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# The Discovery of a Field Methane Dwarf from Sloan Digital Sky Survey Commissioning Data[1]

Michael A. Strauss[2], Xiaohui Fan[2], James E. Gunn[2], S. K. Leggett[3], T.R. Geballe[4], Jeffrey R. Pier[5], Robert H. Lupton[2], G. R. Knapp[2], James Annis[6], J. Brinkmann[7], J. H. Crocker[8], István Csabai[8,9], David A. Golimowski[8], Frederick H. Harris[5], G. S. Hennessy[10], Robert B. Hindsley[10], Željko Ivezić[2], D.Q. Lamb[11], Jeffrey A. Munn[5], Heidi Jo Newberg[6], Ron Rechenmacher[6], Donald P. Schneider[12], J. Allyn Smith[13], Chris Stoughton[6], Douglas L. Tucker[6], Patrick Waddell[14], and Donald G. York[11]

## ABSTRACT

We report the discovery of the coolest field dwarf yet known, selected as a stellar object with extremely red colors from commissioning imaging data of the Sloan Digital Sky Survey. Its spectrum from 0.8 to 2.5$\mu$m is dominated by strong

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

[2] Princeton University Observatory, Princeton, NJ 08544

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

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

[5] U.S. Naval Observatory, Flagstaff Station, P.O. Box 1149, Flagstaff, AZ 86002-1149

[6] Fermi National Accelerator Laboratory, P.O. Box 500, Batavia, IL 60510

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

[8] Department of Physics and Astronomy, The Johns Hopkins University, 3701 San Martin Drive, Baltimore, MD 21218, USA

[9] Department of Physics of Complex Systems, Eötvös University, Pázmány Péter sétány 1/A, Budapest, H-1117, Hungary

[10] U.S. Naval Observatory, 3450 Massachusetts Ave., NW, Washington, DC 20392-5420

[11] University of Chicago, Astronomy & Astrophysics Center, 5640 S. Ellis Ave., Chicago, IL 60637

[12] Department of Astronomy and Astrophysics, The Pennsylvania State University, University Park, PA 16802

[13] University of Michigan, Department of Physics, 500 East University, Ann Arbor, MI 48109

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

bands of $H_2O$ and $CH_4$. Its spectrum and colors over this range are very similar to those of Gliese 229B, the only other known example of a methane dwarf. It is roughly 1.2 mag fainter than Gliese 229B, implying that it lies at a distance of roughly 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.

## 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 five 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 (Tinney, Delfosse, & Forveille 1997), and in radial velocity studies of nearby stars (for a review, see Marcy & Butler 1998). The 2MASS survey has defined a new classification for objects cooler than M stars, referring to these objects as 'L dwarfs'. These objects 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 object, Gliese 229B, which clearly does not fall into the L dwarf category. 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 900K and a mass of 0.024–0.033 $M_\odot$ for an assumed age of 0.5–1.0 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 et al. 1997, Schultz et al. 1998, Oppenheimer et al. 1998) is dominated by strong bands of $H_2O$, $CH_4$, and CO; $CH_4$ is absent in L dwarfs (Noll et al. 1998), as it dissociates at temperatures above 1300 K (e.g., Fegley & Lodders 1996, Burrows et al. 1997). Kirkpatrick et al. (1999) have therefore suggested that Gliese 229B be assigned to its own spectral class, T, a class in which it (until now) has sat alone. Given that such an object never reaches a core temperature hot enough to burn hydrogen, the luminosity and effective temperature are functions of age as well as mass (see, e.g., Figure 7 of Burrows et al. 1997).

The near-infrared photometry of Gliese 229B (Matthews et al. 1996, Golimowski et al. 1998, Leggett et al. 1999) shows that it has quite distinctive near-infrared colors (as predicted by Burrows et al. 1997). However, their intrinsically low luminosity (Gliese 229B has a bolometric luminosity of $6.6 \pm 0.06 \times 10^{-6}$ L$_\odot$; Leggett et al. 1999) means that finding further examples will require deep, wide-angle surveys in the near-infrared. It is clearly of great interest to see whether such objects exist in the field, given the fact that they lie close to the (ill-defined) boundary between planets and brown dwarfs.

The Sloan Digital Sky Survey (SDSS; Gunn & Weinberg 1995, SDSS Collaboration 1996, York et al. 1999) is using a dedicated 2.5m telescope at Apache Point Observatory, New Mexico, to obtain CCD images in five broad optical bands ($u'$, $g'$, $r'$, $i'$, $z'$, centered at 3540Å, 4770Å, 6230Å, 7630Å and 9130Å, 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 20$''$ 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. 1999, Lupton et al. 1999b). The presence of the $z'$ band allows the discovery of extremely red objects, which cannot be effectively identified in surveys whose red cutoff lies shortward of 8500Å. In particular, Fan et al. (1999a) have used early SDSS commissioning data to find 15 new quasars at $z > 3.65$ (including four with $z > 4.5$), which appear as red objects due to absorbing clouds of intergalactic hydrogen, and Fan et al. (1999b) have discovered a number of new L dwarfs from the same dataset. 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 Gliese 229B, but in the field.

## 2. Observations

### 2.1. SDSS Data

The equatorial strip in the region of $\alpha = 16^{\rm h}\,30^{\rm m}$ was observed twice by the SDSS imaging camera (Gunn et al. 1998), once on 28 June 1998, with the telescope pointed 2 hours West, and again on 21 March 1999, with the telescope pointing on the meridian. The effective exposure time in each case was 54.1 sec 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 SDSS J162414.37+002915.6 (which we refer to 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, as 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.

The $i^* - z^*$ color of $3.77 \pm 0.21$ 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 $i^* - z^* \sim 2$ (Fan et al. 1999b). Gliese 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 a color $i - z = 2.4$, in close agreement.

We have only two observations of SDSS 1624+00 separated by 266 days (the object is undetected on either POSS-I or POSS-II; Reid et al. 1991), so we cannot measure both parallax and proper motion from our data. SDSS 1624+00 happens to lie within one of the equatorial astrometric calibration regions established by Stone (1997), which allowed us to determine the position relative to this dense grid of stars. The results are shown in Table 1, which refers to the positions as measured from the $z'$ detection. We found that SDSS 1624+00 moved by $-116 \pm 31$ mas in right ascension and by $-27 \pm 46$ mas in declination from 1998 June to 1999 March, where the error is the scatter we found for 15 other stars within $2'$ of SDSS 1624+00. Thus it appears that the position of SDSS 1624+00 moved significantly in right ascension between the two epochs. Assuming a distance of 10 pc (see below), the change in position due to annual parallax between the two observations would be +140 mas in right ascension and −40 mas in declination. Thus the detected motion is opposite to the sense in which annual parallax would move the object. It is also opposite to the direction in which uncorrected differential chromatic refraction would bias the results (given that this object of extreme colors was observed at different airmasses in the two observations), giving us some confidence that the motion is both real and is due to proper motion.

### 2.2. Optical Spectroscopy

We obtained optical spectra of SDSS 1624+00 on the morning of 20 April 1999 UT using the Double Imaging Spectrograph on the Apache Point 3.5m telescope, with the same instrumental configuration used by Fan et al. (1999a). The resolution is 0.0014$\mu$m, and the spectral coverage is 0.4-1.05$\mu$m. 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 airmass. The resulting spectrum, a co-addition of three 45-minute exposures, is shown in Figure 2. No flux was detected blueward of 0.8$\mu$m, consistent with the very red $i^* - z^*$ color. The spectrum shows a strong $H_2O$ absorption band centered at $\sim 0.94\mu$m (which is robust to the telluric water absorption centered at the same wavelength), the Cs I line at 0.8523$\mu$m (equivalent width of $12.1 \pm 3.2$Å) and a strong absorption line at 1.0017$\mu$m. We have labeled the latter feature as possible FeH, although this is a broad feature in L stars, and its strongest component is over 100Å away, at 0.9896$\mu$m. Moreover, there is a strong sky line centered at that position. There is no strong line at Cs I 0.8943$\mu$m, but this region is affected by telluric $H_2O$ features. There is a *possible* detection of a weak band of $CH_4$ in this region of the spectrum.

## 2.3. Infrared Observations

Near-infrared photometry (broadband $JHK$) was obtained on 21 April 1999 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 an AB system, as synthesized from the spectrum presented below. The colors are almost identical to those of Gliese 229B (Leggett et al. 1999) but SDSS 1624+00 is 1.2 magnitudes fainter. There is no evidence that SDSS 1624+00 is extended beyond the PSF in either the optical or infrared images.

Spectra were obtained in the $J$, $H$, and $K$ bands on the nights of 21 and 22 April and 2 May 1999 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 l/mm grating. The spectral region 1.5–1.95$\mu$m was observed for 800 seconds on 21 April. On 22 April the spectral regions 1.03–1.35, 1.46–2.10, and 1.87–2.51$\mu$m were measured for 1440, 800, and 2560 seconds, respectively, and on 2 May, the 1.19–1.51$\mu$m interval was observed for 2880 seconds. All spectra were obtained in the standard stare/nod mode, with the telescope nodded $7.32''$ (12 array rows) between spectral images. The resolutions in the $J$, $H$, and $K$ bands were 0.0025$\mu$m, 0.0025$\mu$m, and

0.0050$\mu$m, respectively. Wavelength calibration was accomplished using spectra of krypton, argon, and xenon lamps and is accurate to better than 0.001$\mu$m. Removal of telluric and instrumental spectral features and initial flux calibration were achieved using near simultaneous observations of bright F dwarf stars (whose strong Brackett and Paschen series hydrogen recombination lines were removed prior to division) assuming standard visible-infrared colors. The individual spectra were then combined and scaled so as to match the near-infrared photometry.

The final, flux-calibrated spectrum, including the initial discovery spectrum of Figure 2, is shown in Figure 3. The spectrum looks astonishingly like that of Gliese 229B, 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$\mu$m discussed by Geballe et al. (1996) are seen as well. The only significant difference is the slight excess of flux around 1.7$\mu$m in our object, and the somewhat stronger lines of K I 1.2432 and 1.2522$\mu$m. Note also that while the zero-point of the Gliese 229B spectrum is slightly uncertain, due to the possibility of miscorrection for scattered light from Gliese 229A $7''$ away, this is not an issue for our object. Flux is not detected at the bottom of the $H_2O$ band at 1.36–1.40$\mu$m, but is detected in the strongest parts of the $H_2O$ bands at 1.15$\mu$m and 1.8–1.9$\mu$m and also at 2.2–2.5$\mu$m.

## 3. Discussion

We have remarked that the colors and spectra of SDSS 1624+00 are quite similar to those of Gliese 229B. We will assume (although we cannot demonstrate unequivocally) that SDSS 1624+00 has a similar effective temperature and luminosity to Gliese 229B (especially given that the radii of brown dwarfs are almost independent of mass and age; cf., Burrows et al. 1997 and Burrows & Sharp 1999). The Hipparcos measured distance of Gliese 229B is 5.8 pc (ESA 1997). SDSS 1624+00 is roughly 1.2 magnitudes fainter than Gliese 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. Gliese 229A is classified as “young disk” by Leggett (1992), with an inferred age of around 0.6 Gyr, and it is reasonable to assume that it is coeval with Gliese 229B. The luminosity and broad band colors of Gliese 229B are consistent with models of a 0.5 Gyr-old 0.024 $M_\odot$ object. We have no direct measurement of the age of SDSS 1624+00, except to say that it is not obviously associated with a star-forming region. Assuming the temperature and luminosity are similar to those of Gliese 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).

Assuming a distance of 10 pc, the change of position of SDSS 1624+00 in our two observations implies an entirely plausible transverse velocity of $17 \pm 4\,\mathrm{km\,s^{-1}}$. However, we note that the star $\sigma$ Ser, at a distance of 28 pc (ESA 1997), lies only 0.76° away from SDSS 1624+00, and shares its proper motion within $1.5\sigma$. If SDSS 1624+00 were at the same distance, then these two stars could be a wide binary, separated by 0.4 pc. However, this would require a luminosity for SDSS 1624+00 of $10^{-4.3}\,L_\odot$, which would require an implausibly low age and high temperature (approaching that at which $CH_4$ can no longer exist) from the Burrows et al. (1997) models. An accurate parallax will of course tell us whether this should be taken seriously.

SDSS 1624+00 is the reddest object found in the SDSS database from roughly 400 square degrees of 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 of order 25 of them (as it will survey 1/4 of the celestial sphere). Indeed, 400 square degrees may be an overestimate of the effective area from which SDSS 1624+00 was selected, as 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. In any case, 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 volume density of 0.03 objects per cubic parsec, which would imply that the nearest of these objects is less than 4 pc away (and therefore more than 2 magnitudes brighter than SDSS 1624+00!). There is not yet a careful measurement of the space density of L dwarfs, but based on the statement in Kirkpatrick et al. (1999) that 6/25 L dwarfs are within 25 pc, one infers a lower limit to their space density of 0.01 objects per cubic parsec. 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, we quickly reach our photometric limits of $i^* \approx 22.5$, $z^* \approx 20.8$ for $5\sigma$ 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.

The Sloan Digital Sky Survey (SDSS) is a joint project of the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, The Johns Hopkins University, the Max-Planck-Institute for Astronomy, Princeton University, the United States

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Table 1. Optical Positions and SDSS Photometry of Methane Dwarf

| Position | $u^*$ | $g^*$ | $r^*$ | $i^*$ | $z^*$ | Date |
|---|---|---|---|---|---|---|
| 16:24:14.37 +00:29:15.8 | $25.07 \pm 0.39$ | $25.95 \pm 0.35$ | $25.34 \pm 0.56$ | $22.70 \pm 0.27$ | $19.02 \pm 0.04$ | June 1998 |
| 16:24:14.36 +00:29:15.7 | $24.29 \pm 0.33$ | $24.29 \pm 0.39$ | $24.18 \pm 0.53$ | $22.88 \pm 0.32$ | $19.03 \pm 0.04$ | March 1999 |

Astrometry is given in J2000 coordinates. Photometry is reported in terms of asinh magnitudes, which smoothly goes to a linear scale in the limits of low signal-to-noise ratio; see Lupton, Gunn & Szalay (1999) and Fan et al. (1999a) for details. The $u^*$, $g^*$, and $r^*$ values all represent non-detections (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). 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.

Table 2. Near-Infrared Photometry of Methane Dwarf

| $i$ | $z$ | $J$ | $H$ | $K$ | |
|---|---|---|---|---|---|
| 21.2 | 18.79 | $15.53 \pm 0.03$ | $15.57 \pm 0.05$ | $15.70 \pm 0.05$ | Vega system |
| 21.6 | 19.21 | $16.44 \pm 0.03$ | $16.95 \pm 0.05$ | $17.56 \pm 0.05$ | AB system |

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 Figure 3.

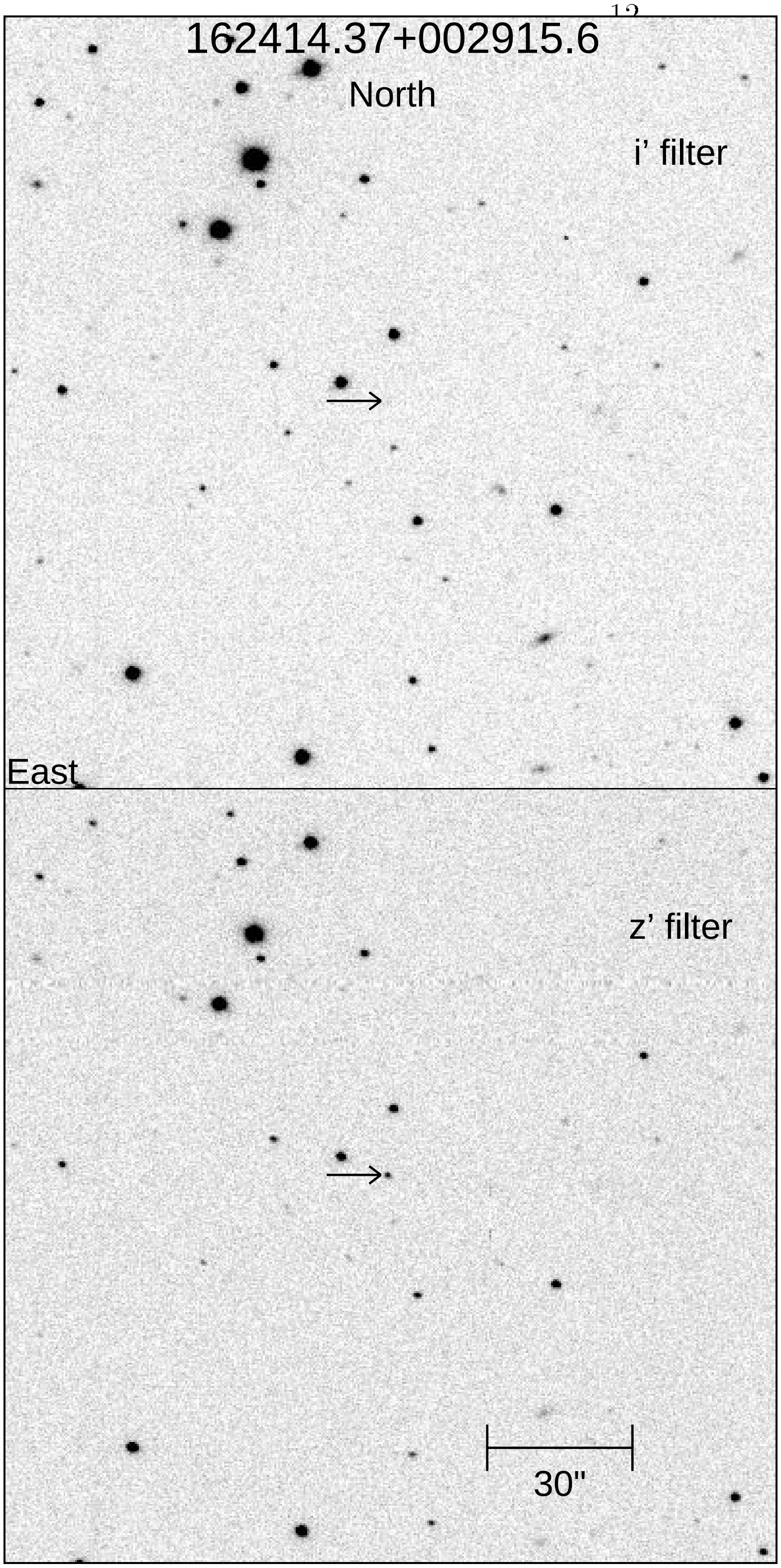

Figure 1. Finding chart for SDSS 1624+00 (discovery image from the SDSS). The field is 160″ on a side. The field is given in both the $i'$ and $z'$ bands (54.1 sec exposure time) from data taken on 21 March 1999. North is up; East is to the left.

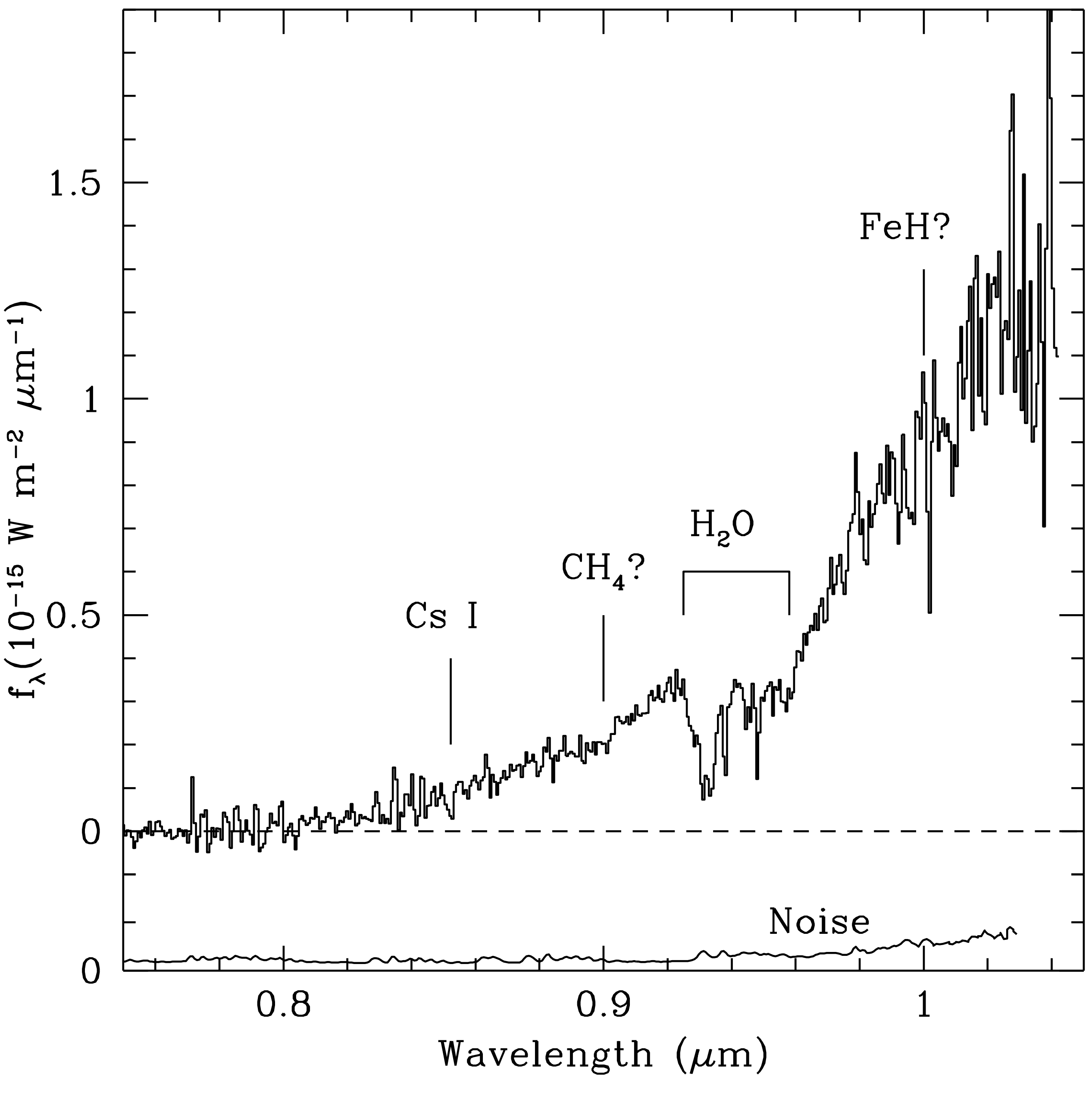

Figure 2. The discovery optical spectrum of SDSS 1624+00, from the DIS spectrograph on the Apache Point 3.5m, at 0.0014$\mu$m resolution. The estimated noise in this spectrum is given as well. Observed features are marked.

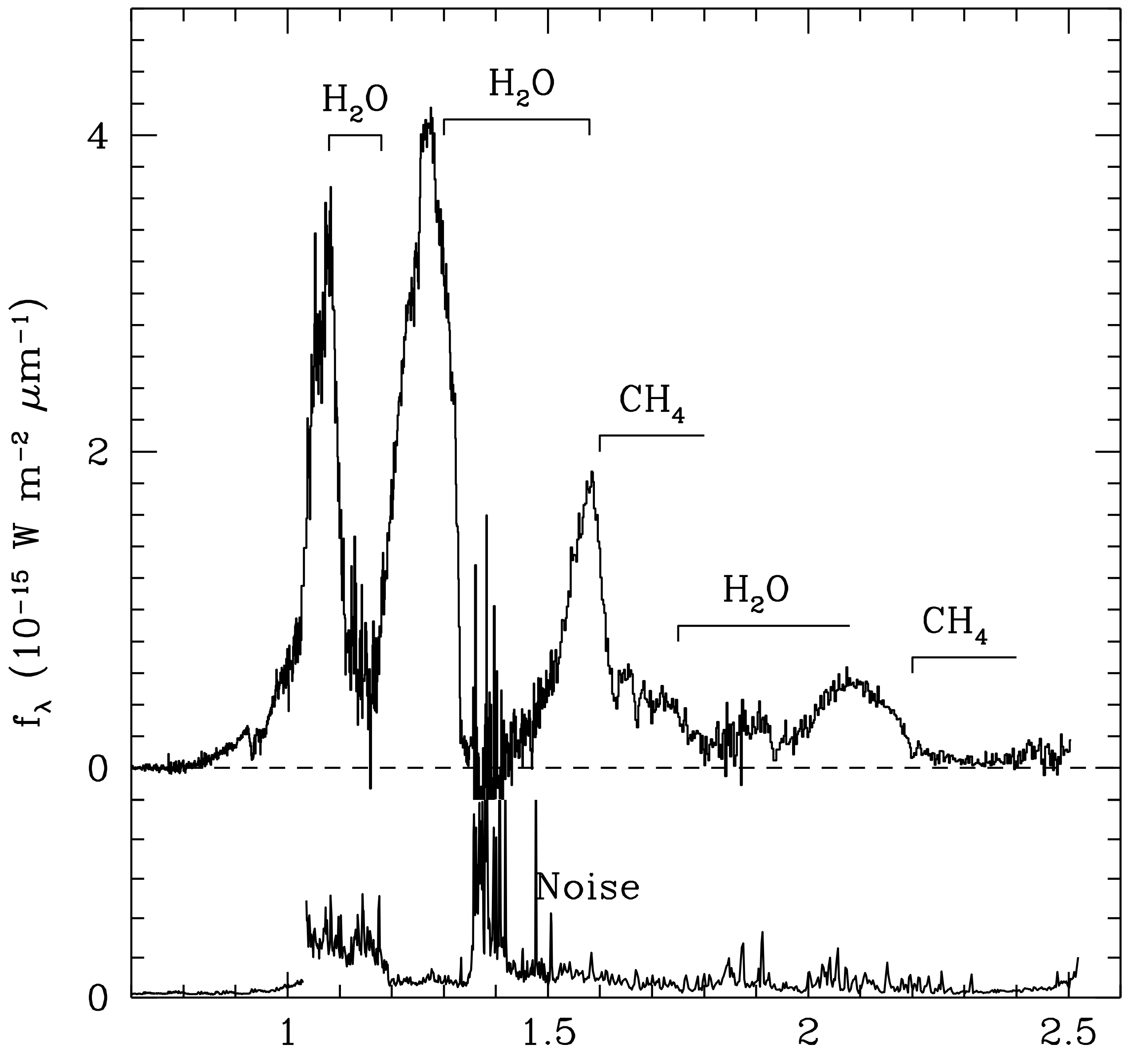

Figure 3. The combined optical and *JHK* spectrum of SDSS 1624+00; the latter was taken with the CGS4 at UKIRT, with 0.0025–0.0050$\mu$m resolution. The estimated noise in this spectrum is given as well. The prominent bands of $H_2O$ and $CH_4$ are marked. Most of the narrow spectral features at 1.2–1.3, 1.5–1.7, and 1.95–2.1$\mu$m are real.