Astron. Astrophys. 338, 127–131 (1998)

ASTRONOMY AND ASTROPHYSICS

Discovery of three very distant M and L dwarfs

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Received 11 May 1998 / Accepted 20 July 1998

Abstract. We report the serendipitous discovery of three very cool distant late type dwarfs. These low-mass stars were found in the 9h- and 16h-fields of the Calar Alto Deep Imaging Survey (CADIS) and named CA09-LMS1, CA16-LMS1 and CA16-LMS2. CA16-LMS1 is the latest object and has a spectral type of >M10 (L1 in the new spectral class L). The other two stars have spectral types of about M9 (CA16-LMS2) and M6.5 (CA09-LMS1). We derive distances of 1150 ± 300 pc for CA09-LMS1, 330 ± 80 pc for CA16-LMS1, and 120 ± 30 pc for CA16-LMS2. The first two of these three objects are probably the most distant late-type M dwarfs for which optical spectra have been obtained.

Key words: stars: individual: CA09-LMS1 (J0913.5+4611); CA16-LMS1 (J1625.0+5544); CA16-LMS2 (J1623.9+5546) – stars: low-mass, brown dwarfs

1. Introduction

Low-mass stars are the most common objects in the solar neighborhood. Despite their large number, only relatively few objects of spectral type M7 and later were known until a few years ago (e.g. Kirkpatrick, Henry & Simons 1995). This situation is changing rapidy, and will probably change dramatically in the near future as more data from optical and NIR surveys become available (e.g. Kirkpatrick, Beichmann, & Skrutskie 1997). The first results from the DENIS and 2MASS surveys indeed indicate that these surveys will be very successful in finding many brown dwarfs or low-mass stars close to the substellar limit (e.g. Delfosse et al. 1997, Tinney et al. 1998, Kirkpatrick et al. 1998). This recent discovery of these relatively numerous cool dwarfs led to a consensus to introduce a new spectral class "L" for these objects (see also Martín et al. 1997, Kirkpatrick 1998).

In this paper we present photometry of three distant M and L dwarfs, as well as optical spectroscopy of two of them. These objects have been serendipitously discovered in the CADIS survey (Meisenheimer et al. 1998), a broad- and narrow-band CCD survey addressing a wide variety of questions ranging from the formation of galaxies to the density of quasars and the evolution of the large-scale structure of the universe. We present here results obtained on two fields covering a total of $215\Box'$, which are centered at $09^h 14\overset{\rm m}{.}8\ +46^\circ 14'$ (J2000, hereafter the 9h field) and $16^h 24\overset{\rm m}{.}5\ +55^\circ 43'$ (J2000, hereafter the 16h field). The full CADIS survey will cover $\approx 0.3\Box^\circ$, therefore we expect about 15 low-mass stars will be found.

Our paper is structured as follows: the observations are described in Sect. 2. Sect. 3 discusses the photometric and spectral properties of the discovered stars. Sect. 4 addresses the distance and possible substellar nature of these objects.

2. Observations

The CADIS survey uses a special set of various broad-band and narrow-band filters. CCD photometry in these filters was performed using the standard instrumentation at Calar Alto Observatory, Spain. CAFOS (Calar Alto Faint Object Spectrograph) was used at the 2.2 m telescope and MOSCA (Multi-Object Spectrograph for Calar Alto) at the 3.5 m telescope for optical imaging and spectroscopy, while Omega Prime (Bizenberger et al. 1998) was used at the 3.5 m telescope for the infrared imaging. The data presented here were obtained during several observing runs between May 1996 and October 1997.

All objects were first identified through their very red colors. CA16-LMS1 and LMS2, for example, were found by blinking the R-band image with the K'-band image, while searching for extremely red extragalactic objects (Thompson et al. 1998). CA09-LMS1 was found by selecting objects in the 9h field with $R - I > 2$.

Two main alternative interpretations can explain the red color of these objects: they could either be quasars at redshift $z > 5$, or they could be very cool, possibly substellar objects in the solar neighborhood. We therefore obtained follow-up spectroscopy on two of these objects in order to distinguish between these possibilities.

CA16-LMS1 was observed on 1997 August 22 with the LRIS (Oke et al. 1995) spectrograph on the Keck II telescope. Three frames of 1500 s each were obtained through a $1\overset{''}{.}0$ wide longslit with the 400 l/mm grating blazed at 850.0 nm, covering the wavelength range 650.0-1000.0 nm at 1.3 nm resolution. Observations of the spectrophotometric standard star LDS 749b (Oke 1990) were used to flux calibrate the spectrum. CA09-LMS2 was observed on 1998 January 30 with the same grating, through a multiobject mask with $1\overset{''}{.}8$ wide slits. Two frames were exposed for 1200 s each. When the standard star Hz 44

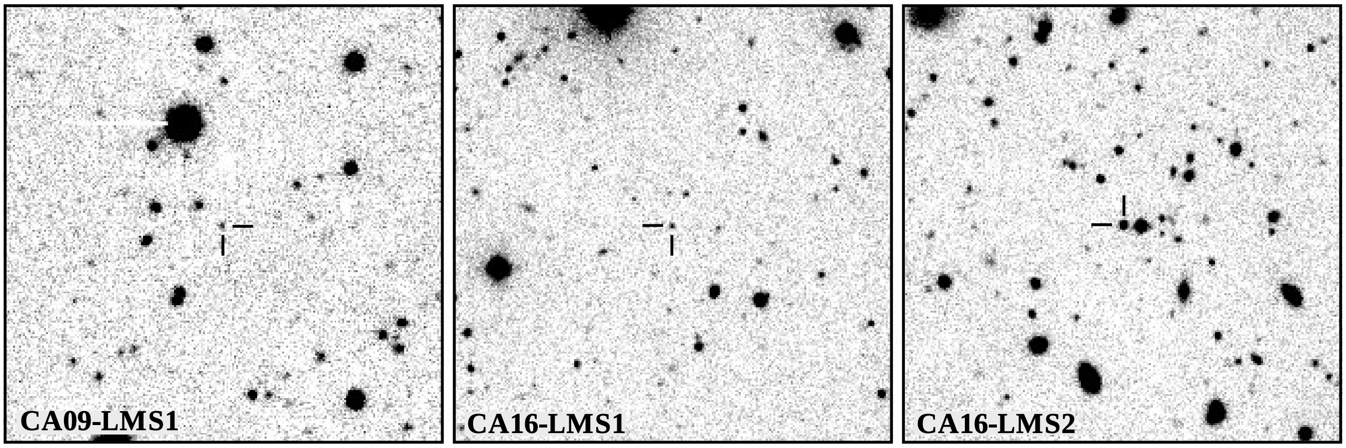

Fig. 1. I band (815 nm) finding charts for CA09-LMS1 (left), CA16-LMS1 (center), and CA16-LMS2 (right). Each image is $2' \times 2'$, with north up and east to the left.

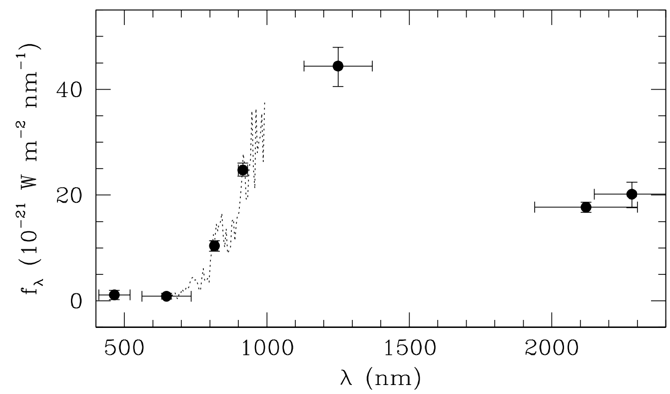

Fig. 2. Broadband photometry of CA16-LMS1 in (from left to right) the B, R, I_{815}, I_{910}, J, K' and K_{CH_4} filters. The Keck spectrum, binned to low resolution, is also plotted, showing excellent agreement between the spectrum and photometric data points.

Table 1. Object positions.

Object	α_{2000}	δ_{2000}	Epoch
CA09-LMS1	$09^h13^m31\overset{s}{.}33$	$46°11'31\overset{''}{.}5$	Feb 97
CA16-LMS1	$16^h25^m00\overset{s}{.}63$	$55°44'44\overset{''}{.}3$	Jun 96
CA16-LMS2	$16^h23^m57\overset{s}{.}24$	$55°46'27\overset{''}{.}5$	Jun 96

was observed, the sky had already brightened in dawn, so these data are not flux calibrated. Furthermore, difficulties with the sky subtraction due to the wider slit limit the usable wavelength range of this spectrum.

3. Results

3.1. Positions and photometry

In Table 1 we list the coordinates of the three low-mass stars together with the epoch of the observations. The positions have an accuracy of $\pm0\overset{''}{.}1$ in each coordinate, measured relative to secondary standards derived from the POSS-II plates and PPM (Röser & Bastian 1991) stars. I-band finding charts are given in Fig. 1.

Magnitudes for the three low-mass stars in various filters are listed in Table 2. Several non-standard filters are used in the CADIS survey, and their central wavelength and full-width at half-maximum (FWHM) are also listed in Table 2. The data reduction and photometry follows the procedures detailed in Röser & Meisenheimer (1991).

For all three stars, the magnitude in a standard broadband K filter was calculated using the transformation $K = K' - 0\overset{m}{.}07$, a correction appropriate for very red stars (Wainscoat & Cowie 1992). The standard Kron-Cousins I_C magnitude for CA16-LMS1 was derived from the Keck spectrum using the I_C filter curve defined in Bessell (1979). This method also reproduced the observed magnitudes in the other filter bandpasses to better than 0.1 mag over the observed range of the spectrum. The I_C magnitudes for CA16-LMS2 and CA09-LMS1 were then estimated by applying an $I_C - I_{815}$ correction value proportional to the $I_{815} - K'$ color and the correction derived for CA16-LMS1.

The most detailed photometric information is available for CA16-LMS1. For this object, we have data in four broadband filters (CADIS-B, CADIS-R, J, and K') and three medium-band filters (CADIS-I_{815} and I_{910}, centered around 815 nm and 910 nm (see Table 2), and K_{CH_4}). In I_{815} and I_{910}, CA16-LMS1 is clearly detected, displaying a very steep rise in the spectrum between about 700 and 800 nm. Additional IR colors for this object were obtained at Calar Alto by imaging in the J-band and in a K-band methane filter. This K_{CH_4}-filter is centered at a wavelength of 2.28 μ, with a FWHM of 0.26 μ and was calibrated relative to the K' image using 19 objects near CA16-LMS1 in common to both images. The filter was designed to cover the strong CH_4 absorption feature typical for the spectra of very cool (T $\lesssim$ 1000 K) old brown dwarfs (Oppenheimer et al. 1995) and giant planets (Rosenthal, Gurwell & Ho 1996). As

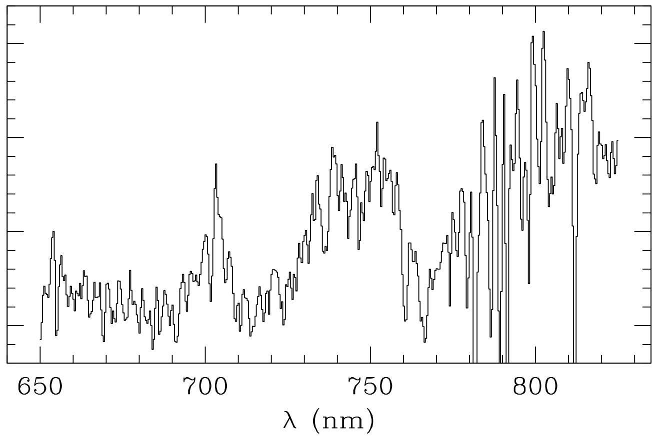

Fig. 3. This spectrum of CA09-LMS1 is not flux calibrated and displays the features of typical late type M stars.

Table 2. Multiband photometric magnitudes for the three low-mass stars. The central wavelength and FWHM of the CADIS filters are given in nm. Limiting magnitudes at 3σ are listed when the star is undetected in that filter. See text for derivation of I_c and K magnitudes.

Filter	CA09-LMS1	CA16-LMS1	CA16-LMS2
B (466/95)	> 26.0	> 26.0	> 26.0
R (648/173)	> 24.8	> 25.6	23.06 ± 0.09
I_{752} (752/28)	22.90 ± 0.12		
I_{815} (815/25)	22.62 ± 0.11	22.47 ± 0.08	20.09 ± 0.02
I_{910} (910/32)	21.68 ± 0.11	21.42 ± 0.05	
J		19.64 ± 0.09	
K'	19.86 ± 0.25	18.57 ± 0.10	16.32 ± 0.05
K_{CH_4}		18.18 ± 0.13	
I_C	23.04 ± 0.20	23.06 ± 0.20	20.66 ± 0.20
K	19.79 ± 0.25	18.50 ± 0.12	16.25 ± 0.07
$I_C - K$	3.25 ± 0.30	4.56 ± 0.23	4.41 ± 0.22

expected from the derived spectral type of CA16-LMS1 (see below) it does not show at the CH_4-absorption feature a flux significantly different from the K' flux.

3.2. Spectral classification

We show our optical spectrum of CA16-LMS1 in Fig. 4, with the spectra of other late M and L dwarfs for comparison. One of the L dwarfs (DENIS-PJ1228.2-1547) is a confirmed brown dwarf. In this figure, adopted from Tinney, Delfosse & Forveille (1997), the various objects are ordered by temperature, with the highest temperature objects at the bottom. On the basis of the L type spectra available from the Kirkpatrick et al. 1998 paper we classified CA16-LMS1 as an L1 dwarf. The classification of the two other L dwarf spectra in Fig. 3 (of DENIS-P J1058.7-1548 and DENIS-PJ1228.2-1547) has been adopted from Kirkpatrick et al. (1998).

It is obvious from Fig. 3 that CA16-LMS1 is later than BRI 0021-0214 (≥M9.5) but earlier than DENIS-P J1058.7-1548 (L2.5). For example in CA16-LMS1, the pseudocontinuum PC feature at ≈858 nm is weaker than in DENIS-P J1058.7-1548, but stronger than in BRI 0021-0214. The same is true for the absorption feature at ≈850 nm. For an identification of the various absorption and pseudocontinuum (PC) features we refer to Tinney et al. (1998). The PC feature at ≈858 nm, for example, is due to a CrH bandhead at 861 nm and the above mentioned absorption feature at ≈850 nm probably results from a CsI λ852.1 nm resonance line blended with a VO and TiO band.

Table 3. Derived values for spectral type, color, luminosity and distance of the three late-type stars.

Object	Type	$I_c - K$	M$_K$	D [pc]
CA09-LMS1	M6.5	3.25 ± 0.30	9.5 ± 0.5	1150 ± 300
CA16-LMS1	L1	4.56 ± 0.23	10.9 ± 0.5	330 ± 80
CA16-LMS2	M9	4.41 ± 0.22	10.8 ± 0.5	120 ± 30

There seems to be an inconsistency between the derived spectral type of CA16-LMS1 of L1 (“M11”) and the spectral type versus $I_c - J$ relation of Leggett (1992). CA16-LMS1 has an $I_c - J$ color of 3.4±0.25. This is the color expected for a star of spectral type ≈M9. A star of spectral type L1 should have a $I_c - J$ color of about 3.9±0.1, if we assume that the Leggett relation can be extrapolated beyond spectral type M9, which is latest spectral type in this relation. Since we are fairly sure that CA16-LMS1 is not earlier than L0.5 this apparent inconsistency can have the following two reasons, or a combination of both: 1. our $I_c - J$ is too small by about 0.5 mag, 2. the extrapolation of the Leggett relation to such late spectral types is too unreliable. The latter would be not surprising since this relation is only defined by four data points for $I_c - J > 2.7$ (>M7).

It was not possible for us to compare the $I_c - K$ colors of CA16-LMS1 with those of other early L stars, since no such data are yet published. We could only compare with the $I_c - K$ colors of three M9 and one M9.5 stars given in Kirkpatrick et al. (1995) These four stars have an average $I_c - K$ color of 4.44 ± 0.1 mag, which is 0.1 mag bluer than CA16-LMS1. The ≥ M9.5 star BRI 0021-0214 is also about 0.1 mag bluer than CA16-LMS1. Since the $I_c - K$ color of CA16-LMS1 has an error of about 0.2 mag, a spectral type of L1 is apparently consistent with the measured $I_c - K$ color.

In Fig. 3, we display our spectrum of CA09-LMS1. This spectrum is not flux calibrated, and difficulties in subtracting the night sky lines redward of 825 nm limit the useful range to 650–825 nm. The spectrum shows the typical absorption and PC features of late-type stars. We used the $I_c - K$ and $I_c - J$ correlations to derive a spectral type of M6.5 for this star.

CA16-LMS2 has an $I_c - K$ color of 4.41 ± 0.22, identical to the average color of 4.44 ± 0.1 for the four M9/M9.5 stars of Kirkpatrick et al. (1995). We therefore adopt a spectral type of M9 for CA16-LMS2. The same result is obtained when using the $I_c - J$ correlation of Leggett.

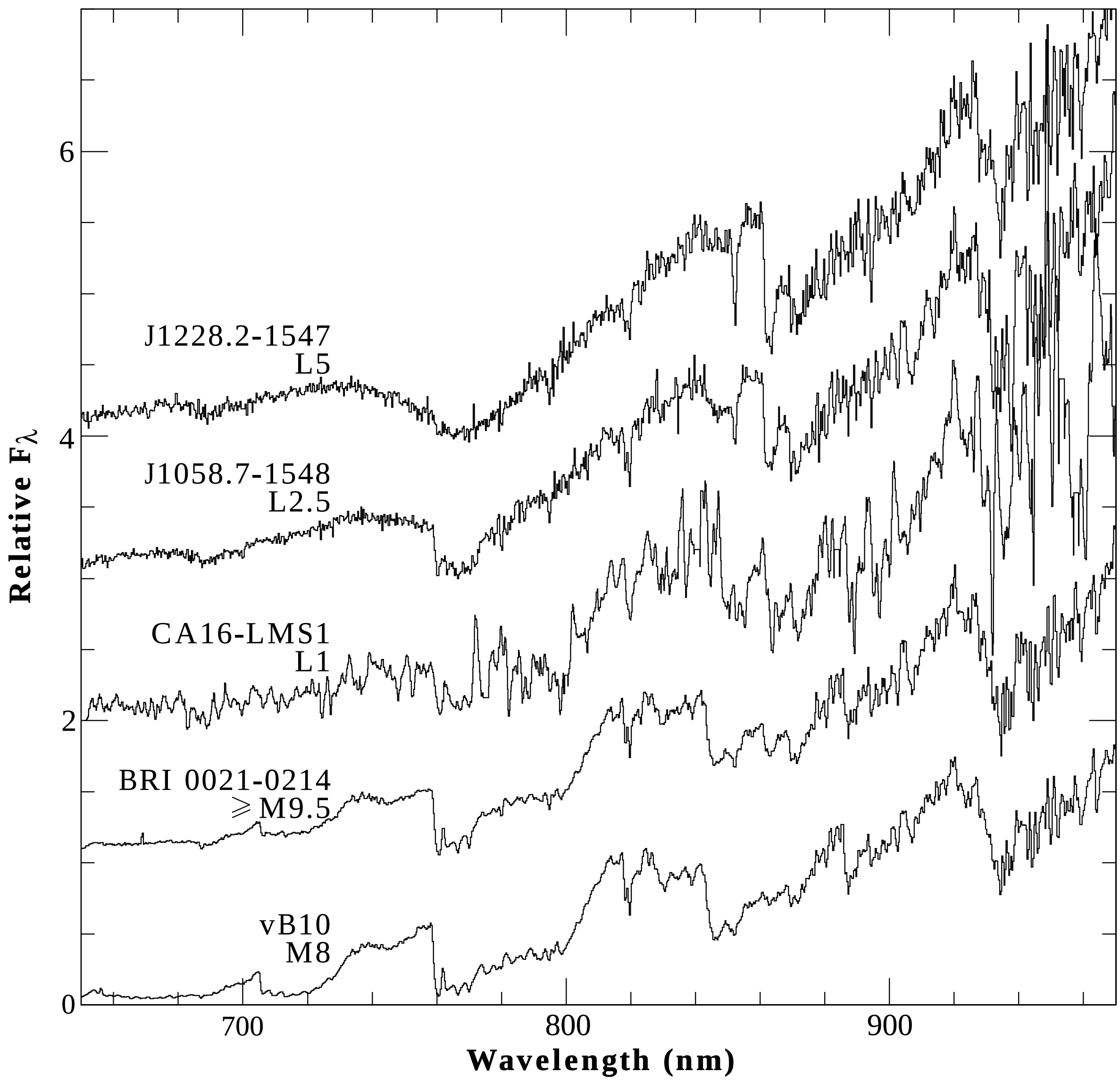

Fig. 4. The spectrum of CA16-LMS1, along with several M and L dwarfs for comparison (see text for details). Each spectrum has been normalised to unity at 880 nm and offset in unit steps for clarity, as in Tinney, Delfosse & Forveille (1997). Our spectrum is considerably noisier than the comparison stars and shows some nightsky artifacts, e. g. the line at 772 nm.

4. Discussion

To estimate the distance of the objects studied here, we have to determine the absolute magnitudes from the observed colors. For this purpose we use the M_K versus $I_c - K$ relation of Tinney (1995). The derived M_K and distance values are listed in Table 3. For $I_c - K$ colors of ≈ 4.5, the M_K versus $I_c - K$ relation is very poorly defined by a few objects, and the M_K values and distances have relatively large errors. With distances of about 330 pc for CA16-LMS1 and 1150 pc for CA09-LMS1, these two stars are probably the most distant late-type M and early L dwarfs for which optical spectra have been obtained. We note that M dwarfs of comparable distance have been identified on deep HST images (e.g. Gould, Bahcall, & Flynn 1997).

Could CA16-LMS1 be a brown dwarf or is it a low-mass star which is close to, but above, the hydrogen burning limit of about 0.07 $M_\odot$? The star is too faint to observe the Li line (see e.g. Rebolo, Martín & Magazzú 1992, Basri, Marcy & Graham 1996), even with a 10 m-telescope. Even if this star were bright enough to carry out the Li test, this test would provide an unambiguous proof for the nature of the object only for a certain mass and age regime. For example, brown dwarfs with masses ≥ 0.060 $M_\odot$ and ages $\geq 10^9$ have depleted most of their Li (e.g. Martín et al. 1997).

Since brown dwarfs decrease rapidly in luminosity with age the brown dwarf nature of an object with a spectral type around L1 can be only proven if its age is known. Baraffe & Chabrier (1996) constructed models for the relationship of spectral type to mass. Stars younger than 1 Gyr with a spectral type later than L0 (M10) and of solar metallicity are brown dwarfs. If we assume that these models are correct at their low-temperature end (despite the fact that they are calibrated there with only a few stars) CA16-LMS1 would be a brown dwarf if it were younger than 1 Gyr. Constraints on the age of CA16-LMS1 could in principal be provided by its kinematical properties which would require proper motion and radial velocity measurements. The latter would require spectra of at least five times higher spectral resolution with the Keck telescope, but such a study is probably not worthwhile for this distant object. Although the nature of CA16-LMS1 is unlikely to ever be determined, it is obvious that a flux-limited sample, like the one presented here, has a much higher likelihood in finding the more luminous and younger brown dwarfs.

Acknowledgements. The authors thank C.G. Tinney for providing the comparison spectra in Fig. 4, and France Allard for helpful comments. We also thank the Calar Alto staff for their help and support during the several observing runs at that observatory. Of very great help for the spectral classification of CA16-LMS1 were copies of some of the figures and tables of the Kirkpatrick et al. (1998) paper, which were made available to us by Jim Liebert. We would finally like to thank an anonymous referee for her/his detailed comments. The Second Palomar Observatory Sky Survey (POSS-II) was made by the California Institute of Technology with funds from the National Science Foundation Geographic Society, the Sloan Foundation, the Samuel Oschin Foundation, and the Eastman Kodak Corporation.

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