using tools developed as part of the Virtual Observatory. This is a long-term project with several global objectives, in this work we focus on develop efficient criteria to search for ultracool subdwarfs and increase their number to bridge the gap between M and L subdwarfs.

2. Photometric and astrometric selection

We carried out 2 main cross-matches: SDSS DR9 (Sloan Digital Sky Survey[1] Data Release 9; York et al. 2000) vs UKIDSS (UKIRT Infrared Deep Sky Survey[2]) LAS DR10 (Large Area Survey, Data Release 10; Lawrence et al. 2007), and SDSS DR7 vs 2MASS[3] (Two-Micron All Sky Survey; Skrutskie et al. 2006). The common area between SDSS DR9 and UKIDSS LAS DR10 is of 3457 square degrees and 11663 square degrees for SDSS DR7 vs 2MASS. We used the following photometric and astrometric criteria to look for ultracool subdwarfs:

$$\begin{aligned} r-i &\geq 1.0\,\text{mag} \\ g-r &\geq 1.8\,\text{mag} \\ r-z &\geq 1.6\,\text{mag} \\ J-K &\leq 0.7\,\text{mag} \end{aligned}$$

$Hr \geq 20.7$ mag, where $Hr = r + 5 \times \log(\mu) + 5$, being μ the proper motion.

In Figure 1 we plot our 100 candidates, those identified in the SDSS vs 2MASS cross-match are plotted with their 2MASS photometry unless they are covered by UKIDSS. The coolest subdwarfs are the reddest in $i-J$.

Figure 2 represents the reduced proper motion diagram Hr vs $r-z$ where three sequences

[1] www.sdss.org
[2] www.ukidss.org
[3] www.ipac.caltech.edu/2mass

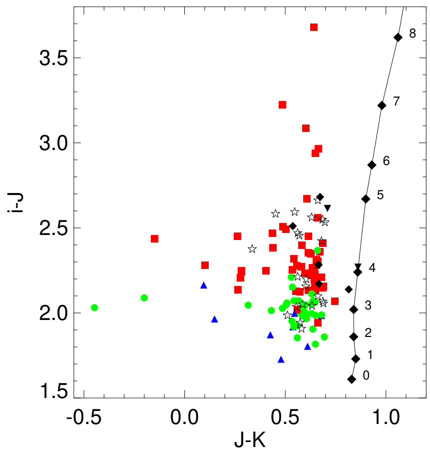

Fig. 1. Our 100 candidates to ultracool subdwarfs identified in this work: subdwarfs (squares), extreme subdwarfs (circles), ultra subdwarfs (triangles), solar-metallicity dwarfs (diamonds), uncertain subdwarfs (upside down triangles), and candidates without optical spectra (stars). The vertical solid line shows a sequence of known M dwarfs with solar-metallicity from West et al. (2008). The photometry here is in the MKO photometric system (Hewett et al. 2006).

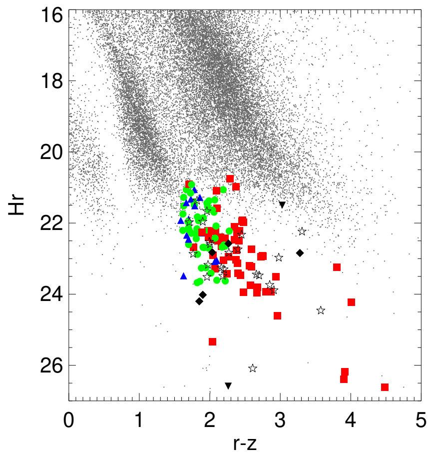

Fig. 2. Reduced proper motion diagram ($r-z$, Hr) including our candidates to ultracool subdwarfs (same symbols as in Figure 1). Three sequences are seen: white dwarfs (left), subdwarfs (middle), and solar-metallicity dwarfs (right).

Table 1. A subsample including the latest M subdwarf and extreme subdwarf found, also 2 new L subdwarfs added to the literature. The latest ultra subdwarf found is not included for space and because was already published in Lépine & Scholz (2008). The columns correspond to the identifier number of the candidate (ID), coordinates (in J2000) from SDSS DR9, total proper motion (in arcsec yr^{-1}) calculated using VO tools, reduced proper motion (Hr), $r-z$ colour, $i-J$ colour, $J-K$ colour, and the Data Release of SDSS and UKIDSS LAS (cross-match).

ID	R.A. hh:mm:ss.ss	Dec. dd:mm:ss.s	μ_{VO} $'' yr^{-1}$	Hr_{VO} mag	$r-z$ mag	$i-J$ mag	$J-K$ mag	SDSS DR	UKIDSS LAS DR
30	01:04:48.47	+15:35:01.9	0.298	24.610	2.961	2.436	-0.148	7	6
32	02:12:58.07	+06:41:17.6	0.422	26.386	3.899	3.679	0.642	7	6
61	13:18:22.81	-01:11:50.2	0.185	22.677	2.175	2.046	0.316	7	8
63	14:14:05.74	-01:42:02.7	0.239	24.230	4.008	2.964	0.664	7	8

are seen: white dwarfs on the left, subdwarfs in the middle, and solar-metallicity dwarfs on the right. Our candidates and known subdwarfs are plotted with the same symbols as in Figure 1. The small grey dots correspond to objects from the Lépine and Shara (2005) catalogue with SDSS photometry. We selected subdwarf candidates with several tools: STILTS[4] (Taylor 2006), TOPCAT[5] (Taylor 2005), and Aladin[6] (Bonnarel et al. 2000). A preliminary value of the proper motion was calculated using VO tools considering the positions and epochs given in the 2MASS, SDSS, and UKIDSS catalogues. We refined their proper motions by performing accurate astrometric studies of the bidimensional images retrieved from the databases to reject potential false candidates before spectroscopic follow-up. We did a fit and obtained a more accurate value of the proper motion with reference stars (about 30) in the images and using IRAF (`http://iraf.noao.edu`) tasks like DAOFIND, XYXYMATCH, GEOMAP, and GEOXYTRAN.

3. Observations and data reduction

We obtained long-slit optical spectra with different telescope/instrument configurations: 11 at the Gran Telescopio de Canarias (GTC) with OSIRIS[7] (Optical System for Imaging and low Resolution Integrated Spectroscopy) at a resolution of R~500 between January 2010 and April 2013; six at the Nordic Optical Telescope (NOT) with ALFOSC[8] (Andalucia Faint Object Spectrograph and Camera) at a resolution of R~450 between January and August 2009; thirty nine at the Very Large Telescope (VLT) using FORS2[9] (visual and near UV FOcal Reducer and low dispersion Spectrograph) at a resolution of R~350 between January 2012 and March 2013. We checked the SDSS spectroscopic database and we found that 30 of the candidates have a spectrum in SDSS, 9 of them in common with our spectroscopic follow-up. We performed the data reduction with IRAF, including bias and flat correction, optimal extraction of the spectrum, wavelength and flux calibration with a spectrophotometric standard.

4. Spectral classification: indices and templates

We derived spectral types for our candidates using the scheme presented by Lépine et al. (2007). We also determined spectral types using spectral templates of known subdwarfs downloading the spectrum of the brightest ob-

[4] `www.star.bris.ac.uk/~mbt/stilts`
[5] `www.star.bris.ac.uk/~mbt/topcat`
[6] `http://aladin.u-strasbg.fr`
[7] `www.gtc.iac.es/instruments/osiris`
[8] `www.not.iac.es/instruments/alfosc`
[9] `www.eso.org/sci/facilities/paranal/instruments/fors`

Table 2. Spectral indices and classification according to the scheme of Lépine et al. (2007), and final spectral types derived from spectral templates (uncertainty of 0.5) for the objects in Figure 3.

ID	TiO5	CaH1	CaH2	CaH3	TiO5z	SpT Lepine	SpT final	Telescope
30	0.518	0.363	0.110	0.208	-0.025	esdM9.5	sdM9.5	VLT
32	0.098	0.041	0.150	0.390	0.056	dM7.5	sdL0.5	GTC
61	0.790	0.378	0.203	0.305	0.041	esdM7.5	esdM8.0	VLT
63	0.263	0.549	0.043	0.259	-0.029	sdM9.5	sdL0.5	VLT

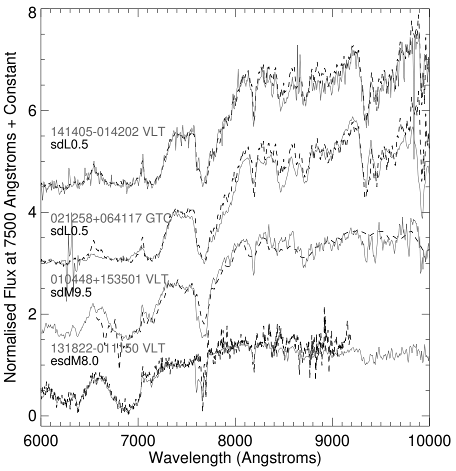

Fig. 3. Subsample from table 1 (plotted in grey). Overplotted in black dashed lines are the templates corresponding to the spectral type adopted in each case.

ject of each spectral type (from M0 to the latest M subtype available) for the three classes of subdwarfs and for the solar-metallicity M dwarfs from the SDSS spectroscopic database. We also included in our templates some of late-M and L subdwarfs with spectra available from the literature. The results are summarized in Table 2 and the spectra of this subsample are shown in Figure 3.

5. Results of the search

We confirmed 26 of 29 candidates as ultracool subdwarfs from the SDSS DR7 vs 2MASS cross-match, yielding a success rate of 86%. We confirmed 46 of 48 candidates as ultracool subdwarfs from the SDSS DR9 vs UKIDSS LAS DR10 cross-match, yielding a success rate of 96%. These success rates are considering the initial sample, before obtain refined values of proper motions. To summarize, there are 77 candidates with optical spectra: 36 sdM, 2 sdL, 26 esdM, 6 usdM, 2 dM/sdM, and 5 dM. The two objects with class dM/sdM are uncertain subdwarfs, because they show features of a subdwarf sdM6.5, but they also look similar to solar-type dwarf (one has features of a dM3 and the other of a dM4.5). Since they could be considered sdM6.5 they are included in the success rates. The candidate classified as an sdM3.0 is not included in the success rate. We developed a very efficient photometric and astrometric method to look for ultracool subdwarfs: we increased by 4 the number of known ultracool subdwarfs and we added 4 new L subdwarfs (considering the 2 in Lodieu et al. 2012). Also, we found some contaminants: solar-metallicity M dwarfs and one subdwarf classified as sdM3. This is mainly due to false values of proper motions which is used to calculate the reduced proper motion (Hr), a key parameter to look for low-metallicity M dwarfs. False proper motions could occur because the coordinates of the object given in the catalogues are not exact (this can be checked looking at the image) or because there is another object very close which results in a false cross-match.

6. Subdwarfs in WISE

The Wide-field Infrared Survey Explorer[10] (WISE; Wright et al. 2010) mapped the sky at 3.4 (W1), 4.6 (W2), 12 (W3), and 22 (W4) μm.

[10] http://wise.ssl.berkeley.edu

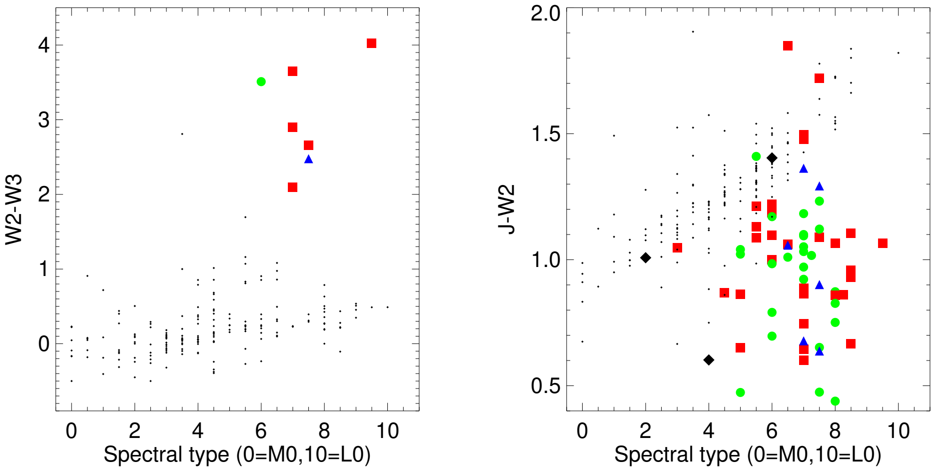

Fig. 4. Colour vs spectral type diagrams: $W2 - W3$ (left) and $J - W2$ (right) showing known and our new subdwarfs (same symbols as Figure 1), small dots are M dwarfs from DwarfsArchive.org.

In Figure 5 we plot our new subdwarfs and known subdwarfs (Lodieu et al. 2012; Lépine & Scholz 2008) with WISE photometry in two diagrams showing their colours vs spectral types. Black dots correspond to solar-metallicity M dwarfs from DwarfsArchive.org with WISE photometry. The typical error bars in the $W2 - W3$ and $J - W2$ colours are of 0.5 mag and 0.2 mag respectively. We observe that low-metallicity dwarfs with spectral types later than M4 appear significantly redder in $W2 - W3$ and bluer in $J - W2$ than their solar-abundance counterparts, in marked contrast with the typically blue near-infrared and $J - W2$ colours. These colours appear to depend on metallicity. The blue nature of the $J - W2$ index can be explained by the onset of collision-induced H2 opacity operating at near-infrared wavelengths. The origin of the very red W2-W3 color is less clear. This trend could be used to define new criteria to find cooler ultracool subdwarfs in WISE.

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