TWENTY-THREE NEW ULTRACOOL SUBDWARFS FROM THE SLOAN DIGITAL SKY SURVEY

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ABSTRACT

A search of the Sloan Digital Sky Survey spectroscopic database has turned up 23 new ultracool subdwarfs, low-mass metal-poor stars of spectral subtype M 7.0 or later. Spectra from these red objects all show very strong molecular bands of CaH but relatively weak bands of TiO, indicative of a cool, metal-poor atmosphere. Five of the stars are formally classified as M subdwarfs (sdM7.0–sdM8.5), 13 as more metal-poor extreme subdwarfs (esdM7.0–esdM8.0), and five as extremely metal-poor ultra subdwarfs (usdM7.0–usdM7.5). In the \([H_\alpha, r-z]\) reduced proper motion diagram, these subdwarfs clearly populate the locus of low-luminosity stars with halo kinematics. It is argued that the objects are all very low mass, metal-poor stars from the Galactic halo (Population II). These new discoveries more than double the census of spectroscopically confirmed ultracool subdwarfs. We show that the stars stand out remarkably in the \([g-r, r-i]\) color-color diagram; a proposed color and proper motion selection scheme is expected to be extremely efficient in identifying more of these old, very low mass stars in the vicinity of the Sun.

Subject headings: Galaxy: halo — Galaxy: stellar content — solar neighborhood — stars: late-type — subdwarfs

1. INTRODUCTION

Ultracool dwarfs are very red objects with spectral subtype M7.0 or later. The class includes very low mass stars, with masses just above the hydrogen-burning limit, and extends into the substellar (brown dwarf) regime. While ultracool dwarfs are expected to be common, their low luminosities make them very challenging objects to find and study, outside of the immediate vicinity of the Sun. The census of spectroscopically confirmed ultracool dwarfs remains quite small compared with the very large numbers of low-mass stars now formally classified as M0–M6 dwarfs (West et al. 2008).

Ultracool subdwarfs are the metal-poor analogs of the ultracool dwarfs. While representatives of the latter group have been known for some time (Kirkpatrick et al. 1991; Kirkpatrick et al. 1995), it is only recently that ultracool subdwarfs have been spectroscopically identified. In the solar vicinity, ultracool subdwarfs are kinematically associated with the Galactic halo (Lépine et al. 2003a) and represent the low-mass end of the local Population II. As such, their local density is quite low, which explains their scarcity in the solar vicinity.

Dwarfs and subdwarfs of spectral type M have optical spectra dominated by molecular bands of metal hydrides (CaH, FeH) and metal oxides (TiO, VO). Under the classification system recently proposed by Lépine et al. (2007) that expands the system of Gizis (1997), main-sequence M stars are segregated into four “metallicity classes.” These are assigned on the basis of the relative strength of oxide and hydride bands, which dominate the optical-red spectrum and whose ratio is believed to be a function of \(\log Z\) (Gizis & Reid 1997). Solar-metallicity objects are classified as dwarfs (M, or dM), while the more metal-poor stars are classified as subdwarfs (sdM), extreme subdwarfs (esdM), and ultra subdwarfs (usdM), in order of decreasing metallicity. At the turn of the century, only two ultracool subdwarfs were known: the sdM7.0 subdwarf LHS 377 (Gizis 1997), and the esdM7.0 extreme subdwarf APMPM J0559–2903 (Schweitzer et al. 1999). Since then, a dozen more objects have been discovered, spanning the spectral type ranges sdM7.0–sdM9.5, esdM7.0–esdM8.5, and usdM7.0–usdM7.5 (Lépine et al. 2003b, 2004; Scholz et al. 2004a, 2004b; Gizis & Harvin 2006; Burgasser & Kirkpatrick 2006; Burgasser et al. 2007; Lépine et al. 2007).

In addition, metal-poor stars have also been found into the L spectral type regime (Burgasser et al. 2003; Burgasser 2004). These objects are clearly substellar in nature and believed to be Population II brown dwarfs. A case in contention is the star LSR J1610–0040, initially classified as an sdL (Lépine et al. 2003c), but which may be a peculiar sdM (Cushing & Vacca 2006; Reiners & Basri 2006). One thing is clear at this time: the census of local ultracool subdwarfs is largely incomplete and our knowledge fragmentary. Much more extensive samples are required, which would be critical in constraining the low end of the Galactic halo mass function and understanding the properties of cool, metal-poor atmospheres.

This Letter reports the discovery of 23 new ultracool subdwarfs from the Sloan Digital Sky Survey (SDSS) spectroscopic database. This more than doubles the current census of spectroscopically confirmed ultracool subdwarfs and suggests a simple method for the identification of more such stars. The search and identification is described in § 2, where the spectra are also presented. Colors and reduced proper motions are analyzed in § 3. Results are discussed in § 4.

2. SPECTROSCOPIC IDENTIFICATION

A search for cool subdwarfs was performed on the spectroscopic database of the Sloan Digital Sky Survey (Gunn et al. 1998; York et al. 2000). A subsample of 44,600 SDSS spectra from the sixth data release (Adelman-McCarthy et al. 2008)
Fig. 1.—SDSS medium-resolution spectra of all ultracool subdwarfs identified in the SDSS database, all new objects except for the usdM7.5 classification standard LSR J0822+1700 (bottom right). The most prominent feature in all those very red spectra is the deep CaH molecular absorption band just blueward of 7000 Å. The strength of the TiO bands redward of 7000 Å is used to assign metallicity classes, as the ratio of TiO to CaH is assumed to be proportional to log Z.

was retrieved, including all spectra from pointlike sources (STAR and STAR LATE flags) with colors \( g - r > 1.0 \). Each spectrum was automatically matched against a grid of composite spectra of M dwarfs and subdwarfs assembled by S. Lépine (2008, in preparation). This grid, built on the four-class metallicity system of Lépine et al. (2007), includes reference spectra for M stars of all four metallicity subclasses (dM, sdM, esdM, usdM), covering all known spectral subtypes with a 0.5-subtype resolution. The new grid expands and complements the M dwarf classification templates assembled by Bochanski et al. (2007).

Spectral classes and subtypes are assigned on the basis of a least-squares fit over the full 6100–7900 Å spectral range. This improves on the standard classification scheme for M subdwarfs, which is based on the absolute and relative strengths of the three line indices CaH2, CaH3, and TiO5 (Reid et al. 1995; Gizis 1997; Lépine et al. 2003a, 2007). The main problem with those molecular line indices is that they are defined over relatively narrow spectral ranges, making them unreliable in low signal-to-noise spectra. A fit over a much broader spectral region made it possible to classify SDSS spectra from very faint sources, with a signal-to-noise ratio per resolution element as low as \( S/N \sim 5 \). Since the classification grid is built from a combination of those same SDSS spectra, several iterations were made on which the grid was modified and vetted against the spectral index classification system.

Our automated analysis of the 44,600 red stellar spectra in the end yielded the formal identification of 24 M subdwarfs of spectral subtype 7.0 or later. One of the spectra was found to be of the nearby high proper motion star LSR J0822+1700, recently selected as a subdwarf classification standard (usdM7.5) by Lépine et al. (2007). All the other stars are identified here as ultracool subdwarfs for the first time. The final tally includes five subdwarfs (sdM7.5–sdM8.5), 13 extreme
for only a few stars. We instead determined the proper motions up in 2MASS. Proper motions were found in the SDSS catalog ultracool M subdwarfs; 15 of them are even too faint to show

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locus at very low metallicities.

subdwarfs (esdM7.0–esdM8.0), and five ultra subdwarfs (usdM7.0–usdM7.5). Spectra of all 23 new ultracool subdwarfs are presented in Figure 1, along with the spectrum of LSR J0822+1700.

Basic astrometry and photometry is presented in Table 1, along with SDSS griz photometry (Gunn et al. 1998; Fukugita et al. 1996), and J magnitude from the 2MASS All-Sky Catalog of Point Sources (Cutri et al. 2003). All except one (SDSS J1351 +5506) are fainter than any of the previously known ultracool M subdwarfs; 15 of them are even too faint to show up in 2MASS. Proper motions were found in the SDSS catalog for only a few stars. We instead determined the proper motions for all the stars from their photographic plate counterparts, as found in the SuperCOSMOS sky survey (Hambly et al. 2001) and the APM-North catalog (McMahon et al. 2000). Proper motions were calculated from a linear regression of the early-epoch plate positions and later SDSS coordinates. Results are shown in Table 1.

3. COLORS AND REDUCED PROPER MOTION

Figure 2 shows the location of our ultracool subdwarfs in the [\( g-r, r-i \)] diagram (left panel). For comparison, a sub-sample of 50,000 random SDSS point sources is also displayed (dots). The ultracool subdwarfs are found to stand out significantly from the locus of the field stars, confirming the trend observed for earlier M subdwarfs by West et al. (2004). Stars are also segregated by metallicity subclass, with the sdM having

![Fig. 2.—Left panel: Color-color magnitude diagram [\( g-r, r-i \)] of SDSS ultracool subdwarfs (symbols). The subdwarfs are clear outliers to the standard locus of field stars, here denoted with a random sample of 50,000 SDSS point sources (dots). The ultracool subdwarfs are also clearly segregated by spectral class, which suggests a stellar locus strongly dependent on metallicity, from the strong ”elbow-shaped” locus for stars of solar abundances to an almost “straight-line” locus at very low metallicities. Right panel: Reduced proper motion diagram of the SDSS ultracool subdwarfs (symbols). The stars populate the low-luminosity end of the Population II main sequence, which unambiguously identifies them as low-mass subdwarfs. A distribution of high proper motion stars from the LSPM-North catalog (Lépine & Shara 2005) with SDSS counterparts is shown for comparison (dots); the distinct loci of disk dwarfs, halo subdwarfs, and white dwarfs (in layers from upper right to lower left, respectively) are clearly defined.](image-url)
larger $r - i$ colors and usdM smaller $r - i$ values. The trend suggests that at lower metallicities, cool stars tend to fall more in line with the extrapolarated color–color sequence of the more massive stars (dashed line), consistent with a spectral energy distribution more similar to that of a blackbody.

Stars for which proper motions are available all have $\mu > 200$ mas yr$^{-1}$, which suggests that they are either high-velocity objects and/or have very low luminosities. The right panel in Figure 2 shows the $[H_r, r - z]$ reduced proper motion diagram for all the SDSS ultracool subdwarfs with recorded $\mu > 200$ mas yr$^{-1}$. The objects are all located along the extension of the Population II sequence (Yong & Lambert 2003; Lépine et al. 2007), which runs between the Population I sequence (upper right) and the white dwarf sequence (lower left). This unambiguously demonstrates that the stars are low-mass objects at the bottom of the main sequence and kinematically associated with the Galactic halo population.

The very distinctive distribution of colors and reduced proper motions suggests an efficient method to identify ultracool subdwarfs. They should be found among stellar sources with $g - r > 1.85$ and $g - i > 3.1$ (see Fig. 2). Additional proper motion or reduced proper motion constraints would optimally select for those low-luminosity objects, with minimal background contamination. This would work best at high Galactic latitudes, where interstellar reddening is minimal.

4. DISCUSSION AND CONCLUSIONS

Our successful search for ultracool subdwarfs demonstrates that these stars can be identified in deep optical surveys like SDSS. The stars stand out in the $g - r$, $r - i$ color–color diagram, their locus clearly distinct from that of solar-metallicity objects. This makes them easy to identify from point sources in fields imaged in the SDSS ugriz color system. It is expected that ultracool subdwarfs will be easy to identify in future, deep imaging surveys, provided they use similar gri bandpasses. The fact that ultracool subdwarfs are segregated by metallicity in color–color space also makes them highly valuable tracers of Galactic halo structure and history.

In color–color space, the ultracool subdwarfs populate a region typically occupied by extragalactic objects such as QSOs (Richards et al. 2002). Indeed, all 23 new ultracool subdwarfs presented in this Letter were QSO targets in the SDSS spectroscopic survey. Interestingly, this is not the first time that ultracool stars are discovered as a by-product of QSO surveys; ultracool dwarfs were also identified in early surveys of high-redshift quasars (Kirkpatrick et al. 1997). But just like subdwarfs are a contaminant for QSO surveys, QSOs would also be a common contaminant of subdwarf surveys. Absolute proper motion cuts would be necessary to limit the contamination from extragalactic sources. It is fortunate that subdwarfs are kinematically associated with the local Galactic halo population and tend to be high-velocity stars in the vicinity of the Sun. A combination of color cuts and minimal proper motion requirement would be the most efficient technique to select ultracool subdwarfs.

In the meantime, the spectra collected here will be used to further refine the classification templates and assist in the identification and classification of ultracool subdwarfs in upcoming SDSS data releases. The subdwarf classification routine is now being integrated to the SEGUE spectral reduction pipeline, and ultracool subdwarfs are now expected to be routinely identified in the SDSS survey.

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