FOUR NEARBY L DWARFS
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ABSTRACT

We present spectroscopic, photometric and astrometric observations of four bright L dwarfs identified in the course of the 2MASS near-infrared survey. Our spectroscopic data extend to wavelengths shortward of 5000 Å in the L0 dwarf 2MASS J0746 +2000 and the L4 dwarf 2MASS J0036 +1840, allowing the identification of absorption bands due to MgH and CaOH. The atomic resonance lines Ca I λ4227 and Na I λλ5890/5896 are extremely strong, with the latter having an equivalent width of 240 Å in the L4 dwarf. By spectral type L5, the D lines extend over ~1000 Å and absorb a substantial fraction of the flux emitted in the V band, with a corresponding effect on the (V − I) broadband color. The K I resonance doublet at 7665/7699 Å increases in equivalent width from spectral type M3 to M7, but decreases in strength from M7 to L0 before broadening substantially at later types. These variations are likely driven by dust formation in these cool atmospheres.

Key words: Galaxy: stellar content — stars: low-mass, brown dwarfs — stars: luminosity function, mass function

1. INTRODUCTION

Familiarity with one’s immediate neighbors is, in general, good policy. In the case of the solar neighborhood, our knowledge of the local constituents forms the basis for the determination of fundamental statistical quantities such as the luminosity function, the mass function, the local mass density, and the star formation history of the disk. Moreover, as the apparently brightest members of their respective spectral classes, the nearest celestial neighbors are most accessible to detailed astrophysical analysis. The latter consideration is of particular importance for objects of intrinsically low luminosity, such as old, low-temperature white dwarfs and ultracool, very low-mass (VLM) main-sequence dwarfs.

Until recently, the main resource for the identification of VLM dwarfs remained the proper motion catalogues compiled by Luyten from photographic material obtained in the 1950s and 1960s using the Palomar 1.2 m Oschin Schmidt Telescope. The development of higher sensitivity red and photographic-infrared emulsions in the 1970s permitted photometric surveys to extend to somewhat larger depths, but this field of study has been revolutionized through the advent of deep, near-infrared all-sky surveys, such as DENIS (Epchstein et al. 1994) and 2MASS (Skrutskie et al. 1997). Follow-up observations of sources with extremely red JHK or optical-to-infrared (RIJHK) colors (Delfosse et al. 1997; Kirkpatrick et al. 1999, hereafter Paper I) have resulted in the identification of numerous ultracool dwarfs. Many are spectroscopically similar to the previously unique white dwarf companion, GD 165B, which has been transformed from an anomaly to a prototype. The far-red optical spectra of these dwarfs are characterized by the disappearance of TiO and VO absorption bands, the defining signature of spectral class M, and the presence of metal hydride (CaH, FeH, CrH) bands and neutral alkali (Cs, Rb, sometimes Li) lines. The progression of those features was ordered in Paper I to define a new spectral class, type L.

The initial sample of ultracool L dwarfs discovered by 2MASS (20 objects) and other surveys (five dwarfs) includes only two objects with magnitudes brighter than K = 12: Kelu 1 (Ruiz, Leggett, & Allard 1997) and 2MASS J1439284 +192915. As a result, apart from Ruiz et al.’s observations of Kelu 1, spectroscopy of these sources has been confined largely to wavelengths longward of 6400 Å. We have since extended the areal coverage of our 2MASS analysis by almost a factor of 3, concentrating on identifying late-type L dwarfs. Our current sample includes 74 spectroscopically confirmed L dwarfs (Kirkpatrick et al. 2000, hereafter Paper II). Four (including 2MASS J1439284 +192915) are of particular interest, since their properties imply that they lie at distances of no more than 15 parsecs. All are sufficiently bright that they supply an
2. OBSERVATIONS

The four L dwarfs discussed in this paper were all identified as candidate low-temperature objects based on analysis of $JHK_S$ photometric catalogues derived from the 2-Micron All-Sky Survey (Skrutskie et al. 1997). 2MASSW J1439284+192915 forms part of the original L dwarf sample discussed in Paper I; 2MASSW J0746425+200032 was selected amongst a sample of candidate bright, ultracool late-type dwarfs (discussed further by Gizis et al. 2000); 2MASSW J0036159+182110 and 2MASSW J1507476-162738 were identified as likely to be mid- to late-type L dwarfs based on their having $(J-K_s)$ colors redder than 1.3 magnitudes. For brevity, we shall refer to these sources as 2M0036, 2M0746, 2M1439, and 2M1507 throughout the rest of this paper. The individual photometric measurements of each object are listed in Table 1: 2M0036 and 2M1507 fall in overlap regions between separate scans and the $JHK_s$ magnitudes are averages of the two observations.

A finding chart for 2M1439 is available in Paper I, and finding charts for the other three dwarfs are presented in Paper II.

2.1. Spectroscopy

Each L dwarf has been observed using the Low-Resolution Imaging Spectrograph (Oke et al. 1995) on the Keck II Telescope. Initial observations were obtained using a 1″ slit and the 400 line mm$^{-1}$ grating blazed at 8500 Å, covering the wavelength range 6300–10200 Å at a resolution of 9 Å. An OG570 filter was used to eliminate second-order flux. This is the standard instrumental set-up used in our L dwarf observations, and data reduction and calibration followed the procedures described in Paper I. The UT dates of the individual observations were 1998 December 14 and 16 (2M0036), 1998 December 24 (2M0746), 1997 December 8 (2M1439), and 1998 December 24 (2M1507). 2M0746 was also observed on 1998 December 4, using the modular spectrograph on the Las Campanas Observatory Du Pont 2.5 m telescope (see Gizis et al. 2000 for further details), while the 2M1439 observations are described in Paper I. Spectral types have been derived for each dwarf based on the LRIS spectra plotted in Figure 1 following the precepts given in Paper I (see Kirkpatrick et al. 2000, ApJ, submitted for further details).

We have supplemented these intermediate-resolution red spectra with a range of other observations.

LRIS: blue spectra.—We also have shorter wavelength LRIS observations of 2M0036, 2M0746, and 2M1507, using the 300 line mm$^{-1}$ grating blazed at 5000 Å. These spectra were obtained on 1998 December 25 (2M0036), 1999 March 5 (2M0746), and 1999 July 17. The respective exposure times were 1800, 1800 and 3600 s, respectively. As with the standard far-red observations, we used a 1″ slit, providing a spectral resolution of ~6 Å and wavelength coverage from ~3900 to 7800 Å. The respective exposure times were 1800, 1800 and 3600 s, respectively. As with the standard far-red observations, we used a 1″ slit, providing a spectral resolution of ~6 Å and wavelength coverage from ~3900 to 7800 Å. For brevity, we shall refer to these sources as 2M0036, 2M0746, 2M1439, and 2M1507 throughout the rest of this paper. The individual photometric measurements of each object are listed in Table 1: 2M0036 and 2M1507 fall in overlap regions between separate scans and the $JHK_s$ magnitudes are averages of the two observations.

A finding chart for 2M1439 is available in Paper I, and finding charts for the other three dwarfs are presented in Paper II.

![Fig. 1.—Far-red optical spectra of the four bright L dwarfs discussed in this paper.](image)

| Name       | Spectral Type | $(B-V)$ | $(V-R)_{BP}$ | $V$   | $I_C$    | $J$   | $H$   | $K_S$ |
|------------|---------------|---------|--------------|-------|----------|-------|-------|-------|
| 2M0036.....| L3.5          | 1.7 ± 0.2| 3.0 ± 0.1    | 21.33 ± 0.06| 16.10 ± 0.02| 12.44 | 11.58 | 11.03 |
| 2M0746.....| L0.5          | 2.1 ± 0.2| 2.3 ± 0.1    | 19.87 ± 0.06| 15.11 ± 0.02| 11.74 | 11.00 | 10.49 |
| 2M1439.....| L1            | ...     | ...          | 21.04 ± 0.02| 16.12 ± 0.02| 12.76 | 12.05 | 11.58 |
| 2M1507.....| L5            | ...     | ...          | 22.9 ± 0.5  | 16.65 ± 0.02| 12.82 | 11.90 | 11.30 |

Note: In particular, the increasing strength of both the potassium $\lambda\lambda 7665/7699$ and sodium $\lambda\lambda 5890/5896$ features is evident in the spectra of 2M0036, 2M0746, and 2M1507, while 2M1439 shows a relatively weaker sodium line.
resonance doublets as one progresses from spectral type M9.5–L5.

HIRES observations.—Finally, we have obtained higher-resolution echelle spectra of all four L dwarfs using HIRES (Vogt et al. 1994) on the Keck I Telescope. The observations were obtained 1998 August 24 (2M0036, 2M1439), 1999 March 6 (2M0746), and 1999 June 14 (2M1507). In each case, the data provide partial coverage of the wavelength range 6000–8500 Å, including important features such as Li i λ6708 Å, K i λλ7665/7699, Rb i λ7800 and λ7948, and the Na i λλ8183/8195 doublet. Total exposure times of 6000 s were accrued on each source. As discussed further below, lithium was not detected in any of these four L dwarfs.

The HIRES data were flat field–corrected and the spectra extracted using programs written by T. Barlow. The wavelength calibration, based on Th-Ar arc lamp exposures, was determined using the IRAF routines ECIDENTIFY and DISPCOR. We have not attempted to set these data on a flux scale. Radial velocities were computed for each star either from the measured wavelength of the Hα emission line (in 2M0746 and 2M1439) or by measuring the central wavelengths of atomic lines due to Cs and Rb, adopting heliocentric corrections given by the IRAF RV package. Our radial velocity measurements for M dwarfs from the Marcy & Benitz (1989) sample indicate that the latter technique can give velocities accurate to ±1.5 km s⁻¹. However, the atomic lines are relatively broad in the L dwarfs, and an internal comparison of the individual measurements suggests that the uncertainty is 2–3 km s⁻¹. Save for 2M1439, the uncertainties in the derived space motions are dominated by the parallax measurements.

2.2. Photometry

CCD images in several passbands have been obtained of all four L dwarfs discussed in this paper. The observations were made using the 1 m telescope at the Flagstaff station of the US Naval Observatory. Full details of the data reduction and calibration process are given by Dahn et al. (in preparation). Those data are listed in Table 1.

In addition to these direct measurements, we have used the calibrated spectra plotted in Figures 1 and 2 to synthesize (B – V), (V – R), and (V – I) colors. As in Paper I, square passbands are adopted for each filter, and the flux zero points are those of the Johnson/Kron-Cousins system (Bessell 1979). In general, there is reasonable agreement between the spectroscopic colors and the available direct measurements.

Finally, we have estimated bolometric magnitudes for each dwarf. While none of these sources, and relatively few late-type M or L dwarfs in general, have observations at wavelengths longward of 2.2 μm, the available data suggest that m_bol can be estimated with reasonable accuracy from the observed magnitude at the 1.25 μm J band. Leggett et al. (1996) derive BC_J = 2.07 mag for the M6.5 dwarf GJ 1111; Tinney, Mould, & Reid (1993) infer BC_J = 1.7 mag for the L4 dwarf GD165B; and Leggett et al. (1999) have...
derived $BC_J = 2.19$ mag for Gl 229B. These results indicate that there is relatively little variation in $BC_J$ over this temperature range ($\sim 2700$–$\sim 950$ K) and we have adopted a uniform correction of $M_{\text{bol}} = M_J + 1.75$ mag for each object in the current sample.

### 2.3. Astrometry

All four L dwarfs discussed in this paper have been placed on the US Naval Observatory (Flagstaff) CCD parallax program (Monet et al. 1992). Preliminary absolute parallaxes are available in each case, and those data are listed in Table 2. These observations are also used to derive absolute proper motions, and the results for 2M0036, 2M0746, and 2M1439 are listed in Table 2. In the case of 2M1507, the USNO observations span a period of only 107 days, leading to significant uncertainties in $\mu$ and $\theta$. Fortunately, that dwarf is visible on both the first and second epoch plates taken by the UK Schmidt Telescope as part of the southern sky survey. Most of the L dwarfs listed in Paper I are visible on the POSS II IVN I-band plates, and several are also detected on POSS II IIIaF (R-band) plate material. 2M1507 is unusual in that it is sufficiently bright to be detected on even the IIIaJ (blue-green) 1st-epoch UKST plates. The time difference between the two UKST observations is 11 years, sufficient to allow a more accurate estimate of the proper motion than provided by current CCD observations. We have used standard profile-fitting techniques to measure the displacement between the two epochs and derive an annual proper motion close to 1 $\mu$arcsec yr$^{-1}$ directed almost due south. Note that three of the four L dwarfs have motions consistent with their inclusion in the Luyten half-second (LHS) catalog.

### 3. DISCUSSION

These new observations allow us to investigate further the spectral energy distribution and atmospheric composition of L dwarfs. In addition, we can determine space velocities for the four objects in the present sample.

#### 3.1. Molecular Features

Far-red optical spectra of L dwarfs show that metal hydride bands, notably CaH, FeH, and CrH, become increasingly prominent with decreasing temperature (later spectral types). This behavior is reminiscent of that observed in late-type metal-poor subdwarfs. In both cases, the greater visibility of the hydride bands reflects decreasing strength of TiO and VO absorption, albeit governed by two different mechanisms: in the subdwarfs, the weak oxides are due to an overall scarcity of metals; in the L dwarfs, TiO and VO are depleted as dust particles, mainly perovskite, CaTiO$_3$, and solid-phase VO, respectively. Other minerals, such as enstatite (Mg$_3$Si$_2$O$_6$) and forsterite (Mg$_2$SiO$_4$), are also expected to condense at temperatures between $\sim 2100$ and 1500 K (Fegley & Lodders 1996; Burrows & Sharp 1999; Lodders 1999).

By analogy with cool subdwarfs, other hydrides are expected to be visible at shorter wavelengths—in particular, MgH (Cottrell 1978). Figure 4 plots our LRIS observations of three extreme ([M/H] $< -1.5$) dwarfs: LHS 489 (esdM0 on the system defined by Gizis 1997), LHS 453 (esdM3.5), and LHS 375 (esdM5). Those observations were obtained on 1999 July 17 using the same instrumental setup and data reduction process as in our observations of 2M1507. Com-

| Parameter          | 2M0036        | 2M0746        | 2M1439        | 2M1507        |
|--------------------|---------------|---------------|---------------|---------------|
| $mu$ yr$^{-1}$     | 0.833 ± 0.073 | 0.464 ± 0.091 | 1.2943 ± 0.0012 | 0.99 ± 0.05   |
| $\theta$ degrees   | 80 ± 15       | 250 ± 2       | 288.3 ± 0.1   | 174 ± 5       |
| $\pi$ milliarcsec | 92.2 ± 16.3   | 69.4 ± 16     | 69.5 ± 0.6    | 117.5 ± 25.2  |
| $V_{\text{rad}}$ km s$^{-1}$ | 21.7 ± 3.0     | 56.6 ± 2.0    | -23.9 ± 2.0   | -36.4 ± 3.0   |
| $M_K$              | 10.86 ± 0.35  | 9.70 ± 0.45   | 10.70 ± 0.02  | 11.65 ± 0.42  |
| $M_{\text{bol}}$  | 14.00         | 12.70         | 13.65         | 14.90         |
| $U$ km s$^{-1}$    | -46.3         | -60.6         | -80.7         | -15.8         |
| $V$ km s$^{-1}$    | -4.1          | -21.5         | -39.1         | -17.5         |
| $W$ km s$^{-1}$    | -11.9         | -8.8          | 17.9          | -48.6         |
| $V_{\text{tot}}$ km s$^{-1}$ | 48.0 ± 8.5 | 64.9 ± 13.9 | 91.4 ± 2.5 | 54.0 ± 9.5 |
paring spectra for the two sets of objects reveals both signif-
ificant similarities and differences. The L dwarfs are
substantially cooler than the \( \sim 3000\text{--}4000 \) K esdMs,
leading to much steeper spectral energy distributions in
the former than the latter. In both cases, however, the most
prominent molecular absorption is due to metal hydrides,
with the \( 5200 \) \( \text{Å} \) MgH feature obvious in all of the L dwarfs.
The \( 4788 \) \( \text{Å} \) band is clearly present in the L5, 2M1507, and
is barely detected in 2M0036.

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\text{TiO bands at 4761, 4954, and 5448} \text{Å are evident in}
2M0746, but have disappeared by spectral type L4. All of
the L dwarfs also exhibit strong absorption at \( \sim 5500 \) \( \text{Å}
with the band most prominent in 2M0746. This feature is
likely to be calcium hydroxide, CaOH, originally identified
in mid-type M dwarfs by Pesch (1972) and increasingly
strong in later-type M dwarfs. This molecule also contrib-
utes a diffuse band at \( \sim 6230 \) \( \text{Å} \) (Pearse & Gaydon 1965),
which is blended with the \( ^{6}P_{1/2} \rightarrow ^{4}S_{3/2} \) TiO band in M dwarfs
(Boeshaar 1976). The latter two bands are likely responsible
for the substantial, double-bottomed absorption feature at
\( \sim 6200 \) \( \text{Å} \) in 2M0746, evident as a shallower depression in A
the L4, 2M0036. Both CaOH and MgH can be identified
in the spectrum of Kelu 1 presented by Ruiz et al. (1997).
Finally, the VO \( 5736 \) band is probably responsible for a
relatively weak absorption feature in 2M0746.

### 3.2. Atomic Lines

Table 3 lists equivalent widths for some of the more
prominent atomic lines present in the spectra of these
objects. We list results from measurements of both the LRIS
spectra plotted in figure 1 and of our HIRES data. The
latter provide only incomplete wavelength coverage, but the
higher resolution data allow more accurate measurements
of weaker lines. In particular, the Ca \( \lambda \lambda 6572 \) and 8256
absorption lines and Hz emission are barely detectable in the
LRIS spectra, where the measured equivalent widths have a
1 \( \sigma \) uncertainty of \( \pm 0.5 \) \( \text{Å} \).

One of the strongest features, either atomic or molecular,
in the far-red spectra of L dwarfs is the K \( \lambda \lambda 7665/7699
resonance doublet. Those lines have individual equivalent
widths of 10--12 \( \text{Å} \) at spectral type L0, but increase dramat-
ically in strength with decreasing temperature to the extent
that the lines effectively merge at \( \sim L5 \), where the composite
feature has a width exceeding 100 \( \text{Å} \). Similarly, the Rb \( \lambda \) and
Cs \( \lambda \) lines show distinctly nonlinear behavior, increasing
substantially in strength between the L4 dwarf 2M0036 and
2M1507 (L5).

In Paper I we proposed that this behavior is another con-
sequence of dust formation. As discussed further in § 3.5,
dust initially contributes a scattering layer at late-type M
dwarfs, but in lower temperature atmospheres (later spectral
types) the dust particles either "rain out" to greater
depths (below the photosphere) or form larger particles, in
either case reducing scattering at optical wavelengths. The
overall atmospheric transparency is further increased as
metals are transformed to solid phase, both by the removal
of TiO and VO molecular absorption, and through the
scarcity of free electrons and the resulting reduced level of H\(^-\)
continuum opacity.

The \( \tau = 1 \) photosphere lies at a large physical depth
within the low-opacity L-dwarf atmosphere, with the result
that the column density of (relatively) undepleted elements,
such as the alkali metals, can reach very substantial values.
In addition, gas pressure increases with increasing depth
leading to substantial van der Waal's broadening, as in
degenerate white dwarfs. Both effects lead to strong atomic
lines. As discussed in Paper I, the relative strengths of the
resonance lines of those species visible in the far red (K, Cs,
Rb) are consistent with their relative abundances in the Sun.
(The Ca \( \lambda \lambda 6572 \) line and the Na \( \lambda \lambda 8183/8194 \) doublet are
higher order transitions.) Sodium is not expected to form
gains until temperatures of less than 1200 K (the T-dwarf
regime) and, with a higher abundance than potassium
([Na] = 6.31 as compared to [K] = 5.13 for [H] = 12.0,
where [m] is the logarithmic abundance), the D lines at
5890, 5896 \( \text{Å} \) are predicted to grow in strength at earlier
spectral types than the K \( \lambda \) doublet.

This prediction is confirmed by the spectra plotted in
Figures 2 and 3. The sodium lines, which already have the
substantial equivalent width of \( \sim 36 \) \( \text{Å} \) in the M9.5 BRI

### Table 3

| Line       | LRIS       | HIRES     |
|------------|------------|-----------|
|            | 2M0746 L0.5| 2M1439 L1 | 2M0036 L3.5| 2M1507 L5 |
| K \( \lambda \lambda 7665 \) | 9.6 \( \pm 0.5 \) \( \text{Å} \) | 19 \( \pm 0.5 \) \( \text{Å} \) | \(< 85 \) \( \text{Å} \) | \( > 150 \) \( \text{Å} \) |
| K \( \lambda \lambda 7699 \) | 8.8 | 9.7 | ... | ... |
| Rb \( \lambda \lambda 7800 \) | 2.0 | 3.0 | 3.3 | 6.7 |
| Rb \( \lambda \lambda 7947 \) | 3.1 | 3.0 | 4.0 | 7.6 |
| Na \( \lambda \lambda 8183/94 \) | 9.1 | 9.9 | 7.5 | 5.1 |
| Cs \( \lambda \lambda 8251 \) | 2.7 | 2.1 | 2.5 | 4.6 |
| Cs \( \lambda \lambda 85943 \) | 2.2 | 1.7 | 3.6 | 3.5 |
| Hz \( \lambda \lambda 3121 \) | 1.38 \( \pm 0.05 \) | 1.13 \( \pm 0.05 \) | \(< 0.1 \) | \(< 0.5 \) |
| Ca \( \lambda \lambda 6708 \) | 0.69 | 0.55 | 0.86 | ... |
| Li \( \lambda \lambda 6708 \) | \(< 0.2 \) | \(< 0.05 \) | \(< 0.1 \) | \(< 0.1 \) |
| Rb \( \lambda \lambda 7800 \) | ... | ... | 4.32 | ... |
| Rb \( \lambda \lambda 7947 \) | ... | 2.0 | 3.59 | 4.3 |
| Na \( \lambda \lambda 8183 \) | 1.58 | ... | 2.04 | 1.39 |
| Na \( \lambda \lambda 8194 \) | 3.26 | ... | 3.76 | 1.82 |
| Cs \( \lambda \lambda 8256 \) | ... | 0.57 | 0.57 | ... |
| Cs \( \lambda \lambda 8521 \) | ... | 1.14 | 2.15 | 3.44 |
0021 have doubled in strength to ~80 Å by spectral type L0.5 (2M0746). We measure an equivalent width of ~170 Å in the L2 dwarf Kelu 1, and our spectrum of 2M0036 yields an equivalent width of ~240 Å for that L3.5 dwarf, although identifying appropriate pseudo-continuum points is becoming problematic at these later spectral types.

Initial observations of 2M1507 with the Palomar double spectograph revealed a steeply declining spectrum shortward of 6700 Å, with no significant flux detected shortward of ~6000 Å. Our surmise that this might reflect increased sodium absorption is confirmed spectacularly by the LRIS data plotted in Figure 2. Superimposed on the steeply rising underlying spectrum, the D lines produce a smooth, concave feature spanning over 1500 Å, with MgH the only identifiable absorption feature between 4500 and 6500 Å. The blue wing of this atomic doublet extends to ~5000 Å, where the spectral energy distribution reaches a mild peak before declining toward shorter wavelengths. The red wing of the Ca I \( \lambda 4227 \) resonance line probably contributes to that smooth decline. Similar behavior in the K I \( \lambda \lambda 7665/7699 \) doublet at much cooler temperatures is partly responsible for the steep flux gradient between 8000 and 9000 Å in the energy distribution of methane-rich T dwarfs such as Gl 229B (Oppenheimer et al. 1998).

3.3. Chromospheric Activity and Lithium Absorption

Hz emission has long been known as an indicator of chromospheric activity amongst M dwarfs, and earlier studies suggested that emission became increasingly common amongst later spectral types. Gizis et al. (2000), however, have reexamined the distribution of chromospheric activity as a function of spectral types, using 2MASS observations to define a photometrically selected sample of M dwarfs that includes a significantly larger number of ultracool (>M7) objects than was previously available. Analysis of that sample shows that the frequency of Hz emission peaks at close to 100% at spectral type M7 and declines thereafter. Only 45% of known early-type (≤L3) L dwarfs have emission lines with equivalent widths exceeding ~2 Å while none of the later-type L dwarfs in Paper I have detectable emission, despite the low continuum flux in the latter objects.

The four sources considered here show behavior similar to the dwarfs in the Paper I sample. Both of the earlier type dwarfs have weak Hz emission, while no emission is detectable in the two later type dwarfs. Figure 5 plots our HIRES data for the Hz region of the spectrum in three objects—the 2M1507 data are of low signal-to-noise ratio at these wavelengths and essentially featureless. Both of the Hz profiles, but particularly 2M1439, appear to have a narrow core centered on a broader pedestal. This is morphology is also found in approximately 10% of the ultracool M dwarfs.

None of these dwarfs is particularly active. We can use our flux-calibrated LRIS spectra to determine emission line fluxes from our measured equivalent widths. In the case of 2M0746, we derive \( F_\nu \sim 2.6 \times 10^{-16} \) ergs cm\(^{-2}\) s\(^{-1}\), while for 2M1439 we find \( F_\nu \sim 7.8 \times 10^{-17} \) ergs cm\(^{-2}\) s\(^{-1}\). These correspond to activity ratios, \( L_a/L_{bol} \), of \( 10^{-5.5} \) and \( 10^{-5.4} \), respectively, values that are almost 2 orders of magnitude lower than the typical level of activity amongst M dwarfs, \( \langle L_a/L_{bol} \rangle \sim 10^{-5.8} \) (Hawley, Gizis, & Reid 1996; Gizis et al. 2000) and an order of magnitude below the quiescent state of the ultracool M9.5e dwarf, 2MASSW J014900+295613 \( \langle L_a/L_{bol} \rangle \sim 10^{-4.6} \) (Liebert et al. 1999). The upper limits corresponding to nondetection imply even lower activity ratios for the two later type dwarfs.

Our HIRES observations also allow us to set limits on the equivalent width of the Li I \( \lambda 6708 \) absorption line in these four dwarfs. The presence of atmospheric lithium in late-type dwarfs is now well recognized as an indicator of substellar mass (Rebolo, Martin, & Magazzu 1992; Magazzu, Martin, & Rebolo 1993). Recent models indicate that all dwarfs with masses exceeding 0.06 \( M_\odot \) should have depleted lithium by the time that their surface temperature has fallen to ~2400 K, equivalent to spectral type M7 (Baraffe et al. 1998). Based on the scale derived in Paper I, we estimate temperatures between ~2100 K (2M0746) and ~1700 K (2M1507) for the four dwarfs considered here. None has lithium absorption exceeding 200 mA. Approximately one in four of the 80 L dwarfs identified to date from 2MASS data have detectable lithium absorption, with equivalent widths rising to ~20 Å amongst the later spectral types (Kirkpatrick et al., in preparation). Thus, the absence of detectable lithium in these dwarfs implies that all have depleted their primordial store of lithium: that is, all have masses that exceed 0.06 \( M_\odot \).

That these four L dwarfs have masses relatively close to the hydrogen-burning limit is not surprising. Figure 19 in Paper I shows the predicted time evolution of temperature for models spanning the mass range 0.01 to 0.1 \( M_\odot \). Both the calculations by Baraffe et al. (1998) and Burrows et al. (1997) predict that objects with masses as high as ~0.08 \( M_\odot \) (i.e., very low-mass stars) can achieve temperatures of 2100 K, the value we associate with spectral class L0. Similarly, the upper mass limit at \( T_{eff} \sim 1700 \) K (L5) is 0.07–0.075 \( M_\odot \). In both cases, higher mass objects spend several Gyr at those temperatures, while brown dwarfs with masses below ~0.06 \( M_\odot \) have total residence times of no more than ~10\(^8\) yr. Those circumstances lead to much higher probabilities of detecting high-mass brown dwarfs and very low-mass stars at early and mid-L spectral types. Lower mass brown dwarfs make a larger contribution to samples of late L dwarfs.

3.4. Kinematics

Table 2 shows that all four L dwarfs have substantial velocities relative to the Sun. The correlation between space
motion and age is statistical rather than direct, but since velocity dispersion increases with age, there is less ambiguity in interpreting a high velocity as implying a relatively old age than in taking a low velocity as implying youth. Representative tracers of the "young disk" population (A stars, active late-type dwarfs, Cepheids) indicate that a 1 Gyr old population can be modeled as a Schwarzschild ellipsoid with \((U = -10, V = -10, W = -7; \sigma_U = 38, \sigma_V = 26, \sigma_W = 21 \text{ km s}^{-1})\) (Soderblom 1990). The average space velocity for those kinematics is \(V_{\text{tot}} = 34 \text{ km s}^{-1}\), and even the lowest velocity L dwarf in the current sample, 2M1507, lies at the 75th percentile of the predicted velocity distribution, albeit within 1 \(\sigma\) of the mean.

The measured velocities are more characteristic of an older stellar population. Hawley et al. (1996) derive the following ellipsoid from observations of nearby M dwarfs: \((U = -0, V = -21, W = -8; \sigma_U = 38, \sigma_V = 26, \sigma_W = 21 \text{ km s}^{-1})\). Matched against that distribution, 2M0036, 2M0746, 2M1439, and 2M1507 fall at the 48th, 68th, 93d, and 39th percentiles. It therefore seems unlikely that these dwarfs are younger than \(\sim 1\) Gyr, further corroborating their identification as high-mass brown dwarfs or low-mass stars.

3.5. Color-Magnitude Diagrams

Our spectrophotometry provides the first opportunity of examining the \(BV\) colors of L dwarfs. It is notable that the \((B-V)\) color inferred from the spectrophotometry for 2M0036 is \(\sim 0.5\) mag bluer than that for the L0 dwarf, 2M0746. This counter-intuitive blueward evolution with decreasing temperature can be ascribed in large part to the increasing strength of the Na D lines. A complementary effect can be expected in the \((V-I)\) color.

Figure 6 plots the \([M_V, (V-I)]\) color magnitude diagram for nearby stars with accurate parallaxes and reliable photometry (Bessell 1990; Leggett 1992) supplemented by our own data for the four bright L dwarfs discussed in this paper. 2M1507 has a formal visual absolute magnitude of \(M_V \sim 22.9\). Among M dwarfs, \((V-I)\) reaches a local maximum at spectral type \(\approx M7\): VB8 (M7) has \((V-I) = 4.56\) mag, while VB10 is only slightly redder at \((V-I) \sim 4.7\) mag. Later type M dwarfs, such as LHS 2924 [M9, \((V-I) \sim 4.37\)], have lower luminosities, but bluer \((V-I)\) colors (Monet et al. 1992). Our new data show that the march redward resumes amongst the L dwarfs, with the growing strength of the sodium D lines contributing to the decreased flux in the \(V\) band, notably the nearly 1 magnitude offset in \((V-I)\) between 2M0036 (L4) and 2M1507 (L5).

The cause of the reversal in \((V-I)\) color amongst the later type M dwarfs has received little discussion in the literature. Spectroscopy shows no evidence for increased molecular absorption in the far red, which might decrease the emergent flux in the \(I\) band. Indeed, the strongest molecular absorber, TiO, peaks between \(\sim M6\) and \(M8\) (the \(\gamma 7050\) band is strongest at \(M6.5\)) and decreases in strength in dwarfs of later spectral type, while other species, such as VO, have less extensive absorption bands. These same stars show a near-monotonic trend toward redder colors with decreasing luminosity in optical to infrared colors, such as \((I-J)\) (Fig. 4). This suggests that the color reversal in \((V-I)\) stems primarily from increased flux in the \(V\) band rather than a deficit in \(I\) band. The \([M_V, (I-J)]\) diagram beautifully illustrates the "step" in the main sequence at spectral type \(\approx M4\), originally highlighted by Reid & Gizis (1997) and probably due to the onset of convection. The L0 dwarf 2M0746 lies \(\sim 0.7\) mag above the "main sequence" in this plane, raising the possibility that it is an equal-mass binary.

Note, however, that the growth in strength of the K \(\lambda 7665/7699\) resonance lines amongst the later L dwarfs is likely to result in an effect on \(M_J\) analogous to the effect of the \(D\) lines on \(M_J\), between spectral types L4 and L5. Gl 229B is almost 1 mag redder in \((I-J)\) than the L8 dwarf 2MASSW J1632291+190441.
We suggest that the behavior in the \((V - I)\) color is driven by the formation of dust in the upper atmospheric layers of mid-type M dwarfs, and by the subsequent evolution of the particle size and/or spatial distribution at lower effective temperatures. Tsuji et al. (1996) originally demonstrated that dust formation has an important effect on the emergent spectral energy distribution of cool dwarfs, notably a reduction in the strength of the near-infrared bands due to atmospheric heating through dust reradiation. Allowing for the latter effect reconciles a long-standing discrepancy between theoretical models and observations of late-type M dwarfs (see Reid & Gilmore 1984). Our hypothesis is that the color reversal in \((V - I)\) has the same origin.

Tsuji et al. (1996) place the onset of dust formation at \(T_{\text{eff}} \sim 2600\) K. Leggett et al. (1996) estimate \(T_{\text{eff}} \sim 2700\) K for the M6.5 dwarf GJ 1111, suggesting that dust should become evident at spectral types of \(\approx M7\) and later. Supporting evidence for dust formation at this spectral type comes from variations in the equivalent width of the \(\lambda\lambda 7665/7699\) \(K\) \(I\) doublet in mid- late-M dwarfs. Figure 7 plots HIRES data covering this region of the spectrum for eight dwarfs with spectral types between M3 and L4. While the detailed profile of the shorter wavelength component is obscured partially by terrestrial O\(_2\) absorption (the \(A\) band), it is clear that the overall variation mimics that of the \((V - I)\) color. The equivalent widths rise to a maximum at spectral type M6.5/M7, declines noticeably in strength to spectral type M9.5/L0, before increasing dramatically throughout the L dwarf sequence, as discussed above and in Paper I.

We explain this behavior as a combination of two effects. First, at spectral types M7–M9.5, dust is present in the atmosphere in sufficient quantities to act as a scattering layer, raising the atmospheric opacity and hence reducing the physical depth (and hence both gas pressure and column density) of the \(\tau = 1\) layer for line formation; second, dust reradiation not only reduces the strength of the H\(_2\)O bands, but also increases the flux emitted at visual wavelengths, resulting in bluer \((V - I)\) colors. Dust formation may also reduce the overall molecular (mainly TiO) opacity to a greater extent at visual wavelengths than at 0.8 \(\mu\)m. In late M dwarfs, such as LHS 2924, the total flux emitted at visual wavelengths amounts to less than 0.1\% of the bolometric flux, so a small flux redistribution can have a large effect on \(F_V\). Section 3.2 summarizes the likely explanations for the increased equivalent widths in all of the alkali lines at spectral types beyond L0: increased particle size or rain out. More detailed spectrophotometry of mid- to late-type M dwarfs at blue and visual wavelengths can test the overall validity of this hypothesis.

**4. SUMMARY AND CONCLUSIONS**

We have presented spectroscopic and photometric data for four bright L dwarfs lying at distances of less than 15 parsecs from the Sun. Our observations permit the first detailed examination of the properties of these objects at blue and visual wavelengths, revealing the presence of MgH and CaOH molecular absorption. In addition, the sodium D lines are extremely strong, reaching equivalent widths in excess of 240 \(\AA\) in later type L dwarfs. This behavior likely stems from the low atmospheric opacity in the latter objects and the consequent substantial pressure broadening. The growth in strength of the Na D lines is also responsible for the \((V - I)\) color becoming significantly redder between spectral types L4 and L5. The \(K\) \(\lambda\lambda 7665/7699\) doublet probably has a similar effect on the \(I\)-band flux between spectral types L8+ and T.

Dust formation is clearly an important factor governing spectral evolution at these low temperatures. Theoretical models suggest that dust first forms, primarily as TiO-based agglomerates, at \(\sim 2600\) K, a prediction that is supported by the behavior of the \(K\) \(I\) lines at 7665/7699 \(\AA\) at spectral types between M3 and L0. Indeed, we suggest that the reversal in the \([M_V, (V - I)]\) relation at spectral type \(\approx M7\) may be a consequence of both lower molecular opacities and dust reradiation heating the atmosphere, with a consequent increase in the flux emitted at visual wavelengths.

None of the four L dwarfs considered here has detectable lithium absorption, indicating masses of at least 0.06 \(M_\odot\). All, however, are also chromospherically inactive, implying masses close to, if not below, the hydrogen-burning limit, and the relatively high space motions suggest ages of \(\sim 1\) Gyr or more. Taken together, these indicators suggest masses of from 0.07 to 0.09 \(M_\odot\). Further detailed observations of these and other bright L dwarfs will prove important in determining the general physical characteristics of these objects.

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