Understanding Fundamental Properties and Atmospheric Features of Subdwarfs via a Case Study of SDSS J125637.13–022452.4

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Abstract

We present the distance-calibrated spectral energy distribution (SED) of the sdL3.5 subdwarf SDSS J125637.13–022452.4 (J1256–0224) using its Gaia DR2 parallax. We report the bolometric luminosity and semi-empirical fundamental parameters, as well as updated UVW velocities. The SED of J1256–0224 is compared to field-age and low-gravity dwarfs of the same effective temperature ($T_{\text{eff}}$) and bolometric luminosity. In the former comparison, we find that the SED of J1256–0224 is brighter than the field source in the optical, but dims in comparison beyond the $J$ band, where it becomes fainter than the field from the $H$ through $W2$ bands. Compared to the young source, it is fainter at all wavelengths. We conclude that J1256–0224 is depleted of condensates compared to both objects. A near-infrared band-by-band analysis of the spectral features of J1256–0224 is done and is compared to the equivalent $T_{\text{eff}}$ sample. From this analysis, we find a peculiar behavior of the $J$-band K1 doublets whereby the 1.17 $\mu$m doublet is stronger than the field or young source, as expected, while the 1.25 $\mu$m doublet shows indications of low gravity. In examining a sample of 10 subdwarfs with comparable data, we confirm this trend across different subtypes indicating that the 1.25 $\mu$m doublet is a poor indicator of gravity for low-metallicity objects. In the $K$-band analysis of J1256–0224, we detect the 2.29 $\mu$m CO line of J1256–0224, previously unseen in the low-resolution SpeX data. We also present fundamental parameters using Gaia parallaxes for nine additional subdwarfs with spectral types M7–L7 for comparison. The 10 subdwarfs are placed in a temperature sequence, and we find a poor linear correlation with spectral type. We present polynomial relations for absolute magnitude in JHKW1W2, effective temperature, and bolometric luminosity versus spectral type for subdwarfs.

Key words: brown dwarfs – stars: fundamental parameters – stars: individual (SDSS J125637.13–022452.4, Gaia DR2 3685444645661181696) – stars: low-mass – subdwarfs

1. Introduction

Brown dwarfs are low-mass, low-temperature objects that are unable to sustain stable hydrogen burning in their cores and thus cool throughout their lifetime. With masses $\lesssim 75$ $M_{\text{Jup}}$, brown dwarfs lie between the boundary of low-mass stars and planets (Saumon et al. 1996; Chabrier & Baraffe 1997). Classified based on their red optical or near-infrared (NIR) spectra, the observed population of brown dwarfs have effective temperatures of 250–3000 K corresponding to late-type M, L, T, and Y spectral types (Burgasser et al. 2002; Kirkpatrick 2005; Cushing et al. 2011).

The majority of brown dwarfs fall into three age subpopulations: field dwarfs, low surface gravity dwarfs, and subdwarfs. Effective temperature drives the atmospheric chemistry of brown dwarfs, thus creating differences in the observable spectroscopic and photometric features. Field dwarfs anchor the brown dwarf spectral classification methodology. Low-gravity dwarfs and subdwarfs have secondary parameters such as age, metallicity, and clouds that can alter their observable properties. Low-gravity dwarfs are identified by red near-infrared colors, weak alkali lines, and enhanced metal-oxide absorption in the optical (Kirkpatrick et al. 2006, 2010; Cruz et al. 2009; Allers et al. 2010). Many have been shown to be bona fide high-likelihood or candidate members of young nearby moving groups (e.g., Liu et al. 2013; Faherty et al. 2016; Kellogg et al. 2016; Schneider et al. 2016; Gagné et al. 2017). M and L subdwarfs are low-luminosity, metal-poor stars and brown dwarfs that typically display blue near-infrared $J$ – $K_s$ colors (Burgasser et al. 2003, 2009). Subdwarf spectra exhibit enhanced metal-hydride absorption bands (e.g., FeH), weak or absent metal oxides (TiO, CO, VO), and enhanced collision-induced H$_2$ absorption compared to the field dwarfs (Burgasser et al. 2003 and references therein). They exhibit high proper motions, substantial radial velocity, and inclined, eccentric, and sometimes retrograde Galactic orbits indicating membership in the Galactic halo (Burgasser et al. 2008b; Dahn et al. 2008; Cushing et al. 2009).

In comparison to field dwarfs, the low metallicity of M and L subdwarfs leads to atmospheres containing a lower abundance
of metal-oxide molecules such as TiO, VO, and CO. Consequently, this results in strong hydride bands of FeH, CaH, CrH, MgH, and AlH. The reduced abundance of these metal-oxide molecules indicates that metals in subdwarfs are prominently seen in metal-hydride species or as individual lines. With a reduced amount of metals in the atmosphere, condensate formation is difficult, thus resulting in a lack of clouds (Kirkpatrick et al. 2010). This reduction in condensate formation allows metals to remain in the atmosphere to lower temperatures, thus lines of Ca I, Ti I, Ca II, and Rb I are visible at temperatures lower than normally expected. An increased strength in the alkali lines of K I, Fe I, Rb I, and Cs I are also visible in subdwarf spectra.

The metal-deficient atmosphere of subdwarfs causes increased collision-induced H$_2$ absorption in the H and K bands, which is believed to be what produces their blue J $-$ K$_s$ color (Kirkpatrick et al. 2010). This is a consequence of their higher atmospheric pressure, caused by their higher mass at a fixed temperature. Likely young objects exhibit red J $-$ K$_s$ colors corresponding to their low surface gravity (Faherty et al. 2016), while subdwarfs exhibit blue J $-$ K$_s$ color corresponding to their low metallicity and likely also indicating their high surface gravity.

There are on the order of 80 subdwarfs of type sdM7 and later, which are of particular interest because they lie in the temperature range (<3000 K) that is comparable to directly imaged exoplanets (e.g., FW Tau b, Beta Pic b; Lagrange et al. 2010; Kraus et al. 2014), and they give us a handle on how low-metallicity and high-surface-gravity differences may impact observables. For this study we use the archetypal subdwarf J1256$-$0224 as a case example for how low metallicity and high surface gravity change observables.

Data from the literature on J1256$-$0224 are presented in Section 2. New MKO K-band photometric data taken for J1256$-$0224 and new NIR FIRE spectra taken for J1256$-$0224 and 2MASS J02235464$-$5815067 (hereafter J0223$-$5815) are discussed in Section 3. Section 4 discusses how we derive the fundamental parameters of J1256$-$0224 using its distance-calibrated spectral energy distribution (SED) and the Filippenko et al. (2015) method. In Section 5, a comparison of J1256$-$0224 with field-age and low-gravity dwarfs of the same effective temperature and bolometric luminosity is completed in order to examine how the overall SED shape differs with age. To understand how low metallicity affects spectral features, a band-by-band comparison of the spectra in the Y, J, H, and K bands for the T$_{\text{eff}}$ and L$_{\text{bol}}$ samples are discussed in Section 6. Finally, Section 7 places J1256$-$0224 in context with subdwarfs with parallaxes spectral typed as sdM7 and later in order to better understand the subdwarf population.

2. Published Data on J1256$-$0224

J1256$-$0224 was discovered by Sivarani et al. (2009) as part of a search for L subdwarfs in the Sloan Digital Sky Survey data release 2 (SDSS DR2) spectral database. Its spectral type is discussed in Sivarani et al. (2009), Scholz et al. (2009), Burgasser et al. (2009), Kirkpatrick et al. (2016), and Zhang et al. (2017b). Sivarani et al. (2009) tentatively classified J1256$-$0224 as an "sdL4." With additional data, Scholz et al. (2009) were able to separate spectral type as sdL4 $\pm$ 1 based on its optical spectrum, the width of its 0.77 $\mu$m KI doublet, its blue near-infrared colors, and halo kinematics. Burgasser et al. (2009) revised the spectral type to sdL3.5, based on the Burgasser et al. (2007) method. Allers & Liu (2013) classified the near-infrared spectra of J1256$-$0224 using their method as an M6 and with field gravity, noting the stark contrast to the optical spectral type of sdL3.5. Most recently, Zhang et al. (2017b) reclassified J1256$-$0224 as an usdL3 using the 0.73$-$0.88 $\mu$m region of the optical spectrum, which was based on their classification scheme anchored to the work of Lépine et al. (2007).

Optical spectra for J1256$-$0224 are presented in Sivarani et al. (2009; SDSS), Scholz et al. (2009; VLT/FORS1), Burgasser et al. (2009; LDSS3), Lodieu et al. (2015; VLT/ FORS2), and Kirkpatrick et al. (2016; Palomar/DSpec). Near-infrared spectra are presented in Burgasser et al. (2009; SpeX), Martin et al. (2017; NIRSPEC), and this paper (FIRE). Some notable spectral features include the deep K I doublet at 0.77 $\mu$m, strong bands of CrH and FeH at 0.86 $\mu$m, atomic lines of Rb I, and well-defined bands of CaH and TiO near 0.705 $\mu$m (Sivarani et al. 2009).

Pavlenko (2016) computed synthetic SED spectra for J1256$-$0224 using a NextGen model atmosphere with T$_{\text{eff}}$ = 2600 K, log g = 5.0, and [Fe/H] = $-$2.0. They found that synthetic model spectra with collision-induced absorption (CIA) fit J1256$-$0224 better than models without CIA, which was most visible in the near-infrared where CIA is most significant.

Sivarani et al. (2009) note that the r $-$ z color of J1256$-$0224 is much redder than the coolest known M subdwarfs, while the optical to NIR colors are much bluer than those of field L dwarfs. Schilbach et al. (2009) calculated their own photometric J, H, K$_s$ magnitudes.

Sivarani et al. (2009) determined that J1256$-$0224 is a high proper motion object with $(\mu_{\alpha}, \mu_{\delta})$ = $(470 \pm 64, -378 \pm 64)$ mas yr$^{-1}$. Schilbach et al. (2009) also calculated a proper motion and determined a parallax of 11.10 $\pm$ 2.88 mas for J1256$-$0224. Based on its kinematics, Burgasser et al. (2009) designated J1256$-$0224 as a member of the Milky Way’s inner halo. Burgasser et al. (2009) measured a radial velocity of $V_r = -130 \pm 11$ km s$^{-1}$ and determined UVW velocities of ($-115 \pm 11$, $-101 \pm 18$, $-150 \pm 9$) km s$^{-1}$ based on a distance from the Cushing et al. (2009) absolute magnitude/spectral type relations. We note that the statement of improved radial velocity and space velocities of J1256$-$0224 in Lodieu et al. (2015) is incorrect due to their use of proper motion and parallax for SSSPM J1256$-$1408 instead of those of J1256$-$0224. With the recent release of Gaia DR2 (Gaia Collaboration et al. 2016, 2018; Lindegren et al. 2018) the parallax and proper motions of J1256$-$0224 have improved and are listed in Table 1.

An effective temperature value for J1256$-$0224 was determined in Sivarani et al. (2009), where they found $T_{\text{eff}}$ $\sim$ 1800 K based on the Burrows et al. (2001) evolutionary models. Schilbach et al. (2009) determined a metallicity estimate of [M/H] = $-1.3$ according to the Chabrier & Baraffe et al. (1997) models. From synthetic GAIA COND-PHOENIX and DRIFT-PHOENIX model spectra and colors, Burgasser et al. (2009) found $T_{\text{eff}}$ $\sim$ 2100$-$2500 K, log g = 5.0$-$5.5, and [M/H] = $-1.5$ to $-1.0$. Using the Burgasser et al. (2009) spectra and NextGen atmosphere models with modified line lists, Lodieu et al. (2015) determined the best-fit synthetic spectra to have $T_{\text{eff}}$ = 2600 K, [M/H] = $-2.0$, and log g = 5.0. We note that Lodieu et al. (2015) also determined $T_{\text{eff}}$, L$_{\text{bol}}$, and radius values for J1256$-$0224; however, these values used the parallax and proper motion of J1256$-$1408 instead; therefore, they are not valid.

Finally, Zhang et al. (2017b) derived $T_{\text{eff}}$ = 2250 $\pm$ 120 K,
et al. 2017) is determined based off of the median of the assigned score for the four indices measured; however, they state that they exclude subdwarfs from their gravity typing. The best values for previously published data on J1256–0224, as well as values we present in this paper, are listed Table 1.

3. Observations

3.1. FIRE Data

We used the 6.5 m Baade Magellan telescope and the Folded-port InfraRed Echellelette (FIRE; Simcoe et al. 2013) spectrograph to obtain near-infrared spectra of J1256–0224 as well as the comparative young source J0223–5815. Observations were made on 2016 August 12 for J1256–0224 and 2015 September 25 for J0223–5815. For all observations, we used the echellelette mode and the 0.5′ slit (resolution λ/Δλ ~ 6000) covering the full 0.8–2.5 μm band with a spatial resolution of 0.9′′/pixel−1. Total exposure times of 2400 s (four ABBA nods of 600 s) and 1600 s (four ABBA nods of 400 s) were taken for J0223–5815 and J1256–0224, respectively. Immediately after each science image, we obtained an A star for telluric correction and obtained a ThAr lamp spectra (HD25986 for J0223–5815 and HD110587 for J1256–0224). At the start of the night, we obtained dome flats and Xe flash lamps to construct a pixel-to-pixel response calibration. Data were reduced using the FIREHOSE package, which is based on the MASE and SpeX reduction tools (Vacca et al. 2003; Cushing et al. 2004; Bochanski et al. 2009).

3.2. Photometric Data

MKO K-band observations of J1256–0224 were obtained at the Mont Mégantic 1.6 m telescope with the CPAPIR infrared camera (Artigau et al. 2004) on 2017 April 13. We obtained a sequence of 100 frames, each consisting of three co-additions, each with an 8.1 s exposure time for a total integration time of 40 minutes. The sequence was dithered randomly over a 3 arcmin circle. We used our custom IDL code for the data reduction. The reduction includes the division by a flat field taken on the dome, a sky subtraction made by using a running median of the images. The astrometric correction (second order) and registering of frames was done by cross-matching with GAIA DR1 catalog stars in the field. For the photometry, we used an aperture photometry code (a modified version of aper.pro in astrolib). The aperture radius is 1 FWHM and the sky radius is 2 to 4 FWHM. The FWHM and fluxes are measured directly in the final combined image. The uncertainties are estimated by taking aperture measurements in blank areas of the field and measuring the dispersion of the blank sky values. This is only correct if we are in the background-limited regime, which is the case here. The resultant photometry is listed in Table 1. The MKO K measurement provides an uncertainty and is in agreement with the previous 2MASS K, upper limit.

4. Fundamental Parameters of J1256–0224

The fundamental parameters for J1256–0224 were determined using the technique of Filippazzo et al. (2015), where we create a distance-calibrated SED using the spectra, photometry, and parallax. The SED of J1256–0224 uses the LDSS3
optical and near-infrared (NIR) is the fuzzy, blue-green portion of the SED. Observation references can be found in Tables 1 and 4. The optical spectrum from Burgasser et al. (2009), near-infrared FIRE spectrum from this paper, and the photometry (excluding 2MASS $K_s$) and parallax listed in Table 1.

Using the optical and NIR spectra, a composite spectrum is constructed and scaled to the absolute magnitudes in each filter. The overlapping red optical region in the range 0.95–1.03 $\mu$m was combined as an average. Details for SED generation can be found in Filippazzo et al. (2015). The SED of J1256–0224 is shown in Figure 1, with the various components labeled. The bolometric luminosity is determined by integrating under the SED. The effective temperature is calculated using a radius determined from the Saumon & Marley (2008) low-metallicity (−0.3 dex) cloudless evolutionary model along with the bolometric luminosity using the Stefan–Boltzmann law. An age range of $5–10$ Gyr was used for J1256–0224, which conservatively encompasses possible subdwarf ages.

Using the semi-empirical approach, we derived the following parameters: $L_{\text{bol}} = -3.63 \pm 0.05$, $T_{\text{eff}} = 2307 \pm 71$ K, $R = 0.94 \pm 0.02 R_{\odot}$, $M = 83.2 \pm 1.9 M_{\odot}$, $\log g = 5.37 \pm 0.01$ dex. If the Saumon & Marley (2008) solar-metallicity cloudless models were instead used, the derived effective temperature would be 36 K cooler. The fundamental parameters derived for J1256–0224 can be seen in Table 1. Our values for the bolometric luminosity and radius differ from those of Lodieu et al. (2015) because they have used an incorrect parallax value in their calculations. Our derived values for $T_{\text{eff}}$ and $\log g$ are consistent with the model based values from Zhang et al. (2017b).

From their metallicity versus effective temperature relation, Zhang et al. (2017a) classified J1256–0224 as a brown dwarf, i.e., a mass below the hydrogen burning boundary. Using their relation, we too would classify J1256–0224 as a brown dwarf. We concluded this using our $T_{\text{eff}}$ and mass values, along with a $[\text{Fe/H}] = -1.8$ for J1256–0224 and the hydrogen burning minimum mass for $[\text{Fe/H}] = -1.8$ from Zhang et al. (2017b). We note that on the metallicity versus effective temperature figure from Zhang et al. (2017a), field objects of the same effective temperature as J1256–0224 are late-M dwarfs. We also found late-M-type field dwarfs were comparison sources for the same $T_{\text{eff}}$ as J1256–0224.

5. A Comparative Sample for J1256–0224

5.1. Sample Selection and Properties

In order to better understand the fundamental parameters of J1256–0224 and how they affect its SED, two comparative samples were constructed. The first sample consists of objects with similar effective temperature and the second consists of objects with similar bolometric luminosity. We did not compare objects of the same spectral type because, within the same subclass, secondary parameters (e.g., metallicity) influence the spectral features. To try to disentangle these secondary parameters, we chose to look at objects with similar fundamental parameters. Effective temperature was chosen as a comparison parameter because it strongly affects the atmospheric chemistry. Bolometric luminosity was chosen to examine how the same amount of flux is distributed differently across wavelengths among objects of various radii and hence various ages. When these two parameters are fixed, clouds and metallicity remain the likely causes for differences between objects in the samples. For both comparative samples, we chose a low-gravity (likely young) object and a field-age object.

Individual sources were chosen from the samples of Faherty et al. (2016), which looked at a large sample of low-gravity objects.
dwarfs, and Filippazzo et al. (2015), which examined both field- and low-gravity objects. The bolometric luminosities in both the Faherty et al. (2016) and Filippazzo et al. (2015) samples were empirically derived, while their effective temperatures are semi-empirical derived using radii from the Saumon & Marley (2008) hybrid cloud models. In addition, objects from both samples were required to have medium-resolution NIR data ($\lambda/\Delta \lambda > 1000$ at the J band), in order to resolve features in a band-by-band comparative analysis of the spectra. Field dwarf comparison SEDs chosen from Filippazzo et al. (2015) were reconstructed with the same data used in that work, with the exception of replacing their low-resolution SpeX data with medium-resolution NIR data in this work and using updated Gaia DR2 parallaxes when available. Low-gravity dwarf comparison SEDs from Faherty et al. (2016) were constructed with new NIR FIRE data or re-reduced spectra as well as updated Gaia DR2 parallaxes. The low-gravity source in the $T_{\text{eff}}$ sample and both comparison objects in the $L_{\text{bol}}$ sample originally included synthetic photometric values in their SEDs, where details on how these values were calculated are discussed in Filippazzo et al. (2015). Only measured photometric values were used in the generation of the SEDs in our samples. These three modifications result in differences up to 1$\sigma$ in the values reported by Filippazzo et al. (2015) and Faherty et al. (2016).

Our comparative sample of similar effective temperatures consists of 2MASS J00242463$-$0158201 (hereafter J0024$-$0158) and 2MASS J20004841$-$7523070 (hereafter J2000$-$7523). J0024$-$0158 is a field brown dwarf discovered by Cruz & Reid (2002) and spectral typed as an M9.5 in both the optical by Kirkpatrick et al. (1995) and the infrared by Geballe et al. (2002). J2000$-$7523 was discovered by Costa et al. (2006) and is stated to be an M9$\gamma$ in both the optical and IR in Faherty et al. (2016). As reported in Faherty et al. (2016), J2000$-$7523 is a member of the $\beta$ Pictoris moving group and thus has an age ranging from 21–27 Myr (Bell et al. 2015). Our comparative sample of similar bolometric luminosity sources consists of DENIS–P J1048.0–3956 (hereafter J1048$-$3956) and 2MASS J02235464$-$5815067 (hereafter J0223$-$5815). J1048$-$3956 was discovered and optically spectral typed as an M9 by Montes et al. (2001). J1048$-$3956 was discovered by Reid et al. (2008) and optically spectral typed as a L0$\gamma$ by Cruz et al. (2009). As reported in Faherty et al. (2016), J0223$-$5815 is a member of the Tucana-Horologium moving group with an age ranging from 41–49 Myr (Bell et al. 2015). Discovery and spectral type references for both samples are listed in Table 2. Properties, such as photometry and parallax, for the $T_{\text{eff}}$ and $L_{\text{bol}}$ samples are listed in Table 3, while spectra used in the SED construction are listed in Table 4.

### 6. Spectral Analysis

Using their own spectral-typing system, Zhang et al. (2017b) found that L subdwarfs have temperatures between 100 and 400 K higher compared to field L dwarfs of the same spectral type, dependent on the metallicity subclass and spectral subtype of the subdwarf. Subdwarfs can therefore have effective temperatures similar to objects classified 2–3 subtypes earlier. Zhang et al. (2017b) noted that in addition to metallicity differences, there is a large spread in mass, log g, and age with any spectral type for subdwarfs. NIR spectra are mainly affected by $T_{\text{eff}}$ and metallicity, while optical spectra are most sensitive to $T_{\text{eff}}$ (Zhang et al. 2017b).

As stated in Sivarani et al. (2009), J1256$-$0224 appears to display a combination of late-M and mid-L spectral features, which is most prominently seen in the 0.6–0.9 $\mu$m region. Figure 2 contains a field- and low-gravity source of the same effective temperature and a field dwarf of the same spectral type as J1256$-$0224 for comparison. At 0.75 $\mu$m, there is a spectral type transition where at shorter wavelengths, the spectrum of J1256$-$0224 appears more similar to the M9, and onward of 0.75 $\mu$m, the spectra match better to the L3.5 dwarf. Due to this combination of M and L dwarf spectral features, we tested for the presence of a binary companion using the SpeX prism spectrum for J1256$-$0224 and the technique of Bardalez Bagliafetti et al. (2014). The results showed a 28% confidence that the binary hypothesis is statistically significant over the single hypothesis, i.e., J1256$-$0224 is not a spectral binary.

In this section, the SED of J1256$-$0224 is placed into context by comparing its overall shape to young- and field-age sources with equivalent temperatures and bolometric luminosities. We also utilized the optical and NIR medium-resolution spectral data to compare the red optical and individual $Y$, $J$, $H$, and $K$ bandpasses of each source, similar to the analysis of Faherty et al. (2014).

#### 6.1. Comparison of Full SEDs for the Fixed-$T_{\text{eff}}$ Sample

Figure 3 contains the full SEDs of the fixed-$T_{\text{eff}}$ sample across the 0.45–16 $\mu$m region. J1256$-$0224 is brighter than the field source in the optical, but dims in comparison beyond

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**Table 2**

| R.A.       | Decl.      | Designation          | Shortname | Discovery References | Opt. SpT | Spt References |
|-----------|------------|----------------------|-----------|----------------------|----------|----------------|
| 12 56 37.13 | −02 24 52.4 | SDSS J125637.13−022452.4 | J1256−0224 | 1                     | sdL3.5   | 2              |

**References.** (1) Sivarani et al. (2009), (2) Burgasser et al. (2009), (3) Cruz & Reid (2002), (4) Kirkpatrick et al. (1995), (5) Costa et al. (2006), (6) Faherty et al. (2016), (7) Montes et al. (2001), (8) Reid et al. (2008), (9) Cruz et al. (2009).
the J band, where it becomes fainter than the field from mid-J through W2 bands. While there are vague similarities around 1 μm between J1256−0224 and J2000−7523, the later is far brighter at nearly all wavelengths. Previous work found evidence that subdwarfs are likely cloudless, while young sources have thicker or higher-lying clouds (Faherty et al. 2012, 2016). Differing atmospheric conditions between these three equivalent temperature sources shown in Figure 3 may be representative of how the atmosphere of J1256−0224 is depleted of condensates, while J2000−7526 is enhanced compared to the field dwarf. Faherty et al. (2012) compared Saumon & Marley (2008) evolutionary models, with a cloud sedimentation parameter and three gravities to the NIR color–magnitude diagram for L and T dwarfs. They found by varying the sedimentation parameter that the models could fit portions of L and T dwarfs with various degrees. Faherty et al. (2012) showed that the cloudless model was the only one that reached the location of the two L subdwarfs (J0532+8246 and J1626+3925 in the NIR color–magnitude diagram. Faherty et al. (2012) also examined the effect of metallicity by using the Burrows (2006) evolutionary models, with cloudless and cloudy models of varying metallicities. The low-metallicity,
cloudless models were the only ones to cross through the space of the subdwarfs. They also showed that for the Burrows models, the largest factor in fitting the L and T dwarfs was the clouds, with metallicity having a smaller effect. Zhang et al. (2017b) fit J1256−0224 with the BT-Settl 2014 model grid over a temperature range of 1400–2600 K,
using a wavelength-dependent Gaussian convolution and are offset by a

Figure 4. Optical comparison of the effective temperature sample. J2000 −7523 (low-gravity, red), J0024−0158 (field-age, gray), and J1256−0224 (subdwarf, blue). All spectra were resampled to the same dispersion relation using a wavelength-dependent Gaussian convolution and are offset by a constant. Spectra were normalized by the average over 0.825−0.840 μm.

Figure 5(b) shows the 1.12−1.35 μm J-band data with FeH and H2O molecular features, as well as the alkali doublets of K I and Na I as labeled. The J-band spectra were normalized by the average flux over the featureless 1.29−1.31 μm region. The 1.12−1.15 μm portion of the spectrum of J1256−0224 is not shown due to the large amount of noise due to telluric absorption in this region, which obscures the Na I line. Therefore, we cannot compare this particular Na I line to the sample objects. We can, however, compare the K I doublets. The most noticeable aspect of these lines is the distinct difference in the depth of the K I doublet near 1.17 μm and the depth of the doublet near 1.25 μm. The deep blue doublet indicates that J1256−0224 is a high-gravity object, while the shallow red doublet indicates low gravity. Martin et al. (2017) used the equivalent widths of both K I doublets along with the FeH2 index and also found that the equivalent width for the red K I doublet indicates a low gravity. Therefore, the K I doublet near 1.17 μm is not a good gravity indicator for J1256−0224, which warrants further investigation. An equivalent width measurement of the K I doublets for this spectrum can be found in M. Alam et al. (2018, in preparation). To see if the K I doublet near 1.17 μm behaves this way for subdwarfs in general, we examine subdwarfs in our subdwarf sample that have medium-resolution J-band data in Section 7.1.2. We also note that the H2O band of J1256−0224 is slightly deeper than both the field- and low-gravity comparisons.

6.2.1 Optical

Figure 4 shows the 0.64−0.95 μm optical data with various features labeled. The Ca I feature near 0.66 μm is visible in the spectrum of J1256−0224, while it is not clearly seen in either the field- or low-gravity sources. The TiO band near 0.7 μm affects all three sources; for J1256−0224 the band is not as wide as J0024−0158 and has a steeper slope near 0.73 μm. J2000−7523 has a broader TiO feature than J1256−0224 and has an almost vertical shape near 0.73 μm. The plateau between ~0.73−0.76 μm for J1256−0224 has a blue slope, while there is a visible dip in the center for both the field- and low-gravity sources where it is broadest for the field dwarf. The K I doublet is broad for all sources; however, the VO for both the low-gravity and field objects affects the longward end of the broadened doublet. When comparing the Na I doublets, it is shallowest for J0024−0158, slightly deeper for J2000−7523, and deepest for J1256−0224. There is no indication of TiO absorption near 0.85 μm or H2O starting near 0.93 μm for J1256−0224, while both features are seen in the field- and low-gravity sources.

6.2.1.1 Y Band

Figure 5(a) shows the 0.95−1.10 μm Y-band data with Ti I, FeH, VO, and H2O features labeled. The spectra for the Y band were normalized by averaging the flux taken across the 0.98−0.988 μm region, which is relatively featureless. A noticeable difference between these three objects is the Ti I lines in the range 0.96−0.98 μm, where many lines are visible in the spectrum of J1256−0224, while only two of the Ti I lines are easily visible for J2000−7523 and J0024−0158. These lines are indicative of inhibited condensate formation (Burgasser et al. 2003; Reiners & Basri 2006). Another noticeable feature is the depth of the Wing-Ford FeH band at 0.9896 μm, which increases in depth with the age of the object, with J1256−0224 having the deepest band. The Wing-Ford band is very strong in M dwarfs; however, here we note that it is stronger in J1256−0224, indicating that J1256−0224 is likely cloudless. With the lack of clouds in J1256−0224, we are able to probe a deeper layer of the atmosphere at the Wing-Ford FeH band, as would be seen for T dwarfs. T dwarfs are thought to be cloudless due to dust settling below the photosphere at ~1000 K (Burgasser et al. 2002). J1256−0224 also lacks the VO absorption from 1.05−1.08 μm and the redward slope caused by the 1.08−1.10 μm H2O band as seen in both J2000−7523 and J0024−0158.

6.2.1.3 H Band

Figure 5(c) shows the 1.42−1.80 μm H-band data with FeH and CH4 molecular features labeled. The H-band spectra were normalized by the average flux over the featureless 1.5−1.52 μm region. The H-band shape of J1256−0224 is significantly different from those of J2000−7523 and J0024−0158. Gravity and K-band collision-induced H2 absorption shapes the longer-wavelength end of the H band. However, this difference in shape could also be due to the varying metallicity of these objects. Zhang et al. (2017b) shows that the H- and K-band flux is significantly decreased for L subdwarfs compared to L dwarfs. Figure 9 of Zhang et al. (2017b) shows this best, with the decrease in flux seen as you go through their metallicity subtypes. Since J1256−0224 is typed as an usdL3 in the Zhang et al. (2017b) system, you
would expect this dramatic decrease in $H$-band flux due to the extremely low metallicity.

6.2.1.4 K Band

Figure 5(d) shows the 2.0–2.35 $\mu$m $K$-band data with H$_2$O, CO, and collision-induced H$_2$ absorption features labeled. The $K$-band spectra were normalized by the average flux over the 2.16–2.20 $\mu$m region due to the relatively flat spectral region. The slope from 2.051–2.283 $\mu$m for J1256–0224 may be due to systematics from the reduction with this order. The $K$-band slope for our FIRE data does not match the SpeX spectra from Burgasser et al. (2009); however, the rest of our NIR spectrum slope matches, thus we caution the use of the $K$-band slope in this region. The most notable feature in the $K$ band is the 2.3 $\mu$m CO absorption. Previously, Burgasser et al. (2009) examined a low-resolution SpeX prism spectrum of J1256–0224 and found no evidence for CO, where weakened or absent CO is a telltale sign for subdwarfs (Burgasser et al. 2003). The CO absorption is comparable between the young object J2000–7523 and the field object J0024–0158. J1256–0224 displays clear CO absorption, but it is weakened in comparison.

6.3. Comparing Objects of the Same Bolometric Luminosity

Figure 6 shows the full SEDs of the fixed-$L_{bol}$ sample across the 0.5–22 $\mu$m region. When comparing objects of the same bolometric luminosity, differences in their radii are most apparent. From the optical to the $Y$ band, a spread in the flux is displayed, where J1256–0224 is overluminous compared to J1048–3956 and J0223–5815 is underluminous compared to J1048–3956. The fluxes of J1256–0224 and J1048–3956 overlap in the $J$ band. From the $H$ band out to the mid-infrared (MIR), J1256–0224 becomes underluminous compared to the field object J1048–3956. The young low-gravity object J0223–5815 is overluminous compared to J1048–3956 in the $K$ band through the MIR. Such a redistribution of flux to the optical for J1256–0224 points to further evidence for a lack of clouds.

A band-by-band analysis with the $L_{bol}$ sample was not informative as spectral features behave similarly to the $T_{eff}$ sample; thus, the corresponding figures are not reported here.

7. J1256–0224 in Context with Parallax-calibrated Subdwarfs

There are 11 subdwarfs of spectral type sdM7 or later that have the necessary observational data to generate distance-
calibrated SEDs. Here, we present these SEDs to put J1256−0224 in context with the other known subdwarfs with parallaxes. Our sample includes seven subdwarfs typed M7–M9.5 and four L subdwarfs ranging from L3.5–L7, including J1256−0224. Four subdwarfs in our sample have optical, NIR, and MIR spectra; four have optical and NIR spectra; one has optical and MIR spectra; while the remaining subdwarfs have an optical or NIR spectra only. Most of the sample had 2MASS and WISE photometry, while some objects also had SDSS or IRAC photometry.

The Kirkpatrick et al. (2016) optical spectrum for J1256−1408 is not publicly available and therefore we could not

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**Table 5: The Subdwarf Sample**

| R.A.  | Decl.  | Designation  | Shortname | Discovery References  | SpT      | SpT References | π (mas) | Pt References |
|------|--------|--------------|-----------|------------------------|----------|----------------|---------|---------------|
| 12 56 37.13 | −02 24 52.4 | SDSS J125637.13 | J1256−0224 | 1 | sdL3.5 | 2 | 12.55 ± 0.72 | 3 |
| 05 32 53.46 | +82 46 46.5 | 2MASS J05325346 | J0532+8246 | 4 | sdL7 | 2 | 40.24 ± 0.64 | 3 |
| 06 16 40.06 | −64 07 19.5 | 2MASS J06164006 | J0616−6407 | 5 | sdL5 | 5 | 19.85 ± 6.45 | 6 |
| 10 13 07.35 | −13 56 20.4 | SSSPM J1013−1356 | J1013−1356 | 7 | sdM9.5 | 7 | 17.87 ± 0.22 | 3 |
| 12 56 14.06 | −14 08 39.6 | SSSPM J1256−1408 | J1256−1408 | 1a | sdM8 | 8 | 32.49 ± 0.23 | 3 |
| 14 25 05.11 | +71 02 09.7 | LSR J1425+7102 | J1425+7102 | 8 | sdM8 | 8 | 13.63 ± 0.13 | 3 |
| 14 34 00.31 | +18 39 38.5 | LHS 377 | ... | 9 | sdM7 | 10 | 25.75 ± 0.10 | 3 |
| 14 44 20.67 | −20 19 22.3 | SSSPM J1444−2019 | J1444−2019 | 11 | sdM9 | 11 | 5.73 ± 0.56 | 12 |
| 16 10 29.00 | −00 40 53.0 | LSR J1610−0040 | J1610−0040 | 13 | sdM7 | 13 | 30.73 ± 0.34 | 14 |
| 16 26 20.34 | +39 25 19.1 | 2MASS J16262034 | J1626+3925 | 1 | sdL4 | 2 | 32.49 ± 0.23 | 3 |
| 20 36 21.65 | +51 00 05.2 | LSR J2036+5059 | J2036+5059 | 15 | sdM7.5 | 16 | 23.10 ± 0.29 | 12 |

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Note:

* Discovered and spectral typed by Scholz et al. via Schilbach et al. (2009).

References: (1) Schilbach et al. (2009), (2) Burgasser et al. (2007), (3) Gaia Collaboration et al. (2016, 2018), Lindegren et al. (2018), (4) Burgasser et al. (2003), (5) Cushing et al. (2009), (6) Faherty et al. (2012), (7) Scholz et al. (2004a), (8) Lépine et al. (2003c), (9) Liebert et al. (1979), (10) Gizis (1997), (11) Scholz et al. (2004b), (12) Dahn et al. (2017), (13) Lépine et al. (2003a), (14) Koren et al. (2016), (15) Lépine et al. (2002), (16) Lépine et al. (2003b).
Table 6
2MASS and WISE Photometry for Subdwarf Comparison SEDs

| Name            | J     | H     | Ks    | W1   | W2   | W3   | References |
|-----------------|-------|-------|-------|------|------|------|------------|
| J0532+8246      | 15.179±0.058 | 14.904±0.091 | 14.92±0.15 | ...  | ...  | ...  | 1          |
| J0616−6407      | 16.40±0.11  | 16.28±0.23  | ...    | 15.65±0.03 | 15.183±0.042 | ...  | 1, 2       |
| J1013−1356      | 14.621±0.032 | 14.382±0.049 | 14.398±0.078 | 13.782±0.028 | 13.545±0.035 | ...  | 1, 3       |
| J1256−1408      | 14.011±0.027 | 13.618±0.033 | 13.444±0.037 | 13.118±0.026 | 12.896±0.028 | ...  | 1, 3       |
| J1425+7102      | 14.775±0.037 | 14.405±0.054 | 14.328±0.092 | 13.892±0.025 | 13.66±0.03  | ...  | 1, 3       |
| LHS 377         | 13.194±0.029 | 12.73±0.03  | 12.479±0.025 | 12.298±0.027 | 12.051±0.025 | 11.67±0.11 | 1, 3       |
| J1444−2019      | 12.546±0.026 | 12.142±0.026 | 11.933±0.026 | 11.464±0.024 | 11.211±0.022 | 10.967±0.09 | 1, 4       |
| J1610−0040      | 12.911±0.022 | 12.302±0.022 | 12.302±0.022 | 11.639±0.025 | 11.639±0.025 | 11.639±0.025 | 1, 3       |
| J1626+3925      | 14.435±0.029 | 14.533±0.050 | 14.466±0.074 | 13.461±0.025 | 13.091±0.028 | ...  | 1, 3       |
| J2036+5059      | 13.611±0.029 | 13.160±0.036 | 12.936±0.033 | ...  | ...  | ...  | 1          |

Note. References listed as: 2MASS, WISE. Photometry with uncertainties greater than 0.25 mag were not included in the SED. References. (1) Cutri et al. (2003), (2) Kirkpatrick et al. (2014), (3) Cutri et al. (2012), (4) Cutri et al. (2013).

Table 7
SDSS Photometry for Subdwarf Comparison SEDs

| Name           | u     | g     | r     | i     | z     | References |
|----------------|-------|-------|-------|-------|-------|------------|
| J0532+8246     | ...   | ...   | 22.43±0.26 | 19.966±0.054 | 17.04±0.02 | 1          |
| LHS 377        | 21.89±0.13 | 19.384±0.011 | 17.681±0.006 | 15.696±0.005 | 14.707±0.006 | 2          |
| J1610−0040     | ...   | ...   | 17.976±0.007 | 15.903±0.004 | 14.663±0.005 | 3          |
| J1626+3925     | ...   | 23.08±0.16 | 20.65±0.04  | 17.92±0.01  | 16.13±0.01  | 4          |

Note. Photometry with uncertainties greater than 0.3 mag were not included in the SED. References. (1) Alam et al. (2015), (2) Ahn et al. (2012), (3) Adelman-McCarthy et al. (2009), (4) Adelman-McCarthy et al. (2008).

Table 8
IRAC Photometry for Subdwarf Comparison SEDs

| Name            | 3.6   | 4.5   | 5.8   | 8.0   | References |
|-----------------|-------|-------|-------|-------|------------|
| J0532+8246      | 13.37±0.03 | 13.22±0.02 | 13.23±0.1 | 13.03±0.1 | 1          |
| J1626+3925      | ...   | ...   | ...   | 12.82±0.18 | 2          |

Note. (1) Patten et al. (2006), (2) Spitzer PID251.

Table 9
Spectra Used to Construct the Subdwarf Sample SEDs

| Name            | OPT    | OPT Observ. Date | OPT References | NIR    | NIR Observ. Date | NIR References | MIR Observ. Date | MIR References | MIR |
|-----------------|--------|-----------------|---------------|--------|-----------------|---------------|-----------------|----------------|-----|
| J0532+8246      | LRIS   | 2003 Jan 03     | 1 NIRSPEC     | 2002 Dec 24 | 1 IRs            | 2005 Mar 23   | 2                |
| J0616−6407      | GMOS−S | 2007 Sep 13     | 3 X-Shooter   | 2016 Jan 24 | 4 ...            | ...            | ...             |
| J1013−1356      | GMOS-N | 2004 Nov 21     | 5 SpeX        | 2004 Mar 12 | 6 IRs            | 2005 Jun 07   | 7                |
| J1256−1408      | ...    | ...             | ...           | ...     | ...             | ...           | ...             |
| J1425+7102      | KPNO 4 m: R−C Spec | 2002 May 19 | 8 ...     | ...     | ...             | ...           | ...             |
| LHS 377         | X-Shooter (UVB, VIS) | 2014 Feb 20 | 9 X-Shooter  | 2014 Feb 20 | 9 IRs           | 2005 Jul 01    | 7                |
| J1444−2019      | EFOSC2 | 2004 Mar 16     | 10 SpeX      | 2005 Mar 23 | 11 ...          | ...           | ...             |
| J1610−0040      | MIIII  | 2003 Feb 19     | 12 SpeX      | 2003 Jul 06 | 13 ...          | ...           | ...             |
| J1626+3925      | OSIRIS | ...*            | 14 SpeX      | 2004 Jul 23 | 6 IRs           | 2005 Jun 03    | 7                |
| J2036+5059      | KAST   | 2001-12-09      | 15 SpeX      | 2003 Oct 06 | 13 ...          | ...           | ...             |

Note. * Combined spectrum of observations on 2011 February 5, 12 and 2011 April 13.
References (1) Burgasser et al. (2003), (2) Spitzer PID51, (3) Cushing et al. (2009), (4) Zhang et al. (2017b), (5) Burgasser et al. (2007), (6) Burgasser (2004), (7) Spitzer PID251, (8) Lépine et al. (2003c), (9) Rajpurohit et al. (2016), (10) Scholz et al. (2004b), (11) Bardalez Gagliuffi et al. (2014), (12) Lépine et al. (2003a), (13) Cushing & Vacca (2006), (14) Lodieu et al. (2015), (15) Lépine et al. (2003b).

complete its SED. The subdwarf sample SEDs were generated using the Saumon & Marley (2008) low-metallicity (~0.3 dex) cloudless models. If instead the Saumon & Marley (2008) solar-metallicity cloudless models were used, the derived temperatures would be on average ~25 K cooler. Table 5 contains the full subdwarf sample and their parallaxes, Tables 6–8 contain the photometry, and Table 9 contains spectra used for generating the SEDs.
Note. The effective temperature is determined based on age estimates and evolutionary models. 

\* J1610-0040 is an astrometric binary; thus, we caution the reader on the use of these parameters.

### Table 10
Subdwarf Sample Fundamental Parameters Determined with SEDkit

| Name          | Optical SpT | $L_{bol}$ | $T_{eff}$ (K) | Radius ($R_\odot$) | Mass ($M_\odot$) | log($g$) (dex) | Age (Gyr) | Distance (pc) |
|---------------|-------------|-----------|---------------|---------------------|------------------|----------------|-----------|--------------|
| J1256−0224    | sdL3.5      | $-3.625 \pm 0.05$ | 2307 ± 71     | 0.94 ± 0.02         | 83.2 ± 1.9       | 5.37 ± 0.01   | 5–10     | 79.7 ± 4.6   |
| J0532+8246    | sdL7        | $-4.277 \pm 0.015$ | 1677 ± 25     | 0.84 ± 0.02         | 72.1 ± 5.2       | 5.4 ± 0.05    | 5–10     | 24.85 ± 0.39 |
| J0616−6407    | sdL5        | $-4.24 \pm 0.28$  | 1720 ± 280    | 0.84 ± 0.04         | 70.5 ± 9.2       | 5.39 ± 0.08   | 5–10     | 50 ± 16      |
| J1013−1356    | sdM9.5      | $-3.307 \pm 0.012$ | 2621 ± 22     | 1.05 ± 0.01         | 91.89 ± 0.55     | 5.32 ± 0.05   | 5–10     | 55.96 ± 0.69 |
| J1256−1408    | sdM8        | ...         | ...           | ...                | ...              | ...           | ...      | ...          |
| J1425−7102    | sdM8        | $-3.059 \pm 0.011$ | 2829 ± 22     | 1.2 ± 0.01          | 104.48 ± 0.76    | 5.25 ± 0.05   | 5–10     | 73.36 ± 0.71 |
| LHS 377      | sdM7        | $-3.038 \pm 0.004$ | 2839 ± 6      | 1.22 ± 0.05         | 105.88 ± 0.34    | 5.25 ± 0.05   | 5–10     | 38.84 ± 0.16 |
| J1444−2019    | sdM9        | $-3.457 \pm 0.009$ | 2477 ± 13     | 0.99 ± 0.05         | 87.35 ± 0.58     | 5.35 ± 0.05   | 5–10     | 17.3 ± 0.17  |
| J1610−0040$^*$ | sdL7       | $-2.97 \pm 0.01$  | 2890 ± 20     | 1.27 ± 0.01         | 110.72 ± 0.85    | 5.23 ± 0.05   | 5–10     | 32.54 ± 0.36 |
| J1626−3925    | sdL4        | $-3.787 \pm 0.006$ | 2148 ± 14     | 0.9 ± 0.01          | 80.2 ± 1.6       | 5.39 ± 0.01   | 5–10     | 30.78 ± 0.22 |
| J2036−5059    | sdM7.5      | $-2.833 \pm 0.011$ | 2983 ± 22     | 1.4 ± 0.01          | 123.5 ± 1.3      | 5.19 ± 0.05   | 5–10     | 43.29 ± 0.54 |

7.1. Fundamental Parameters and Spectral Features of J1256−0224 in Comparison to the Subdwarf Sample

The semi-empirical fundamental parameters for the subdwarf parallax sample are shown in Table 10. Figure 7 shows the subdwarf sample displayed in the effective temperature sequence from 0.6–2.2 μm with $T_{eff}$ decreasing from yellow (hot) to purple (cool), with J1256−0224 highlighted in black.

Figure 8 shows a zoom-in on the red optical wavelength region with molecular and line features labeled.

As seen in Figure 7, our derived subdwarf temperature sequence does not closely follow the spectral type sequence. For the M subdwarfs in particular, subtypes half a type cooler (i.e., sd M7.5) are typically found to be warmer than that of the integer type (i.e., sd M7). J1013−135 sticks out as an sdM9.5 between a hotter sdM7 and a cooler sdM9. This mixed spectral...
type order indicates that ordering subdwarfs via spectral type is not a good temperature proxy. There are variations of the spectral types for three subdwarfs due to different spectral-typing schemes. For example, J1444−2019 is typed as an sdM9 in Scholz et al. (2004b), in Kirkpatrick et al. (2016) it is spectral typed as an sdL0, and in Zhang et al. (2017b) as an esdL1. Spectral schemes such as that of Zhang et al. (2017b) attempt to improve upon the relation between spectral type and temperature; however, as shown in this work, spectral type remains a poor temperature proxy for subdwarfs.

7.1.1 Variations in Subdwarf Spectral Lines as a Function of Temperature

In Figure 8, features are labeled with the objects plotted in decreasing temperature sequence, allowing us to examine how spectral features change as a function of temperature instead of spectral type. As the temperature decreases, the 0.63 μm CaH molecular band strengthens slightly from ~3000 K to 2600 K, then disappears around 2400 K. The Ca I feature near 0.66 μm also strengthens and then becomes less visible as the temperature decreases. The 0.66–0.71 μm TiO- and CaH-
subdwarfs, all of these optical spectral features appear to be near 0.87 \mu m. For subdwarfs with medium-resolution spectra, all spectra were resampled to the that of J1256 +0224, but then appears to decrease in strength below the temperature of J1013 −8246. The Na I doublet is of \sim 0.78 \mu m, bounded by TiO at 0.71 \mu m is visible for all subdwarfs in our sample. The feature shrinks as the TiO on the left and a K I doublet on the right, is visible down to the temperature of J1626 +3925, and is no longer visible below that temperature due to the broadening of the K I doublet. The K I doublet broadens as the atmospheric temperature cools. The individual lines of the K I doublet are only roughly visible above the temperature of J1013 −1356, \sim 2600 K. The 0.78 \mu m Rb I line is clearly visible for J1256 +0224 only. The 0.79 \mu m Rb I line, however, strengthens as the temperature decreases to that of J1256 +0224, but then appears to decrease in strength for J0616 −6407 and J0532 +8246. The Na I doublet is of similar depth for all objects between \sim 3000−2300 K and is not easily visible below those temperatures. The Ti I line near 0.84 \mu m strengthens as the temperature cools down to that of J1256 +0224 and then appears to weaken below \sim 2300 K. The Cs I line at 0.8521 \mu m, however, appears to strengthen as the temperature decreases. For subdwarfs, all of these optical spectral features appear to be primarily driven by temperature.

Figure 9. J band between 1.16−1.26 \mu m focused on the K I doublets of the subdwarfs with medium-resolution spectra. All spectra were resampled to the same dispersion relation using a wavelength-dependent Gaussian convolution. The sculpted region widens and flattens as the temperature decreases, eventually becoming undetectable for J0532 +8246. Kirkpatrick et al. (2014) noted that M/L transition subdwarfs have a noticeable peak between the CaH and TiO bands around 0.70 \mu m and that the slope of the plateau between approximately 0.73 \mu m and 0.76 \mu m changes from red to blue from types sdM9 to sdL1. The peak-shaped feature between CaH and TiO at 0.71 \mu m is visible for all subdwarfs in our sample. The feature shrinks as the TiO on the right weakens and disappears, leaving only a small bump visible between the CaH and TiO when the temperature decreases to that of J0532 +8246. The plateau between 0.73−0.76 \mu m, bounded by TiO on the left and a K I doublet on the right, is visible down to the temperature of J1626 +3925, and is no longer visible below that temperature due to the broadening of the K I doublet. The K I doublet broadens as the atmospheric temperature cools. The individual lines of the K I doublet are only roughly visible above the temperature of J1013 −1356, \sim 2600 K. The 0.78 \mu m Rb I line is clearly visible for J1256 +0224 only. The 0.79 \mu m Rb I line, however, strengthens as the temperature decreases to that of J1256 +0224, but then appears to decrease in strength for J0616 −6407 and J0532 +8246. The Na I doublet is of similar depth for all objects between \sim 3000−2300 K and is not easily visible below those temperatures. The Ti I line near 0.84 \mu m strengthens as the temperature cools down to that of J1256 +0224 and then appears to weaken below \sim 2300 K. The Cs I line at 0.8521 \mu m, however, appears to strengthen as the temperature decreases. For subdwarfs, all of these optical spectral features appear to be primarily driven by temperature.

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![Figure 9](image_url)

We examined the J band for subdwarfs with medium-resolution NIR data in order to put the K I doublets of J1256 +0224 in context with other subdwarfs. The blue K I doublet, near 1.17 \mu m, of J1256 +0224 indicates high gravity while the red doublet, near 1.25 \mu m, conversely indicates a low surface gravity. Figure 9 shows the five subdwarfs that have medium-resolution J-band data across the 1.16−1.26 \mu m region. In general, the blue K I doublet is deeper than the red doublet for all of these subdwarfs. The depths of both K I doublets do not change monotonically as a function of temperature. The doublets of J1256 +0224 show the largest difference in depth between the two sets, compared to the other subdwarfs, and its blue doublet is the deepest overall. LHS 377 is the only subdwarf in this set to have a large difference in depth between the first and second line in the 1.17 \mu m K I doublet. Obtaining more medium-resolution J-band spectra of subdwarfs would help determine the underlying cause of these conflicting indications of gravity with K I doublets. Thus, we conclude that the 1.25 \mu m K I doublet is a poor indicator of gravity for subdwarfs, while the 1.17 \mu m doublet needs to be studied more to determine if it is still a suitable gravity indicator for subdwarfs.

### 7.1.2. Analysis of the J-band K I Doublets in the Subdwarf Sample

We examined the J band for subdwarfs with medium-resolution NIR data in order to put the K I doublets of J1256 +0224 in context with other subdwarfs. The blue K I doublet, near 1.17 \mu m, of J1256 +0224 indicates high gravity while the red doublet, near 1.25 \mu m, conversely indicates a low surface gravity. Figure 9 shows the five subdwarfs that have medium-resolution J-band data across the 1.16−1.26 \mu m region. In general, the blue K I doublet is deeper than the red doublet for all of these subdwarfs. The depths of both K I doublets do not change monotonically as a function of temperature. The doublets of J1256 +0224 show the largest difference in depth between the two sets, compared to the other subdwarfs, and its blue doublet is the deepest overall. LHS 377 is the only subdwarf in this set to have a large difference in depth between the first and second line in the 1.17 \mu m K I doublet. Obtaining more medium-resolution J-band spectra of subdwarfs would help determine the underlying cause of these conflicting indications of gravity with K I doublets. Thus, we conclude that the 1.25 \mu m K I doublet is a poor indicator of gravity for subdwarfs, while the 1.17 \mu m doublet needs to be studied more to determine if it is still a suitable gravity indicator for subdwarfs.

### 7.2. Subdwarf Fundamental Parameters Compared to Field-age and Young Dwarfs

Figure 10 compares spectral type versus \text{L}_{\text{bol}} for subdwarfs and field- and low-gravity objects. The subdwarfs are entangled with the field- and low-gravity sequences. The unclear bolometric luminosity separation at the same spectral type for these populations indicates that spectral typing is not a good proxy for the effective temperature of subdwarfs. This is also the case for low-gravity objects (Filippazzo et al. 2015; Faherty et al. 2016). A linear fit for the subdwarfs (see Figure 10 and Table 11 for fit coefficients) appears to be located slightly above the field sequence, but since we only have 11 subdwarfs in this sample, it is difficult to determine if this fit is the best assessment for the entire subdwarf population.

As seen in Figure 11, the spectral type versus \text{T}_{\text{eff}} of the subdwarfs compared to field- and low-gravity sources show the subdwarfs above the field sequence, with warmer temperatures than field objects of the same spectral type. The low-gravity sources lie below the field sequence, and hence are cooler (e.g., see Filippazzo et al. 2015; Faherty et al. 2016). The difference

Table 11

| Relation | \text{C}_0^a | \text{C}_1 | \sigma^b |
|----------|-------------|-------------|----------|
| \text{M}_1 | 0.263 ± 0.027 | 8.49 ± 0.28 | 0.258 ± 0.075 |
| \text{M}_2 | 0.304 ± 0.026 | 7.77 ± 0.27 | 0.236 ± 0.082 |
| \text{M}_3 | 0.344 ± 0.024 | 7.29 ± 0.25 | 0.208 ± 0.074 |
| \text{M}_4 | 0.241 ± 0.043 | 7.72 ± 0.42 | 0.274 ± 0.099 |
| \text{M}_5 | 0.228 ± 0.039 | 7.62 ± 0.38 | 0.238 ± 0.088 |
| \text{T}_{\text{eff}} | −117 ± 13 | 3721 ± 132 | 108 ± 39 |
| \text{L}_{\text{bol}} | −0.125 ± 0.015 | −2.10 ± 0.16 | 0.144 ± 0.048 |

Notes. All coefficients and intrinsic dispersions were determined using a Markov Chain Monte Carlo (MCMC) calculation with a Gaussian prior, 3 walkers, and 1000 iterations.

\(^a\) \text{y} = \text{C}_0 + \text{C}_1 \text{t}.

\(^b\) Intrinsic dispersion.
in effective temperature for low-gravity sources appears to become more differentiated at later spectral types. The subdwarfs may also follow this trend; however, more subdwarfs of type sdL3 and later are needed to verify this trend. A linear fit was determined for the subdwarf population, which shows subdwarfs lying above the field sequence. This indicates that our model mass estimations have a good relative accuracy for the field. The subdwarfs do not lie very far above the field sequence or dynamical mass measurements. A few of the Dupuy & Liu (2017) objects in the sample have absolute magnitudes, with a few of theDupuy & Liu (2017) objects in the same positions as the subdwarfs. Thus, dynamical mass measurements of subdwarfs are needed to provide better information on how subdwarfs distinguish themselves from the field sequence when comparing spectral type and mass. At this time, there is only one close subdwarf binary, J1610−0040, an sdM7 whose dynamical mass measurements are estimated in Koren et al. (2016) as 0.09−0.10 M⊙ for the primary and 0.06−0.075 M⊙ for the secondary. Our estimated total mass of the J1610−0040 system is less than the value determined from Koren et al. (2016) by an appreciable amount, indicating that low-metallicity models may be underestimating masses. The components of J1610−0040 can be placed in Figure 12 for comparison to Dupuy & Liu (2017) once spectral types are determined.

7.3. Subdwarf Absolute Magnitudes Comparisons

As an extension of the spectral type to absolute magnitude relations for subdwarfs in Figure 13 of Faherty et al. (2012), Figures 13 and 14 display spectral type versus absolute magnitude in 2MASS J, H, K, and WISE W1 and W2 photometric bands. Each absolute magnitude band versus spectral type was fit with a polynomial for the subdwarf sample. The coefficients of these fits are listed in Table 11. As mentioned in Burgasser et al. (2008a) and Faherty et al. (2012), the subdwarfs move from being brighter in MJ to normal or slightly fainter than the field at MK, with this effect less prominent for the late-M subdwarfs. From MK to MH2 we see the subdwarfs remain normal, with the exception of the L subdwarf J0616−6407, which becomes slightly fainter than the field. From MK to MH2 J1256−0224, however, remains normal compared to the field.

8. Conclusions

In this work, we present the distance-calibrated SED of J1256−0224 and compared it to objects of the same effective temperature and bolometric luminosity. Using derived
fundamental parameters, we show that the best comparison objects are not of the same spectral type (L3.5), but instead are field- and low-gravity objects three to four subtypes earlier (M9-L0). We expect a cloudless atmosphere for J1256−0224, based on the larger amount of flux visible in the optical and the reduced flux in the \( H, K \), and mid-infrared bands. Comparing spectral features of the effective temperature sample in the near-infrared subdwarfs have stronger FeH and K1 features and visible lines of Ti1. The K1 doublets in the \( J \) band for J1256−0224 show indications of low gravity for the 1.17 \( \mu \)m doublet and high gravity for the 1.25 \( \mu \)m doublet. We note that the subdwarfs in our comparison sample with medium-resolution \( J \)-band data also show both low and high gravity for the K1 doublets, and thus we do not believe that the 1.25 \( \mu \)m doublet is a good indicator of surface gravity for subdwarfs. We also see an indication of CO in the \( K \) band for J1256−0224, which previously went undetected in the SpeX spectrum from Burgasser et al. (2009).
In order to place J1256−0224 in context with subdwarfs, we present distance-calibrated SEDs of the 11 subdwarfs typed sdM7 and later with parallaxes. The SEDs are displayed in a decreasing temperature sequence in order to understand how subdwarf spectral lines change with temperature. As the temperature cools, the 0.73–0.76 Å plateau feature moves from a red slope to a blue slope, the KI doublet near 0.77 μm broadens, and CrH and FeH strengthen in the red optical. The spectra of J1013−1356 and J1256−0224 have Ca I absorption at 6571 Å visible in the red optical. We show that spectral type is not a good proxy for subdwarf effective temperature and note in our sample that we see half-subtypes are warmer than integer subtypes when calculating $T_{\text{eff}}$ via SED fitting. Sequences were determined for subdwarfs for spectral type versus $L_{\text{bol}}$, spectral type versus $T_{\text{eff}}$, spectral type versus mass and are compared to the field- and low-gravity sequences for each. We show that all populations are indistinguishable based on only spectral type versus $L_{\text{bol}}$; however, populations separate using spectral type versus $T_{\text{eff}}$, with subdwarfs ∼300 K warmer on average than equivalent spectral typed field objects. We also expanded the spectral type versus absolute magnitude sequences down to W1 and W2, where subdwarfs are normal to slightly fainter than the field dwarfs. Subdwarfs are an important link in understanding how brown dwarf atmospheres have changed over time and thus how metallicity affects spectral features.

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