LETTER TO THE EDITOR

Trigonometric parallaxes of ten ultracool subdwarfs*,**

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ABSTRACT

Aims. We measure absolute trigonometric parallaxes and proper motions with respect to many background galaxies for a sample of ten ultracool subdwarfs.

Methods. Observations were taken in the H-band with the OMEGA2000 camera on the 3.5 m-telescope at Calar Alto, Spain during a time period of 3.5 years. For the first time, the reduction of the astrometric measurements was carried out directly with respect to background galaxies. We obtained absolute parallaxes with mean errors ranging between 1 and 3 mas.

Results. With six completely new parallaxes we more than doubled the number of benchmark ultracool (>sdM7) subdwarfs. Six stars in the $M_K$ vs. $J-K$ diagram fit perfectly to model subdwarf sequences from M7 to L4 with $[M/H]$ between $-1.0$ and $-1.5$, whereas 4 are consistent with a moderately low metallicity ($[M/H] ≈ -0.5$) from M7 to T6. All but one of our objects have large tangential velocities between 200 and 320 km s$^{-1}$ typical of the Galactic halo population.

Our results are in good agreement with recent independent measurements for three of our targets and confirm the previously measured parallax and absolute magnitude $M_K$ of the nearest and coolest (T-type) subdwarf 2MASS 0937+29 with higher accuracy. For all targets, we also obtained infrared $J$, $H$, $K$ photometry at a level of a few milli-magnitudes relative to 2MASS standards.

Key words. astrometry – stars: distances – stars: kinematics – stars: low-mass, brown dwarfs – subdwarfs – solar neighborhood

1. Introduction

Subdwarfs were originally defined by Kuiper (1939) as stars with spectral types A–K lying “not over 2–3 mag below the main sequence” in optical colour–magnitude diagrams. They are low-metallicity stars which typically have large space velocities. They are local representatives of the Galactic thick disk and halo populations and show up preferentially in high proper motion surveys. However, compared to thin disk stars with solar metallicities, subdwarfs are a rare species. In the well-investigated surveys. However, compared to thin disk stars with solar metallicities, subdwarfs are a rare species. In the well-investigated surveys.

The coolest subdwarfs with late-K and M spectral types were described about ten years ago by Gizis (1997). He developed a corresponding spectroscopic classification scheme separating normal M dwarfs with solar metallicities ($[M/H] ≈ 0.0$) from M subdwarfs (sdM) with metallicities ($[M/H] ≈ -1.2$) and extreme subdwarfs (esdM) with even lower metallicities ($[M/H] ≈ -2.0$). The latest-type subdwarf classified by Gizis (1997) is the high proper motion star LHS 377 with a spectral type of sdM7.

The search for very low-mass stars and brown dwarfs has experienced enormous progress in the last decade, mainly thanks to new deep optical and near-infrared (NIR) all-sky surveys, which also enable and support new high proper motion searches. Many objects even cooler than M dwarfs have been discovered; the new spectral types L and T have been invented to describe them (see Kirkpatrick 2005, and references therein), and their current census has reached nearly 700 objects (Gelino et al. 2008). A question of particular interest is the formation of low-mass stars and brown dwarfs in the low-metallicity regime. Relics of the early Galaxy and the first generations of star formation may be detectable among the faintest objects in the local Galactic halo population.

Trigonometric parallax measurements of these new UCSDs are essential to determine their absolute brightnesses, effective temperatures and space motions. The first (sub-)stellar UCSDs with accurate distance estimates will serve as benchmark sources for our understanding of this new population and for their detailed classification. A new classification scheme for UCSDs is still under debate (Gizis & Harvin 2006; Burgasser et al. 2007).

Recently, Lépine et al. (2007) have revised the Gizis (1997) scheme for M subdwarfs and introduced a third class, the so-called ultrasubdwarfs (usdM), for the lowest metallicities. In
Table 1. Targets with previously known proper motions, $JHK_s$ photometry and spectral types.

| Name          | $J$     | $H$     | $K_s$ | SpType | Ref. |
|---------------|---------|---------|-------|---------|------|
|               | (2MASS) | (2MASS) | (2MASS) |         |      |
| 2MASS 0532+8246 | 15.179  | 14.904  | 14.918 | sdL7    | 5.3,11 |
| 2MASS 0937+2931 | 14.648  | 14.703  | 15.267 | d/sdT6  | 7.1,11 |
| SSSP 1013–1356 | 14.621  | 14.382  | 14.398 | sdM9.5  | 3.3,11 |
| SSSP 1256–1408 | 14.011  | 13.618  | 13.444 | 12;–    |      |
| SDSS 1256–0224 | 16.099  | 15.792  | 15.439 | sdL4:   | 12:4,11 |
| LSR 1425+7102  | 14.775  | 14.405  | 14.328 | sdM8:   | 12:8,11 |
| SSSP 1444–2019 | 12.546  | 12.142  | 11.933 | d/sdM9  | 10:10,11 |
| LSR 1610–0040  | 12.911  | 12.302  | 12.019 | d/sdM7.7 | 12:2,11 |
| 2MASS 1626+3925 | 14.435  | 14.533  | 14.466 | sdL4:   | 6:6,11 |
| LSR 2036+5059* | 13.611  | 13.160  | 12.936 | sdM7.5  | 12:9,11 |

References: (Col. 6, first index for proper motion, others for sp. type): 1 – Burgasser et al. (2002); 2 – Lépine et al. (2003c); 3 – Scholz et al. (2004a); 4 – Sivarani et al. (2004); 5 – Burgasser et al. (2003a); 6 – Burgasser (2004); 7 – Vrba et al. (2004); 8 – Lépine et al. (2003b); 9 – Lépine et al. (2003a); 10 – Scholz et al. (2004b); 11 – Burgasser et al. (2007); 12 – Scholz et al. (unpublished, preliminary proper motion solution based on available SSS and 2MASS data).

– Discovered by Lépine et al. (2003c) as the first possible L sub-dwarf. Cushing & Vacca (2006) described it as a very peculiar object (M6p sdM), and Dahn et al. (2008) recently found it to be an astrometric binary of the Galactic halo population consisting of a mildly metal-poor M dwarf and a substellar companion.

* – Lépine et al. (2002) listed an erroneous position and proper motion for this object.

2. Target selection

In 2004, when we initiated our subdwarf parallax programme, there were only nine UCSDs known, and all happened to be visible from a northern telescope site like Calar Alto. Among them, there were five M-type objects originally detected in optical high proper motion surveys by Lépine and co-workers (LSR 1425+7102, LSR 1610–0040, LSR 2036+5059) and Scholz and co-workers (SSSPPM 1013–1356, SSSPMP 1444–2019), three L- and T-type objects originally detected in the NIR Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) by Burgasser and co-workers (2MASS 0532+8246, 2MASS 0937+2931, 2MASS 1626+3925), and one object detected in the spectroscopic database of the deep optical Sloan Digital Sky Survey (SDSS; York et al. 2000) by Sivarani et al. (2004). The 2MASS photometry as well as spectral types from different sources are given in Table 1. We have included one more object (SSSPPM 1256–1408), also detected in the high proper motion survey by Scholz et al. (unpublished) using the SuperCOSMOS Sky Surveys (SSS) data (Hambly et al. 2001), which is still lacking a spectral type. Its large optical-to-NIR ($R−J = +4.8$; $R$ from SSS) and small NIR ($J−K_s = +0.57$) colour indices are however typical of late-M UCSDs.

When we started our observations, only one of our targets (2MASS 0937+2931) had a preliminary trigonometric parallax measurement by Vrba et al. (2004). Meanwhile, there are three more parallaxes, all published in 2008, for 2MASS 0532+8246 (Burgasser et al. 2008), LSR 1425+7102 and LSR 1610–0040 (Dahn et al. 2008).

3. Observations and data reduction

The observations were made with the OMEGA2000 camera on the 3.5 m-telescope of the Centro Astronómico Hispano Alemán (CAHA) at Calar Alto, Spain. OMEGA2000 is a prime focus, near-infrared, wide-field camera that uses a 2k × 2k HAWAII-2 focal plane array with a sensitivity of the $z$ to the $K$ band. The optics of the camera consists of a cryogenic focal reducer providing a 15.4” × 15.4” field of view with a resolution of 0.45’’/pixel. The astrometric observations were all obtained in the $H$-band. In all cases, at each epoch, we took 16 individual exposures of 60 s each (frames), with small offsets of a few arc-seconds, thus totalling 16 mn exposure time per object and night. The observations were taken between January 2005 and June 2008. The maximum epoch difference per target ranges from 3.1 to 3.4 years, with the number of useful epochs (nights) from 17 to 26. In addition, one observation (i.e., 16 individual frames) in the $J$ and $K_s$ bands has been taken for each target.

Object detection and centroiding was carried out by use of the SExtractor software (Bertin & Arnouts 1996). For the photometric reduction, standard stars are taken from 2MASS. On average, 100 stars per field with an accuracy better than 0.1 mag in 2MASS were used as a reference. In a given photometric band, each of 16 frames has been reduced to the 2MASS photometric system, separately. As a rule, a linear fit was sufficient for stars fainter than 9th mag. For each object in a field, the final $J$-, $H$- and $K_s$-magnitudes were computed as averages of 16 values. The limiting magnitudes slightly vary from field to field and they reach $J = 19$, $H = 18$, $K_s = 17.5$, at least.

For each target, the astrometric data reduction was performed in several steps. At first, an appropriate “reference” frame was chosen. Each frame was reduced to the “reference” frame using a classical 2nd-order polynomial fit. As reference points for the “frame-to-frame” reduction we use anonymous field stars with $H$ magnitudes between 14 and 16.5; the number of reference stars varied between 75 for target 2MASS 0937+29 and 1250 for LSR 2036+5059. The “reference” frame was transformed to an intermediate equatorial reference system defined by 2MASS stars in a given sky area. Again, a 2nd-order plate fit was carried out. The number of reference stars from 2MASS varied between 85 and 1650, the latter in the field around LSR 2036+5059.

In this intermediate system, mean positions, proper motions and parallax were obtained via a rigorous single least-squares fit to the 5 unknowns, coupling the observational equations in RA and Dec via the parallax factor. Although mathematically correct, the solution may suffer from a relatively short time baseline and a non-uniform distribution of observations. Thus correlations may influence the results for proper motions and parallax. In order to check the robustness of the solutions, two additional least-squares procedures were carried out. The first of these treated the equations in RA and Dec separately, yielding two solutions for the parallax. In this check, correlations between RA and Dec are prohibited. Evidently, the formal contrast, Jao et al. (2008) have considered novel methods for assigning spectral types from K3 to M6 dwarfs, discrediting the previous subdwarf metallicity classes and suggesting instead a more complex investigation of temperature, metallicity and gravity features. Such a three-dimensional scheme (temperature/clouds, metallicity, gravity) has also been proposed by Kirkpatrick (2005) for late-M, L and T dwarfs. However, the numbers of well-investigated subdwarfs are still too small (see Burgasser et al. 2007, for an overview) to fill the required grid of subtypes with benchmark sources.
Table 2. Absolute parallaxes ($\pi$(abs)), absolute proper motions ($\mu_x$, $\mu_y$, $\mu_z$), and infrared magnitudes ($J$, $H$, $K_s$) of ultracool Subdwarfs.

| Name          | RA J2000.00 | Dec J2000.00 | $\pi$(abs) [mas] | $\Delta_\pi$ [mas] | $\mu_x$, $\mu_y$, $\mu_z$ [mas/yr] | $J$ [mmag] | $H$ [mmag] | $K_s$ [mmag] | $M_{K_s}$ [mag] | $V_{(LSR)}$ [km s$^{-1}$] |
|---------------|-------------|-------------|-----------------|-------------------|-------------------------------------|------------|------------|-------------|----------------|-------------------|
| 2MASS 0532+82 | 5.348452    | 82.7729208 | 42.28 ± 5.36    | 2039.40 ± 1001.79 | 15.14 ± 2.8 ± 0.5 ± 0.09 ± 0.12     |            |            |             |                |                   |
| 2MASS 0937+29 | 9.626350    | 29.528189  | 163.39 ± 3.39   | 944.15 ± 1319.78  | 14.62 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |
| SSSPM 1256–14| 10.218708   | −13.939245 | 20.28 ± 5.11    | 69.44 ± 1028.93   | 14.63 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |
| SSSPM 1256–14| 12.937228   | −14.144533 | 18.76 ± 0.38    | −741.11 ± 1002.13 | 14.00 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |
| LSR 1425+7102 | 14.418059  | 71.035998  | 12.19 ± 0.73    | −602.38 ± 177.71  | 14.82 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |
| LSR 1425+7102 | 14.738983   | −20.323730 | 61.67 ± 2.41    | −2906.15 ± 1963.12| 12.60 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |
| LSR 1610−0040 | 16.174711   | −0.681642  | 33.10 ± 2.63    | −773.84 ± 1231.58 | 12.87 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |
| LSR 1610−0040 | 16.438927   | 39.422076  | 29.85 ± 1.10    | −1374.14 ± 238.01 | 14.46 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |
| LSR 2036+5059 | 20.606002   | 51.001279  | 21.60 ± 1.00    | 751.93 ± 1252.22  | 13.68 ± 7 ± 14 ± 0.03 ± 1           |            |            |             |                |                   |

The parallax solutions from the observations with the 1.55 m Strand Astrometric Reflector at the USNO Flagstaff Station. The number of reference stars used varied between 6 and 16. Photometric data were taken mainly from the 2MASS Catalog. In spite of the differences between the published parallaxes coincide reasonably well with our results, i.e. the differences between two corresponding values are smaller than 2 times their mean errors. The parallax solutions from the observations with the 1.55 m Strand Astrometric Reflector at the USNO Flagstaff Station. The number of reference stars used varied between 6 and 16. Photometric data were taken mainly from the 2MASS Catalog.
to the Gizis (1997) classification. Its moderately low metallicity has also been suggested by Scholz et al. (2004b) based on comparison with model colours \((I - J)\) and \((J - K)\). Therefore, we think these three objects can be used as benchmarks for the type “sd” with \([M/H] = -0.5\) from M7 to L7.

Of the remaining 6 objects, only one has a previously determined trigonometric parallax, LSR 1425+7102, measured by Dahn et al. (2008), and classified as sdM8 by Burgasser et al. (2007). The sdM7 LHS 377, which was not on our target list, is a close neighbour to LSR 1425+7102 in the CMD. All our 6 objects populate the area between \([M/H] = -1.0\) and \([M/H] = -1.5\) in the Baraffe et al. (1997) isochrones. All are classified as “sd” by Burgasser et al. (2007) except our newly detected object SSSPM 1256-14, which we would classify as sdM8 based on its position in the CMD. The coolest object, the sdL4 2MASS 1626+39 has \(M/M_\odot = 0.083\) and \(T_{\text{eff}} = 2300\) K when compared with the Baraffe et al. (1997) isochrones for \([M/H] = -1.0\). Our faintest (by apparent magnitude) target SDSS 1256-13 had the \(K_s\) magnitude in 2MASS given with a problem flag. Its 2MASS colour of \(J - K_s = 0.66\) changes to 0.09 according to our photometry, and hence its metallicity in the Baraffe et al. (1997) models changes from \(-0.5\) to \(-1.3\).

Our 6 targets as well as LHS 377 serve as benchmarks for the subdwarf population between M7 (LHS 377) and L4 (2MASS 1626+39) in the metallicity range between \([M/H] = -1.0\) and \(-1.5\). Baraffe et al. (2003) recently published new evolutionary models for the coolest brown dwarfs (T dwarfs), which they refer to as the COND models. In these models, dust opacity in the radiative transfer equation is neglected. The COND isochrone is shown in Fig. 1 only for objects with \(M/M_\odot < 0.075\). For masses up to \(M/M_\odot = 0.08\) it formally coincides with the \([M/H] = -0.5\) isochrone. So, our targets from the \([M/H] = -0.5\) group have loci close to the COND isochrone, but the targets from the \([M/H] = -1.3\) class lie significantly above this isochrone.

2MASS 0937+29 may be the faintest object along the extrapolated \([M/H] = -0.5\) isochrone in Fig. 1. It was also characterised as slightly metal-poor \((-0.4 < [M/H] < -0.1)\) by Burgasser et al. (2003b; 2006) using spectral model comparisons. Compared to the 2MASS colour, our new photometry lead to a bluer \(J - K_s\), which again supports a sub-solar metallicity if we compare its location in Fig. 1 with the COND model points. Its relatively low tangential velocity \(V_{\text{T,LSR}}\) of about 50 km s\(^{-1}\) does not, however, reject a higher spatial velocity of 2MASS 0937+29 with respect to the local standard of rest (LSR). The presently unknown \(V_{\text{rad}}\) of 2MASS 0937+29 contributes to its space velocity components as \((U, V, W)_{\text{rad}} = (38-0.64\ V_{\odot}, -30-0.21\ V_{\odot}, +0.74\ V_{\odot})\). Therefore, as long as the radial velocity of 2MASS 0937+29 is unknown, one cannot exclude the possibility that 2MASS 0937+29 is a member of the thick disk or even of the halo population.

In summary, we have measured infrared trigonometric parallaxes of ten ultracool subdwarfs, six of which for the first time. Absolute parallaxes have been determined with respect to galaxies, also for the first time. Compared to theoretical models, 4 stars have moderately low metallicity, \([M/H] = -0.5\), whereas 6 are consistent with \([M/H] = -1.0\) and \(-1.5\). Nine out of ten definitely show halo kinematics from their tangential velocities, while 2MASS 0937+29 needs a large radial velocity to be kinematically excluded as a member of the disk.

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