ABSTRACT

We report the discovery of a high proper motion L subdwarf ($\mu = 0\farcs617 \, \text{yr}^{-1}$) in the Sloan Digital Sky Survey (SDSS) spectral database. The optical spectrum from the star SDSS J125637–022452 has mixed spectral features of both late-M spectral subtype (strong TiO and CaH at 7000 Å) and mid-L spectral subtype (strong wings of KI at 7700 Å, CrH, and FeH), which is interpreted as the signature of a very low-mass, metal-poor star (ultracool subdwarf) of spectral-type sdL. The near-infrared (NIR) ($J-K_s$) colors from 2MASS show the object to be significantly bluer compared to normal L dwarfs, which is probably due to a strong collision-induced absorption (CIA) from the H$_2$ molecule. This is consistent with the idea that CIA from H$_2$ is more pronounced at low metallicities. Proper motion and radial velocity measurements also indicate that the star is kinematically “hot” and probably associated with the Galactic halo population.

Key words: Galaxy: halo – stars: individual (SDSS J125637–022452) – stars: low-mass, brown dwarfs – subdwarfs

1. INTRODUCTION

Ultracool dwarfs, low-mass objects of low temperature extending beyond the classical main sequence, have been identified in significant numbers from recent large-optical and near-infrared (NIR) surveys, such as the Deep Near Infrared Survey (DENIS; Epchtein et al. 1997), the Sloan Digital Sky Survey (SDSS; York et al. 2000), and the Two Micron All Sky Survey (2MASS; Cutri et al. 2003). Two new spectral types and T dwarfs classified to date (Kirkpatrick et al. 1999, 2000; Geballe et al. 2002; Hawley et al. 2002; Geballe et al. 2002; Burgasser et al. 2003a). Most stars classified as L and T dwarfs are relatively metal-rich, and associated with the Galactic disk population.

One also expects the Solar neighborhood to be host to ultracool members of the Galactic halo (Population II). However, Pop II stars are rare in the vicinity of the Sun, where they account for roughly one out of every 200 stars. Conversely, one expects ultracool subdwarfs (sdL, sdT) to be equally rare. In any case, old metal-poor stars and brown dwarfs are expected to display a distinct spectral signature, making their identification straightforward. In stars of spectral-type M, metal depletion is known to result in a weakening of metal oxide bands, usually prominent in M stars (Kuiper 1939). M subdwarfs are thus organized following distinct classification sequences as subdwarfs (sdM), extreme subdwarfs (esdM), and ultrasubdwarfs (usdM), depending on the magnitude of metal-depletion effects in their spectra (Gizis 1997; Lépine et al. 2007). Note that spectroscopically confirmed M subdwarfs number only in the hundreds (Lépine et al. 2007), compared with the tens of thousands of stars now classified as M dwarfs.

Very few subdwarfs of spectral subtype sdM7 or later (ultracool subdwarf) have been identified to date. Most have been discovered in follow-up spectroscopic surveys of faint stars with very large proper motions (Lépine et al. 2002, 2003a), others from the massive SDSS spectroscopic database (West et al. 2004; Lépine 2008). Extending the M subdwarf sequence to subtypes later than sdM7/esdM7/usdM7 has been straightforward as the metal-poor stars display the same weakening of the TiO bands as documented for earlier subtypes. More challenging has been the identification of metal-poor stars beyond the spectral type M, in the range of surface temperatures characteristic of the L and T stars, and designated as L and T subdwarfs (sdL, sdT).

The first star to be unambiguously identified as a subdwarf spectral-type L is 2MASS 0532+8246 (Burgasser et al. 2003b). The optical spectrum had mixed spectral features corresponding to early and late L spectral types. The NIR spectrum has strong collision-induced absorption (CIA) due to H$_2$ molecules, giving a blue color similar to a T dwarf. Another star with similar features (2MASS 1626+3925) was discovered by Burgasser et al. (2004) and also tentatively classified as sdL. A third object, the star LHS 1610–0040, was initially claimed to be an early-type subdwarf (Lépine et al. 2003b), but further analysis has failed to substantiate the claim (Reiners & Basri 2006; Cushing & Vacca 2006); the star is now believed to be a peculiar late-type dwarf, possibly displaying anomalous metal abundances (Dahn et al. 2008).

In this Letter, we present the discovery of another object with spectral characteristic consistent with a metal-poor “L subdwarf.” The star SDSS 125637–0224 was identified from the SDSS spectroscopic database, and is found to be significantly cooler than all known M subdwarfs, but warmer than 2MASS 0532+8246 and 2MASS 1626+3925. We examine the spectral characteristics and kinematics of the star.

2. SEARCH AND IDENTIFICATION

The SDSS obtains spectra from a variety of objects based on various color- and magnitude-selection cuts (Stoughton et al. 2002). The survey is not complete in most of the star categories, as a limited number of fibers (640) are used in each of the SDSS fields, and stellar targets are assigned only after the primary categories (QSOs, galaxies). The spectra cover the full 3300–9500 Å wavelength range, which includes the main molecular features used to identify cool dwarfs and subdwarfs.
The SDSS second data release (DR2) listed 13,379 spectra of sources identified as cool and ultracool stars (spectral subtype M and later). The DR2 covered a total survey area of 2627 deg$^2$ or a little over 6.5% of the sky. In an attempt to detect ultracool L subdwarfs from this sample, we have systematically examined the spectra form all stellar sources with very red optical-to-infrared color. First, we identified all possible counterparts to the 13,379 late-type stars in the 2MASS All-Sky catalog of point source (2MASS; Cutri et al. 2003). Then we assembled spectra of all the stars with magnitude $r > 18$ and color $(r-K_s) > 6.0$, which eliminating from the sample of most objects with spectral subtypes M6 or earlier. We visually inspected all the spectra in search of any star with a peculiar spectral energy distribution (SED). All spectra were found to be consistent with either late-type M dwarfs or L dwarfs, except for only one which clearly stood out from the group: the spectrum of the star SDSS 125637–0224.

Sloan photometry shows SDSS 125637–0224 to be very faint in the optical infrared catalog, but it has relatively bright counterparts in both the 2MASS and DENIS infrared catalogs; the object is clearly very red. It is undetected in the Digital Sky Survey blue (IIIaJ) and red plates (IIIaF), but has a counterpart on the infrared (IVn) plates—and is thus registered in the SuperCOSMOS Sky Archive (SSA). Data on this unusual object are recorded in Table 1.

3. CLASSIFICATION AND SPECTRAL FEATURES

The very red spectrum of SDSS 125637–0224 is displayed in Figure 1. The star shows many spectral features typical of late-M and L dwarfs, which confirms that it is a very cool object and not a background star, affected by reddening. The dominant feature is a deep K$_\text{i}$ doublet at 7700 Å, with strong pressure broadened wings, similar to what is observed in mid-type L dwarfs (Kirkpatrick et al. 1999; Geballe et al. 2002). The spectrum also displays strong bands of CrH and FeH at 8600 Å and atomic lines of RbI, all typically observed in L dwarfs.

Paradoxically, SDSS 125637–0224 also displays well-defined bands of CaH and TiO around 7500 Å in what looks in all other respect like an L dwarf. Indeed redward of 7500 Å, the spectrum is strongly reminiscent of a late-type M dwarf.

Overall, the spectrum does not fit within the standard M/L dwarf classification scheme (Kirkpatrick et al. 1999, 2000), and appears to be a hybrid of M-type and L-type spectral features. However, the spectrum is strikingly similar to the optical spectrum of the “sdL” star 2MASS 1626+3925 (Gizis & Harvin 2006; Burgasser et al. 2007), with prominent bands of TiO and CaH redward of 7500 Å in what looks in all other respect like an L dwarf. The lingering presence of TiO bands in those ultracool

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**Table 1**

| Datum     | Value       | Source                |
|-----------|-------------|-----------------------|
| R.A.      | 12h 56m 37.1s | SDSS–DR6              |
| Decl.     | −02° 24'52.5" | SDSS–DR6             |
| $\mu$R.A. | −470 ± 64 mas yr$^{-1}$ | SDSS–DR6             |
| $\mu$Decl. | −378 ± 64 mas yr$^{-1}$ | SDSS–DR6             |
| u         | 24.74 ± 1.18 mag$^a$ | SDSS–DR6            |
| g         | 23.71 ± 0.37 mag | SDSS–DR6            |
| r         | 21.82 ± 0.11 mag | SDSS–DR6            |
| i         | 19.41 ± 0.02 mag | SDSS–DR6            |
| z         | 17.71 ± 0.02 mag | SDSS–DR6            |
| Extinction_r | 0.06 mag    | Schlegel et al. (1998)|
| J         | 16.10 ± 0.11 mag | 2MASS               |
| H         | 15.79 ± 0.15 mag | 2MASS               |
| K$_\text{s}$ | 15.44: mag | 2MASS               |
| Distance  | 42$^{+17}_{-19}$ pc | SDSS–DR2        |
| U         | −17 km s$^{-1}$ |                      |
| V         | −143 km s$^{-1}$ |                      |
| W         | +43 km s$^{-1}$ |                      |

**Notes.**

$^a$ psf magnitude.

$^b$ I-band magnitude from second epoch DSS plates from SSA.
objects is interpreted as the signature of a metal-poor atmosphere in which dust formation is inefficient and which maintains metal oxides in a gaseous form even at very low temperature.

In any case, SDSS 125637–0224 is too cool to be classified as an M subdwarf. With $(r − z) = 4.15$, SDSS 125637–0224 is significantly redder in the optical spectrum than the coolest known M subdwarfs (Lépine 2008). But again paradoxically, the optical-to-infrared colors are significantly bluer than the coolest L subdwarf 2MASS 0532+82 (Burgasser et al. 2003b), which further suggests that they are of a similar class. In 2MASS SDSS 125637–0224 is significantly bluer than any known field L dwarfs, which all have $(J − K_s) > 1.0$ (Hawley et al. 2002). The same blue $(J − K_s)$ color is observed in the L subdwarf 2MASS 0532+82 (Burgasser et al. 2003b), which further suggests that they are of a similar class. In 2MASS 0532+82, the blue IR color is found to be due to a strong CIA band from $H_2$. Such unusually strong CIA is also suggested to be a consequence of low metallicity (Borysow et al. 1997), and results in a significant redistribution of the flux in the optical. All in all, the photometry of SDSS 125637–0224 also supports the idea that it is a metal-depleted, ultracool dwarf.

We found an unusually strong FeH band head at 8692 Å relative to CrH at 8611 Å. Kirkpatrick et al. (1999) found that the CrH band peaks at spectral type L7, and the FeH band peaks at L2–L4, consistent with a condensation temperature for CrH about few hundred degrees cooler than for FeH. However, CrH and FeH are equally strong at L0, and CrH/FeH just marginally increase at L2 and the bands become equal again at L4. Then CrH/FeH increase again, but around L6 both FeH and CrH start to grow weaker. In SDSS J125637–0224, for the first time, we see FeH stronger than CrH. In 2MASS 0532+8246, the L subdwarf identified by Burgasser et al. (2003b), CrH and FeH are of equal strength; however, one naturally expects a stronger CrH band relative to FeH in this very cool object (∼L7), as observed also in DENIS 0205–1159AB (Burgasser et al. 2003a). The most likely explanation for the larger FeH in SDSS 125637–0224 is that it reflects a low relative abundance from Cr to Fe, compared with solar metallicity L dwarfs. Indeed, in abundance analyses of halo stars of low metallicities ([Fe/H] < −1.0), Cr has been found to be underabundant by about 0.4 dex relative to Fe (McWilliam et al. 1995; Cayrel et al. 2004).

With all evidence pointing to an ultracool subdwarf, and based on the SED in the optical and the breadth of the line).
mid-type L subdwarf, we apply the color–magnitude relationships of Dahn et al. (2002) and Hawley et al. (2002). For an L4 dwarf, the typical absolute $J$ magnitude is $M_J \approx 13.0$, which we assume to be a reasonable estimate. In any case, it seems unlikely that SDSS 125637–0224 should be more luminous than a late-type M dwarf ($M_J \approx 11.5$), and it should be somewhat more luminous than a late-type L dwarf ($M_J \approx 14.5$). Based on these values, we estimate a spectroscopic distance of about 42 pc, with an actual distance possibly ranging between 21 pc and 79 pc.

We derive the space velocities, following the equations from Johnson & Soderblom (1987) and find $[U, V, W] = [-16, -142, +43]$ km s$^{-1}$ for the 42 pc distance. If we vary the distance, we obtain somewhat different values, but the component of V remains consistently large ($<-90$ km s$^{-1}$) which rules out membership in the young disk and again suggests that SDSS 125637–0224 is relatively old. The space velocities are more consistent with inner halo kinematics (Chiba & Beers 2000) and are similar to the known M subdwarfs (Lépine et al. 2003a).

We compared the evolutionary models of Burrows et al. (2001) for a age of 10–15 Gyr and found that for a temperature of about 1800 K for L4 spectral type (Kirkpatrick et al. 1999), the initial mass is just at the hydrogen burning limit.

5. CONCLUSION

There are only three L subdwarfs known at present, and classification schemes based on colors and spectral line indexes are difficult on the basis of three objects. The theoretical spectrum synthesis models are in the preliminary stages, due to the complicated dust chemistry and molecular formation at low temperatures. This makes it difficult to formally characterize SDSS J125637–0224, but evidence strongly suggests that the star should be classified as a mid-type L subdwarf5 (tentatively “sdL4”). This discovery adds up to the only two other objects also tentatively classified as “sdL” (Burgasser et al. 2003b, 2004).

Clear morphological difference between this object and normal L dwarfs shows it is possible to detect such objects at low resolution. SDSS 125637–0224 also stands out in the NIR with bluer color than solar metallicity L dwarfs. However, since these colors are similar to field M dwarfs, photometric identification would be a challenge without proper motion data. Proper motion surveys in the infrared and spectroscopic surveys in the optical infrared and NIR of extreme red objects would provide the best chance to identify more objects of this kind and to establish proper classification sequences.

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5 Schilbach et al. (2009) suggest that SDSS J125637–0224 is a sdL4 subdwarf and has low metallicity, based on their trignometric parallax and accurate NIR colors.