OPTICAL AND NEAR-INFRARED SPECTROSCOPY OF THE L SUBDWARF SDSS J125637.13–022452.4*

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ABSTRACT

Red optical and near-infrared spectroscopy are presented for SDSS J125637.13–022452.4, one of only four L subdwarfs reported to date. These data confirm the low-temperature, metal-poor nature of this source, as indicated by prominent metal-hydride bands, alkali lines, and collision-induced H₂ absorption. The optical and near-infrared spectra of SDSS J1256–0224 are similar to those of the sdL4 2MASS J16262034+3925190, and we derive a classification of sdL5.5 based on the preliminary scheme of Burgasser, Cruz, and Kirkpatrick. The kinematics of SDSS J1256–0224 are consistent with membership in the Galactic inner halo, with estimated UVW space velocities indicating a slightly prograde, eccentric, and inclined Galactic orbit (3.5 ≲ R ≲ 11 kpc; |Z_{max}| ≈ 7.5 kpc). Comparison to synthetic spectra computed with the PHOENIX code, including the recent implementation of kinetic condensate formation (DRIFT-PHOENIX), indicates T_{eff} ≈ 2100–2500 K and [M/H] ≈ −1.5 to −1.0 for log g ≈ 5.0–5.5 (cgs), although there are clear discrepancies between model and observed spectra particularly in the red optical region. As such, any conclusions on the role of metallicity in condensate and grain formation are probably premature. Indeed, a shift in the temperature scale of L subdwarfs relative to L dwarfs may obviate the need for modified condensate and grain chemistry in low metallicity atmospheres.

Key words: stars: chemically peculiar – stars: individual (SDSS J125637.13–022452.4) – stars: low-mass, brown dwarfs – subdwarfs

Online-only material: color figures

1. INTRODUCTION

L subdwarfs are the lowest luminosity and least-massive halo population dwarf stars currently known (Burgasser et al. 2005). They derive their name from their gross spectral similarities to the local L dwarf population of very low mass stars and brown dwarfs (see Kirkpatrick 2005, and references therein), but are distinguished by specific spectral anomalies, including the presence of enhanced metal-hydride absorption bands and unusually blue near-infrared colors. These features are indicative of subsolar atmospheric abundances, as similar peculiarities distinguish metal-poor M subdwarfs from M dwarfs (e.g., Mould & Hyland 1976; Gizis 1997; Leggett et al. 2000). L subdwarfs, like M subdwarfs, exhibit kinematics consistent with membership in the Galactic halo, with inclined, eccentric, and in some cases retrograde Galactic orbits indicative of formation outside the Galactic disk (Dahn et al. 2008; Burgasser et al. 2008; Cushing et al. 2009). The low luminosities (log L_{bol}/L_☉ < −3) and effective temperatures of L subdwarfs (T_{eff} < 3000 K; Leggett et al. 2000; Reiners & Basri 2006; Burgasser et al. 2008), coupled with their nonsolar atmospheric abundances, are of interest for studies of low-temperature atmospheres, particularly thermochemistry and condensate formation processes in chemically peculiar environments (e.g., Ackerman & Marley 2001; Lodders 2002; Helling & Woitke 2006). In addition, as their inferred masses extend down to and below the metallicity-dependent hydrogen-burning minimum mass (Burrows et al. 1993; Burgasser et al. 2003), L subdwarfs can potentially test metallicity dependences on low-mass star formation and brown dwarf evolution, as traced for instance by the terminus of the main sequence in globular clusters (e.g., Richer et al. 2008).

Despite their utility to atmospheric, star formation, and Galactic population studies, only four L subdwarfs have been reported to date: the prototype 2MASS J05325346+8246465 (hereafter 2MASS 0532+8246; Burgasser et al. 2003), 2MASS J16262034+3925190 (hereafter 2MASS J1626+3925; Burgasser 2004), 2MASS J06164006–6407194 (hereafter 2MASS J0616–6407; Cushing & Vacca 2006; Cushing et al. 2009; Gizis & Harvin 2006; Reiners & Basri 2006; Patten et al. 2006; Scholz et al. 2009). SDSS J125637.13–022452.4 (hereafter SDSS J1256–0224; Sivarani et al. 2009). The first three sources were identified serendipitously in the Two Micron All Sky Survey (hereafter 2MASS; Skrutskie et al. 2006), and have been studied extensively at optical and near-infrared wavelengths (e.g., Burgasser et al. 2007, 2008; Cushing & Vacca 2006; Cushing et al. 2009; Gizis & Harvin 2006; Reiners & Basri 2006; Patten et al. 2006; Scholz et al. 2009; Schilbach et al. 2009). SDSS J1256–0224 (Table 1) was found in the Sloan Digital Sky Survey (hereafter SDSS; York et al. 2000) as part of a directed search for unusual red sources. Both Sivarani et al. (2009) and Scholz et al. (2009) characterize SDSS J1256–0224 as an L subdwarf based on its optical spectrum (L-type, with unusually strong metal-hydride bands), blue near-infrared colors (J–K_s = 0.10 ± 0.03; Schilbach et al. 2009), and halo kinematics. However, a detailed study of the optical and near-infrared spectral properties of this unusual source has not yet been made.

In this paper, we present new observations of SDSS J1256–0224 and conduct a detailed analysis of its spectral and kinematic properties. Spectroscopic observations spanning the red optical and near-infrared are described in Section 2. The empirical properties of SDSS J1256–0224 are assessed in Section 3.
including classification (on the preliminary scheme of Burgasser et al. 2007), distance estimation, kinematics and Galactic orbit. In Section 4, we examine the atmospheric properties of this source by comparing its colors and spectra to the latest generation of the Cond-Phoenix atmosphere simulations (Hauschildt et al. 1997) and to the Drift-Phoenix model atmospheres (Dehn 2007; Helling et al. 2008a; Witte et al. 2009), the latter of which includes a kinetic approach to phase-nonlinequilibrium dust formation. Results are summarized in Section 5.

2. OBSERVATIONS

2.1. Red Optical Spectroscopy

Optical spectra of SDSS J1256–0224 were obtained on 2006 May 7 (UT) using the low-dispersion survey spectrograph (LDSS-3) mounted on the Magellan 6.5 m Clay Telescope. LDSS-3 is an imaging spectrograph, upgraded from the original LDSS-2 (Allington-Smith et al. 1994) for improved red sensitivity. Conditions during the observations were clear with excellent seeing (0.6′′ at the i′' band). The VPH-red grism (660 lines mm⁻¹) with a 0.75 wide (4 pixels) long-slit mask was used, with the slit aligned to the parallactic angle. This configuration provides a spectral resolution of λ/Δλ ≈ 1800 and dispersion along the chip of ~1.2 Å pixel⁻¹. The OG590 longpass filter was used to eliminate second-order light shortward of 6000 Å. Two slow-read exposures of 750 s each were obtained at an air mass of 1.12. We also observed the G2 V star G 104-335 (V = 11.7) immediately after the SDSS J1256–0224 observation and at a similar air mass (1.14) for telluric absorption correction. The flux standard LTT 7987 (a.k.a. GJ 2147; Hamuy et al. 1994) was observed on the same night using an identical slit and grism combination. All spectral observations were accompanied by HeNeAr arc lamp exposures and pixel response calibration.

LDSS-3 data were reduced in the IRAF⁴ environment (Tody 1986). Raw images were first corrected for amplifier bias voltage, stitched together, and subtracted by a median-combined set of slow-read bias frames taken during the afternoon. These processed images were then divided by a median-combined, bias-subtracted, and normalized set of flat-field frames. The spectrum of SDSS J1256–0224 was then extracted using the G star dispersion trace as a template. Dispersion solutions were determined from arc lamp spectra extracted using the same dispersion trace; solutions were accurate to ~0.08 pixels, or ~0.1 Å. Flux calibration (instrumental response correction) was determined using the tasks STANDARD and SENSFUNC with observations of LTT 7987, which we have found provide sufficient calibration to <10% over the 6000–9000 Å spectral band (Burgasser et al. 2007). Corrections to telluric O2 (6855–6955 Å B band, 7580–7740 Å A band) and H2O (7160–7340 Å, 8125–8350 Å, 9270–9680 Å) absorption bands were determined by linearly interpolating over these features in the G dwarf spectrum, dividing by the uncorrected spectrum, and multiplying the result with the spectrum of SDSS J1256–0224.

The two spectra of SDSS J1256–0224 were then co-added to improve signal to noise, which ranged from ~15 at the 6600 Å peak to a maximum of ~45 at 8500 Å.

The reduced red optical spectrum of SDSS J1256–0224 is shown in Figure 1, compared with equivalent data for the sdM9.5 SSSPM J1013–1356 (Scholz et al. 2004a) and 2MASS J1626+3925 (Burgasser et al. 2007). Our data for SDSS J1256–0224 have considerably higher signal to noise than the original SDSS discovery spectrum (Sivarani et al. 2009) and higher resolution than contemporaneous observations by Scholz et al. (2009). As originally pointed out by Sivarani et al. (2009), the optical spectrum of SDSS J1256–0224 exhibits several characteristics indicative of an L dwarf, including an overall red spectral slope from 6000 to 8500 Å; strong molecular bands of CrH (8600 Å) and FeH (8700 and 9900 Å); and alkali line absorption from K i (7700 Å doublet), Na i (8182/8193 Å doublet), Rb i (7798 and 7946 Å) and Cs i (8519 and possibly 8941 Å). Equivalent width (EW) measurements for these lines are listed in Table 2. The K i doublet is extremely broadened, producing a V-shape notch in the spectrum that spans 7300–8100 Å, also characteristic of L dwarf spectra. There are a number of peculiar features in the spectrum of SDSS J1256–0224 that are not common to L dwarf spectra, however, including unusually strong bands of CaH (6900 Å) and TiO (7200 and 8400 Å), and numerous metal lines from Ca i (6571 Å), Ca ii (8541 Å), and Ti i (7204, 8433 and 9600–9700 Å). The absence of these species in L dwarf spectra is largely attributed to the formation of Ca–Ti and Ca–Al mineral condensates (e.g., Allard et al. 2001; Lodders 2002; Helling et al. 2008b), and their presence in L subdwarf spectra has been interpreted as an indication of inhibited condensate formation (Burgasser et al. 2003; Reiners & Basri 2006). Whether or not this is an accurate interpretation (see Section 4.4), unusually strong CaH and metal-line absorption is a characteristic trait of metal-poor M subdwarf spectra (e.g., Mould & Hyland 1976; Gizis 1997) and the presence of these features in the spectrum of SDSS J1256–0224 supports its characterization as a metal-poor, low-temperature dwarf.

Specific comparison of SDSS J1256–0224 to 2MASS J1626+3925 reveals remarkable similarities in their spectra, although the latter exhibits somewhat stronger FeH, CrH, Rb i, and Cs i absorption features and somewhat weaker Na i lines. Indeed, the variation in features between the three spectra shown in Figure 1 suggests a sequence of very late-type, metal-poor dwarfs, with SDSS J1256–0224 having intermediate line and band strengths. The specific spectral classification of SDSS J1256–0224 is discussed in detail in Section 3.1. Note that no significant Hα emission or absorption is detected in any of these spectra.

2.2. Near-infrared Spectroscopy

Low-resolution near-infrared spectral data for SDSS J1256–0224 were obtained in clear conditions on 2005 March 23 (UT) using the SpeX spectrograph (Rayner et al. 2003) mounted on the 3 m NASA Infrared Telescope Facility (IRTF). We used the prism-dispersed mode of SpeX with a 0.5′′ slit (aligned to the parallactic angle), providing 0.75–2.5 μm spectroscopy with resolution λ/Δλ ≈ 120 and dispersion across the chip of 20–30 Å pixel⁻¹. SDSS J1256–0224 was observed at an air mass of 1.08. Four exposures of 180 s each were obtained in an ABBA dither pattern along the slit. The A0 V star HD 111744 was a reference star and was observed for correction of any instrumental effects. Equivalent width (EW) measurements for these lines are listed in Table 2. The K i doublet is extremely broadened, producing a V-shape notch in the spectrum that spans 7300–8100 Å, also characteristic of L dwarf spectra. There are a number of peculiar features in the spectrum of SDSS J1256–0224 that are not common to L dwarf spectra, however, including unusually strong bands of CaH (6900 Å) and TiO (7200 and 8400 Å), and numerous metal lines from Ca i (6571 Å), Ca ii (8541 Å), and Ti i (7204, 8433 and 9600–9700 Å). The absence of these species in L dwarf spectra is largely attributed to the formation of Ca–Ti and Ca–Al mineral condensates (e.g., Allard et al. 2001; Lodders 2002; Helling et al. 2008b), and their presence in L subdwarf spectra has been interpreted as an indication of inhibited condensate formation (Burgasser et al. 2003; Reiners & Basri 2006). Whether or not this is an accurate interpretation (see Section 4.4), unusually strong CaH and metal-line absorption is a characteristic trait of metal-poor M subdwarf spectra (e.g., Mould & Hyland 1976; Gizis 1997) and the presence of these features in the spectrum of SDSS J1256–0224 supports its characterization as a metal-poor, low-temperature dwarf.

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5 These data were obtained with the Gemini Multi-Object Spectrometer (Hook et al. 2004).
6 Absorption in the 9600–9700 Å spectrum of 2MASS J1626+3925 was incorrectly associated with TiH by Burgasser (2004). Cushing & Vacca (2006) and Reiners & Basri (2006) have since identified these features as arising from the 5F–z 5F multiplet of Ti i, and we adopt these identifications here.

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4 IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
Figure 1. Red optical spectra of SSSPM J1013–1356 (top), SDSS J1256–0224 (middle), and 2MASS J1626+3925 (bottom). Spectra are normalized in the 8500–8600 Å region and offset for comparison (dotted lines). Primary spectral features are indicated, as well as regions of strong telluric absorption (⊕) in the spectra of SSSPM J1013–1356 and 2MASS J1626+3925.

Table 1

| Parameter | Value | References |
|-----------|-------|------------|
| αJ2000    | 12h56m37.16 | 1 |
| δJ2000    | 02°24′52″21 | 1 |
| Spectral type | sdL3.5 | 2 |
| i′–J    | 3.253 ± 0.024 | 3, 4 |
| J−Ks | 0.097 ± 0.026 | 4 |
| MJ a      | 12.23 ± 0.22 | 2, 5 |
| MKs a | 11.81 ± 0.23 | 2, 5 |
| dabs (pc)b | 66 ± 9 | 2, 4, 5 |
| Vabs (km s⁻¹) | 186 ± 26 | 2, 4 |
| Vr (km s⁻¹) | −130 ± 11 | 2 |
| U (km s⁻¹) | −115 ± 11 | 2 |
| V (km s⁻¹) | −101 ± 18 | 2 |
| W (km s⁻¹) | −150 ± 9 | 2 |
| Teff (K) | ~2100–2500 | 2 |
| log g (cgs) | ~5.0–5.5 | 2 |
| [M/H] (dex) | ~−1.5…−1.0 | 2 |

Notes.

a Estimated absolute magnitudes based on the absolute magnitude/spectral type relations of Cushing et al. (2009) and spectral type sdL3.5.
b Note that Schilbach et al. (2009) measure an astrometric distance of 90 ± 23 pc for this source, formally consistent with our more precise estimate based on the Cushing et al. (2009) absolute magnitude/spectral type relations.

References. (1) 2MASS (Skrutskie et al. 2006); (2) This paper; (3) SDSS (Adelman-McCarthy et al. 2008); (4) Schilbach et al. (2009); (5) Cushing et al. (2009).

observed immediately before SDSS J1256–0224 at a similar air mass (1.07) for telluric absorption and flux calibration. Internal flat-field and Ar arc lamps were observed with the target and calibrator source for pixel response and wavelength calibration.

Data were reduced using the SpeXtool package, version 3.1 (Cushing et al. 2004), using standard settings. Raw science images were first corrected for linearity, pairwise subtracted, and divided by the corresponding median-combined flat-field image. Spectra were optimally extracted using the default settings for aperture and background source regions, and wavelength calibration was determined from arc lamp and sky emission lines. The multiple spectral observations were then median-combined after scaling individual spectra to match the highest signal-to-noise observation. Telluric and instrumental response corrections for the science data were determined using the method...
smoothed to the same resolution (Δλ/λ ~ 120). Spectra are normalized in the 0.9–1.0 μm region and offset for comparison (dotted lines). Primary spectral features are indicated.

The reduced near-infrared spectrum of SDSS J1256–0224 is shown in Figure 2, again compared to equivalent SpeX prism data for SSSPM J1013–1356 and 2MASS J1626+3925 (Burgasser 2004). All three spectra show similar overall spectral morphologies, with strong molecular absorption features and relatively blue 1.0–2.5 μm spectral slopes. Again, 2MASS J1626+3925 appears to be most similar to SDSS J1256–0224 in terms of detailed spectral features. The strong FeH band at 0.5 μm present in the optical spectrum of SDSS J1256–0224 by the telluric correction spectrum, typically accurate to within 10% across the 0.8–2.5 μm window (see Burgasser et al. 2006). Instrumental response was determined through the ratio of the observed A0 V spectrum to a scaled, shifted and deconvolved Kurucz7 model spectrum of Vega. Signal to noise ranged from ∼80 at the J-band peak (∼1 μm) to ∼15 at the K band (∼2.2 μm).

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3. CHARACTERIZATION OF SDSS J1256–0224

3.1. Spectral Classification

The most basic characterization of a late-type dwarf like SDSS J1256–0224 is its spectral classification. However, while a well defined red optical classification scheme exists for L dwarfs (Kirkpatrick et al. 1999b, 2000; see also Geballe et al. 2002 for discussion on the near-infrared classification of L dwarfs), there are simply too few L subdwarfs to define a robust scheme. We therefore followed the approach outlined in Burgasser et al. (2007), comparing the 7300–9000 Å spectrum of SDSS J1256–0224 to equivalent resolution spectra of the L dwarf spectral standards defined in Kirkpatrick et al. (1999b). Figure 3 shows the two best-matching standards, the L3 2MASS J11463449+2230527 and the L4 2MASS J11550087+2307058 (data from Kirkpatrick et al. 1999b).8 Focusing on the 7300–9000 Å region, the spectrum of SDSS J1256–0224 appears to lie intermediate between these two standards, based on the height of the 7300 Å spectral peak; the depth and breadth of the 7700 Å K i doublet; and the depths of the 8500 Å TiO, 8600 Å CrH, and 8700 Å FeH bands. There are some discrepancies between SDSS J1256–0224 and the L dwarf standards in this region, notably the spectral slope between 7800 Å and 8400 Å, the depth of the 8200 Å Na i doublet (stronger in SDSS J1256–0224), and the presence of additional Ca i, Ca ii, and Ti i lines in the spectrum of SDSS J1256–0224. However, these differences are not nearly as extreme as those at shorter (i.e., the CaH and TiO bands between 6600 and 7300 Å) or longer wavelengths (i.e., the strong H2 absorption in the near-infrared). The comparisons shown in Figure 3 indicate a spectral type of sdL3.5 for SDSSJ1256–0224 on the Burgasser et al. (2007) scheme. This is only 0.5 subtypes earlier than the sdL4 classification of 2MASS J1626+3925, consistent with both the overall similarities between the spectra of these two sources and slight differences in their atomic line and molecular band strengths.

3.2. Absolute Brightness and Distance

Parallax distance measurements have recently become available for low-temperature subdwarfs spanning types sdM7 to sdL7 (Mone et al. 1992; Dahn et al. 2008; Burgasser et al. 2008; Schilbach et al. 2009), including SDSS J1256–0224 for which Schilbach et al. (2009) determine d = 90 ± 23 pc. This measurement is fairly uncertain, so we have compared it to the linear absolute magnitude/spectral type relations recently quantified by Cushing et al. (2009) for ultracool subdwarfs:

\[ M_J = 8.02 + 0.313 \times \text{SpT}, \]

\[ M_H = 7.77 + 0.300 \times \text{SpT}, \]

\[ M_{K_s} = 7.44 + 0.320 \times \text{SpT}, \]

8 Note that the 2MASS J–Ks = 0.66 color reported by Sivarani et al. (2009) is in fact an upper limit; this source was not detected by 2MASS in the Ks band.

9 These data were obtained with the Low Resolution Imaging Spectrograph (Oke et al. 1995).
where SpT(sdM7) = 7, SpT(sdL0) = 10, etc. These relations predict $M_J = 12.23 \pm 0.22$, $M_H = 11.81 \pm 0.23$, and $M_K_s = 11.75 \pm 0.25$ for a type of sdL3.5 ± 0.5, and hence $d = 66 \pm 9$ pc for SDSS J1256–0224 based on the photometry of Schilbach et al. (2009). The distance uncertainty includes contributions from photometry, a 0.5 subtype classification uncertainty, covariance matrix elements for the Cushing et al. (2009) relations, and variation in distance estimates between $JHK_s$ values. This estimate is considerably closer to the Sun than the mean value from Schilbach et al. (2009), but nevertheless consistent within experimental uncertainties. It is also roughly half the 120 pc estimate of Burgasser et al. (2007) due to the reduction in the estimated distance. Nevertheless, it is indicative of halo kinematics. A radial velocity ($V_r$) was computed from the optical spectrum by comparing the measured line centers of the atomic lines listed in Table 2 to vacuum wavelengths obtained from the NIST atomic line database10 (Ralchenko et al. 2008). A heliocentric Doppler shift of $-130 \pm 11$ km s$^{-1}$ was determined, which includes a barycentric motion correction of $-15$ km s$^{-1}$. The uncertainty in $V_r$ includes the standard deviation in the line centers and a systematic uncertainty of 4 km s$^{-1}$ based on the uncertainty of the wavelength dispersion solution. This value is nominally consistent with the $-90 \pm 40$ km s$^{-1}$ cross-correlation measurement of Sivarani et al. (2009); our improvement in precision is likely due to our higher signal-to-noise spectral data.

Adding in our radial velocity measurements, we find space velocities 

\[\begin{bmatrix} U, V, W \end{bmatrix} = \begin{bmatrix} -115 \pm 11, -101 \pm 18, -150 \pm 9 \end{bmatrix} \text{ km s}^{-1}\]

in the local standard of rest (LSR), assuming an LSR solar motion of $\begin{bmatrix} U, V, W \end{bmatrix}_\odot = \begin{bmatrix} 10, 5.25, 7.17 \end{bmatrix}$ km s$^{-1}$ (Dehnen & Binney 1998). Note that we adopt a right-handed velocity coordinate system with positive $U$ pointing radially inward toward the Galactic center. The large space motions in all three LSR components are again strong indications of Galactic halo membership for SDSS J1256–0224.

3.4. Galactic Orbit

To explore the kinematics of SDSS J1256–0224 in more detail, we calculated its Galactic orbit using the inferred $UVW$ velocities as initial conditions. These velocities were first converted to a Galactic inertial frame (assuming $V_{LSR} = +220$ km s$^{-1}$; Kerr & Lynden-Bell 1986), and the position and distance of SDSS J1256–0224 transformed to galactocentric rectangular coordinates $[X, Y, Z]$ aligned with $[U, V, W]$, assuming a solar position of $[-8.5, 0, 0.027]$ kpc (Kerr & Lynden-Bell 1986; Chen et al. 2001). We adopt the convention of positive $X$ pointing toward the Galactic center to align with our definition for $U$. The Galaxy was modeled using a set of static potentials comprising a spherically symmetric halo and bulge.
Figure 4. Galactic orbit of SDSS J1256–0224 over 1 Gyr centered on the current epoch, based on Galactic Model I from Binney & Tremaine (2008). The upper left and right panels show orbit in $[X, Y]$ and $[R, Z]$ inertial frame coordinates; the current position of the Sun ($X_\odot = -8.5$ kpc, $Z_\odot = +27$ pc; Kerr & Lynden-Bell 1986; Chen et al. 2001) is indicated by the black point. Bottom panels show time evolution of $R$ and $Z$. In all panels, past motion is indicated by dashed lines, future motion by solid lines.

and an axisymmetric, thin exponential disk. This model is a simplified version of that described in Dehnen & Binney (1998) and includes the three density distributions:

$$
\rho_{\text{bulge}}(r) = \rho_{b0} \left( \frac{r}{a_b} \right)^{-\alpha_b},
$$
$$
\rho_{\text{halo}}(r) = \rho_{h0} \left( \frac{r}{a_h} \right)^{-\alpha_h} \left( 1 - \frac{r}{a_h} \right)^{\alpha_h - \beta_h},
$$
$$
\rho_{\text{disk}}(R, z) = \Sigma_0 e^{-R/R_d} \delta(z),
$$

with spherical and polar coordinates $r \equiv \sqrt{X^2 + Y^2 + Z^2}$ and $R \equiv \sqrt{X^2 + Y^2}$. With these simplifications, the potentials corresponding to the bulge and halo densities can be expressed in terms of special functions, and the potential of the disk evaluated on a grid by numerical integration. The parameters $\rho_{b0}, \alpha_b, \rho_{h0}, \alpha_h, \rho_{d0}, \Sigma_0, R_d$ were adopted as given for Models I and II in Table 2.3 of Binney & Tremaine (2008), which fit the measured rotation curve of the Galaxy but bracket the range of allowable disk/halo mass ratio in the solar circle (Model I describes a Galaxy dominated by the disk mass at the solar circle, in Model II the halo mass dominates at the solar circle). The orbit of SDSS J1256–0224 was integrated using a second-order leapfrog method (kick–drift–kick) with a constant time step of 1 kyr over a total simulation of 1 Gyr centered on the present epoch. Energy was conserved to better than 1 part in $10^{-4}$ over the full length of the simulation, with the error dominated by the resolution of the grid on which the disk force and potential were interpolated. The $Z$ component of angular momentum was conserved to 1 part in $10^{-13}$.

Figure 4 displays the resulting orbit of SDSS J1256–0224 using Model I; Model II provides essentially identical results. The general character of this orbit is similar to several other ultracool subdwarfs, with a prograde eccentric orbit with apoaps near the solar radius ($3.5 \lesssim R \lesssim 11$ kpc, $e = 0.5$) and substantial deviations from the Galactic plane ($Z_{\max} \approx \pm 7.5$ kpc). In terms of eccentricity, the orbit of SDSS J1256–0224 is more similar to that of 2MASS J0532+8246 ($e = 0.5$, $3 \lesssim R \lesssim 8.5$; Burgasser et al. 2008) and less ballistic than that of the sdM8 LSR 1425+7102 (Lépine et al. 2003) which plunges to within 1 kpc from the Galactic center (Dahn et al. 2008). The inclination of SDSS J1256–0224’s orbit, $\tan i \approx R_{\max}/Z_{\max}$, is quite a bit larger, nearly 45° with respect to the Galactic plane as compared with $\sim 15°$ and $\sim 30°$ for 2MASS J0532+8246 and LSR 1425+7102, respectively.

The orbital characteristics of SDSS J1256–0224, 2MASS J0532+8246, and LSR 1425+7102 are all consistent with membership in the Galaxy’s inner halo population (Chiba & Beers 2001; Carollo et al. 2007). The inner halo is believed to dominate the halo population in the inner 10–15 kpc of the Galaxy and has a typical metallicity of $[M/H] \sim -1.6$ (Carollo et al. 2007; see also Gizis 1997). Membership in the inner halo suggests an origin in the dissipative mergers of satellite galaxies (e.g., Searle & Zinn 1978; Chiba & Beers 2001; Bell et al. 2008). It is possible that the similarity of these orbits arise from selection effects. Stars spend a larger percentage of their
orbital periods near apoaps (in this case near the Sun), and short, highly eccentric orbits would more frequently align with the Sun’s Galactic position. However, the recent discovery of the L subdwarf 2MASS J0616–6406, whose highly retrograde orbit extends out to $\gtrsim 30$ kpc, making it a likely member of the Galaxy’s outer halo population (Cushing et al. 2009), suggests that ultracool subdwarf populations may be well mixed in the vicinity of the Sun.

4. ATMOSPHERIC PROPERTIES

The distance and kinematics of SDSS J1256–0224 do not provide useful constraints on its atmospheric properties: $T_{\text{eff}}$, surface gravity (log g), and metallicity ([M/H]). Such determinations require empirical calibrations (e.g., well characterized coeval companions or cluster properties; Gizis & Reid 1997; Wolff & Wallerstein 2006) or direct comparison to spectral models (e.g., Burgasser et al. 2007). As SDSS J1256–0224 is a seemingly isolated source, we used the latter approach, employing the most recent generation of the Cond-Phoenix atmosphere simulations (Hauschildt et al. 1997, 1999; Baraffe et al. 2003) and the Drift-Phoenix model atmospheres (Dehn 2007; Helling et al. 2008a; Witte et al. 2009).

4.1. Spectral Models

Phoenix is a general-purpose model atmosphere code, using plane-parallel geometry, thermochemical equilibrium calculations, and opacity sampling to self-consistently solve for the temperature–pressure profile, chemical abundances, and radiative/convective energy transfer through the atmosphere. Several implementations of Phoenix have been used to study late-type dwarfs, incorporating various assumptions on elemental abundances, atomic and molecular opacities, line profiles, condensate formation, and convective overshoot (e.g., Hauschildt et al. 1999; Allard et al. 2001; Johnas et al. 2008; Helling et al. 2008a).

Here, we examine two implementations of Phoenix, the GAIA-Cond models (Hauschildt et al. 2003) and the Drift models (Dehn 2007; Helling et al. 2008a; Witte et al. 2009), which differ only in their treatment of the dust cloud layers. The former are most similar to the Cond-Phoenix model set developed by Allard et al. (2001), in which condensates species are treated as element sinks only and phase equilibrium is assumed. Hence, Cond-Phoenix models simulate dust-free but element-depleted atmospheres. The Drift-Phoenix models apply an advanced model of nonequilibrium grain formation, including seed formation, growth, evaporation, sedimentation, and convective upmixing to simulate the size distribution, abundances, and vertical distribution of grains and their material composition (Woitke & Helling 2003, 2004; Helling & Woitke 2006; Helling et al. 2008b). In this approach, each size-variable grain is made of a variety of compounds which changes with height according to its formation history. Alternate prescriptions for modeling condensate grain formation in cool dwarf atmospheres have been explored by Ackerman & Marley (2001), Allard et al. (2003), Cooper et al. (2003), Tsuji (2002, 2005), Tsuji et al. (2004), and Burrows et al. (2006); a thorough comparison of these cloud models is given in Helling et al. (2008c).

For this study, we employed both GAIA Cond-Phoenix and Drift-Phoenix atmosphere models spanning $2000 \leq T_{\text{eff}} \leq 3500$ K (steps of 100 K), log $g = 5.0$ and 5.5 (cgs) and $-3.0 \leq [\text{M/H}] \leq 0.0$ (steps of 0.5 dex; solar [M/H] = 0). Elemental abundances are scaled from Anders & Grevesse (1989) and Grevesse et al. (1992).

4.2. Color Comparisons

We pursued a two-step comparison of SDSS J1256–0224 to the models, first examining optical/near-infrared colors $i′$–$J$ and $J$–$K_s$ (see also Scholz et al. 2004b; Dahm et al. 2008; Schlabach et al. 2009). Synthetic colors were computed directly from the model atmosphere spectra by convolving each with filter profiles from SDSS (Fukugita et al. 1996, on the AB magnitude system) and 2MASS (Cohen et al. 2003, on the Vega magnitude system). The filter profiles include the effects of detector quantum efficiency, telescope throughput and atmospheric transmission, all of which are essential for the complex spectra of late-type dwarfs (e.g., Stephens & Leggett 2004).

Figure 5 displays colors for both model sets for log $g = 5.5$ and the full range of $T_{\text{eff}}$ and [M/H]. In addition to measurements for SDSS J1256–0224, we plot color data for five subdwarfs classified sdM8 and later: the sdM8 LSR 1425+7102 (Lépine et al. 2003); the sdM8.5 2MASS J01421353+0523258 (hereafter 2MASS J0142+0523; Burgasser et al. 2007); SSSPM J1013–1356, 2MASS J1626+3925; and 2MASS J0532+8246. Near-infrared photometry for all sources are from 2MASS or Schlabach et al. (2009), with the exception of 2MASS J0142+0523 for which a synthetic $J$–$K_s$ color was calculated using near-infrared spectral data from Burgasser et al. (2004). SDSS $i′$ magnitudes for SDSS J1256–0224 and 2MASS J1626+3925 are from SDSS DR6; for the other sources, $i′$ magnitudes were bootstrapped from $K_s$ photometry from the Super-Cosmos Sky Survey (SSS; Hambly et al. 2001a, 2001b, 2001c) by calculating synthetic $i′$–$K_s$ colors from published optical spectral data for these sources (Burgasser et al. 2003; Lépine et al. 2003; Scholz et al. 2004b; Burgasser et al. 2007). The uncertainties for the spectroscopy-based magnitudes were assumed to be 0.1 mag, based on prior work (e.g., Burgasser et al. 2002).

For the GAIA Cond-Phoenix models, predicted colors encompass the measured values of all the subdwarfs shown with the exception of 2MASS J0532+8246. Lower temperatures for a given metallicity generally yield redder $i′$–$J$ and bluer $J$–$K_s$ colors, except for [M/H] < -2.0 for which $i′$–$J$ colors actually turn blue. Lower metallicities at a given $T_{\text{eff}}$ lead to bluer $i′$–$J$ and $J$–$K_s$ colors. SDSS J1256–0224 and 2MASS J1626+3925 both fall along the [M/H] = -1.0 line in this diagram (as do LSR 1425+7102 and 2MASS J0142+0523) around $T_{\text{eff}} = 2300$ and 2150 K, respectively. For log $g = 5.0$, colors for these sources correspond to metallicities and temperatures that are $\sim$0.2 dex and $\sim$100 K lower, respectively. The inferred model parameters based on these colors must be treated with caution, however, as the [M/H] = 0 GAIA Cond-Phoenix models do not track well with mean $i′$–$J$ versus $J$–$K_s$ colors of M0–L0 field dwarfs as compiled by West et al. (2008). The divergence is likely due to the absence of condensate opacity in the GAIA models, which is necessary to reproduce the colors of late-type M and L dwarfs (e.g., Allard et al. 2001).

The Drift-Phoenix models exhibit very different color trends below $T_{\text{eff}} \approx 2500$ K as condensates become a prominent opacity source in the photosphere. Both $i′$–$J$ and $J$–$K_s$ colors trend redder for lower $T_{\text{eff}}$ for [M/H] > -2.5, with a notable kink in color tracks at $T_{\text{eff}} \approx 2200$–2300 not present in the GAIA Cond-Phoenix models. The additional reddening places the [M/H] = 0 models into closer agreement with the mean colors of L0 dwarfs, although they still diverge from M5–M9.
4.3. Spectral Comparisons

To further assess the agreement between models with observations, we compared the observed spectrum of SDSS J1256–0224 directly to the GAIA Cond-Phoenix and Drift-Phoenix model spectra for the same range of parameters shown in Figure 5. These comparisons were made to the combined red optical and near-infrared spectrum, which was stitched together by first smoothing the individual spectra to a common resolution of \( \lambda/\Delta \lambda = 100 \), scaling the spectra to match flux densities in the 0.8–0.9 \( \mu \)m range, and then combining the red optical spectral data for \( \lambda < 0.9 \mu \)m with the near-infrared data for \( \lambda > 0.9 \mu \)m\(^{11} \) (see Figure 2). The uncertainty spectrum (flux uncertainty as a function of wavelength) was combined using the same scaling factors and wavelength cutoffs. We then interpolated the entire spectrum onto a linear wavelength scale; a wavelength scale uniform in frequency produced identical results.

Observational and model spectra were initially normalized over the 0.9–1.0 \( \mu \)m range; then, for each model spectrum, a goodness-of-fit statistic was calculated:

\[
\Gamma(p) = \sum_{\lambda} W(\lambda) \frac{(F(\lambda) - \alpha S\mu(\lambda))^2}{\alpha S\sigma(\lambda) \sigma(\lambda)}.
\]

Here, \( F(\lambda) \) and \( \sigma(\lambda) \) are the observed spectrum and uncertainty; \( S\mu(\lambda) \) is the model spectrum for model parameters \( p = \{ T_{\text{eff}}, \log g, [\text{M/H}] \} \); \( \alpha \) is a normalization scale factor for the model spectrum; and \( W(\lambda) \) is a weighting function that satisfies \( \sum_{\lambda} W(\lambda) = 1 \). This form was chosen as a compromise between an expectation-weighted \( \chi^2 \) formulation (e.g., \( \sum (F - S)^2/S \)) and an error-weighted \( \chi^2 \) formulation (e.g., \( \sum (F - S)^2/\sigma^2 \)), as the former places too much emphasis on the lowest signal regions (i.e., strong absorption features) while the latter places too much emphasis on the highest signal-to-noise continuum regions (e.g., the 0.9–1.1 \( \mu \)m peak). For alternate approaches, see Takeda (1995) and Cushing et al. (2008). The sums were computed over the spectral range \( \lambda \approx 0.64–2.4 \mu m \). The normalization factor \( \alpha \) was allowed to vary over 0.5–1.5 to account for continuum offsets between the observed and model spectra, and the normalization with the minimum \( \Gamma \) was retained. Various weighting functions \( W(\lambda) \) were considered, but ultimately we settled on one that was constant for all wavelengths.\(^{12} \) Note that we do not consider \( \Gamma \) a robust estimator; it merely provides a quantitative measure of the best-fit model to the data. The best fits (minimum \( \Gamma \)) were also visually compared to verify that they did indeed provide a good match to the data.

Table 3 lists the parameters for the five best fits for the GAIA Cond-Phoenix and Drift-Phoenix models; the single best-fit models are compared with the data in Figure 6. The best-fit model parameters are similar between the two sets, with \( T_{\text{eff}} = 2300–2500 \) K and \([\text{M/H}] = -1.5 \) to \( -1.0 \) for the GAIA Cond-Phoenix models, and \( T_{\text{eff}} = 2100–2400 \) K and \([\text{M/H}] = -1.5 \) and for the Drift-Phoenix models. These parameters include models with \( \log g = 5.0 \) and 5.5. Lower

\(^{11} \) Red optical data were only used up to 0.9 \( \mu \)m due to concerns over the relative flux calibration of these data over the 0.9–1.0 \( \mu \)m range; see discussion in Burgasser et al. (2007).

\(^{12} \) Cushing et al. (2008), in their analysis of optical and infrared spectra of late-type dwarfs, considered a weighting function that scaled with the width of each spectral wavelength bin. As we interpolate the observed and model spectra onto a common, linear wavelength scale, our constant weighting scheme is equivalent.
gravities are generally matched with lower metallicities, which may simply indicate a tradeoff in the photospheric pressure ($P_{\text{ph}} \propto g/\kappa$, where $\kappa$ is the Rosseland mean opacity and is generally smaller for lower metallicities). A higher surface gravity is in fact preferred if this object is a low-mass member of the halo population. Evolutionary models predict that a 5 Gyr source with $T_{\text{eff}} = 2100$–2500 K should have $\log g = 5.3$–$5.5$ and mass 0.08–0.085 $M_\odot$ (Burrows et al. 2001; Baraffe et al. 2003). Indeed, there are more best-fitting models with $\log g = 5.5$ than $\log g = 5.0$.

Encouragingly, the best-fit parameters for both GAIA COND-PHoenix and Drift-PHoenix models are similar to the best-fit parameters from the GAIA COND-PHoenix color comparison. The metallicities inferred from both color and spectral comparisons are also consistent with the mean metallicities of inner halo stars (Carollo et al. 2007). In addition, we find that both sets of models do a reasonably good job at matching the overall spectral energy distribution of SDSS J1256–0224, in particular fitting the blue spectral slope from 1.3–2.4 $\mu$m and the depth of the 1.4 and 1.9 $\mu$m H$_2$O bands. The GAIA COND-PHoenix models also provide a fairly good match to the 0.9–1.3 $\mu$m spectral peak, reproducing the strong FeH bands at 0.99 and 1.25 $\mu$m but predicting excessively strong alkali lines in this region. The Drift-PHoenix models do a poorer job in this region, failing to reproduce the 1.1 $\mu$m spectral peak and, like the GAIA COND-PHoenix models, exhibiting excessively strong alkali lines.

There are more significant deficiencies in the red optical region, however, with both model sets failing to reproduce spectral features in detail, particularly around the spectral peaks at 6600 and 7400 Å. The models predict excessively strong Rb i and Na i alkali lines, and appear to be missing CrH and FeH opacity in the 8600–8700 Å region. The Drift-PHoenix models exhibit excessively strong TiO absorption at 8400 Å, and pronounced discrepancies in the 6700 Å CaH and 7200 Å TiO bands. Surprisingly, the older GAIA COND-PHoenix models provide overall better fits to the red optical data, although there are still clear problems in alkali line strengths, excessive emission in the pseudoccontinua between 6000 and 7500 Å, and missing CrH and FeH opacity. These discrepancies, which influence model $i'–J$ color trends (Figure 5), are attributable in part to inadequate treatment of the far-wing line profiles of the pressure-broadened Na i and K i doublets, as more recent opacity calculations are not incorporated in the present models (Burrows & Volobuyev 2003; Johnas et al. 2008). The treatment of dust formation can influence these line profiles due to feedback on the temperature structure (Johnas et al. 2008). It is therefore promising that the K i line cores and other alkali line strengths are reproduced better in the Drift-PHoenix models.

Incompleteness in molecular opacities (e.g., TiO, CrH, and FeH) is also likely responsible, a well-known problem in modeling the optical spectra of normal L dwarfs (e.g., Kirkpatrick et al. 1999a). We cannot rule out the additional influence of elemental composition variations, which are present in subsolar metallicity stars (e.g., Edvardsson et al. 1993; Fulbright 2000; Asplund et al. 2006) and can influence the overall atmospheric chemical pathways. The red optical region clearly remains problematic for low-temperature model atmospheres regardless of metallicity (see also Burgasser et al. 2007), although the incorporation of condensate dust formation appears to be aiding alkali line fits somewhat.

### 4.4. Discussion

While it appears that the inclusion of condensate grain formation as specified by the Drift-PHoenix models provides some improvement to the near-infrared colors and alkali line profiles of low-temperature dwarfs (see also Schmidt et al. 2008), the better overall spectral and color fits to SDSS J1256–0224 by the condensate-free GAIA COND-PHoenix models might suggest that condensates are unimportant in metal-poor atmospheres. Indeed, this is essentially the conclusion reached by several studies, citing the presence of enhanced metal-oxide bands, strong lines from refractory species, and blue near-infrared colors as consistent with largely condensate-free photospheres (Burgasser et al. 2003, 2007; Gizis & Harvin 2006; Reiners & Basri 2006).

However, there are problems with this simple interpretation. It is clear that TiO and VO features weaken from the M subdwarfs to the L subdwarfs, and through the current L subdwarf sequence (e.g., Burgasser et al. 2007). This trend is consistent with the depletion of refractory gas-phase elements with decreasing temperature. For comparison, TiO and VO bands strengthen in later type (lower-temperature) M giant spectra where low-atmospheric pressure inhibits condensation (see Lodders 2002). Suggestions that gaseous TiO and VO bands are enhanced in L subdwarf spectra may also be biased by the equilibrium condensation chemistry employed by many atmosphere models. Helling et al. (2008b) have shown that rare-element compounds, including Ca- and Ti-bearing condensates, never achieve phase equilibrium in low-temperature atmospheres; hence, the abundances of gas molecules are generally higher in nonequilibrium cloud models such as Drift-PHoenix. The fact that the metal-oxide bands observed in the spectrum of SDSS J1256–0224 are actually weaker than predicted by the best-fit Drift-PHoenix cloud models suggests that condensate grain formation may actually be more efficient than the Drift-PHoenix models predict. There are other complications as well. Incomplete molecular and pressure-broadened line opacities are clearly an issue for low-temperature atmosphere models, affecting in particular pressure–temperature profiles and associated chemistry throughout the photosphere. Witte et al. (2009) have also found that convective energy transport decreases with lower metallicities, resulting in reduced upmixing of undepleted gas and hence weaker cloud development and reduced total dust opacity in subdwarf atmospheres. With the wide variety of possible metallicity effects on condensate chemistry and grain formation processes, and the limitations of current opacity line lists, it is clear that conclusive statements on metallicity effects in condensate cloud formation would be premature.

### Table 3

| Model       | log $g$ | $T_{\text{eff}}$ | [M/H] | $\Gamma$ |
|-------------|--------|-----------------|-------|---------|
| GAIA COND-PHoenix | 5.5   | 2300            | −1.0  | 0.51    |
|             | 5.5   | 2400            | −1.0  | 0.53    |
|             | 5.0   | 2400            | −1.5  | 0.56    |
|             | 5.0   | 2300            | −1.5  | 0.57    |
|             | 5.5   | 2500            | −1.0  | 0.72    |
|             | 5.0   | 2300            | −1.5  | 0.64    |
|             | 5.0   | 2200            | −1.5  | 0.66    |
|             | 5.5   | 2300            | −1.5  | 0.67    |
|             | 5.5   | 2400            | −1.0  | 0.75    |
|             | 5.5   | 2100            | −1.5  | 0.76    |

**Notes.** Top five best-fit models for combined optical and near-infrared spectrum of SDSS J1256–0224, ranked by $\Gamma$. Best-fit models are shown in Figure 6.
Another consideration, independent of the state of current model atmospheres, is the possibility that L subdwarfs are simply warmer than equivalently classified L dwarfs. The $T_{\text{eff}}$ inferred for SDSS J1256–0224, roughly in the range 2100–2500 K, is comparable to those for solar-metallicity L0–L2 dwarfs (e.g., Vrba et al. 2004). At these temperatures, condensates play a less prominent role in atmospheric opacity than for cooler/later type dwarfs. Similarly, the sdL7 2MASS J0532+8246 has been shown to have a $T_{\text{eff}} = 1730 \pm 90$ K, comparable to L4–L5 dwarfs. This shift is due in large part to the classification methodology proposed by Burgasser et al. (2007). Comparison of L dwarf and subdwarf optical spectra in the 7300–9000 Å range places considerable emphasis on the pressure-broadened 7700 Å K i doublet. This feature is inherently pressure sensitive, and at a given temperature will be deeper and broader in the higher pressure, metal-poor (small $\kappa$) photospheres of L subdwarfs. As such, the apparent persistence of TiO absorption in L subdwarfs may simply reflect a shift in temperature scale and not condensation abnormalities (see also Burgasser & Kirkpatrick 2006).

Shifts in temperature and metallicity trends as a function of spectral type have been considered by some as an inherent weakness in classification schemes of ultracool subdwarfs in general (e.g., Jao et al. 2008). However, the current state of evolution in theoretical models, particularly those involving condensate cloud formation, emphasizes the importance of divorcing classification schemes from inferred physical parameters or theoretical models. As more examples of L subdwarfs are uncovered, measurement of luminosities and $T_{\text{eff}}$s, and improved theoretical modeling particularly of optical spectra, will enable a more precise mapping of classification parameters to physical properties, and hence more robust assessments of issues such as condensate grain formation in metal-poor environments. The classification ladder, however, must be empirical in design if it is to flexibly respond to improvements in our theoretical understanding of these rare, low-temperature, metal-poor sources.
5. SUMMARY

We have presented a thorough analysis of the red optical and near-infrared spectrum of the L subdwarf SDSS J1256−0224, originally identified by Sivarani et al. (2009) in the SDSS survey. This source is similar to the sdL4 2MASS J1626+3925 at both optical and near-infrared wavelengths, and we determine an sdL3.5 classification following the preliminary scheme of Burgasser et al. (2007). Using the absolute magnitude/spectral type relations for ultracool subdwarfs recently defined by Cush- ing et al. (2009), we estimate a distance of 66 ± 9 pc to this source, formally consistent with the less precise 90 ± 23 pc parallax distance measurement made by Schlafbch et al. (2009). Combined with its high proper motion and radial velocity, we confirm that SDSS J1256−0224 is a kinematic member of the Galactic inner halo, with a moderately eccentric and highly inclined Galactic orbit whose apoapsis is near the Sun. A comparison of the colors and spectra of SDSS J1256−0224 to GAIA COND-PHOENIX and DRIFT-PHOENIX atmospheric models indicate best-fit atmospheric parameters of $T_{\text{eff}} = 2100–2500$ K and $[\text{M/H}] = -1.5$ to $-1.0$ for log g = 5.0–5.5, although discrepancies between the models and the data, particularly in the red optical region, indicate that these parameters be treated with caution. Comparisons to the DRIFT-PHOENIX models contradict prior conclusions that condensate formation may be inhibited in metal-poor, low-temperature atmospheres. Nonequilibrium grain species abundances, particularly for Ti- and Ca-bearing species, predict even stronger metal-oxide bands than those observed in the spectrum of SDSS J1256−0224, indicating that condensate formation does occur in the atmospheres of low-temperature, metal-poor subdwarfs. However, improvements to the model atmospheres, particularly in the red optical region, are necessary before any conclusions can be made on metallicity effects in condensate grain and cloud formation. In addition, the possibility that the temperature scale of L subdwarfs is warmer than that of L dwarfs may provide a sufficient explanation for strong metal-oxide bands irrespective of grain chemistry.

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