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SDSS J125637-022452: A HIGH PROPER MOTION L SUBDWARF

T. SIVARANI[1,3], S. LÉPINE[2], A. K. KEMBHAVI[3], & J. GUPCHUP[3,4]

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ABSTRACT

We report the discovery of a high proper motion L subdwarf ($\mu = 0.617'' \mathrm{yr}^{-1}$) in the Sloan Digital Sky Survey 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 7000Å) and mid-L spectral subtype (strong wings of KI at 7700Å, CrH and FeH), which is interpreted as the signature of a very low-mass, metal-poor star (ultra-cool subdwarf) of spectral type sdL. The near infrared (NIR) $(J-K_s)$ colors from 2MASS shows the object to be significantly bluer compared to normal L dwarfs, which is probably due a strong collision induced absorption (CIA) due to 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.

Subject headings: Galaxy: halo – stars: low mass, brown dwarf, subdwarf – star: individual SDSS J125637-022452

1. INTRODUCTION

Ultra-cool 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 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 type (L,T) have been added to classify those extremely cool objects, and these are now widely in use, with several hundred L 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. 2003). 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 of 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.

Electronic address:
[1] Department of Astronomy, University of Florida, 211 Bryant Space Science Center, Gainesville, FL, 32611-2055, USA
[2] Department of Astrophysics, Division of Physical Sciences, American Museum of Natural History, Central Park West at 79th Street, New York, NY 10024, USA
[3] Inter University Center for Astronomy and Astrophysics (IUCAA), Pune University Campus,Pune 411 007, India
[4] Department of Computer Science, Johns Hopkins University, 3400 N. Charles street. Baltimore MD 21218, USA

Very few subdwarfs of spectral subtype sdM7 or later ("ultra-cool subdwarfs") 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; Lépine et al. 2003), others from the massive Sloan Digital Sky Survey 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 document for earlier subtypes. More challenging has been the identification of metal-poor stars beyond the spectral type M, in the range of surface temperature characteristic of the L and T stars, and designated as L and T subdwarfs (sdL, sdT).

The first star to be unambiguously identification as a subdwarf spectral type L is 2MASS 0532+8246 (Burgasser et al. 2003). The optical spectrum had mixed spectral features corresponding to early and late L spectral types. The NIR spectrum have 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. (2003c), 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 paper 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 Sloan Digital Sky Survey 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 Sloan Digital Sky Survey 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)

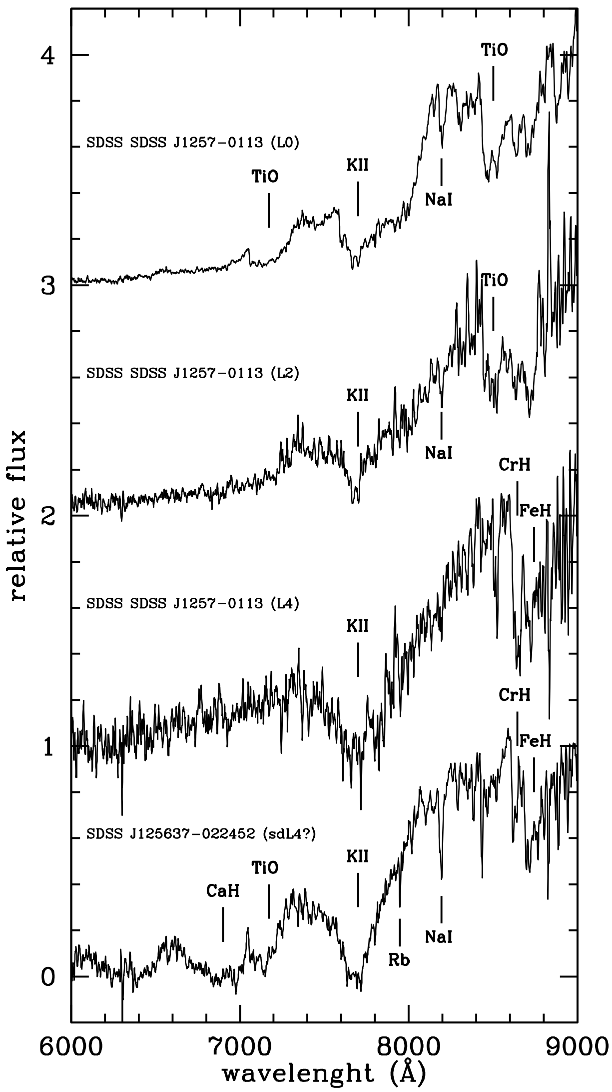

FIG. 1.— Optical SDSS spectrum of the candidate L subdwarf SDSS J125637.1–022452 (bottom), compared with spectra of early-type L dwarfs, also from SDSS. The deep and broadened KI 7700Å doublet, is similar to that of an L4 dwarf. However, SDSS J1256 also displays well defined CaH and TiO molecular bands at 7000Å, typically seen only in M dwarfs. Elsewhere the hydride bands (FeH, CrH) are strong while the oxide (TiO, VO) are weak or absent, which is a defining feature of the metal-poor M subdwarfs. This suggests that SDSS J1256 should be classified as a subdwarf of type L.

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 3300Å-9500Å 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 ultra-cool stars (spectral subtype M and later). The DR2 covered a total survey area of 2627 square degrees or a little over 6.5% of the sky. In an attempt to detect ultra-cool 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 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. 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, 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 I doublet at 7700Å, 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 8600Å 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 7050Å, which are usually observed in M dwarfs and are normally absent in subtypes later than M9, due to the condensation of oxides into dust grains. Indeed redward of 7500Å 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 7500Å in what looks in all other respect like an L dwarf. The lingering presence of TiO bands in those ultra-cool objects is interpreted as the signature of a metal-poor atmosphere in which dust formation is inefficient, and which maintains metal oxides in gaseous form even at very low temperature.

In any case, SDSS 125637−0224 is too cool to be classified an M subdwarf. With $(r-z) = 4.15$, SDSS 125637−0224 is significantly redder in the optical than the coolest known M subdwarfs (Lépine 2008). But again paradoxically, the optical-to-infrared colors are significantly bluer than in field L dwarfs, and the $(i-J) = 3.31$ is more in line with subtype M6-M7 (Hawley et al. 2002). Furthermore, the infrared colors of SDSS 125637−0224 are unusual: with $(J-K_s) = 0.66$, SDSS 125637−0224 is significantly bluer that 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. 2003), which further suggest they are of a similar class. In 2MASS 0532+82 the blue IR color is found to be due to a strong collision induced absorption (CIA) band from H_2. Such unusually strong CIA is also suggested to be a consequence of low-metallicity Borysow, Jorgensen, & Zheng (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

TABLE 1
DATA: SDSS 125637-022452

Datum	Value	Source
R.A.	$12^h\ 56^m\ 37.1^s$	SDSS-DR6
Decl.	-02°24′52.5″	SDSS-DR6
$\mu_{R.A.}$	-470 ± 64 mas yr^{-1}	
$\mu_{Decl.}$	-378 ± 64 mas yr^{-1}	
u	24.74±1.18 mag[1]	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)
I	18.02 mag	SSA-DSS 2[2]
I	18.36 mag	SSA-DSS 2[2]
J	16.10±0.11 mag	2MASS
H	15.79±0.15 mag	2MASS
K_s	15.44: mag	2MASS
RV	-90±40 km s^{-1}	SDSS-DR2
Distance	42^{+37}_{-21} pc	
U	-17 km s^{-1}	
V	-143 km s^{-1}	
W	+43 km s^{-1}	

[1] psf magnitude[2] I band magnitude from second epoch DSS plates from SuperCOSMOS Sky Archive (SSA)

TABLE 2
OBSERVATION DETAILS

Date	RA	DEC	Source
14/03/1987	12 56 37.60	-02 24 48.0	SERC I-UKST[1]
15/05/1996	12 56 37.27	-02 24 50.7	DENIS
31/05/1997	12 56 37.22	-02 24 50.3	POSS-II N[2]
11/03/1999	12 56 37.14	-02 24 51.6	UKST[3]
11/02/1999	12 56 37.17	-02 24 52.2	2MASS
30/05/2000	12 56 37.13	-02 24 52.4	SDSS-DR2

[1] SERC I, deep I plates made by the Second Epoch Survey of the southern sky in I band taken with UK Schmidt Telescope(UKST) and digitized by SuperCOSMOS digitizing Machine.[2] Second Epoch Survey of the northern sky in I band by the Palomar Observatory Sky Survey (POSS II N) digitized by Space Telescope Science Institute Digital Sky Survey.[3] Second Epoch Survey of the southern sky in I band taken with UKST and digitized by SuperCOSMOS digitizing Machine.

it a metal-depleted, ultra-cool dwarf.

We found an unusually strong FeH bandhead at 8692Å, relative to CrH at 8611Å. 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. (2003), 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. 2003). The most likely explanation for the larger FeH in SDSS 125637–0224 is that it reflects a low relative abundance of 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 under-abundant by about 0.4 *dex* relative to Fe (McWilliam et al. 1995; Cayrel et al. 2004).

With all evidence pointing to an ultra-cool subdwarf, and based on the spectral energy distribution in the optical and the breadth of the K I doublet, we classify SDSS 125637–0224 as a mid-type L-subdwarf (tentatively “sdL4”) although complete sequences of such objects would be required to formally establish spectral subtypes.

4. DISTANCE AND KINEMATICS

The DENIS and SDSS images on which SDSS 125637–0224 is identified are separated by $\simeq 3.7$yr, which is sufficient to extract a proper motion. We compared the DENIS and SDSS positions of all the stars within 10′ of SDSS 125637–0224 to determine any offset between the DENIS and SDSS coordinate systems, and to estimate the astrometric errors. For the background stars, we found mean offset consistent with a shift of -108 mas yr^{-1} in R.A. and -65 mas yr^{-1} in Decl. between the two epochs, with

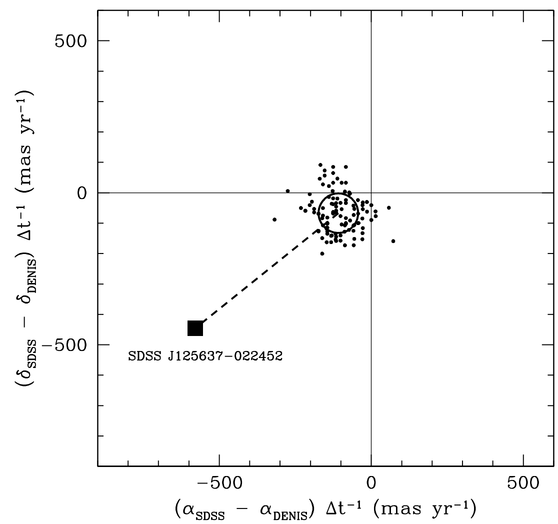

FIG. 2.— Offset between quoted positions in the SDSS catalog (epoch=2000.1) and DENIS catalog (epoch=1996.3) for SDSS 125637–0224 and 110 stars within 10′ of its position. The significant offset of SDSS 125637–0224 between the two epochs is consistent with a large proper motion $[\mu_\alpha, \mu_\delta]$ = $[-470 \pm 64, -378 \pm 64]$ *mas* yr^{-1} relative to the background stars (dashed line).

a 1-σ dispersion of 64 mas yr^{-1} in both coordinates. For SDSS 125637–0224 we find a significantly larger offset which, after correcting for the mean offset, indicates a proper motion relative to background stars of $[\mu_\alpha, \mu_\delta]$ = $[-470 \pm 64, -378 \pm 64]$ *mas* yr^{-1} (Figure 2).

Radial velocity for SDSS 125637–0224 is obtained directly from the SDSS pipeline, where it is measured by cross-correlation with a template from a star of similar spectral energy distribution (most likely an L dwarf), and is reduced to the heliocentric frame after correcting for Earth’s motion. The quoted radial velocity is 90±40 km s^{-1} . We have verified this value by cross-correlating the spectrum with L3 and L5 templates (Kirkpatrick et al. 2000), and obtained 127 km s^{-1} and 109 km s^{-1} respectively. In both cases the cross correlation width is ~ 40 km s^{-1} .

Without any parallax measurement, any distance estimate for SDSS 125637–0224 should be considered with caution. Because of its unusual spectral energy distribution, it is unclear whether any of the color-magnitude relationships defined for M and L dwarfs should apply. Assuming SDSS 125637–0224 to be analogous to a 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 $M_J \simeq 13.0$, 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 ($M_J \simeq 11.5$), 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] $\mathrm{km\,s^{-1}}$ 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) 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. 2003). We compared the evolutionary models of Burrows et al. (2001) for a age of 10-15Gyrs, and found that for a temperature of about 1800K 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 subdwarf known at present and the classification schemes based on colors and spectral line indexes is difficult based on 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 suggest the star should be classified as a mid-type L subdwarf (tentatively “sdL4”). This discovery adds up to the only two other objects also tentatively classified as “sdL” Burgasser et al. (2003, 2004).

Clear morphological difference between this object and normal L dwarfs shows it is possibility to detect such objects at low resolution. SDSS 125637−0224 also stands out in the NIR, with bluer colors than solar metallicity L dwarfs. However since those 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 and NIR of extreme red objects would provide the best chance at identifying more objects of this kind and establishing proper classification sequences.

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