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

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ABSTRACT

We report the discovery of the coolest field dwarf yet known, selected as an unresolved object with extremely red colors from commissioning imaging data of the Sloan Digital Sky Survey. Its spectrum from 0.8 to 2.5 μm is dominated by strong bands of H_2O and CH_4. Its spectrum and colors over this range are very similar to those of Gl 229B, the only other known example of a methane dwarf. It is roughly 1.2 mag fainter than Gl 229B, suggesting that it lies at a distance of ~10 pc. Such a cool object must have a mass well below the hydrogen-burning limit of 0.08 $M_\odot$ and therefore is a genuine brown dwarf, with a probable mass in the range 0.015–0.06 $M_\odot$ for an age range of 0.3–5 Gyr.

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

1. INTRODUCTION

For decades, astronomers have speculated on the nature of substellar objects or brown dwarfs, objects below the mass necessary to sustain equilibrium hydrogen thermonuclear burning in their cores (see the reviews by Stevenson 1991 and Burrows & Liebert 1993). The past 5 years have finally yielded observational evidence for such objects, from deep near-infrared searches in nearby open clusters (e.g., Hambly 1998, and references therein), in the vicinity of nearby stars (Nakajima et al. 1995), from proper-motion studies (Ruiz, Leggett, & Allard 1997), from the databases of the Two Micron All Sky Survey (2MASS; Kirkpatrick et al. 1999) and the DENIS survey (Delfosse et al. 1997), and in radial velocity studies of nearby stars (for a review, see Marcy & Butler 1998). A new spectral class, L, has been proposed for objects cooler than M stars (Martin et al. 1997; Kirkpatrick et al. 1999). These L dwarfs have surface temperatures low enough (1400–2000 K) that the TiO and VO bands that dominate the optical spectra of M stars vanish and absorption lines of Cs and Rb are seen.

There is one even cooler object, Gl 229B, whose spectrum is distinct from that of L dwarfs. It was discovered (Nakajima et al. 1995) in an imaging survey of close companions to nearby young stars (Najakima et al. 1994); its luminosity and spectrum indicate that it has a temperature of roughly 900 K and a mass of 0.02–0.04 $M_\odot$ for an assumed age of 0.5–1.5 Gyr (Leggett et al. 1999; see Marley et al. 1996 and Allard et al. 1996 for earlier work). The infrared spectrum of this object (Oppenheimer et al. 1995; Geballe et al. 1996; Noll, Geballe, & Marley 1997; Oppenheimer et al. 1998) is dominated by strong bands of H_2O, CH_4, and CO; CH_4 is thought to be absent in L dwarfs (Noll et al. 1998), since it dissociates at temperatures above 1300 K (e.g., Fegley & Lodders 1996; Burrows et al. 1997). Given that such objects never reach a core temperature hot enough to burn hydrogen, their luminosity and effective temperature are functions of age as well as mass (see, e.g., Fig. 7 of Burrows et al. 1997).

The Sloan Digital Sky Survey (SDSS; Gunn & Weinberg 1995; SDSS Collaboration 1996;[16] York et al. 1999[17]) is using a dedicated 2.5 m telescope at Apache Point Observatory, New Mexico, to obtain CCD images in five broad optical bands (u', g', r', i', and z', centered at 3540, 4770, 6230, 7630, and 9130 Å; Fukugita et al. 1996) over 10,000 deg^2 of the high Galactic latitude sky centered approximately on the north Galactic pole. Photometric calibration is provided by an auxiliary telescope at the same site. The survey data processing software carries out astrometric and photometric calibrations and finds and measures properties of all objects in the data (Pier et al.

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[16] Available at http://www.astro.princeton.edu/BBOOK/.
[17] See also http://www.astro.princeton.edu/BBOOK/INTRO/intro.html.

TABLE 1
Optical Positions and SDSS Photometry of Methane Dwarf

Position (J2000)	u^*	g^*	r^*	i^*	z^*	Date
$16^h24^m14^s.37+00°29'15''.8$	25.07 ± 0.39	25.95 ± 0.35	25.34 ± 0.56	22.70 ± 0.27	19.02 ± 0.04	1998 Jun
$16^h24^m14^s.36+00°29'15''.7$	24.29 ± 0.33	24.29 ± 0.39	24.18 ± 0.53	22.88 ± 0.32	19.03 ± 0.04	1999 Mar

Note.—Photometry is reported in terms of asinh magnitudes on the AB system, which becomes a linear scale in flux when the absolute value of the signal-to-noise ratio is less than about 5; see Lupton, Gunn, & Szalay 1999 and Fan et al. 1999a for details. The u^*, g^*, and r^* values all represent nondetections (for comparison, in our system, zero flux corresponds to 24.24, 24.91, 24.53, 23.89, and 22.47 in u^*, g^*, r^*, i^*, and z^*, respectively; larger magnitudes refer to negative flux values). The definition of the photometric system is still uncertain at the level of roughly 0.05 mag in all bands; we quote measured values using asterisks (to represent preliminary photometry) rather than the primes of the final system.

1999;[18] Lupton et al. 1999b[19]). The depth of the survey and the presence of the z' band allows the discovery of extremely red objects, which cannot be effectively identified in surveys whose red cutoffs lie shortward of 8500 Å. In particular, Fan et al. (1999a, 1999b) have used early SDSS commissioning data to find 15 new quasars at $z > 3.65$ and a number of new L dwarfs. We here report on follow-up spectroscopy of an extremely red object in the SDSS imaging data; we find it to be a near twin of Gl 229B, but in the field.

2. OBSERVATIONS

The equatorial strip in the region of $\alpha = 16^h30^m$ was observed twice by the SDSS imaging camera (Gunn et al. 1998), once on 1998 June 28, with the telescope pointed 2 hr west, and again on 1999 March 21, with the telescope pointing on the meridian. The effective exposure time in each case was 54.1 s in each band. In both cases, the telescope was pointed at the celestial equator and did not move during these drift-scanning observations. The seeing in the z' band during these two observations was 1''.4 and 1''.2, respectively. The object SDSSp J162414.37+002915.6 (the name being its preliminary astrometry in J2000 coordinates; we refer to it hereafter as SDSS 1624+00 for brevity) was selected for its extremely red color. Tables 1 and 2 give the results of the astrometry and photometry in these two observations of SDSS 1624+00. It was undetected in u', g', and r'. Data are quoted as asinh magnitudes (Lupton, Gunn, & Szalay 1999; Fan et al. 1999a) and are on the AB system (Fukugita et al. 1996). The i' detection is at low signal-to-noise ratio, but is consistent between the two observations. The z' detection is of very high significance and again is consistent between the two observations. The absolute calibration of the photometry is uncertain at the 5% level, since the primary standard star network had not been completely established when these data were taken; for this reason, we indicate our photometry with asterisks rather than the primes of the final system, although we continue to refer to the filters themselves with the prime notation. Finding charts for SDSS 1624+00 in the i' and z' bands are shown in Figure 1.

[18] See also http://www.astro.princeton.edu/BBOOK/ASTROM/astrom.html.
[19] See http://www.astro.princeton.edu/BBOOK/DATASYS/datasys.html.

TABLE 2
Near-Infrared Photometry of Methane Dwarf

System	i or i_{AB}	z or z_{AB}	J or J_{AB}	H or H_{AB}	K or K_{AB}
Vega	20.9	18.4	15.53 ± 0.03	15.57 ± 0.05	15.70 ± 0.05
AB	21.3	18.8	16.44 ± 0.03	16.95 ± 0.05	17.56 ± 0.05

Note.—The *JHK* photometry on the first line is on the UKIRT system, which references colors to the color of Vega. The i and z photometry is on the Gunn-Thuan system; it, and the *JHK* AB photometry, are synthesized from the composite spectrum of Fig. 2.

The i^*-z^* color of 3.77 ± 0.21 is unprecedented in the SDSS imaging data taken to date. For comparison, M dwarfs with $i^*-z^* > 1.4$ are quite rare (Fan 1999; Fan et al. 1999a), while L dwarfs get as red as $i^*-z^* \sim 2.5$ (Fan et al. 1999b). Gl 229B has not been observed in the SDSS photometric system, but observations in the Gunn-Thuan system show it to have $i-z = 2.2 \pm 0.3$ (Nakajima et al. 1995). Synthesizing Gunn-Thuan photometry from our spectrophotometry of SDSS 1624+00 (see below) gives $i-z = 2.5$, in close agreement.

With only two observations of SDSS 1624+00 separated by 266 days, we cannot measure both parallax and proper motion. We determined the position of SDSS 1624+00 measured in the z' band (Table 1) relative to the dense grid of stars in the equatorial astrometric calibration region established by Stone (1997) in which it happens to lie. The geocentric mean place of SDSS 1624+00 moved by −116 ± 31 mas in right ascension and by −27 ± 46 mas in declination from 1998 June to 1999 March, where the error is the scatter for 15 other stars within 2' of SDSS 1624+00. Assuming a distance of 10 pc (see below), the motion implies a transverse velocity of 18 ± 4 km s^{-1}. The detected motion is opposite to the sense in which annual parallax would move the object as well as the direction in which uncorrected differential chromatic refraction would bias the results (given that this object of extreme colors was observed at different air masses in the two observations), giving us some confidence that the motion is both real and mostly due to proper motion.

We obtained optical spectra of SDSS 1624+00 in three 45 minute exposures on the morning of 1999 April 20 UT using the Double Imaging Spectrograph on the Apache Point 3.5 m telescope, with the same instrumental configuration used by Fan et al. (1999a). The resolution is 0.0014 μm, and the spectral coverage is 0.4–1.05 μm. Observations of the F subdwarf standard BD +26°2606 (Oke & Gunn 1983) provided flux calibration and allowed removal of the atmospheric absorption bands. The seeing was better than 1''.2 on this photometric night, and the observations were carried out at low air mass. No flux was detected blueward of 0.8 μm, consistent with the very red i^*-z^* color. The spectrum shows a strong H_2O absorption band centered at ~0.94 μm (which is robust to the telluric water absorption centered at the same wavelength) and the Cs I line at 0.8523 μm (equivalent width of 12.1 ± 3.2 Å). Puzzlingly, there is no strong line at Cs I 0.8943 μm; it is possible that this is affected by telluric H_2O features.

Near-infrared photometry (broadband *JHK*) was obtained on 1999 April 21 UT on the United Kingdom Infrared Telescope (UKIRT) using IRCAM, a camera with a 256 × 256 InSb array. The night was photometric, although the seeing was poor (1''–1''.5). The data were obtained using the standard dither technique and calibrated using UKIRT faint standards (Casali & Hawarden 1992). The results are shown in Table 2, where the data are on the UKIRT system; the table also gives the results of photometry on the AB system. The colors are almost

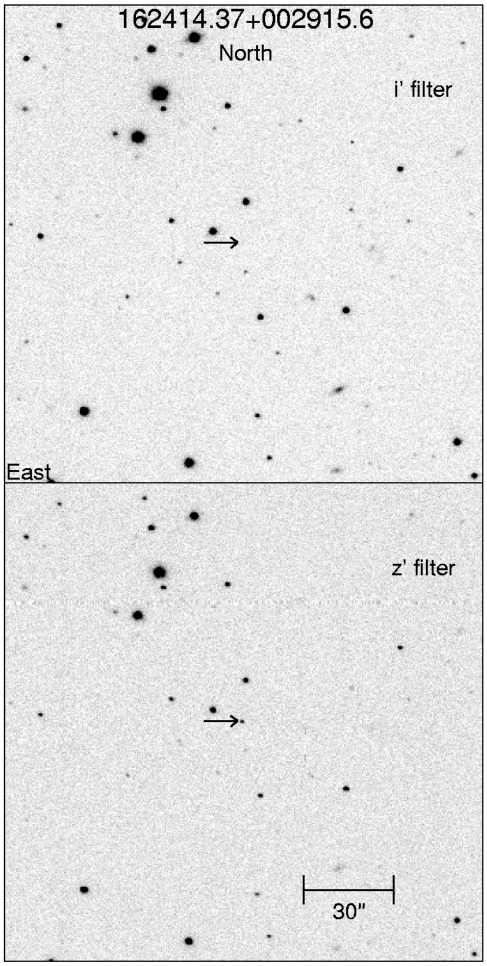

FIG. 1.—Finding chart for SDSS 1624+00 (discovery image from the SDSS). The field is 160″ on a side. The field is given in both the i' and z' bands (54.1 s exposure time) from data taken on 1999 March 21. North is up; east is to the left.

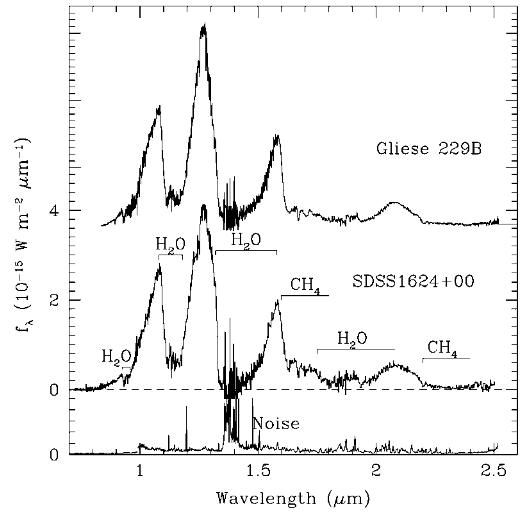

FIG. 2.—Combined optical and *JHK* spectrum of SDSS 1624+00; the latter was taken with the CGS4 at UKIRT, with 0.0025–0.0050 μm resolution. The estimated noise in this spectrum is given as well, as is the spectrum of Gl 229B, for comparison. The relative calibration of the optical and near-infrared spectrum at 1 μm is somewhat uncertain, due to the large contribution to the z^* flux in the red tail of the z' response curve. The prominent bands of H_2O and CH_4 are marked. Most of the narrow spectral features at 1.2–1.3, 1.5–1.7, and 1.95–2.1 μm are real.

identical to those of Gl 229B (Matthews et al. 1996; Golimowski et al. 1998; Leggett et al. 1999), but SDSS 1624+00 is 1.2 mag fainter. There is no evidence that SDSS 1624+00 is extended beyond the point-spread function in either the optical or infrared images.

Spectra were obtained in the *J*, *H*, and *K* bands on the nights of 1999 April 21 and 22 and May 2 and 28 UT at UKIRT using the facility grating spectrometer CGS4 (Mountain et al. 1990), which incorporates a 256 × 256 InSb array. CGS4 was configured with a 1″.2 wide slit, 300 mm camera optics, and a 40 line mm^{-1} grating. Each region of the spectrum was observed for a total of roughly 3000 s. All spectra were obtained in the standard stare/nod mode. The resolution is 0.0025 μm below 1.5 μm, and 0.0050 μm above. Wavelength calibration, based on spectra of arc lamps, is accurate to better than 0.001 μm. Removal of telluric and instrumental spectral features and initial flux calibration were achieved using near simultaneous observations of bright F dwarf stars, assuming standard visible-infrared colors for F stars. The individual spectra were then combined and scaled so as to match the UKIRT photometry.

The final, flux-calibrated spectrum is shown in Figure 2. The spectrum looks astonishingly like that of Gl 229B as shown in the figure (from Oppenheimer et al. 1998 and Geballe et al. 1996, as recalibrated by Leggett et al. 1999). In particular, strong absorption bands of H_2O and CH_4 dominate the spectrum, and the individual absorption lines of H_2O at 2.0–2.1 μm discussed by Geballe et al. (1996) are seen as well. The only significant difference is the slight excess of flux around 1.7 μm in SDSS 1624+00 and the somewhat stronger lines of K I 1.2432 and 1.2522 μm. Note also that while the zero point of the Gl 229B spectrum is slightly uncertain because of the possibility of miscorrection for scattered light from Gl 229A 7″ away, this is not an issue for SDSS 1624+00. Flux is not detected at the bottom of the H_2O band at 1.36–1.40 μm, but is detected in the strongest parts of the H_2O bands at 1.15 and 1.8–1.9 μm and also at 2.2–2.5 μm.

3. DISCUSSION

We have remarked that the colors and spectra of SDSS 1624+00 are quite similar to those of Gl 229B. We will assume that SDSS 1624+00 has a similar effective temperature and luminosity to Gl 229B (especially given that the radii of brown dwarfs are almost independent of mass and age; see Burrows et al. 1997 and Burrows & Sharp 1999). The *Hipparcos* measured distance of Gl 229A is 5.8 pc (Perryman 1997). SDSS 1624+00 is roughly 1.2 mag fainter than Gl 229B in *J*, *H*, and *K*, implying that it has a distance of 10 pc.

Objects as cool as SDSS 1624+00 never reach equilibrium, and so one cannot infer a mass without independent constraints on either its age or its surface gravity. The surface gravity may be available in the future with more detailed spectral modeling and higher resolution spectra. Gl 229A is classified as a "young disk" by Leggett (1992), with an inferred age of around 0.5 Gyr, and it is reasonable to assume that it is coeval with Gl 229B. The luminosity and broadband colors of Gl 229B are consistent with models of a 0.5 Gyr old 0.024 $M_\odot$ object. There is no direct measurement of the age of SDSS 1624+00, but we note that it is not obviously associated with a star-forming region. Assuming the temperature and luminosity are similar to those of Gl 229B, the mass of SDSS 1624+00 probably lies in the range 0.015–0.06 $M_\odot$ for an age range of 0.3–5 Gyr, based on a comparison to models by Burrows et al. (1997).

SDSS 1624+00 was selected from roughly 400 deg^2 of SDSS imaging data, or roughly 1% of the celestial sphere. If this region of sky is typical, there should be of order 100 comparable objects in the sky, and the SDSS in particular will discover on the order of 25 of them (since it will survey one-fourth of the celestial sphere). Indeed, 400 deg^2 is an overestimate of the effective area from which SDSS 1624+00 was selected, since not all of the area surveyed was observed in optimal seeing, and we used the fact that we obtained consistent photometry of SDSS 1624+00 on two separate observations to bolster our confidence that the photometry was correct. Assuming that SDSS 1624+00 is at 10 pc and recognizing the dangers of statistical arguments based on a single object, we can infer a lower limit to the volume density of 0.03 objects pc^{-3}, which would imply that the nearest of these objects is less than 4 pc away (and therefore more than 2 mag brighter than SDSS 1624+00!). Reid et al. (1999) model the L-dwarf number counts of Kirkpatrick et al. (1999) and infer a (model dependent) volume density of 0.10 objects pc^{-3}. Therefore, the data are consistent with roughly comparable space densities of L dwarfs and methane dwarfs.

The SDSS is not sensitive to objects of this temperature that are substantially fainter than $z^* = 19$. With an $i^* - z^*$ of 3.5, it reaches its photometric limits of $i^* \approx 22.5$, $z^* \approx 20.8$ for 5 σ detections of stellar sources in 1″ seeing (Gunn et al. 1998). However, the combination of i' and z' photometry from the SDSS and *JHK* photometry from the 2MASS survey will be particularly powerful for finding such objects.

Note added in manuscript.—Shortly after the discovery of SDSS 1624+00, a second field methane dwarf, SDSSp J134646.45−003150.4, was discovered from the same 400 deg^2 of SDSS commissioning data; optical and near-infrared spectroscopy confirm its identification as a methane dwarf. A paper describing this second discovery is in preparation (Tsvetanov 1999). In addition, Burgasser et al. (1999) describe the discovery of four additional methane dwarfs from the 2MASS database.

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