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Letter to the Editor

One more neighbor: The first brown dwarf in the VVV survey*

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ABSTRACT

Context. The discovery of brown dwarfs (BDs) in the solar neighborhood and young star clusters has helped to constraint the low-mass end of the stellar mass function and the initial mass function. We use data of the Vista Variables in the Vía Láctea (VVV), a near-infrared (NIR) multi-wavelength ($ZYJH\,K_s$) multi-epoch (K_s) ESO Public Survey mapping the Milky Way bulge and southern Galactic plane to search for nearby BDs.

Aims. The ultimate aim of the project is to improve the completeness of the census of nearby stellar and substellar objects towards the Galactic bulge and inner disk regions.

Methods. Taking advantage of the homogeneous sample of VVV multi-epoch data, we identified stars with high proper motion ($\geq 0.1''$ yr^{-1}), and then selected low-mass objects using NIR colors. We searched for a possible parallax signature using the all available K_s band epochs. We set some constraints on the month-to-year scale K_s band variability of our candidates, and even searched for possible transiting companions. We obtained NIR spectra to properly classify spectral type and then the physical properties of the final list of candidates.

Results. We report the discovery of VVV BD001, a new member of the local volume-limited sample (within 20 pc from the Sun) with well defined proper motion, distance, and luminosity. The spectral type of this new object is an L5 ± 1, unusually blue dwarf. The proper motion for this BD is PM(α) = $-0.5455 \pm 0.004''$ yr^{-1}, PM(δ) = $-0.3255 \pm 0.004''$ yr^{-1}, and it has a parallax of 57 ± 4 mas which translates into a distance of 17.5 ± 1.1 pc. VVV BD001 shows no evidence of variability ($\Delta K_s < 0.05$ mag) over two years, especially constrained on a six month scale during the year 2012.

Key words. brown dwarfs – methods: observational – techniques: imaging spectroscopy – surveys – proper motions – astrometry

1. Introduction

Brown dwarfs (BD) are substellar objects with very low surface temperatures ($300 \lesssim T \lesssim 2200$ K) that are unable to sustain hydrogen fusion in their interiors. The presence of molecules in their atmospheres, such H_2O, CO, and CH_4, is important at these low temperatures because the strong molecular absorption determines their near infrared (NIR) colors (Reid & Hawley 2005). Different teams working in large surveys have found hundreds of brown dwarfs all over the sky using appropriate color constraints (e.g., DENIS, 2MASS, UKIDSS, and the recent WISE; Epchtein et al. 1999; Skrutskie et al. 2006; Lawrence et al. 2007; Wright et al. 2010). Some of these surveys (i.e., WISE) were optimized to detect objects with typical colors of BDs. The only regions in the sky where the color selection might not be optimal are very crowded regions, such as the Galactic bulge and the inner Galactic disk where the source confusion, and the high level of extinction, make the color selection far less useful than in less dense environments.

One successful strategy for discovering cool nearby objects is to search high proper motion (HPM) objects using optical and NIR, or only NIR observations. Various authors have found several ultra-cool dwarfs in high stellar density and low galactic latitude regions cross-matching sources from DENIS, 2MASS and UKIDSS (e.g., Folkes et al. 2007; Phan-Bao et al. 2008; Deacon et al. 2009; Artigau et al. 2010). The strength of this approach is illustrated by Luhman (2013), who found the closest BD to the Sun only 2 pc away, using astrometric information from WISE catalogs to select HPM objects. This is a binary system composed of an L8 and a T1 BD (Burgasser et al. 2013; Kniazev et al. 2013).

The ESO public survey Vista Variables in the Vía Láctea (VVV; Minniti et al. 2010; Saito et al. 2012) has the potential of being a large and homogeneous multi-epoch NIR database with high sensitivity and high spatial resolution for detecting low-mass stellar and substellar objects via selection of HPM sources. The survey is a multiwavelength ($ZYJH\,K_s$) photometric survey observing towards the Milky Way bulge and southern Galactic plane. Upon completion, the VVV Survey will have a variability campaign covering a time baseline of around seven

* Based on observations taken within the ESO VISTA Public Survey VVV, Programme ID 179.B-2002.

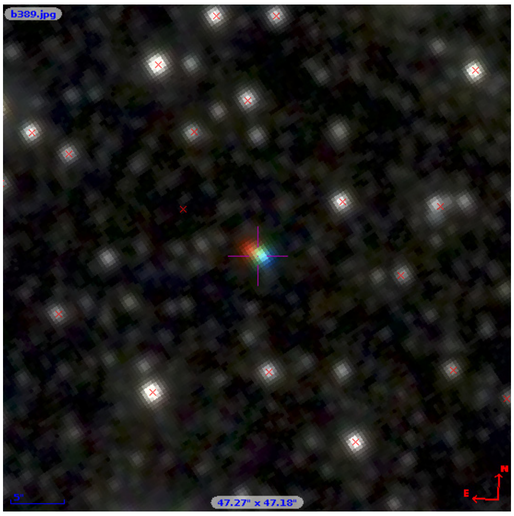

Fig. 1. Finding chart for VVV BD001. Composition of three K_s band epochs (Red 2010, Green 2011, Blue 2012). In red crosses are objects in the 2MASS Point source catalog.

years, with about 100 visits per pointing in the K_s band. The VVV limiting magnitude in the K_s band is ~4 mag deeper than previous large scale NIR surveys such as 2MASS and DENIS and the spatial resolution is also better. The variability campaign will allow us to 1) detect possible eclipses/transits in our HPMs sources and 2) put some upper limits on the variability of BDs in the K_s band. Variability of BD is an interesting because it allows constraining cloud formation, climate evolution, and magnetic activity that has been proven to exist in these very low-mass objects (e.g., Apai et al. 2013; Heinze et al. 2013). As an example, the cooler component of Luhman's BD binary is highly variable, and it shows changes in the cloud structure on a time scale of days (Gillon et al. 2013). The VVV survey will probe BDs variability on multiple time scales from days up to years.

In Sect. 2 we give the observations and discovery method of VVV BD001, and in Sect. 3 we analyze the characteristics of the new BD. Finally the conclusions and future perspectives are detailed in Sect. 4.

2. Observations and method

The VVV survey observations were carried out with the 4.1m VISTA telescope at ESO Paranal Observatory, using the VIRCAM instrument[1]. This instrument is made up of 16 detectors of 2048 × 2048 pixels, with a resolution of 0.34″/pix. Each pointing, covering 0.6 deg^2, is called a "pawprint", and six overlapping pawprints are used to build one final image (Tile) covering twice an area of 1.5 deg^2. The total area coverage of VVV survey is ~560 deg^2 The individual pawprints and tiles are processed by the Cambridge Astronomical Unit (CASU). They provide aperture photometry and astrometry for the images[2]. The VVV data are publicly available through the VISTA Science Archive[3] (VSA, Cross et al. 2012). More technical information about the VVV survey can be found in Saito et al. (2012) and Soto et al. (2013).

To search for HPM objects we first made a visual inspection of VVV false color images, where "red", "green", and "blue" colors correspond to three K_s-band observations taken in 2010, 2011, and 2012, respectively. The HPM objects leave a characteristic color trace as we can see in Fig. 1.

The method for finding HPM objects is as follows:

- Pick three K_s band epochs (2010, 2011, 2012);
- cross match the first and second epochs and then the second and third epochs, with a matching radius of 4″, and $\Delta K_s \leq$ 0.3 mag.;
- keep only objects with $K_s \leq 14.0$ mag.;
- use only objects with flags "stellar", "saturated" or "borderline stellar" (Saito et al. 2012);
- keep only objects with consistent PM ≥ 0.1″yr^{-1} and a position angle consistent within 10°.

The WCS solution of VVV images is based on 2MASS positions, therefore the positions and the proper motions are relative instead of absolute. However, the bulk motion of the references stars used to derive the WCS solution is far below our threshold for selecting HPM stars. For a typical individual chip, the RMS of the WCS solution is ~0.″08, and this is the main source of error for point sources brighter than $K_s \sim 14$ mag.

The candidates are confirmed via visual inspection of the false color images and by blinking the VVV images, also checking the 2MASS and SuperCosmos images to see that there is an object in the predicted position at that particular epoch. Using this method we detected about 200 HPM objects at the time of writing. VVV BD001 is the first one among them characterized using spectroscopic follow-up observations. More details on the search method, limitations, and a catalog of HPM objects will appear in a forthcoming paper.

This object was observed with a Folded-port InfraRed Echellette (FIRE, Simcoe et al. 2013) at the Magellan Baade telescope, on the night of Mar 29/30, 2013. We used the low-resolution prism mode, with a 0.6″ wide slit, to obtain four 63.4 s spectra, in ABBA nodding pattern. The usual data reduction steps for NIR spectroscopy were followed: flat fielding, and A-B pair subtraction to remove first-order sky emission. Then, we traced the continua to extract one-dimensional spectra for each of the four spectra, with the IRAF[4] task *apall*. We removed any remaining sky emission with the *apall* background removal facility task. Next, we applied the tracing of the objects to subtract one-dimensional NeAr lamp spectra and wavelength-calibrated the science spectra before combining them in wavelength space. Finally, we corrected the science spectra for telluric absorption with observations of the A star HD 329472, reduced following an identical procedure.

3. Discovery and characterization of VVV BD001

VVV BD001 (VVV J172640.2-273803) is located towards the Galactic bulge, l, b = 358.85216, 4.21662. This position makes VVV BD001 the closest BD towards the Galactic center position and the first to be detected in this very crowded part of the sky. This object stands out for its particular HPM and colors compatible with an L or early T dwarf type (see Table 1). We retrieved entries from the 2MASS PSC catalog (Skrutskie et al. 2006) and the images with the position expected for the object about ten years ago. The position and magnitudes agree with the VVV measurements. We also searched for optical counterparts in the SuperCosmos images, but nothing was detected or visible in any band. VVV BD001 appeared in the

[1] http://www.eso.org/sci/facilities/paranal/instruments/vircam/
[2] http://casu.ast.cam.ac.uk/surveys-projects/vista
[3] http://horus.roe.ac.uk/vsa/

[4] IRAF is distributed by the NOAO, which is operated by the AURA under cooperative agreement with the NSF.

Table 1. Properties of VVV BD001.

Parameter	Value
Z	15.507 ± 0.015 mag
Y	14.379 ± 0.012 mag
J	13.267 ± 0.017 mag
H	12.668 ± 0.016 mag
K_s	12.194 ± 0.015 mag
IRAC 3.6 μm	11.526 ± 0.049 mag
IRAC 4.5 μm	11.404 ± 0.054 mag
IRAC 5.8 μm	11.178 ± 0.065 mag
IRAC 8.0 μm	11.098 ± 0.047 mag
Spectral Type	~L5 ±1
ΔK_s	<0.05 mag
$\Delta\alpha\cos(\delta)$	$-0.5455 \pm 0.004''$ yr^{-1}
$\Delta\delta$	$-0.3255 \pm 0.004''$ yr^{-1}
π	57 ± 4 mas

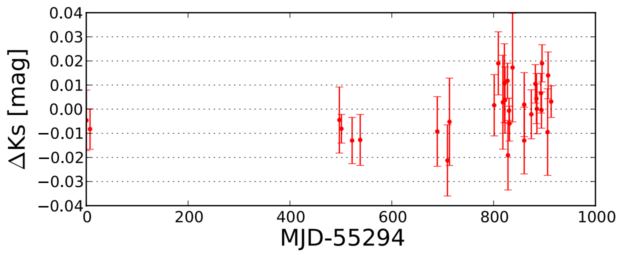

Fig. 2. Differential light curve of VVV BD001 with respect to 4 nearby stars with a similar mean magnitude ($|K_s^{BD} - K_s^i| \leq 0.3$ mag). The light curve was shifted 0.015 mag, so $\langle \Delta K_s \rangle = 0$ mag. No evidence of periodic variability is detected for VVV BD001, using neither phase dispersion minimization (PDM) nor Lomb-Scargle periodogram.

DENIS I, J, K_s images, but I mag is not listed in the DENIS catalog (Epchtein et al. 1999). The object is visible in WISE images, but since it is near a brighter star, its photometry is not in the catalog. The *Spitzer*/IRAC photometry from the GLIMPSEII Legacy Survey (Churchwell et al. 2009) is available for this source and is detailed in Table 1. Using the expected colors for M, L, and T dwarfs from Patten et al. (2006), the GLIMPSEII and VVV photometry suggest that the object is an early L dwarf (L0-L6). As mentioned in Sect. 1, our method does not rely primarily on color selection, but the colors (particularly those using the shorter wavelength Z and Y filters) prove useful for estimating spectral types for HPM objects.

We obtained PSF photometry for every multiepoch VVV image available to date using a new version of DoPhot (Schechter et al. 1993; Alonso-García et al. 2012). The light curve with 31 observations of VVV BD001 is shown in Fig. 2, where each point of the BD light curve is the average of two observations taken about one minute apart. The same process was followed for the comparison stars. We selected the four closest stars, with an average magnitude difference from the BD candidate that was no greater than 0.3 mag in K_s , and then we looked for a possible periodic signal. No signal of variability was seen for these four stars up to our photometric accuracy of ~0.01 mag. We then averaged the magnitude of these four stars and used them to calculate the photometric erroproperlyr for each averaged epoch. The results can be seen in Fig. 2

We analyzed the VVV BD001 light curve using the phase dispersion minimization routine (PDM; Stellingwerf 1978) and a Lomb-Scargle periodogram and found no evidence of periodic variability. Also from the light curve, we see no variability greater than 0.05 mag in the K_s band during the two years of observations with the VVV survey. We cannot rule out any atmosphere model using the K_s band alone, but the VVV survey is a valuable tool for constraining long term NIR variability of BD and looking for possible eclipses or transits.

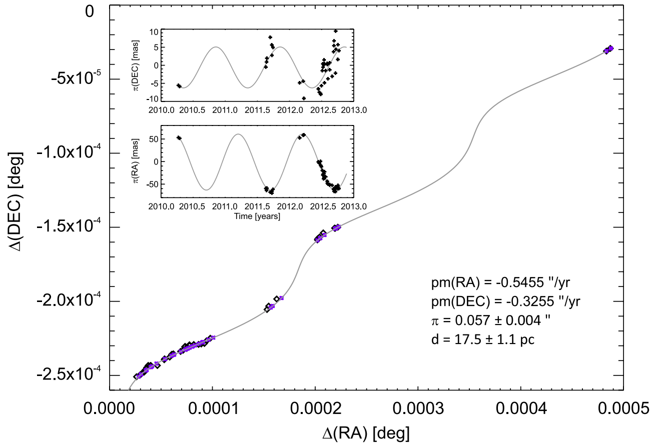

Fig. 3. Proper motion and parallax movement on the sky for VVV BD001. Black diamonds and purple crosses give the observed and calculated best fit coordinates. The parallax motion in RA and DEC after removing the Proper motion are shown in the inner panel, along with the best fit parallax measurement.

The HPM of the object suggests that it is nearby. To obtain the parallax of the target, we used its equatorial coordinates from CASU $ZYJH$ and all K_s epochs available to date. In total, there were 90 positions covering the period of March 2010 to October 2012. Five bright, 13−14 mag, and isolated stars without proper motion around the target were used to obtain the corrections to a common field center for each epoch. Using the averaged value of the shifts, we corrected the individual epoch coordinates of VVV BD001. For each epoch, the mean of the positions measured in individual frames was taken and its uncertainty determined from the dispersion of values in each spatial direction. In this way the positional errors were reduced to internal errors only (~7 mas). The target is presented on two different detectors because of the VISTA tiling procedures, and for each date there are at least two, and in some cases, four positions. Also ZY and JH, together with the first epoch K_s images, respectively, were obtained on the same dates. Averaging date-by-date, finally, we have a sequence of 41 positions, used for obtaining the proper motion and the parallax. A modified version of the *Spitzer* make_parallax_coords.pro: an IDL procedure designed to calculate source coordinates as seen by an observatory was used, correcting for annual parallax and proper motion[5]. The best parallax and proper motion fit given in Fig. 3 leads to PM(α) = $-0.5455 \pm 0.004''$ yr^{-1}, PM(δ) = $-0.3255 \pm 0.004''$ yr^{-1}, and a parallax, $\pi = 57 \pm 4$ mas which translate into a distance of $d = 17.5 \pm 1.1$ pc. The tangential velocity for VVV BD001 is 51.4 ± 3.3 km s^{-1}, which agrees with the velocity for the blue population of L dwarfs (Faherty et al. 2009).

Figure 4 shows the NIR spectrum of VVV BD001 from 0.9−2.3 μm normalized at 1.3 μm, in comparison with template spectra of brown dwarfs from L3 to L7 obtained from the IRTF spectral library[6] (Cushing et al. 2005). A Gaussian kernel

[5] http://irsa.ipac.caltech.edu Author: Carey (SSC), version 12 Feb. 2013.

[6] http://irtfweb.ifa.hawaii.edu/~spex/IRTF_Spectral_Library/

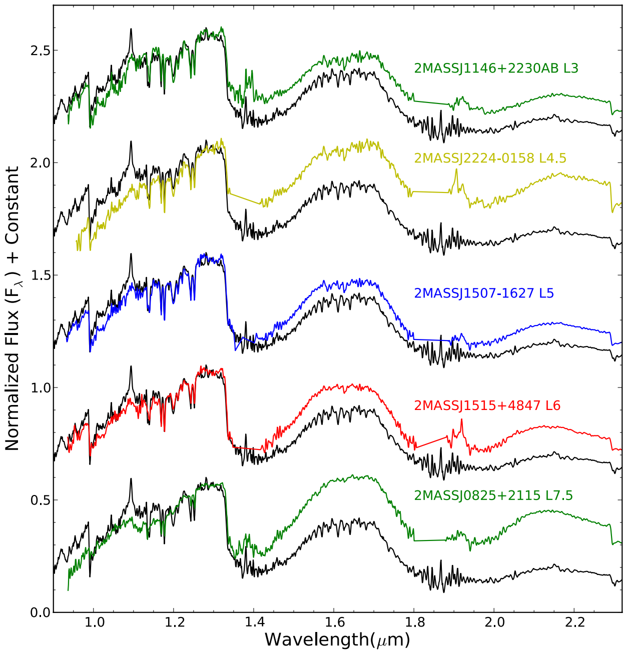

Fig. 4. Spectrum of VVV BD001 (black solid line) compared with BD different spectral types templates. The templates are, from top to bottom: L3 2MASS J11463449+2230527, L4.5 2MASS J22244381-0158521, L5 2MASS J15074769-1627386, L6 2MASS J15150083+4847416, L7 2MASS J08251968+2115521. The flux is normalized at 1.3 μm and each spectra has been shifted in flux for clarity.

was used to convolve the template spectrum in order to compare it with our object. To classify the object, we just focused on the J band region (1.0–1.4 μm). We see in Fig. 4 that the best match is a L5 ± 1. An excess of flux at bluer wavelengths is clearly visible in the spectrum and was suspected from the photometric data. Combining spectro-photometric and proper motion information, we classified VVV BD001 as an unusually blue dwarf. The nature of blue L dwarfs has been discussed in Burgasser et al. (2008a) and Kirkpatrick et al. (2010) and references therein.

We calculated the absolute magnitude in the 2MASS J and K_s filters, applied to the data from the 2MASS Point Source Catalogue, and propagated the errors in distance and photometry. We obtained $M_J = 12.23 \pm 0.15$ mag, $M_{K_s} = 11.06 \pm 0.15$ mag. After comparing M_J and M_{K_s} with the expected magnitudes for a typical L5 (see Fig. 2 of Burgasser et al. 2008b), our candidate is about one magnitude brighter. Luhman et al. (2012) discusses the overluminosity of an unusually blue L5 dwarf (based on spectrophotometric distance) and favor the scenario of thin cloud condensates that could account for the blue nature and overluminosity. More follow-up observations are required to unveil the true nature of VVV BD001, and given its proximity, it is a key object to observe for constraining the physics behind the blue L dwarf population.

4. Conclusions

We have presented the detection of VVV BD001, the first brown dwarf detected by the VVV survey. This is the first BD located towards the Galactic center, in the most crowded region of the sky. We presented new NIR photometry ranging from 0.8–2.5 μm combined with 3.6–8 μm available Spitzer/IRAC data. The colors, distance, and spectrum are compatible with an unusually blue L5 ± 1 dwarf. Based on three years worth of data, we measured a total PM for VVV BD001 of $0.634'' \text{yr}^{-1}$ and a parallax of, $\pi = 57 \pm 4$ mas, yielding a distance of 7.5 ± 1.1 pc from the Sun. This makes VVV BD001 a new brown dwarf, belonging to the local volume-limited sample (within 20 pc from the Sun) with well defined proper motion, distance, and luminosity. From our light curve we cannot exclude any atmospheric model but we provide the long-term behavior of the BD. Photometric multiwavelength follow-up observations on shorter timescales are required to definitely determine atmospheric properties. We expect to discover about two dozen BDs on the VVV survey area based in the number density of brown dwarfs detected to date[7]. This number might be higher due to our higher sensitivity and resolution than previous NIR surveys.

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References

Alonso-García, J., Mateo, M., Sen, B., et al. 2012, AJ, 143, 70
Apai, D., Radigan, J., Buenzli, E., et al. 2013, ApJ, 768, 121
Artigau, É., Radigan, J., Folkes, S., et al. 2010, ApJ, 718, L38
Burgasser, A. J., Looper, D. L., Kirkpatrick, J. D., Cruz, K. L., & Swift, B. J. 2008a, ApJ, 674, 451
Burgasser, A. J., Vrba, F. J., Lépine, S., et al. 2008b, ApJ, 672, 1159
Burgasser, A. J., Sheppard, S. S., & Luhman, K. L. 2013, ApJ, 772, 129
Churchwell, E., Babler, B. L., Meade, M. R., et al. 2009, PASP, 121, 213
Cross, N. J. G., Collins, R. S., Mann, R. G., et al. 2012, A&A, 548, A119
Cushing, M. C., Rayner, J. T., & Vacca, W. D. 2005, ApJ, 623, 1115
Deacon, N. R., Hambly, N. C., King, R. R., & McCaughrean, M. J. 2009, MNRAS, 394, 857
Epchtein, N., Deul, E., Derriere, S., et al. 1999, A&A, 349, 236
Faherty, J. K., Burgasser, A. J., Cruz, K. L., et al. 2009, AJ, 137, 1
Folkes, S. L., Pinfield, D. J., Kendall, T. R., & Jones, H. R. A. 2007, MNRAS, 378, 901
Gillon, M., Triaud, A. H. M. J., Jehin, E., et al. 2013, A&A, 555, L5
Heinze, A. N., Metchev, S., Apai, D., et al. 2013, ApJ, 767, 173
Kirkpatrick, J. D., Looper, D. L., Burgasser, A. J., et al. 2010, ApJS, 190, 100
Kniazev, A. Y., Vaisanen, P., Mužić, K., et al. 2013, ApJ, 770, 124
Lawrence, A., Warren, S. J., Almaini, O., et al. 2007, MNRAS, 379, 1599
Luhman, K. L. 2013, ApJ, 767, L1
Luhman, K. L., Loutrel, N. P., McCurdy, N. S., et al. 2012, ApJ, 760, 152
Minniti, D., Lucas, P. W., Emerson, J. P., et al. 2010, New. Astron., 15, 433
Patten, B. M., Stauffer, J. R., Burrows, A., et al. 2006, ApJ, 651, 502
Phan-Bao, N., Bessell, M. S., Martín, E. L., et al. 2008, MNRAS, 383, 831
Reid, I. N., & Hawley, S. L. 2005, New light on dark stars: red dwarfs, low-mass stars, brown dwarfs (Springer-Praxis)
Saito, R. K., Hempel, M., Minniti, D., et al. 2012, A&A, 537, A107
Schechter, P. L., Mateo, M., & Saha, A. 1993, PASP, 105, 1342
Simcoe, R. A., Burgasser, A. J., Schechter, P. L., et al. 2013, PASP, 125, 270
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Soto, M., Barbá, R., Gunthardt, G., et al. 2013, A&A, 552, A101
Stellingwerf, R. F. 1978, ApJ, 224, 953
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868

[7] The total number of BDs was taken from the dwarf archive at `http://www.dwarfarchives.org`