L Dwarfs Found in Sloan Digital Sky Survey Commissioning Imaging Data

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ABSTRACT

This paper describes the discovery of seven dwarf objects of spectral type L (objects cooler than the latest M dwarfs) in commissioning imaging data taken by the Sloan Digital Sky Survey (SDSS). Low-resolution spectroscopy shows that they have spectral types from L0 to L8. Comparison of the SDSS and the Two Micron All Sky Survey (2MASS) photometry for several of these objects indicates the presence of significant opacity at optical wavelengths. This comparison also demonstrates the high astrometric accuracy (better than 1" for these faint sources) of both surveys. The L dwarfs are shown to occupy a distinctive region of color-color space as measured in the SDSS filters, which should enable their identification in a straightforward way. This should lead eventually to a complete sample of many hundreds of these low-mass objects, or about 1 per 15 deg² to i' ~ 20, in the complete SDSS data set.

Key words: stars: low-mass, brown dwarfs — surveys

I. INTRODUCTION

The long search for substellar objects, or brown dwarfs, has finally been successful. The last three years have seen spectacular advances in this field, from the discovery of low-luminosity objects that are companions to nearby stars (Nakajima et al. 1995; Goldman et al. 1999), are in young

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clusters (Zapatero-Osorio et al. 1997), or are in the field (Ruiz, Leggett, & Allard 1997; Delfosse et al. 1997; Kirk-patrick et al. 1999, hereafter K99). Many of these dwarfs, of spectral type L, have detectable lithium and are therefore brown dwarfs (Rebolo, Martin, & Magazzu 1992). The companion object Gl 229B (Nakajima et al. 1995) is cool enough (T eff ~ 900 K) that its atmosphere resembles that of a giant gas planet, with strong absorption bands of methane. Very recently, several isolated objects with properties similar to those of Gl 229B, the so-called methane, or T, dwarfs (objects with methane bands at K), have been found by deep optical (Strauss et al. 1999; Pier et al. 2000a; Tsvetanov et al. 2000) and infrared (Burgasser, et al. 1999; Cuby et al. 1999) surveys. The large number and range of new discoveries in the field are well summarized in the recent volumes edited by Rebolo, Martin, & Zapatero-Osorio (1998) and Marley & Burrows (2000), and in the review by Liebert (2000).

Because brown dwarfs never reach an equilibrium, or main-sequence, state, there is no one-to-one correspondence between the photometric or spectroscopic properties and the stellar mass. Such substellar objects have until recently been extremely difficult to find: they have very low luminosity (L < 10^{-3} L☉) and are very cool (T eff ≤ 2000 K), with most (> 90%) of their luminosity emitted at wavelengths > 1 μm. This means that, while such objects may well be numerically the most common objects in the Galaxy, they are among the rarest in magnitude-limited surveys, and large areas of sky must be covered to faint magnitude limits to find them. Wide area surveys at optical wavelengths, made with Schmidt photographic plates, have found a few of these objects in the field and in young clusters (Rebolo et al. 1998, and references therein). However, the discovery of most new field objects has come with the new generation of sensitive, all-sky, near-infrared surveys,
DENIS and the Two Micron All Sky Survey, 2MASS (Delfosse et al. 1997; K99).

K99 discuss the selection of candidate cool, low-luminosity objects using 2MASS J, H, and $K_s$ photometry, together with optical upper limits from photographic surveys. They have obtained spectra for a large number of these candidates and have established the continuation of the spectral classification sequence to types later than the coolest M dwarfs.

These L dwarfs (cf. Martin et al. 1997) form a spectral class distinguishable from M dwarfs by the progressive disappearance of the strong TiO and VO bands (implying condensation into solid particles in the atmosphere) and the appearance of bands of metal hydrides and lines of alkali metals.

The present paper discusses the discovery of seven new field L dwarfs from the commissioning imaging data of the Sloan Digital Sky Survey (SDSS). We have no conclusive data to say whether or not these objects are brown dwarfs. We sidestep this issue by confining our discussion to their spectral and photometric properties.

The next section describes the SDSS imaging data in which the candidate L dwarfs were found. The selection of the L dwarf candidates is discussed in § 3, and the spectroscopy in § 4. Section 5 describes the broadband characteristics of these objects at optical and near-infrared wavelengths, using SDSS and 2MASS photometry. Section 6 discusses the sky distribution of objects with L dwarf colors and a very preliminary estimate of their areal density. The conclusions are given in § 7.

2. PHOTOMETRIC OBSERVATIONS

The photometric observations were made from 1998 fall to 1999 spring with the SDSS 2.5 m telescope and imaging camera at the Apache Point Observatory (APO) of the Astrophysical Research Consortium in New Mexico. The SDSS is described by Gunn & Weinberg (1995). The telescope is a modified f/5 Ritchey-Chrétien optical system with a large secondary mirror and first and second corrector lenses above and below the primary mirror, which produces a 3° distortion-free field (Siegmund et al. 2000).

The imaging camera (Gunn et al. 1998) contains two arrays of CCD detectors. The imaging array is a mosaic of 30 2048 × 2048 SITe CCDs with 24 μm (0′.4 on the sky) pixels. The CCDs are arranged in six columns of five CCDs. Each column observes the sky through five broadband filters ($u^\prime$, $g^\prime$, $r^\prime$, $i^\prime$, and $z^\prime$) with effective wavelengths 93540 Å, 4760 Å, 6280 Å, 7690 Å, and 9250 Å, covering the entire atmospheric window from the atmospheric ultraviolet cutoff to the silicon red sensitivity cutoff (Fukugita et al. 1996).

The total integration time for each filter is 54.1 s, and the expected survey depths in the five filters (5 σ detection of a point source with 1″ FWHM images) are 22.3, 23.3, 23.1, 22.5 and 20.8 mag (Gunn et al. 1998). The camera also contains two additional arrays of neutral density-filtered, $r^\prime$ CCDs of 2048 × 400 pixels, which saturate at $r^\prime \sim 8$ and cover the dynamic range between the photometric CCDs and existing astrometric catalogs, providing the astrometric calibration for objects detected by the photometric CCDs (Gunn et al. 1998; Pier et al. 2000).

The photometric data are taken in open-loop time-delay-and-integrate (TDI) mode at sidereal rate, with a given point in the sky passing through each of the filters in succession. This produces a set of six long, continuous imaging scans of the sky, each about 13′ wide and separated by about 90% of the CCD width. Such a set of imaging data is called a strip; a (filled) stripe is the combination of two strips offset by the CCD separation. The data are read from the imaging camera to disk and tape (Petravick et al. 1994, 2000), and the tapes sent to Fermilab for data processing.

The commissioning photometric data on which this paper is based are calibrated by observations of secondary standard stars in the survey area that were made with the 40′ telescope of the US Naval Observatory and a (now-decommissioned) 24′ telescope at APO (see Smith et al. 1998; Tucker et al. 2000). Because the standard star system was still being developed while these data were being taken and because of unmodeled small-scale point-spread function (PSF) variations in the mosaic camera data, the absolute photometric accuracy of the data discussed in the present paper is about 5%–10%. Because of this, we will denote the preliminary SDSS magnitudes we have measured as $u^\star$, $g^\star$, $r^\star$, $i^\star$, and $z^\star$, rather than $u^\prime$, $g^\prime$, $r^\prime$, $i^\prime$, and $z^\prime$, which will be used for the final SDSS photometric system (and is used in this paper to refer to the SDSS filters themselves).

The data were taken by parking the telescope at the celestial equator and allowing the sky to drift by. The scans thus cover ±1.25 centered on the celestial equator. Two strips were observed in most cases (to make a filled stripe), with northern (N) and southern (S) offsets. The particulars of each data run used in this paper are listed in Table 1, which lists the number of each data run, whether it is a north or south strip, the right ascension range (J2000), the date and time of the observation, the approximate area covered, and the FWHM of the point-spread function (PSF). For most of the runs, the PSF is about 1.3. Taking overlaps into account, these scans cover roughly 600 deg².

The imaging data are processed through a series of automated pipelines that carry out astrometric and photometric calibrations, flat-field, bias-subtract, and correct the images for defects, and identify and measure the properties of all detected objects (Kent et al. 2000; Pier et al. 2000; Tucker et al. 2000; Lupton et al. 2000). The SDSS photometric system and its calibration are described by Fukugita et al. (1996) (see eqs. [1] and [2] in that paper). It is based on the AB system of monochromatic magnitudes, referred to an absolute flux scale in Jy.

The SDSS uses a modified magnitude scale μ(f) to handle the low signal-to-noise ratio regime, including slightly negative fluxes f (Lupton, Gunn, & Szalay 1999):

$$\mu(f) = \mu(0) - a \sinh^{-1} \left( \frac{f}{2b^2} \right),$$

17 see also http://www.astro.princeton.edu/PBOOK/astrom.htm.
18 see also http://www.astro.princeton.edu/PBOOK/telescop.htm.
19 see also http://www.astro.princeton.edu/PBOOK/telescop.htm.
20 see also http://www.astro.princeton.edu/PBOOK/datasys.htm.
21 see also http://www.astro.princeton.edu/PBOOK/datasys.htm.
that sets the zero point of the magnitude scale. The quantity

\[ m_b \] described by Fan et al. (1999, 2000).

search for very high redshift quasars, whose results are
for spectroscopic follow-up (described below) as part of a
the reduced SDSS photometric data summarized in Table 1

\[ a = 2.5 \log e \] and \( \mu(0) \) is the normalizing magnitude
that sets the zero point of the magnitude scale. The quantity
\[ b' \] is set so that \( \mu \) undergoes a transition from the usual
logarithmic scale to a linear flux scale at roughly 3 times the
sky noise in a PSF aperture. The values of \( b' \) and \( \mu(0) \) vary
from run to run, and the values for runs 94 and 125 are
given by Fan et al. (1999). Negative fluxes are represented
with values of \( \mu > \mu(0) \); a detection at the 5 \( \sigma \) level has
\( \mu \sim 22.4, 23.1, 22.7, 22.1, \) and 20.7 at \( u' \), \( g' \), \( r' \), \( i' \), and \( z' \).

3. SELECTION OF L DWARF CANDIDATES IN
PHOTOMETRIC DATA

The L dwarfs discussed in this paper were selected from
the reduced SDSS photometric data summarized in Table 1
for spectroscopic follow-up (described below) as part of a
search for very high redshift quasars, whose results are
described by Fan et al. (1999, 2000).

High-redshift quasars \((z \geq 4)\) have \( g' - r' \) colors several
magnitudes redder than any ordinary star but also have
blue \( r' - i' \) colors, as the Ly\( \alpha \) emission moves into the \( r' \)
filter (Fan 1999). Above \( z = 4.5 \), the \( i' - z' \) color of quasars
is bluer than stars of the same \( r' - i' \), as Ly\( \alpha \) moves into the
\( i' \) filter. However, several point-source objects were noted
in the SDSS data on the other side of the stellar locus, namely,
with much redder colors in \( i' - z' \) for their \( r' - i' \) than
ordinary stars.

Figure 1 shows a color–color plot of point-source objects
detected in \( r'^* \), \( i'^* \), and \( z'^* \) from run 94 (see Table 1) with
\( i'^* < 20.2 \). Contours of density in color–color space are shown
for all except the outer parts of the stellar locus. Overlaid on this plot are the colors and spectral classiﬁcations
of the eight objects (seven L dwarfs, one M star) for
which spectroscopy was obtained by the APO 3.5 m tele-
scope (see next section), as are the colors for an additional
SDSS L dwarf observed with the Hobby-Eberly Telescope
(HET) by Schneider et al. (2000). Figure 2 shows a color-
magnitude diagram \((i'^* - z'^* \) vs. \( z'^* \)) from the same data.
Note that the SDSS T dwarfs (Strauss et al. 1999; Pier et al.
2000a; Tsvetanov et al. 2000) are redder yet in \( i'^* - z'^* \) than
are the L dwarfs. While the M dwarf colors lie on the extrapolation of the stellar locus, the L dwarf colors are up
to 1 mag bluer in \( r'^* - i'^* \) for a given \( i'^* - z'^* \) than are the
late M stars, and more than 0.5 mag redder in \( i'^* - z'^* \). This
region is thus well displaced from the stellar locus and its
extrapolation to the red. Figure 1 suggests that L dwarfs
tend to lie in the region for which

\[
\begin{align*}
 i'^* - z'^* & > 1.6, \\
r'^* - i'^* & > 1.8,
\end{align*}
\]

with the demarcation between L and T in these colors not
yet known.

Table 2 lists the positions and photometry for the eight
elements from Figures 1 and 2 for which spectra were
obtained. The objects are named by the J2000 coordinates,
which are accurate to about 0.1 (see § 5 below). Next is the
number of the run in which the object was found. The asinh
magnitudes and their errors are listed in columns (3)–(7).

![Figure 1](image-url)
The $i'$ and $z'$ finding charts for these objects are shown in Figure 3.

4. SPECTROSCOPIC OBSERVATIONS

Spectra of the eight objects in Table 2 were obtained using the Double Imaging Spectrograph (DIS) built by J. Gunn, M. Carr, and R. Lupton on the Astrophysical Research Consortium (ARC) 3.5 m telescope at the Apache Point Observatory, in 1998 November and December and 1999 March and May. The DIS has a transition wavelength of 5350 Å between its red and blue sides. The observations were taken with the low-resolution grating, which gives a dispersion of 6.2 Å pixel$^{-1}$ on the blue side and 7.1 Å pixel$^{-1}$ on the red side. The spectrograph resolution is about 2 pixels, and the joint spectrum extends from 4000 to 10,000 Å. Exposure times ranged from 1200 to 3600 s. Observations of the F subdwarf standard stars BD +17°4708 and HD 19445 (Oke & Gunn 1983) allow correction for the atmospheric absorption bands and flux calibration of the spectra. As some of these observations were made under nonphotometric conditions, the flux calibration was adjusted to the $i^*$ magnitude of each object.

The wavelength scale was calibrated to about 0.5 Å, with a cubic polynomial fit to the lines of an ArHeNe arc lamp. The data were reduced using the IRAF package (Tody 1993). Table 3 summarizes the spectroscopic observations, giving the object name, the date of observation, the approximate flux density at 9500 Å, and the assigned spectral type, found by comparing the spectra with those displayed by K99.

The spectra are shown in spectral sequence in Figure 4, normalizing the flux densities to a common value at 9500 Å. Figure 5 shows the spectrum of the brightest L dwarf in this sample, SDSS 0539-0059, with the major features marked following the identifications of K99. The gradual disappearance of the strong VO and, especially, TiO bands below about 8000 Å is apparent in the spectral sequence in Figure 4, causing the L dwarfs to be bluer in $i^* - r^*$ than the M dwarfs (see Fig. 1). The color temperatures of the L dwarfs are lower and their overall spectral shape much redder than M dwarfs: hence the L dwarfs become increasingly redder in $i^* - z^*$ toward later spectral types. The main absorption features in the far red spectra of L dwarfs are due to alkali metals (K, Rb, Na, and Cs), metal hydrides (CaH, CrH, and FeH), and strong H$_2$O absorption in the 9200–9400 Å range (K99). As discussed by K99, the KI doublet at 7665, 7700 Å increases in width as one continues down the sequence, becoming many hundreds of angstroms broad for late L dwarfs of effective temperature $\leq$1500 K (see Burrows, Marley, & Sharp 2000).

5. COMPARISON WITH 2MASS

The Two Micron All Sky Survey (2MASS; Skrutskie et al. 1997) has scanned the regions of the sky containing six of the objects in Table 2, including the M dwarf. The 2MASS $J, H,$ and $K_s$ magnitudes are listed in Table 4. Table 5 provides a comparison of the SDSS and 2MASS magnitudes, listing a set of joint optical and infrared colors ordered by spectral type. The 2MASS magnitudes are in the standard $J, H, K_s$ system (Elias et al. 1982; Bessell & Brett

| TABLE 2 |
|----------------|
| **SDSS Photometry of Late-Type Dwarfs** |
| Star          | Run (1) | $u^*$ (2) | $g^*$ (3) | $r^*$ (4) | $i^*$ (5) | $z^*$ (6) |
|----------------|
| SDSSp J033035.13–002534.5 .... | 94     | 22.33 ± 0.36 | 24.09 ± 0.79 | **22.21 ± 0.25** | **20.11 ± 0.06** | 17.98 ± 0.04 |
| SDSSp J041320.38–011424.9 .... | 211    | 24.63 ± 1.63 | 24.69 ± 0.87 | **22.48 ± 0.21** | **19.61 ± 0.03** | 17.76 ± 0.02 |
| SDSSp J053951.99–005902.0 .... | 259    | 24.59 ± 1.06 | 24.67 ± 0.68 | **21.49 ± 0.07** | **19.04 ± 0.02** | 16.73 ± 0.01 |
| SDSSp J120358.19+001550.3 .... | 756    | 24.08 ± 0.06 | 24.42 ± 0.39 | **21.31 ± 0.06** | **18.88 ± 0.01** | 16.83 ± 0.01 |
| SDSSp J132629.82–003831.5 .... | 752    | 23.67 ± 0.33 | 23.28 ± 0.44 | **23.68 ± 0.43** | **21.69 ± 0.14** | 19.08 ± 0.05 |
| SDSSp J144001.82+002145.8 .... | 85     | 23.21 ± 0.44 | 25.06 ± 0.49 | **24.63 ± 0.22** | **20.47 ± 0.05** | 18.56 ± 0.03 |
| SDSSp J151547.22–003059.7 .... | 77     | 22.37 ± 0.17 | 21.01 ± 0.06 | **20.03 ± 0.01** | **16.29 ± 0.01** | **16.29 ± 0.01** |
| SDSSp J163600.79–003452.6 .... | 752    | 24.08 ± 0.30 | 24.44 ± 0.40 | **21.30 ± 0.06** | **18.80 ± 0.01** | **16.91 ± 0.01** |

Note.—Asinh magnitudes (Lupton et al. 1999) are quoted; errors are statistical only. Detections are in boldface.
TABLE 3
SPECTROSCOPY OF SDSS L DWARFS

| Object       | Date       | $f_i$ (10^{-17} \text{ergs cm}^{-2} \text{s}^{-1} \text{A}^{-1}) | Spectral Type |
|--------------|------------|---------------------------------------------------------------|---------------|
| SDSS 0330-0025 | 1998 Nov 14 | 12.3                                                          | L2            |
| SDSS 0413-0014 | 1998 Dec 12 | 13.2                                                          | L0            |
| SDSS 0539-0059 | 1999 Mar 20 | 46.1                                                          | L5            |
| SDSS 1203+0015 | 1999 May 25 | 30.6                                                          | L3            |
| SDSS 1326-0038 | 1999 May 14 | 3.2                                                           | L8?           |
| SDSS 1440+0021 | 1999 Mar 22 | 9.5                                                           | L1            |
| SDSS 1515-0030 | 1999 Mar 15 | 49.7                                                          | M7            |
| SDSS 1636-0034 | 1999 May 14 | 32.7                                                          | L0            |

NOTE. The flux density in the third column is measured at 9500 A.
L DWARFS FOUND BY THE DSS

Fig. 4.—Far-red spectra of the M and L dwarfs, observed by the Double Imaging Spectrograph (DIS) on the APO 3.5 m telescope. The vertical scale for each object has been approximately normalized to the flux density of the object at 9500 Å (see Table 3), plus an offset. Top to bottom: Objects in decreasing spectral type and increasing effective temperature. Vertical lines show the wavelengths of the TiO 7053 and 8432 Å band heads (solid lines) and the VO 7400 and 7900 Å band heads (dotted lines).

1988; Persson et al. 1998). All colors show a general increase toward later spectral types, with the exception of $r^* - i^*$, which is bluer for L dwarfs than it is for M dwarfs. Within type L, this color shows very little correspondence with spectral type at all, although the errors on the colors of some stars are large and may mask a subtle trend. The very large magnitude differences between red and infrared (e.g., $i^* - K_s$) are largely due to the very large equivalent widths of the alkali metals, especially the KI line (Burrows et al. 2000). The distinctive colors in Table 4 allow L dwarfs to be easily distinguished in both the SDSS and 2MASS surveys individually; comparison of both surveys will most directly allow the characterization of the transition between M and L dwarfs.

Table 4 also lists the total offset between the 2MASS and SDSS positions. The positional agreement is excellent, which is a tribute to the astrometry of both surveys (carried out by the United States Naval Observatory in both cases), given the completely independent hardware, software, and calibration procedures of the two surveys and the faintness of the objects. This has several interesting implications for future comparison of 2MASS and SDSS. First, the cross identification of both surveys should be very straightforward. Second, if a source in one survey is not matched in the other, one can with some confidence set upper limits (or even 1 or 2 σ measurements) on the flux densities in the nondetected bands by examining the imaging data at the appropriate position (as already done by both surveys individually). Third, one can search for objects that have moved between the two survey epochs, perhaps allowing the proper motions of some of these very faint objects to be measured.

6. AREAL DENSITY OF L DWARFS IN THE SDSS

The L dwarfs described in this paper, together with the L0 dwarf whose spectrum was measured by the HET (Schneider et al. 2000), were selected from data taken over

| Object        | 2MASS          | $J$       | $H$       | $K_s$      | Offset (arcsec) |
|---------------|----------------|----------|-----------|------------|-----------------|
| SDSS 0330 – 0025 …….. | 2MASSW J0330351 – 002534 | 15.29 ± 0.05 | 14.42 ± 0.04 | 13.83 ± 0.05 | 0.1              |
| SDSS 0413 – 0114 …….. | 2MASSW J0413204 – 011424 | 15.33 ± 0.05 | 14.66 ± 0.05 | 14.14 ± 0.06 | 1.1              |
| SDSS 0539 – 0059 …….. | 2MASSW J0539520 – 005901 | 13.99 ± 0.03 | 13.07 ± 0.03 | 12.58 ± 0.03 | 1.0              |
| SDSS 1326 – 0038 …….. | 2MASSW J1326298 – 003831 | 16.11 ± 0.07 | 15.04 ± 0.06 | 14.23 ± 0.07 | 0.3              |
| SDSS 1515 – 0030 …….. | 2MASSW J1515472 – 003059 | 14.18 ± 0.03 | 13.58 ± 0.03 | 13.14 ± 0.04 | 0.8              |
| SDSS 1636 – 0034 …….. | 2MASSW J1636007 – 003452 | 14.59 ± 0.04 | 13.93 ± 0.04 | 13.41 ± 0.04 | 1.4              |

Note.—SDSS 0539 – 0059 is in the overlap region between two scans and was observed twice.
about 600 deg$^2$ and thus give a minimum rate of detection of L dwarfs by SDSS of about 1 per 75 deg$^2$ to $i^* = 20.2$. However, only a small fraction of all the L dwarf candidates in this data set have been observed spectroscopically, and an upper bound on the expected SDSS detection rate can be found simply by counting objects in the L dwarf region of color-color space (eqs. [2] and ([3]). Counting objects will give a reasonable estimate of the L dwarf density provided there is no significant contamination of this region of color-color space by other objects. We are encouraged by the fact that we have not yet taken a spectrum of any object in this region of color-color space that was not an L or T dwarf. The possible sources of such contamination are the following:

**Asteroids:** The proper motion of asteroids between exposures in different filters could yield incorrect colors. However, this motion is looked for in the analysis of every SDSS object.

**Quasars:** As the models by Fan (1999) and the observation of high-redshift quasars by Fan et al. (1999, 2000) show, the L dwarf and quasar regions of color-space do not overlap (at least for quasars with $z < 5.5$), and all objects in this region whose spectra have been measured are indeed L dwarfs.

**M dwarfs:** We have seen that the L dwarfs separate well in $(r^* - i^*, i^* - z^*)$ color-color space from the observed M7 dwarf, but the spectral type for which this color transition occurs is not yet determined.

**Heavily reddened or peculiar stars:** SDSS commissioning imaging scans over the dusty, star-forming regions in Orion in fact yield a clustered population of objects in the L dwarf region of the color-color diagram. We are currently investigating their properties and will discuss them in detail in a future publication. Otherwise, the SDSS photometry, being generally taken at high latitudes, appears to separate (possibly) very late M, L, and T dwarfs from all other point-source objects.

Thus the count of reliably detected point sources in the L dwarf region of color space gives at least an upper bound, probably a reasonable estimate, of how many L dwarfs the SDSS can be expected to find.

Several of the data runs listed in Table 1 were examined for faint objects with L dwarf colors; the results are listed in Table 6. These very preliminary estimates suggest that the SDSS will detect about one L dwarf per 15 deg$^2$ to $i^* = 20.2$, comparable with the 2MASS detection rate to $K_s = 14.5$ (K99), and suggesting that the SDSS will detect perhaps up to 1000 of these objects over the 10,000 deg$^2$ of the survey. The SDSS and 2MASS data sets are likely to be both overlapping and complementary: 2MASS is more sensitive to the very coolest dwarfs, while SDSS will be more sensitive to the hotter objects. Together, these surveys will allow the population below about M5 to be thoroughly characterized.

### 7. Conclusions

This paper discusses members of the new spectral class of L dwarfs (K99) found in commissioning imaging data of the Sloan Digital Sky Survey and confirmed by spectroscopy from 5000 Å to 1 μm with the Double Imaging Spectrograph on the ARC 3.5 m telescope at Apache Point, New Mexico.

1. Seven L dwarfs were spectroscopically confirmed, and an eighth has been confirmed at the HET (Schneider et al. 2000). The expected detection rate for L dwarfs has also been estimated by counting point-source objects in the SDSS imaging data with L dwarf colors. These very preliminary estimates show that the detection rate for L dwarfs in the SDSS will likely lie somewhere between a lower limit of 1 per 75 deg$^2$ and an upper limit of 1 per 15 deg$^2$ to $i^* = 20.2$. If the higher number turns out to be correct, the SDSS detection rate is similar to that of recent, sensitive near-infrared surveys such as 2MASS.

2. L dwarfs are redder in $i^* - z^*$ than the latest M dwarfs and become redder toward later spectral types, as expected from the decrease in color temperatures shown by the spectra. However, they are significantly bluer than the late M dwarfs in $r^* - i^*$ because of the diminished VO and TiO absorption. This makes them easy to identify in the SDSS $(r^* - i^*, i^* - z^*)$ color-color diagram, and SDSS data are likely to lead to a detailed characterization of the number density of the latest M dwarfs and the M dwarf → L dwarf transition.

3. The positions of these faint objects as measured by 2MASS and SDSS agree to better than 1", a tribute to the astrometric integrity of both surveys. Positional correlation

### Table 5

| Object          | Spectral Type | $r^* - i^*$ | $i^* - z^*$ | $z^* - J$ | $J - H$ | $H - K_s$ | $i^* - K_s$ | $z^* - K_s$ |
|-----------------|---------------|-------------|-------------|-----------|---------|-----------|------------|------------|
| SDSS 1515−0030  | M7            | 2.98 ± 0.06 | 1.74 ± 0.02 | 2.11      | 0.60    | 0.44      | 4.89       | 3.15       |
| SDSS 0413−0114  | L0            | 2.46 ± 0.23 | 1.80 ± 0.04 | 2.50      | 0.67    | 0.52      | 5.47       | 3.62       |
| SDSS 1636−0034  | L0            | 2.50 ± 0.06 | 1.89 ± 0.02 | 2.32      | 0.66    | 0.52      | 5.39       | 3.50       |
| SDSS 0330−0025  | L2            | 2.10 ± 0.26 | 2.13 ± 0.07 | 2.69      | 0.87    | 0.59      | 6.29       | 4.16       |
| SDSS 0539−0059  | L5            | 2.45 ± 0.07 | 2.31 ± 0.02 | 2.74      | 0.92    | 0.49      | 6.46       | 4.15       |
| SDSS 1326−0038  | L8?           | >1.99       | 2.61 ± 0.15 | 2.97      | 1.07    | 0.81      | 7.46       | 4.85       |

### Table 6

| Run   | Number (deg$^{-2}$) |
|-------|---------------------|
| 77    | 1/16                |
| 85    | 1/18                |
| 752   | 1/11                |
| 756   | 1/12                |
| Orion | 1/9                 |

Note.—“Orion” refers to those parts of runs 211, 259, and 273 between right ascensions of 52° and 76°, avoiding regions of extremely high extinction.
of the data sets and searches for proper motions will be straightforward.

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