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Discovery of a faint Field Methane Brown Dwarf from ES0 NTT and VLT observations

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Abstract. We report the discovery of an isolated brown dwarf with similar properties to the binary object Gliese 229B and to the newly discovered field brown dwarf SDSS 1624+00. Although exhibiting similar colors, its magnitude of ~ 20.5 is about 6 and 5 magnitudes fainter than Gliese 229B and SDSS 1624+00 respectively. This is the third methane brown dwarf reported to date, the second isolated one in the field and by far the most distant at ~ 100 pc. Its IR spectrum, although at low S/N given the faintness of the object, is remarkably similar to those of the 2 other methane brown dwarfs.

Key words: Techniques: spectroscopic – Stars: low mass, brown dwarfs – Galaxy: stellar content – Infrared: Stars

1. Introduction

Despite large observational efforts during recent years in both wide field and targeted searches for very cold brown dwarfs, the number of such objects known so far remains extremely small. Since 1995, and until June 1999, the only genuine one identified was Gliese 229B (Nakajima 1995, Oppenheimer 1996), the coolest substellar object known, with a temperature below 1000 K, a mass in the range 20-50 M_J (Jupiter mass), and an age in the range 0.5-1 Gyr. A second object of this class, SDSS 1624+00, has been discovered recently in the Sloan Digital Sky Survey (Strauss 1999), having been identified from the survey database by its unusually red color. Follow-up spectroscopy of this object in the visible with the Apache Point 3.5m telescope and in the IR with UKIRT identified

Send offprint requests to: J.G. Cuby (jcuby@eso.org) it as a methane brown dwarf like Gliese 229B. A couple of similar objects have since then been identified (Tzetanov, private communication).

In this paper we report our discovery of a new methane brown dwarf in the NTT Deep Field, a small area of the sky that was the target of very deep exposures in the visible and the near-infrared using the SUSI and SOFI instruments at the ESO New Technology Telescope (NTT) (Arnouts 1999, Saracco 1999). One object, NTTDF 1205-0744, stands out in these images for its very red (i-J) > 6 color index. However, it is very blue at longer wavelengths, with (J-K) = -0.15. Near-infrared spectroscopy with SOFI, and with ISAAC at the ESO Very Large Telescope (VLT), has confirmed the remarkable similarity of this object to Gliese 229B. Due to the very faint apparent magnitude of NTTDF 1205-0744, the observations reported here have been possible only with the availability of two extremely powerful telescopes, the NTT and the VLT, and their near-IR spectrographs, SOFI and ISAAC. Although the raw S/N is limited (1 to 2 per pixel, 5 to 10 after rebinning), our results secure the identification of NTTDF 1205-0744 as a new field methane brown dwarf.

2. Observations and data reduction

The NTT Deep Field covers an area of 2.3×2.3 arcminutes in the visible down to AB magnitude limits of 27.2, 27.0, 26.7 and 26.3 in B, V, r, and i, and 5×5 arcminutes in the IR down to magnitude limits of 24.6 and 22.8 in J and Ks.

The entire dataset of the NTT Deep Field Project, primarily targeted to the study of faint galaxy populations, as well as a detailed information on data acquisition and reduction, are publicly available at http://www.eso.org.

J and i band images of the field containing NTTDF 1205-0744 are shown in figure 1.

After identification of NTTDF 1205-0744 from its unusual extremely red colour (i-J) in April 98, we carried out spectroscopy with SOFI at the NTT using Target of Opportunity Time on 30 June - 1 July 1998. The spectrum, covering the range 0.95-1.65 microns (dispersion: 7 Å per pixel), was obtained under non-photometric conditions using a 1" slit, and nodding along the slit between two positions, for a total effective on-target integration time of 84 minutes. Spectrophotometric calibration and removal of telluric features was achieved using the observation of a B9 type star. The spectrum was scaled to match the IR photometry in the J filter.

The spectrum shows clear H_2O absorptions, leaving peaks in the spectrum at 1.05 and 1.27 μm (the latter peak at a S/N of 1-1.5 per pixel), and a marginally significant detection of a third peak at 1.57 microns.

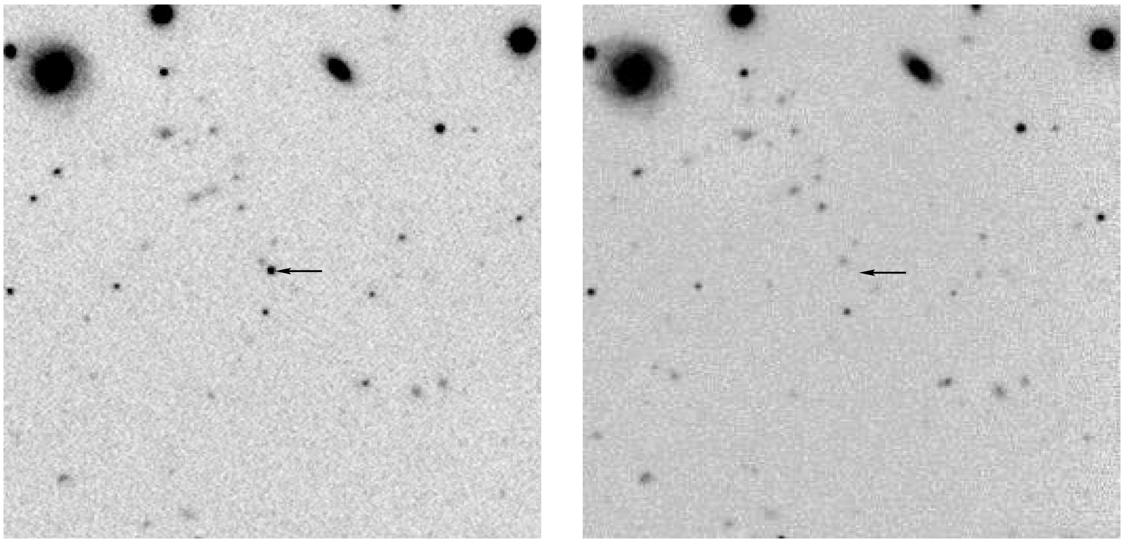

Fig. 1. Image of the NTTDF 1205-0744 field. Left: J SOFI image, Right: i SUSI image. The object position is indicated with an arrow, and is absent from the i image. The field is 1.3 × 1.3 arcminutes, N is up, E is left. The coordinates of NTTDF 1205-0744 are 12:05:20.21 and -07:44:01.0 (J2000).

We subsequently obtained spectroscopy of NTTDF 1205-0744 with ISAAC at the VLT in the H and K bands. All the ISAAC observations were made with a 1 arcsec slit and nodding along the slit.

The K observations were carried out during the nights of 6 and 9 February 1999, for a total amount of time of 1 hour. We used the Low Resolution grating in second order providing a dispersion per pixel of 7 $\AA$. Spectrophotometric calibration was achieved from the observation of a B6 type star observed on a different night. The signal to noise per pixel is below 1 on the peak at 2.1 μm.

The observations in H were carried out during the night of 23 March 1999, again for a total integration time of 1 hour. We used the same Low Resolution grating in third order, providing a dispersion per pixel of 4.7 $\AA$. Spectrophotometric calibration was done from the observation of a B8 type star. The spectrum was arbitrarily scaled so as to correspond to an H magnitude of 20.3. This scaling proved to properly match the SOFI spectrum. The signal to noise ratio per pixel is $\sim$ 2 on the peak at 1.57 μm.

The combined, flux calibrated, spectrum is presented on figure 2, overplotted with the spectrum of Gliese 229B for reference (Geballe 1996).

3. Discussion

The magnitudes, or magnitude lower limits of NTTDF 1205-0744 are given in table 1.

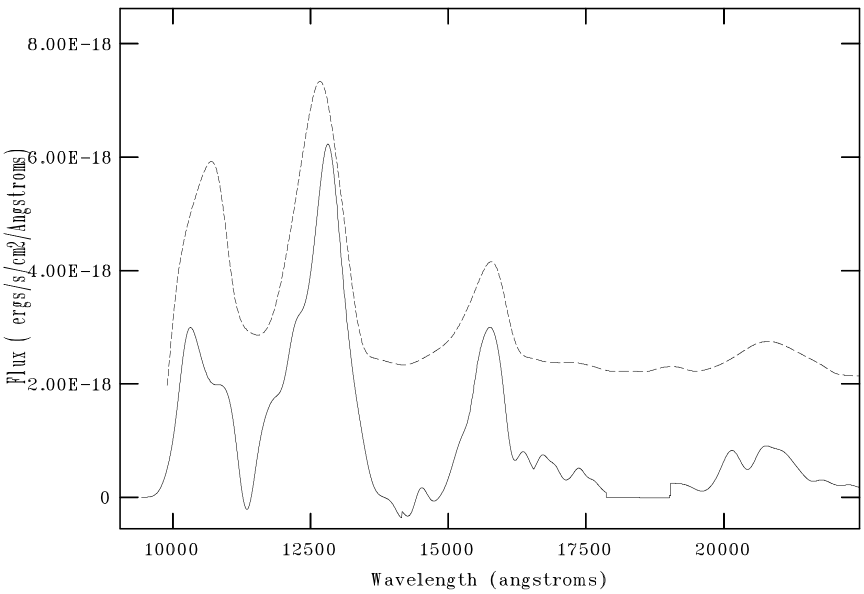

Fig. 2. Spectrum of NTTDF 1205-0744 (plain line). The raw spectrum has been smoothed with a gaussian of FWHM = 47 pixels in the dispersion direction, corresponding to a spectral resolution of $\sim$ 50. The spectrum of Gliese 229B(Geballe 1996) smoothed at the same resolution, is overplotted (with an offset) for reference (dashed line). The similarity between both spectra is striking.

Table 1. Magnitude and magnitude lower limits for NTTDF 1205-0744.

B	V	r	i	J	K
>27.2	>27.0	>26.7	>26.3	20.15	20.3

Both the i-J and the J-K color indices match within less than 0.2 magnitude the color indices of both Gliese 229B and of SDSS 1624+00.

Our infrared spectrum shown in figure 2 has relatively low s/n and some flux calibration uncertainties due to the fact that the observations were made at different times and with different instruments. A detailed discussion of the smaller features is therefore not warranted. For example, the feature in the Ks peak could be real but corresponds to a region of crowded OH sky lines and may just be noise. The most important result here is its striking overall similarity with the spectra of both Gliese 229B and SDSS 1624+00, in particular, the clear presence of the strongest H_20 and CH_4 absorption features, which clearly identifiy it as a methane brown dwarf, and the relative flux distribution which implies a similar temperature.

Assuming not only that the colours but also the absolute magnitude is similar to Gliese 229B which is at 5.8 pc we obtain a distance of $\sim$ 100 pc to NTTDF 1205-0744.

The assumption of a similar absolute magnitude may be justified on the basis of brown dwarf model predictions (Burrows 1997). Although both the colour and the magnitude change over a very large range at any particular brown dwarf age, theoretical isochrones practically overlap in color-magnitude diagrams for the range of colors of interest here. Therefore, even if the mass and the age of NTTDF 1205-0744 may be very different from those of Gliese 229B and SDSS 1624+00, the similar (J-K) color is indicative of a similar absolute magnitude. Thus, although both mass and age are very poorly constrained by our observations (the spectral features placing however the mass safely in the brown dwarf domain), the distance of NTTDF 1205-0744 is considered to be relatively secure.

We have SOFI and ISAAC images taken $\sim$ 14 months apart. We checked for possible proper motion, but nothing could be detected at the level of 0.3 arcsec (2 σ).

NTTDF 1205-0744 stands out as the only object of its type within the 2.3 $\times$ 2.3 arcmin NTT deep field. Although of dubious reliability based on a single object, the implied volume density is 0.5 per cubic parsec (assuming a recognition limit at J=22, see below). This is considerably higher than the 0.01-0.03 per cubic parsec tentatively quoted by Strauss et al. (1999) based on 400 sq. deg. of the Sloan survey implying that our technique is considerably more sensitive or that we were extremely lucky.

The probability of finding a very cold object in a random field with a given limiting magnitude can also be estimated using published brown dwarf models, the local density of low mass stars, and an extrapolation of the initial mass function towards lower masses. We have carried out this exercise using the Burrows et al. (1997) models and the local volume density at 0.1 solar masses from Scalo (1986). We have assumed a constant local formation rate of low mass stars over the last 10 Gyr. The initial mass function (IMF) below 0.1 solar masses has been represented by a power-law of the form $\Phi(M)dM \propto M^{\alpha}dM$, and we have considered values for α ranging from -1.5 to +1. We have then calculated the number of objects with a temperature lower than 1000 K that may be expected to appear in the field with an apparent J magnitude brighter than 22, under the assumption of the different values of α. Although objects much fainter than J=22 are still visible in the J image, the limit chosen is given by the need to be able to recognize the characteristic colors of possible brown dwarfs, namely the extremely red (i-J) and the blue (J-K). The limiting J magnitude that we use is thus actually defined by the limiting K magnitude, combined with the (J-K) colors expected for the objects of interest. The results are given in Table 2.

These values, although also highly uncertain, tend to indicate that the probability of detecting NTTDF 1205-0744 was actually lower than expected for a volume density of even 0.01 per cubic parsec. This also probably explains why dedicated infrared surveys

Table 2. Probability of finding an object with T < 1000 K and J < 22 in 2.5 × 2.5 arcminutes, for different IMF power law indices, using the models of Burrows (1997) relating masses, temperature, age and absolute J magnitudes.

IMF power law index	Probability
-1.5	1.10^{-4}
0	$4.\ 10^{-5}$
1	$2.3\ 10^{-5}$

at much brighter limits (DENIS, 2MASS, see e.g. Reid (1999), Delfosse 1999) have so far failed to identify such objects.

One of the most remarkable features of these objects is the huge I-J color index which should make them difficult to find using visible data alone. Despite the spectacular success of the Sloan Digital Sky Survey which has led to the discovery of SDSS 1624+00, it is clear that the main prospective avenue for further discoveries of such methane brown dwarfs is to resort to relatively deep near IR observations, combined with deep visible imaging. The high I-J (or any visible - J) color index, combined with an almost flat J-K color index, is a very clear indicator for these methane brown dwarfs.

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