THE ASTROPHYSICAL JOURNAL, 531:L61–L65, 2000 March 1

THE DISCOVERY OF A SECOND FIELD METHANE BROWN DWARF FROM SLOAN DIGITAL SKY SURVEY COMMISSIONING DATA[1]

ZLATAN I. TSVETANOV,[2] DAVID A. GOLIMOWSKI,[2] WEI ZHENG,[2] T. R. GEBALLE,[3] S. K. LEGGETT,[4] HOLLAND C. FORD,[2]
ARTHUR F. DAVIDSEN,[2] ALAN UOMOTO,[2] XIAOHUI FAN,[5] G. R. KNAPP,[5] MICHAEL A. STRAUSS,[5] J. BRINKMANN,[6]
D. Q. LAMB,[7] HEIDI JO NEWBERG,[8] RON RECHENMACHER,[8] DONALD P. SCHNEIDER,[9] DONALD G. YORK,[7]
ROBERT H. LUPTON,[5] JEFFREY R. PIER,[10] JAMES ANNIS,[8] ISTVÁN CSABAI,[2,11] ROBERT B. HINDSLEY,[12]
ŽELJKO IVESIĆ,[5] JEFFREY A. MUNN,[10] ANIRUDDHA R. THAKAR,[2] AND PATRICK WADDELL,[13]

Received 1999 October 25; accepted 2000 January 3; published 2000 February 8

ABSTRACT

We report the discovery of a second field methane brown dwarf from the commissioning data of the Sloan Digital Sky Survey (SDSS). The object, SDSS J134646.45−003150.4 (hereafter SDSS 1346−00), was selected because of its very red color and stellar appearance. Its spectrum between 0.8 and 2.5 μm is dominated by strong absorption bands of H_2O and CH_4 and closely mimics those of Gliese 229B and SDSS 162414.37+002915.6 (hereafter SDSS 1624+00), two other known methane brown dwarfs. SDSS 1346−00 is approximately 1.5 mag fainter than Gliese 229B, suggesting that it lies about 11 pc from the Sun. The ratio of flux at 2.1 μm to that at 1.27 μm is larger for SDSS 1346−00 than for Gliese 229B and SDSS 1624+00, which suggests that SDSS 1346−00 has a slightly higher effective temperature than the others. Based on a search area of 130 deg^2 and a detection limit of $z^* = 19.8$, we estimate a space density of 0.05 pc^{-3} for methane brown dwarfs with $T_{\mathrm{eff}} \sim$ 1000 K in the 40 pc^3 volume of our search. This estimate is based on small-sample statistics and should be treated with appropriate caution.

Subject headings: stars: low-mass, brown dwarfs — surveys

1. INTRODUCTION

Over the last 5 years, the study of brown dwarfs has evolved from a theoretical notion to a long-awaited discovery to the classification and modeling of a rapidly increasing known population. Dozens of candidate and bona fide brown dwarfs have now been identified using a variety of techniques, including coronagraphic imaging of nearby stars (Nakajima et al. 1994), spectroscopic tests for primordial lithium (Basri, Marcy, & Graham 1996; Rebolo et al. 1996), searches of young open clusters (Hambly 1998 and references therein), optical and near-infrared sky surveys (Tinney, Delfosse, & Forveille 1997; Kirkpatrick et al. 1999; Strauss et al. 1999; Burgasser et al. 1999), and deep-field studies (Cuby et al. 1999). Until recently, the coolest known brown dwarf was Gliese 229B, a companion to a nearby M1 dwarf (Nakajima et al. 1995). The spectrum of Gliese 229B was singularly remarkable for its exhibition of *H*- and *K*-band absorption features attributable to methane (Oppenheimer et al. 1998; Geballe et al. 1996). Under equilibrium conditions, methane (CH_4) becomes the dominant carbon-bearing molecule for $T_{\mathrm{eff}} < 1200$ K (Fegley & Lodders 1996; Burrows et al. 1997). Models of Gliese 229B's infrared spectrum indicate an effective temperature of 900–1000 K for the brown dwarf (Allard et al. 1996; Marley et al. 1996; Tsuji, Ohnaka, & Aoki 1999; Leggett et al. 1999).

Strauss et al. (1999) recently reported the discovery of a Gliese 229B–like brown dwarf from spectroscopic observations of a candidate identified from commissioning data of the Sloan Digital Sky Survey (SDSS). The optical and near-infrared spectrum of this object, SDSSp J162414.37+002915.6 (hereafter SDSS 1624+00), exhibits strong absorption by H_2O and CH_4 and closely mimics the spectrum of Gliese 229B. Unlike Gliese 229B, which is a companion to a nearby star, SDSS 1624+00 is isolated in the field. Assuming that SDSS 1624+00 has an effective temperature and luminosity identical to those of Gliese 229B, Strauss et al. estimated a distance of 10 pc to SDSS 1624+00.

Within 3 weeks of the discovery of SDSS 1624+00, a second field methane brown dwarf, SDSSp J134646.45−003150.4 (hereafter SDSS 1346−00), was discovered from the same SDSS commissioning data. (SDSS uses J2000 coordinates, and "p" indicates that the astrometric solution is preliminary.) Shortly thereafter, the discoveries of five more methane brown dwarfs were announced—four from the Two-Micron All-Sky Survey (2MASS; Burgasser et al. 1999) and one from the New Technology Telescope (NTT) Deep Field project (Cuby et al. 1999). In this Letter, we report the discovery of SDSS 1346−00, present the first medium-resolution *J*-band spectrum of a methane brown dwarf, and comment on the space density of methane brown dwarfs in the solar neighborhood.

---

[1] Based on observations obtained with the Sloan Digital Sky Survey by the SDSS Collaboration and the Apache Point Observatory 3.5 m telescope, which are owned and operated by the Astrophysical Research Consortium, and with the United Kingdom Infrared Telescope (UKIRT).

[2] Department of Physics and Astronomy, Johns Hopkins University, 3701 San Martin Drive, Baltimore, MD 21218.

[3] Gemini North Observatory, 670 North A'ohoku Place, Hilo, HI 96720.

[4] UKIRT, Joint Astronomy Centre, 660 North A'ohoku Place, Hilo, HI 96720.

[5] Princeton University Observatory, Princeton, NJ 08544.

[6] Apache Point Observatory, 2001 Apache Point Road, P.O. Box 59, Sunspot, NM 88349-0059.

[7] University of Chicago, Department of Astronomy and Astrophysics, 5640 South Ellis Avenue, Chicago, IL 60637.

[8] Fermi National Accelerator Laboratory, P.O. Box 500, 500 Wilson Road, Batavia, IL 60510.

[9] Department of Astronomy and Astrophysics, Pennsylvania State University, 525 Davey Laboratory, University Park, PA 16802.

[10] US Naval Observatory, Flagstaff Station, P.O. Box 1149, Flagstaff, AZ 86002-1149.

[11] Department of Physics of Comlex Systems, Eötvös Loránd University, Pázmány Péter sétány 1/A, Budapest, H-1117, Hungary.

[12] US Naval Observatory, 3450 Massachusetts Avenue, NW, Washington, DC 20392-5420.

[13] University of Washington, Department of Astronomy, Box 351580, Seattle, WA 98195.

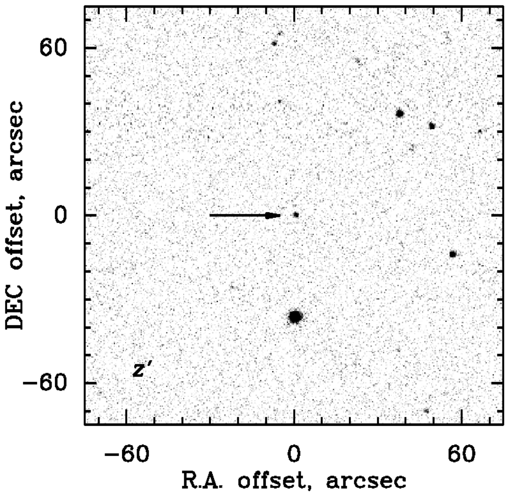

FIG. 1.—Finding chart for SDSS 1346−00. The panel shows a section of the z'-band SDSS scan obtained on UT 1999 March 22.

2. OBSERVATIONS

The SDSS project is described in detail by Gunn & Weinberg (1995).[14] Here we briefly outline the characteristics of SDSS that are relevant to this work.

SDSS images are obtained with a very large format CCD camera (Gunn et al. 1998) attached to a dedicated 3° field-of-view 2.5 m telescope[15] at the Apache Point Observatory, New Mexico. The sky is imaged in drift-scan mode through five broadband filters spanning 0.33–1.05 μm: u', g', r', i', and z', with central wavelengths/effective widths of 3540 Å/599 Å, 4770 Å/1379 Å, 6222 Å/1382 Å, 7632 Å/1535 Å, and 9049 Å/1370 Å, respectively (Fukugita et al. 1996). The exposure time in each band is 54.1 s. The photometric calibration is obtained through contemporaneous observations of a large set of standard stars with an auxiliary 20″ telescope[16] at the same site. The data is processed through an automated pipeline at the Fermi National Accelerator Laboratory, where the software performs photometric and astrometric calibrations and finds and measures properties of all objects in the images.[17]

To date, a number of 2°.5-wide strips centered on the celestial equator have been imaged as part of the SDSS commissioning program. The region spanning right ascensions of $12^{\rm h}$ and $16^{\rm h}30^{\rm m}$ has been imaged twice, first in 1998 June and again in 1999 March. Parts of the region not imaged in 1998 June were imaged twice in 1999 March. Because the network of primary standard stars was not fully established during commissioning, the absolute photometric calibration of these images remains uncertain at the 5% level. Cross-correlating the data from the twice-imaged region removes any uncertainty regarding the identification of faint and very red objects, especially those detected in only one bandpass. Using this technique, we identified all point sources with $i^*-z^* > 2.5$, including sources detected through z' only (see next paragraph for explanation of superscripts). After inspecting the images of each source, we found that the two reddest sources, SDSS 1346−00 and SDSS 1624+00, were also the most credible brown dwarf candidates. SDSS 1346−00 was detected only in the z' images recorded on UT 1999 March 20 and 22. We note that the astrometric positions of SDSS 1346−00 in the two runs are consistent with one another. Figure 1 shows the finding chart for SDSS 1346−00.

Table 1 lists the SDSS magnitudes and uncertainties for SDSS 1346−00. We indicate the preliminary photometric measurements with asterisks but retain the primes for the filters themselves. The SDSS magnitudes are in the AB system (Fukugita et al. 1996) and are given as asinh values (Lupton, Gunn, & Szalay 1999). The u^*, g^*, r^*, and i^* values all represent nondetections—5 σ detections of a point source with 1″ FWHM images correspond to $u^* = 22.3$, $g^* = 23.3$, $r^* = 23.1$, $i^* = 22.5$, and $z^* = 20.8$. The two z^* measurements for SDSS 1346−00 agree to within 1 σ. Its $i^*-z^* \sim 4$ is consistent with the $i^*-z^* = 3.77 \pm 0.21$ measured for SDSS 1624+00 (Strauss et al. 1999). Note that M and L dwarfs are not expected to be redder than $i^*-z^* \sim 2.5$ (Fan et al. 2000).

Near-infrared photometry of SDSS 1346−00 was obtained on UT 1999 May 23 using the IRCAM 256 × 256 InSb array at the UKIRT. The plate scale was 0″.28 pixel^{-1}, and the exposure times at J, H, and K were 5, 14, and 18 minutes, respectively. The conditions were photometric, and the seeing was 0″.8. The object was imaged using the standard dither technique, and the images were calibrated using observations of UKIRT faint standards (Casali & Hawarden 1992).[18] The UKIRT magnitudes of SDSS 1346−00 are listed in Table 1. (Vega has magnitude zero in all UKIRT bandpasses.) The $J-K$ and $H-K$ colors of SDSS 1346−00 are redder by ~0.1 mag than those of Gliese 229B (Leggett et al. 1999) and SDSS 1624+00 (Strauss et al. 1999). The z^*-J color is about the same for two SDSS methane dwarfs. SDSS 1346−00 is fainter than Gliese 229B and SDSS 1624+00 by $\Delta J = 1.5$ and $\Delta J = 0.3$, respectively.

An optical spectrum of SDSS 1346−00 was obtained on UT 1999 May 10 using the Double Imaging Spectrograph on the Apache Point 3.5 m telescope. The spectra were taken using the low-resolution gratings, providing a spectral coverage of 0.4–1.05 μm, with dispersions of 6.2 Å pixel^{-1} on the blue side and 7.1 Å pixel^{-1} on the red side, and a 2″.0 slit. The exposure time was 30 minutes. The conditions were nonphotometric, and the seeing was ~1″.5. The initial flux calibration and removal of atmospheric absorption bands were achieved through observations of the spectrophotometric standard BD +26°2606 (F subdwarf; Oke & Gunn 1983) over several nights. The final flux calibration, however, was obtained by matching the optical spectrum with the near-infrared spectrum in the overlapping region near 1 μm (see below).

TABLE 1
PHOTOMETRY OF SDSS J134646.45−003150.4

u^*	g^*	r^*	i^*	z^*	J	H	K
24.11 ± 0.38	24.20 ± 0.40	24.54 ± 0.62	23.26 ± 0.65	19.29 ± 0.06	15.82 ± 0.05	15.85 ± 0.05	15.84 ± 0.07
24.08 ± 0.39	24.27 ± 0.43	24.07 ± 0.42	23.58 ± 0.75	19.23 ± 0.08			

---

[14] See http://www.astro.princeton.edu/PBOOK/.

[15] See http://www.astro.princeton.edu/PBOOK/telescop/telescop.htm.

[16] See http://www.astro.princeton.edu/PBOOK/photcal/photcal.htm.

[17] See http://www.astro.princeton.edu/PBOOK/datasys/datasys.htm.

[18] See also http://www.jach.hawaii.edu/JACpublic/UKIRT/astronomy/calib/faint_stds.html.

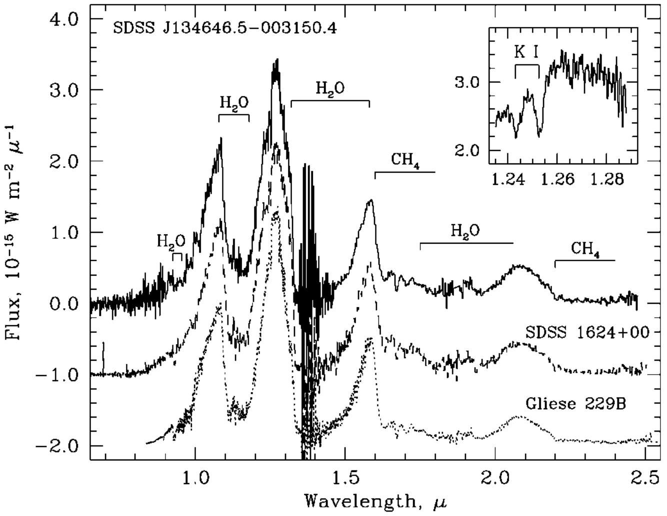

FIG. 2.—Spectrum of SDSS 1346−00 from 0.8 to 2.5 μm. The prominent molecular bands of H_2O and CH_4 are marked. The spectra of SDSS 1624+00 and Gliese 229B are scaled to match the peak of SDSS 1346−00 at ∼1.27 μm and then offset for ease of comparison. The scale factors and offsets are (0.79, −1) and (0.24, −2), respectively. The inset shows a medium-resolution ($R \sim 3000$) spectrum centered about the peak of the *J*-band emission. Absorption lines from the K I doublet at 1.2436 and 1.2536 μm are well resolved.

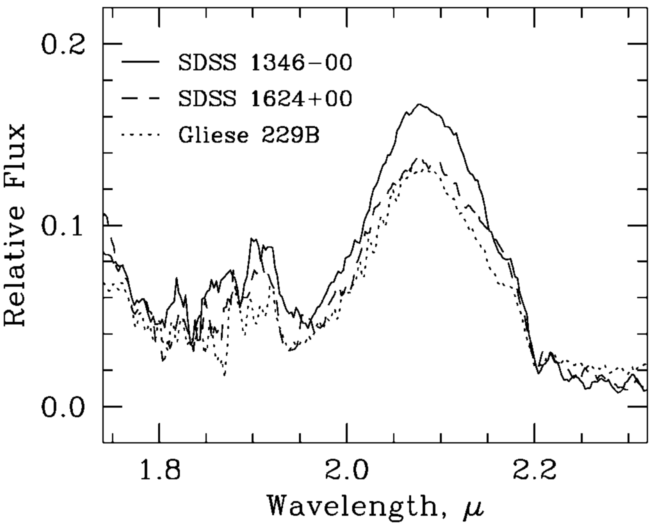

FIG. 3.—Comparison of *K*-band spectra of SDSS 1346−00 (*solid line*), SDSS 1624+00 (*dashed line*), and Gliese 229B (*dotted line*). The three spectra are normalized to the peak of the emerging flux around ∼1.27 μm and smoothed with a boxcar of 5 pixels.

The calibrated optical spectrum is included in Figure 2. Although the spectrum is significantly noisier than that of SDSS 1624+00 (Strauss et al. 1999), it shows similar characteristics. The spectrum rises steeply toward the near-infrared, and its shape matches the SDSS photometry well. A distinct H_2O absorption band centered at ∼0.94 μm remains after subtraction of the telluric absorption feature at the same wavelength. No flux was detected shortward of ∼0.8 μm.

Spectra covering the *J*, *H*, and *K* bands were obtained on the nights of UT 1999 May 23 and June 2 with the facility grating spectrometer CGS4 (Mountain et al. 1990) at UKIRT. The instrument was configured with a 300 mm camera, a 40 line mm^{-1} grating, and a 256 × 256 InSb array. The 1″.2 slit was projected onto two detector pixels, providing a spectral resolving power *R* in the range of 300–500. The *JHK* spectral range was spanned by five overlapping spectra with the following central wavelengths and total exposure times: 0.95 μm (48 minutes), 1.1 μm (56 minutes), 1.4 μm (33 minutes), 1.8 μm (48 minutes), and 2.2 μm (21 minutes). The individual spectra were obtained by nodding the object 7″.32 (12 detector rows) along the slit. The final co-added spectrum has a resolution of 0.0025 μm across the *J* and *H* bands, and 0.0050 μm in the *K* band. Spectra of Kr, Ar, and Xe lamps were used for wavelength calibration and are accurate to ≲0.001 μm. Spectra of bright F dwarfs were obtained repeatedly throughout the observations for initial flux calibration (after removal of prominent H absorption features) and subtraction of telluric absorption lines. The individual spectra were then combined and scaled to match the near-infrared photometry. The resultant spectrum is shown in Figure 2.

On UT 1999 June 7 and 10, we obtained two higher resolution (150 line mm^{-1} grating, $R \sim 3000$) CGS4 spectra of SDSS 1346−00 over the wavelength region $1.235 < \lambda < 1.290$ μm. The observing technique was similar to the one described above, with a total exposure time of 52 minutes. This wavelength region spans the peak of the emergent energy spectrum of the brown dwarf. The inset in Figure 2 shows a smoothed (by 1.5 pixels) average of the two spectra. The resolution of the smoothed spectrum is ∼0.0005 μm, which is the highest yet reported for a cool brown dwarf. The individual spectra, including the many narrow lines at the red end of the spectrum, matched well before being combined. The error bars for the resultant spectrum are ∼7% everywhere but increase to about twice that value near 1.27 μm, where telluric lines of O I are strong and variable. The two broad absorption features at 1.243 and 1.252 μm are due to K I (Kirkpatrick et al. 1993).

3. DISCUSSION

The 0.8–2.5 μm spectrum of SDSS 1346−00 looks astonishingly like that of Gliese 229B, as recalibrated by Leggett et al. (1999), and that of SDSS 1624+00 (Strauss et al. 1999). Strong absorption bands of H_2O and CH_4 dominate the spectrum, and the absorption lines of H_2O at 2.0–2.1 μm discussed by Geballe et al. (1996) are also apparent. Note that while the zero point of Gliese 229B's spectrum is slightly uncertain because of a possible miscorrection for scattered light from Gliese 229A, no such uncertainty exists for our spectrum. Flux is not detected at the bottom of the H_2O band at 1.36–1.40 μm but is detected in the deepest parts of the H_2O bands at 1.15 μm and 1.8–1.9 μm and the CH_4 band at 2.2–2.5 μm.

The only significant differences between the spectrum of SDSS 1346−00 and those of Gliese 229B and SDSS 1624+00 are SDSS 1346−00's somewhat stronger absorption lines of K I at 1.2436 and 1.2536 μm and the slight excess of flux around 1.7 and 2.1 μm. The latter excess is also reflected in the slightly redder $J-K$ and $H-K$ colors of SDSS 1346−00 compared with those of SDSS 1624+00 and Gliese 229B. Figure 3 illustrates the differences between the *K*-band spectra of these three methane brown dwarfs. Burgasser et al. (1999) have also noted differences in the *H*-to-*K* flux ratios of the 2MASS "T" dwarfs and Gliese 229B, and they use these ratios to establish a preliminary spectral sequence for those five brown dwarfs. Following their example, we infer that SDSS 1346−00 is somewhat warmer than SDSS 1624+00 and Gliese 229B. However, accurate modeling of the spectra is required to confirm and calibrate this assessment.

The widths of the K I absorption doublet (EW ≈ 6 and 9 Å, FWHM = 820 ± 50 km s^{-1}) correspond to a rotation rate that greatly exceeds the escape velocity from even the most massive brown dwarf. Thus, rotational broadening alone cannot account for the width of the K I lines. Since the dust-free photospheres of cool brown dwarfs are transparent in this wavelength range to depths with brightness temperatures of ∼1700 K (Matthews et al. 1996) and pressures of ∼30 bar (Marley et al. 1996), the observed widths of the K I doublet are probably caused by pressure broadening. Accurate modeling of this higher resolution spectrum should constrain significantly the gravity, temperature, and pressure profiles of cool brown dwarfs.

Although the signal-to-noise ratio of the optical spectrum of SDSS 1346−00 is insufficient for a rigorous assessment, the overall shape of the continuum may be linked to the pressure-broadened K I lines. The optical spectrum of SDSS 1346−00 is remarkably similar to those of Gliese 229B (Schultz et al. 1998; Oppenheimer et al. 1998) and SDSS 1624+00 (Strauss et al. 1999). Gliese 229B's optical flux is lower by 1–2 dex than the fluxes predicted by the models of dust-free photospheres that reproduce well its near-IR spectrum (Schultz et al. 1998; Golimowski et al. 1998). Possible explanations of this large discrepancy include absorption by aerosols produced photochemically by radiation from Gliese 229A (Griffith, Yelle, & Marley 1998), a warm dust layer deep in the photosphere (Tsuji et al. 1999), and extreme pressure broadening of the K I doublet at 0.76 μm (Tsuji et al. 1999; Burrows, Marley, & Sharp 2000). The similarity between the optical spectra of Gliese 229B and the SDSS field methane dwarfs discourages the notion that photochemically induced aerosols are the absorbing agent. However, absorption by warm dust or pressure-broadened K I remain viable and observationally testable hypotheses.

Given the similarity of the colors and spectra of SDSS 1346−00, SDSS 1624+00, and Gliese 229B, it is reasonable to assume that these three brown dwarfs have similar luminosity. Using this argument and the measured distance to Gliese 229B of 5.8 pc (Perryman 1997), Strauss et al. (1999) estimated a distance to SDSS 1624+00 of 10 pc. The apparent magnitude differences between SDSS 1346−00 and SDSS 1624+00 are $\Delta m = 0.26$ (z'), 0.29 (J), 0.28 (H), and 0.14 (K). The average difference (excluding K) of 0.3 mag puts SDSS 1346−00 at a distance of 11.5 pc. This estimate must be treated with caution, however, since SDSS 1346−00's larger flux around 2.1 μm may reflect a slightly higher temperature (and hence luminosity since the models indicate that the radii of these objects are essentially independent of the temperature or mass) than those of Gliese 229B and SDSS 1624+00.

The SDSS commissioning data obtained to date cover approximately 400 deg^2, or ∼1%, of the sky. To boost our confidence in the one-band detections at faint magnitudes, we have searched only the twice-imaged area of the sky for objects with $z^* \leq 19.8$ (∼12 σ detection) and $i^* - z^* > 2.5$. This strategy restricts the searched area of the survey to 130 deg^2. The two reddest candidates in this restricted area, SDSS 1346−00 and SDSS 1624+00, have been identified spectroscopically as methane brown dwarfs. Recognizing the danger of statistical inferences based on a sample of two objects, we estimate 635 such objects on the sky (of which ∼1/4 will be discovered by SDSS because of its sky coverage) that satisfy our photometric-search criteria. This implies a surface density of 0.015 deg^2. Using our detection limit of $z^* = 19.8$, our search area of 130 deg^2, and Gliese 229B as a standard candle, we estimate our search volume to be ∼40 pc^3 and the space density of Gliese 229B–like brown dwarfs to be 0.05 pc^{-3}.

Our surface-density estimate is ∼3 times larger than that derived by Strauss et al. (1999). This discrepancy is due to our reduction by 68% of the search area and the doubling of the number of detected methane dwarfs. Based on the four objects identified from 1784 deg^2 of 2MASS, Burgasser et al. (1999) estimate ∼90 T dwarfs on the sky brighter than a 10 σ detection limit of $J = 16$. This number corresponds to a surface density of 0.0022 deg^{-2} and a space density of ∼0.01 pc^{-3}. For brown dwarfs with colors like those of SDSS 1346−00, the 2MASS detection limit is equivalent to $z^* \approx 19.5$, i.e., slightly brighter than our selection criterion of $z^* < 19.8$. Despite the nearly equal sensitivity of 2MASS and SDSS to such brown dwarfs, our estimates of surface and space density are larger than the 2MASS estimates by factors of ∼7 and ∼5, respectively. Cuby et al. (1999) infer a space density of 1 pc^{-3} from one confirmed methane brown dwarf in the 2'.3 × 2'.3 NTT Deep Field. This value is ∼20 times higher than our estimate for the same type of object. The large dispersion in the SDSS, 2MASS, and NTT estimates is almost certainly a result of small-sample statistics. We look forward to the imminent routine operation of SDSS as a means of improving these very preliminary statistics.

The SDSS[19] is a joint project of the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, the Max-Planck-Institute for Astronomy, Princeton University, the US Naval Observatory, and the University of Washington. Apache Point Observatory, site of the SDSS, is operated by the Astrophysical Research Consortium. Funding for the project has been provided by the Alfred P. Sloan Foundation, the SDSS member institutions, the National Aeronautics and Space Administration, the National Science Foundation, the US Department of Energy, and the Ministry of Education of Japan. We also thank Karen Gloria for her expert assistance at the Apache Point Observatory. UKIRT is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council. We are grateful to the staff of UKIRT for its support, to A. J. Adamson for use of UKIRT Director's time, and to Tom Kerr for obtaining the medium-resolution J-band spectrum.

---

[19] The SDSS Web site is http://www.sdss.org/.

REFERENCES

Allard, F., Hauschildt, P. H., Baraffe, I., & Chabrier, G. 1996, ApJ, 465, L123
Basri, G., Marcy, G. W., & Graham, J. R. 1996, ApJ, 458, 600
Burgasser, A. J., et al. 1999, ApJ, 522, L65
Burrows, A., et al. 1997, ApJ, 491, 856
Burrows, A., Marley, M. S., & Sharp, C. M. 2000, ApJ, in press
Casali, M., & Hawarden, T. G. 1992, UKIRT Newsl., 4, 33
Cuby, J. G., Saracco, P., Moorwood, A. F. M., D'Odorico, S., Lidman, C., Comerón, F., & Spyromilio, J. 1999, A&A, 349, L41
Fan, X., et al. 2000, AJ, in press (astro-ph/9909263)
Fegley, B., & Lodders, K. 1996, ApJ, 472, L37
Fukugita, M., Ichikawa, T., Gunn, J. E., Doi, M., Shimasaku, K., & Schneider, D. P. 1996, AJ, 111, 1748
Geballe, T. R., Kulkarni, S. R., Woodward, C. E., & Sloan, G. C. 1996, ApJ, 467, L101
Golimowski, D. A., Burrows, C. J., Kulkarni, S. R., Oppenheimer, B. R., & Brukardt, R. A. 1998, AJ, 115, 2579
Griffith, C. A., Yelle, R. V., & Marley, M. S. 1998, Science, 282, 2063
Gunn, J. E., et al. 1998, AJ, 116, 3040

Gunn, J. E., & Weinberg, D. H. 1995, in Wide Field Spectroscopy and the Distant Universe, ed. S. Maddox & A. Aragòn-Salamanca (Singapore: World Scientific), 3

Hambly, N. C. 1998, in ASP Conf. Ser. 134, Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo, E. L. Martín, & M. R. Zapatero Osorio (San Francisco: ASP), 11

Kirkpatrick, J. D., et al. 1993, ApJ, 402, 643

———. 1999, ApJ, 519, 802

Leggett, S. K., Toomey, D. W., Geballe, T. R., & Brown, R. H. 1999, ApJ, 517, L139

Lupton, R. H., Gunn, J. E., & Szalay, A. 1999, AJ, 118, 1406

Marley, M. S., et al. 1996, Science, 272, 1919

Matthews, K., Nakajima, T., Kulkarni, S. R., & Oppenheimer, B. R. 1996, AJ, 112, 1678

Mountain, C. M., Robertson, D., Lee, T. J., & Wade, R. 1990, Proc. SPIE, 1235, 25

Nakajima, T., Durrance, S. T., Golimowski, D. A., & Kulkarni, S. R. 1994, ApJ, 428, 797

Nakajima, T., Oppenheimer, B. R., Kulkarni, S. R., Golimowski, D. A., Matthews, K., & Durrance, S. T. 1995, Nature, 378, 463

Oke, J. B., & Gunn, J. E. 1983, ApJ, 266, 713

Oppenheimer, B. R., Kulkarni, S. R., Matthews, K., & van Kerkwijk, M. H. 1998, ApJ, 502, 932

Perryman, M. A. C., ed. 1997, The *Hipparcos* and Tycho Catalogues (ESA SP-1200; Noordwijk: ESA)

Rebolo, R., Martín, E. L., Basri, G., Marcy, G. W., & Zapatero-Osorio, M. R. 1996, ApJ, 469, L53

Schultz, A. B., et al. 1998, ApJ, 492, L181

Strauss, M. A., et al. 1999, ApJ, 522, L61

Tinney, C. G., Delfosse, X., & Forveille, T. 1997, ApJ, 490, L95

Tsuji, T., Ohnaka, K., & Aoki, W. 1999, ApJ, 520, L119