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DISCOVERY OF A SECOND L SUBDWARF IN THE TWO MICRON ALL SKY SURVEY

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ABSTRACT

I report the discovery of the second L subdwarf identified in the Two Micron All Sky Survey, 2MASS J16262034+3925190. This high proper motion object ($\mu = 1\farcs27 \pm 0\farcs03$ yr^{-1}) exhibits near-infrared spectral features indicative of a subsolar metallicity L dwarf, including strong metal hydride and H_2O absorption bands, pressure-broadened alkali lines, and blue near-infrared colors caused by enhanced collision-induced H_2 absorption. This object is of later type than any of the known M subdwarfs but does not appear to be as cool as the apparently late-type sdL 2MASS 0532+8246. The radial velocity ($V_{\rm rad} = -260 \pm 35$ km s^{-1}) and estimated tangential velocity ($V_{\rm tan} \approx 90$–210 km s^{-1}) of 2MASS 1626+3925 indicate membership in the Galactic halo, and this source is likely near or below the hydrogen-burning minimum mass for a metal-poor star. L subdwarfs such as 2MASS 1626+3925 are useful probes of gas and condensate chemistry in low-temperature stellar and brown dwarf atmospheres, but more examples are needed to study these objects as a population as well as to define a rigorous classification scheme.

Subject headings: solar neighborhood — stars: chemically peculiar — stars: individual (2MASS J16262034+3925190) — stars: low-mass, brown dwarfs — subdwarfs

1. INTRODUCTION

M dwarfs dominate the Galactic stellar population both in number and mass. As long-lived sources, they are important tracers of Galactic star formation history and chemical evolution as well as the initial mass function. Most M dwarfs identified in the vicinity of the Sun are Population I "field" stars, with kinematics consistent with Galactic disk orbits and near-solar metallicities. However, a small fraction (∼0.3%; Digby et al. 2003) are metal-poor. These so-called subdwarfs (sd) typically exhibit halo kinematics ($\langle V \rangle = -202$ km s^{-1}; Gizis 1997) and were likely formed early in the Galaxy's history. Until recently, the latest type subdwarfs known were M stars, identified primarily as high proper motion sources in multiepoch photographic plate surveys (e.g., Luyten 1979). In contrast, hundreds of field dwarfs cooler than type M—the L dwarfs (Kirkpatrick et al. 1999; Martín et al. 1999)—have been identified in wide-field, near-infrared (NIR) surveys such as the Two Micron All Sky Survey (2MASS; Cutri et al. 2003), the Deep Near-Infrared Survey of the Southern Sky (DENIS; Epchtein et al. 1997), and the Sloan Digital Sky Survey (York et al. 2000). The majority of these low-mass stars and brown dwarfs are too faint at optical wavelengths to have been detected on earlier photographic plates.

The first L-type subdwarf was recently identified in the 2MASS database (Burgasser et al. 2003b, hereafter B03). This object, 2MASS 0532+8246, exhibits many spectral features similar to late-type L field dwarfs, including a steep red optical slope, strong alkali lines and metal hydride bands, deep H_2O absorption in the NIR, and pressure-broadened Na I and K I at optical wavelengths. The metal hydride bands in the spectrum of 2MASS 0532+8246 are far stronger than those observed in any field L dwarf, however. This source also has blue NIR colors, $J - K_s \approx 0.3$, in contrast to $J - K_s \approx 1.5$–2.5 typical of field L dwarfs (Kirkpatrick et al. 2000). The spectral and photometric properties of 2MASS 0532+8246, in addition to its high space motion, indicate that it is an L-type halo subdwarf. A second, apparently earlier type, L subdwarf has also been identified by Lepine et al. (2003b) as part of a proper-motion survey using red optical photographic plates (Lepine et al. 2002, 2003a). These discoveries have extended our census of metal-poor halo objects into the substellar regime (B03).

In this Letter, I present the discovery of a second L subdwarf identified in the 2MASS Point Source Catalog, 2MASS J16262034+3925190 (hereafter 2MASS 1626+3925). The identification and subsequent imaging observations of this object are described in § 2, and its NIR spectrum is presented and analyzed in § 3. The importance of this and future L subdwarf discoveries is addressed in § 4.

2. IDENTIFICATION AND IMAGING OBSERVATIONS

2MASS 1626+3925 was initially selected from the 2MASS database in a search for T dwarfs, brown dwarfs cooler than spectral class L (Burgasser et al. 2002, 2003a). Like most T dwarfs, this object has blue NIR colors ($J - K_s = -0.03 \pm 0.08$; Table 1) and no optical counterpart in the USNO-A2.0 catalog (Monet et al. 1998). However, inspection of red (R) and infrared (I_N) photographic plates from the Second Palomar Sky Survey (POSS II; Reid et al. 1991) reveal an offset, moving optical counterpart (Fig. 1) with $R = 19.84$ and $I_N = 16.68$ (Monet et al. 2003, USNO-B1.0). This counterpart was confirmed by J-band IRCam (Murphy et al. 1995) and R-band CCD imaging observations, both conducted at the Palomar 60 inch Meyer Telescope on 2000 April 14 and July 1 (UT), respectively. The offset between the POSS II R plate (epoch 1993.3) and the 2MASS detection (epoch 1998.3) implies a high proper motion, measured[2] to be $\mu = 1\farcs27 \pm 0\farcs03$ yr^{-1} at position angle $\theta = 282\fdg6 \pm 1\fdg4$. Despite being an interesting, late-type source,

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[2] The position of 2MASS 1626+3925 on the R plate was measured by creating a 2MASS-based astrometric reference frame from 25 nearby field stars; see Burgasser et al. (2004). A statistically consistent value of $\mu = 1\farcs37 \pm 0\farcs07$ yr^{-1} at $\theta = 280° \pm 3°$ was measured between the 2MASS detection and the epoch 1995.5 POSS II I_N plate.

TABLE 1
Observational Properties of the L Subdwarf 2MASS 1626+3925

Parameter	Value
α[a]	$16^{\rm h}26^{\rm m}20^{\rm s}.34$
δ[a]	$+39°25'19''.0$
R[b]	19.84
I_N[b]	16.68
2MASS J	14.44 ± 0.03
2MASS $J-H$	-0.10 ± 0.06
2MASS $H-K_s$	0.07 ± 0.09
μ	$1''.27 \pm 0''.03$ yr^{-1}
θ	$282°.6 \pm 1°.4$
d[c]	~15–35 pc
$V_{\rm tan}$[c]	~90–210 km s^{-1}
$V_{\rm rad}$	-260 ± 35 km s^{-1}

[a] 2MASS coordinates, equinox J2000.0 and epoch 1998 April 29 (UT).
[b] Photographic R (IIIaF) and I_N (IV-N) magnitudes from USNO-B1.0 (Monet et al. 2003).
[c] Assuming $M_J \approx 11.5$–13.5; see § 3.

2MASS 1626+3925 was initially rejected as being too optically bright for a T dwarf. However, following the identification of 2MASS 0532+8246 in the same search sample, this source was reexamined to determine if it too is a late-type subdwarf.

3. NEAR-INFRARED SPECTROSCOPY

NIR spectroscopic observations of 2MASS 1626+3925 were obtained during 2004 July 23–24 (UT) using the SpeX instrument (Rayner et al. 2003) mounted on the NASA 3.0 m Infrared Telescope Facility (IRTF). Observing conditions were excellent, with clear skies and 0″.5–0″.7 seeing. Spectral data were obtained in both prism and cross-dispersed modes, with complete 0.7–2.5 μm coverage at spectral resolutions $\lambda/\Delta\lambda \approx 150$ and 1200, respectively, for the employed 0″.5 slit. Additional observations of the A0 V stars HD 153345 and HD 158261 were obtained for flux and telluric absorption calibration. All spectral data were reduced using the SpeXtool package (Cushing et al. 2004). Further details on the experimental design and data reduction are given in Burgasser et al. (2004).

Figure 2 shows the reduced, low-resolution NIR spectrum of 2MASS 1626+3925, along with those of three late-type M subdwarfs—LHS 377 (Gizis 1997), LSR 2036+5059 (Lepine et al. 2003a), and SSSPM 1013−3956 (Scholz et al. 2004)[3]—all obtained with the SpeX spectrograph (A. J. Burgasser et al. 2004, in preparation). These subdwarfs are optically classified sdM7, sdM7.5, and sdM9.5, respectively, according to the scheme of Gizis (1997). All four NIR spectra exhibit signatures typical of late-type dwarfs, with steep red optical spectral slopes, TiO absorption at 0.84 μm, strong alkali lines of Na I and K I (partic-

[3] We note that SSSPM 1013−3956 was also identified in the same 2MASS T dwarf search sample from which 2MASS 0532+8246 and 2MASS 1626+3925 were drawn.

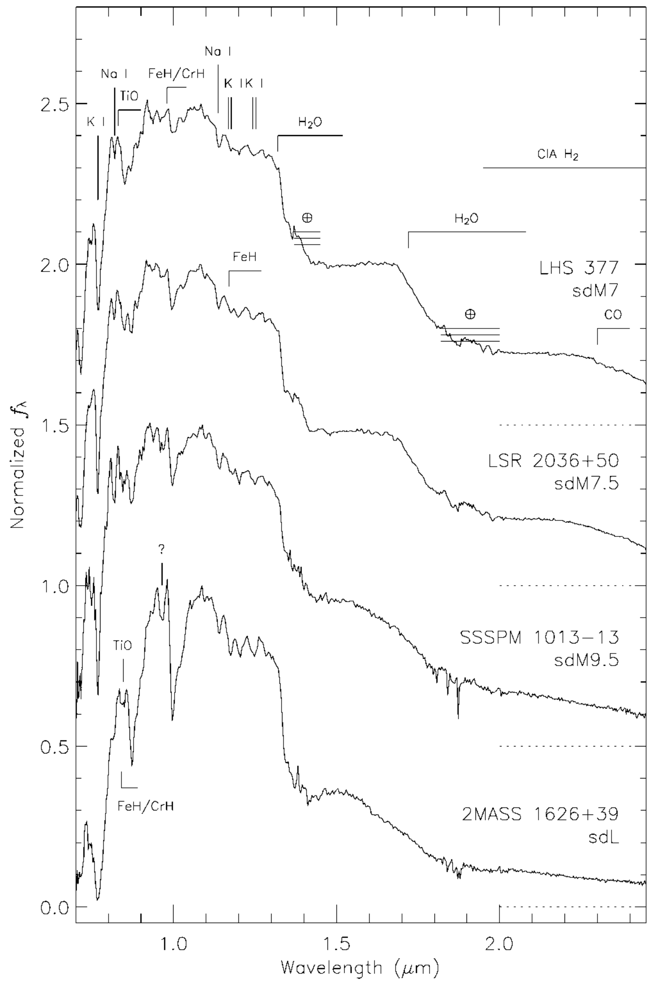

Fig. 2.—SpeX prism spectra of the late M subdwarfs LHS 377 (sdM7), LSR 2036+5059 (sdM7.5), and SSSPM 1013−1356 (sdM9.5) compared to that of 2MASS 1626+3956. Spectra are normalized at their flux peaks and offset by constants (*dotted lines*). Key spectral features are labeled, with the exception of the as yet unidentified band centered at 0.96 μm (B03). Regions of high telluric absorption are indicated by the circled plus signs.

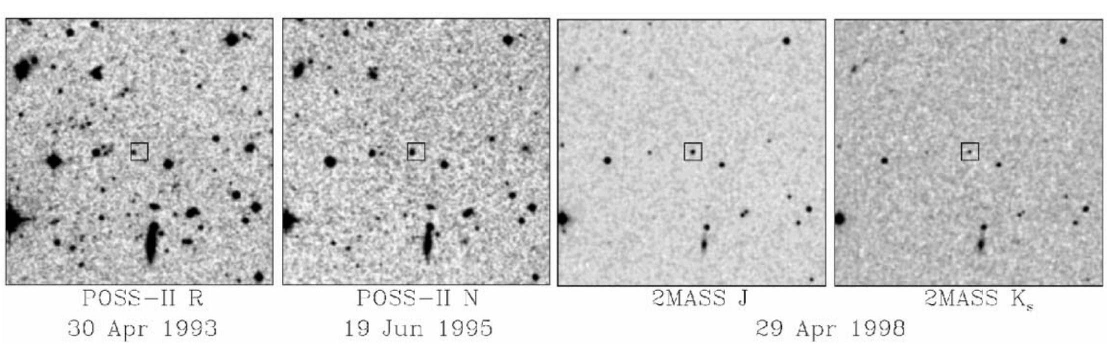

Fig. 1.—POSS II (R and I_N) and 2MASS (J and K_s) images of the 2MASS 1626+3956 field. Images are 5′ on a side and oriented with north up and east to the left. A 10″ diameter box is centered at the 2MASS position of the source. The motion of 2MASS 1626+3956 is clearly visible over the 5 yr period shown here.

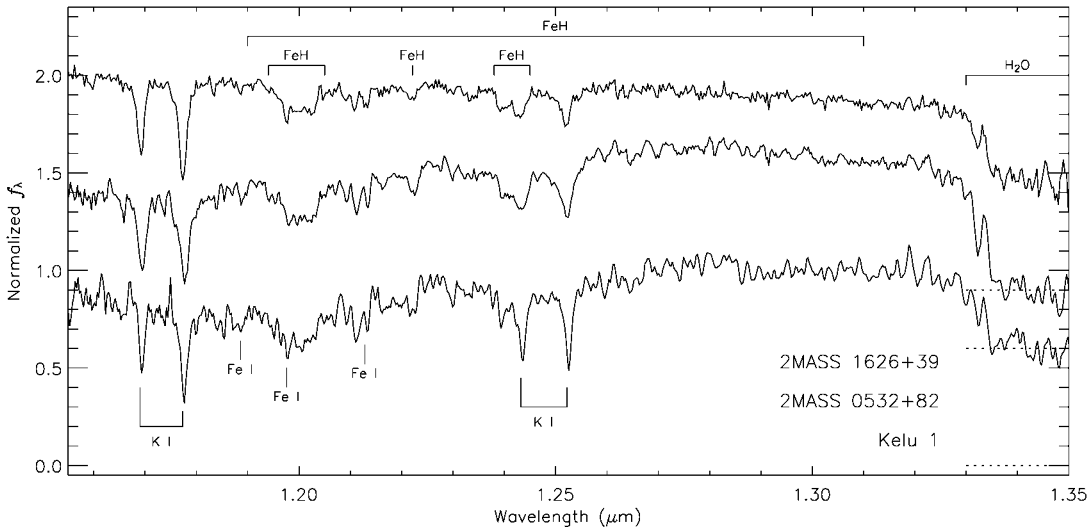

Fig. 3.—Moderate resolution spectra of 2MASS 1626+3956 in the 1.15–1.35 μm region compared to NIRSPEC spectra of the L subdwarf 2MASS 0532+8246 (B03) and the rapidly rotating L2 field dwarf Kelu 1 (McLean et al. 2003). Spectra are normalized at 1.27 μm and offset by constants (*dotted lines*). Strong features arising from FeH, H_2O, and K I are noted, as are weaker lines of Fe I. Note the substantially broadened K I line wings in the L subdwarf spectra.

ularly between 1.1 and 1.3 μm), and stellar H_2O absorption at 1.4 and 1.8 μm. They also exhibit features characteristic of metal-poor stars, including enhanced metal hydride bands (FeH, CrH), weak metal oxide bands (note the weak or absent CO band at 2.3 μm), and blue NIR spectral energy distributions. The blue NIR colors are due to collision-induced, H_2 1–0 quadrupole absorption centered near 2.5 μm, which is enhanced in the higher pressure photospheres of metal-poor cool subdwarfs[4] (Saumon et al. 1994; Borysow et al. 1997; Leggett et al. 2000).

In 2MASS 1626+3956, these low-temperature, metal-poor spectral features become even more pronounced. CrH and FeH bands at 0.86 and 0.87 μm are seen distinctly in the moderate resolution cross-dispersed data, while the 0.99 μm FeH Wing-Ford band is deeper than those of any field M or L dwarf observed to date (Kirkpatrick et al. 1999, 2000). FeH absorption is also strong in the 1.2–1.3 μm region. We detect a weak signature of the $\Lambda\, ^4\Phi$–$X\, ^4\Gamma$ band of TiH at 0.94 μm (Andersson et al. 2003; M. Cushing 2004, private communication) in the moderate resolution data, a feature that can also be seen in the red optical spectrum of 2MASS 0532+8246 (B03; labeled as H_2O in their Fig. 2). This band is not responsible for an as yet unidentified feature centered at 0.96 μm, however, present in the spectra of both 2MASS 1626+3925 and 2MASS 0532+8246. Beyond 1.3 μm, the NIR spectrum of 2MASS 1626+3925 is generally featureless, with the exception of strong H_2O absorption at 1.4 and possibly 1.8 μm. Indeed, the 2.3 μm CO band is completely absent, and *K*-band flux is highly suppressed by H_2 absorption.

Figure 3 displays the moderate resolution 1.15–1.35 μm spectrum of 2MASS 1626+3925, along with those of 2MASS 0532+8246 and the L2 field dwarf Kelu 1 (Ruiz et al. 1997), both measured with the Keck NIRSPEC instrument (McLean et al. 2003; B03). Significant FeH absorption is present in the spectra of all three objects, with strong bands at 1.20, 1.22, and 1.24 μm, and fine features throughout the displayed spectral region (Cushing et al. 2003). Fe I lines may also be present in the spectrum of 2MASS 1626+3925, albeit quite weak. The K I doublet lines at 1.17/1.18 and 1.24/1.25 μm are notably broadened in the subdwarf spectra. A measurement of the FWHM of the shorter wavelength pair yields 16.3 and 19.4 Å at 1.17 and 1.18 μm, respectively, 20% broader than measured for the rapidly rotating Kelu 1 ($v \sin i = 60 \pm 5$ km s^{-1}; Basri et al. 2000).[5] This is indicative of pressure broadening, consistent with the high photospheric pressures implied from enhanced H_2 absorption at the *K* band.

The spectra in Figure 2 show a natural progression of deepening FeH and H_2O bands, strengthening H_2 absorption, and increasingly red optical slopes; 2MASS 1626+3925 is clearly the latest type source of the four, apparently cooler than the sdM9.5 SSSPM 1013−1356. Furthermore, the depth of the 1.4 μm H_2O band is similar to those of early- and mid-type L dwarfs observed with the same instrumental setup (Burgasser et al. 2004), although it is somewhat weaker than that of 2MASS 0532+8246 (Fig. 3). We therefore conclude that 2MASS 1626+3925 is a bona fide L subdwarf but of earlier type than 2MASS 0532+8246.

Furthermore, the kinematics of 2MASS 1626+3925 appear to be consistent with membership in the Galactic halo. The radial velocity of this source was measured by cross-correlating its moderate resolution *J*-band spectrum with NIRSPEC spectra of eight L dwarfs with known radial velocities (Basri et al. 2000; Reid et al. 2002; McLean et al. 2003; Bailer-Jones 2004; see B03). The resulting heliocentric value, $V_{\rm rad} = -260 \pm 35$ km s^{-1}, is much too high for a nearby disk star. Likewise, assuming that 2MASS 1626+3925 has an absolute *J*-band magnitude similar to that of an early- to mid-type L dwarf, $M_J \approx 11.5$–13.5 (Vrba et al. 2004), its estimated spectrophotometric distance of 15–35 pc implies $V_{\rm tan} \approx 90$–210 km s^{-1}, characteristic of thick-disk or halo stars. A more accurate determination of this object's kinematics will require a parallax measurement.

Finally, if 2MASS 1626+3925 has the same effective temperature as an early- or mid-type L dwarf, 1800 K $\lesssim T_{\rm eff} \lesssim$ 2300 K (Golimowski et al. 2004), then it straddles the hydrogen-

[4] The reduced metallicity of a cool subdwarf implies reduced metal opacities and therefore a more transparent atmosphere. The photosphere lies at a deeper, and hence higher temperature and pressure, layer as compared to an equivalent solar-metallicity dwarf (Burrows et al. 2002).

[5] The same K I lines are 20% broader in the spectrum of 2MASS 0532+8246 as compared to its field analog, DENIS 0205−1159AB (B03). The 1.24/1.25 μm K I lines are partly blended with FeH absorption.

burning minimum mass for $Z \sim 0.1\, Z_\odot$ and is substellar for lower metallicities (see Fig. 3 of B03). Again, parallax and bolometric luminosity measurements are needed to verify this possibility.

4. DISCUSSION

The identification of L subdwarfs such as 2MASS 1626+3925 enables a new approach to studying the atmospheric physics of cool stars and brown dwarfs. The chemistry and band strengths of molecular species in the atmospheres of late M and L dwarfs are highly sensitive to the total metal abundance. Metal-poor environments can therefore produce emergent spectra with very different dominant species (i.e., metal hydrides) or enable the detection of species that are otherwise suppressed (i.e., TiH). It remains unclear as to what extent condensate clouds can form in cool metal-poor atmospheres (B03), the suppression of which would have a significant impact on NIR spectral energy distributions and the retention of atmospheric chemical species such as atomic alkalis (Lodders 1999; Burrows et al. 2001). The higher photospheric pressures of cool subdwarfs also make them excellent laboratories for studying the pressure-broadened wings of the K I and Na I fundamental transitions at optical wavelengths (Burrows et al. 2000) as well as pressure-sensitive H_2 absorption in the NIR. The latter is a key absorber in the spectra of cool white dwarfs (Saumon et al. 1994; Hansen 1998).

The unique spectra of L subdwarfs imply that existing classification schemes are inappropriate to characterize these objects. A revised scheme, preferably based on red optical and/or *J*-band spectral features, should be matched closely to established L field dwarf schemes (e.g., Kirkpatrick et al. 1999) to enable the straightforward assessment of metallicity effects. However, the definition of a rigorous classification scheme, as well as more general studies of the L subdwarf population as a whole, requires a systematic search for these objects. This may best be accomplished by a wide-field NIR proper-motion survey, in analogy to the successful photographic plate surveys of the past.

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