A Giant Step: from Milli- to Micro-arcsecond Astrometry
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Astrometric detection and characterization of brown dwarfs

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Abstract. As a result of failed star formation, brown dwarfs (BDs) do not reach the critical mass to ignite the fusion of hydrogen in their cores. Different from their low-mass stellar brothers, the red dwarfs, BDs cool down with their lifetime to very faint magnitudes. Therefore, it was only about 10 to 20 years ago that such ultracool objects began to be detected. Accurate astrometry can be used to detect them indirectly as companions to stars by the signature of the so-called astrometric wobble. Resolved faint BD companions of nearby stars can be identified by their common proper motion (CPM). A direct astrometric detection of the hidden isolated BDs in the Solar neighborhood is possible with deep high proper motion (HPM) surveys. This technique led to the discovery of the first free-floating BD, Kelu 1, and of the nearest BD, ϵ Indi B. Both were meanwhile found to be binary BDs. The astrometric orbital monitoring of ϵ Indi Ba+Bb, for which we know an accurate distance from the Hipparcos measurement of its primary, ϵ Indi A, will allow the determination of individual masses of two low-mass BDs. Hundreds of BDs have been identified for the last decade. Deep optical sky survey (SDSS) and near-infrared sky surveys (DENIS, 2MASS), played a major role in the search mainly based on colours, since BDs emit most of their light at longer wavelengths. However, alternative deep optical HPM surveys based on archival photographic data are not only sensitive enough to detect some of the nearest representatives, they do also uncover many of the rare class of ultracool halo objects crossing the Solar neighborhood at large velocities. SSSPM 1444, with the extremely large proper motion of 3.5 arcsec/yr, is one of the nearest among these subdwarfs with masses at the substellar boundary. We present preliminary parallax results for this and two other ultracool subdwarfs (USDs) from the Calar Alto Omega 2000 parallax program.

Keywords. astrometry, surveys, stars: low-mass, brown dwarfs, binaries: general, stars: distances, stars: kinematics, subdwarfs, solar neighborhood, Galaxy: halo

1. The pioneering role of astrometry in the search for brown dwarfs

After their initial deuterium burning, brown dwarfs (hereafter BDs) cool down throughout their lifetimes and become harder and harder to detect. Whereas young BDs appear as late-type M dwarfs, they fall into the L dwarf regime at an intermediate age between 100 Myr and 1 Gyr after their formation depending on their mass, and later transform into T dwarfs (Burrows *et al.* 2001). The Solar neighborhood preferentially consists of relatively old objects. Therefore, the majority of low-mass BDs near the Sun should be T-type ones, whereas young M-type BDs can probably only be found as members of young open clusters and associations, outside the 25 pc horizon typically defined as the Solar neighborhood "border".

The first BDs were discovered as companions to known nearby stars. Becklin & Zuckerman (1988) found GD 165B (later classified as L4 dwarf), a faint infrared companion of a white dwarf, the common proper motion (hereafter CPM) of which was measured by Zuckerman & Becklin (1992). Nakajima *et al.* (1995) detected Gl 229B (T7), a faint companion of an M2 dwarf providing also a first crude CPM measurement. In the same year, Rebolo *et al.* (1995) discovered the first BD in an open cluster, Teide 1 (M8), for which they confirmed astrometric membership by measuring the CPM with the Pleiades.

The first free-floating BDs in the Solar neighborhood were identified as result of a high proper motion (hereafter HPM) survey by Ruiz *et al.* (1997), and from the DEep Near-Infrared Survey (DENIS) without initial HPM measurements by Delfosse *et al.* (1997). However, there is one HPM object catalogued before all the above mentioned BD discoveries: LP 944-20 (Luyten 1979b), classified as an intermediate-age BD of spectral type M9 by Tinney (1998).

To our knowledge, there is only one successful BD detection by the measurement of the astrometric wobble: Pravdo *et al.* (2005) discovered a substellar-mass object around the nearby M5.5 dwarf GJ 802 within the STEPS (STEllar Planet Survey) program using the Palomar 5-m telescope.

2. Astrometric investigations of L and T dwarfs

In this section we consider only L and T dwarfs as the main reservoir of BDs, keeping in mind that (1) there are many M-type BDs in young open clusters and associations, (2) intermediate-age M-type BDs like LP 944-20 do also exist in the Solar neighborhood in very small numbers, (3) the early- to mid-L dwarfs population is a mixture of low-mass stars and BDs (Kirkpatrick 2005). The main reason for restricting our view to the new spectral types is the availability of a regularly updated complete database.

The L and T dwarf compendium housed at DwarfArchives.org and maintained by Gelino *et al.* (2007) currently contains 626 objects. As can be seen from Fig. 1, the Galactic plane is still a problematic region for searching BDs. Only 78 objects (12%) have trigonometric parallax measurements. These are mostly in the broader equatorial zone. Proper motions are available for 203 objects (32%). Whereas proper motions have been measured for almost all of the brighter ($J < 13.5$) objects, many bright objects are still lacking parallax measurements (Fig. 1).

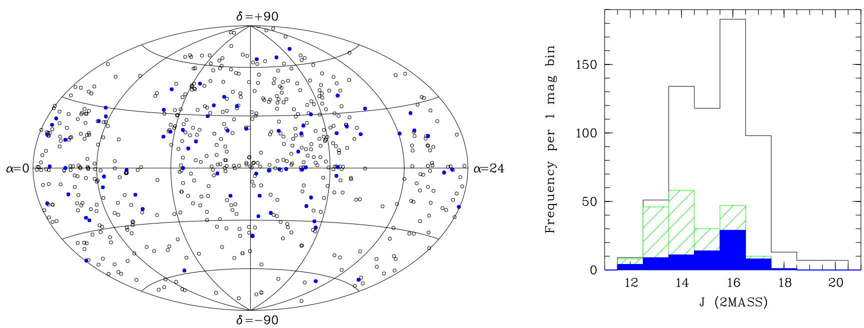

Figure 1. Left: Distribution of all known 626 L and T dwarfs over the sky (Gelino *et al.* 2007). Filled symbols show those 78 objects which have trigonometric parallax measurements. Right: J magnitude histogram of all objects in comparison with those having measured proper motions (hashed) and parallaxes (shaded), respectively.

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Most of the existing parallaxes have been measured by Vrba *et al.* (2004) (28 objects) and Dahn *et al.* (2002) (19 objects). For 19 L and T dwarf companions the parallaxes come from Hipparcos (ESA 1997) measurements of their primary stars. The relatively low completeness concerning the proper motions is due to the fact that most of the L and T dwarfs were discovered in colour-based searches. These objects are generally fainter and more distant than objects discovered by their large proper motion. For 66 objects proper motions have been obtained/revised together with their parallaxes. Large numbers of proper motion measurements were also provided by Schmidt *et al.* (2007) (47 objects), Phan-Bao *et al.* (2007) (18 objects), and Hambly *et al.* (2001) (14 objects). The remaining proper motions have been published in many (discovery) papers dealing with only few L and T dwarfs.

3. The impact of new HPM surveys

HPM objects represent a mixture of *very nearby* neighbors of the Sun in the local population of the Galactic thin disk, and *very fast* representatives of the Galactic thick disk and halo, just passing through the neighborhood. By extending the existing HPM surveys to fainter magnitudes we expect to find the nearest isolated substellar objects with thin disk kinematics (section 4) as well as some of the lowest-mass visitors from the Galactic halo (section 5). Although halo stars are relatively rare when compared to the number density of disk stars, they are over-represented in HPM samples.

Table 1. Recent discoveries of objects with proper motions > 2 arcsec/yr

Name	proper motion [arcsec/yr]	Discovery paper	Distance (plx. ref.) [pc]	object type
SO 0253+1652	5.11	Teegarden+03	3.84 (1)	disk M6.5
ε Indi Ba,Bb	4.70	Scholz+03, McCaughrean+04	3.625 (2)	disk T1+T6
SSSPM 1444−2019	3.51	Scholz+04b	∼20	halo sdM9
2MASS 1114−2618	3.05	Tinney+05	∼7	disk T7.5
SCR 1845−6357 AB	2.66	Pokorny+03, Hambly+04, Biller+06	3.854 (1)	disk M8.5+T6
2MASS 0532+8246	2.60	Burgasser+03	26.7 (5)	halo sdL7
PM J13420−3415	2.55	Lépine, Rich & Shara 05	∼18	halo WD
LEHPM 3396	2.45	Pokorny+03, Phan-Bao+06	∼8	disk M9.0
LSR 1826+3014	2.38	Lépine+02	∼14	halo M8.5
F351-50	2.33	Ibata+00	35 (4)	halo cool WD
2MASS 0415−0935	2.26	Burgasser+02	5.74 (3)	disk T8.5
2MASS 0251−0352	2.17	Cruz+03, Schmidt+07	∼12	disk(?) L3.0
SCR 1138−7721	2.15	Hambly+04, Scholz+04a	8.18 (1)	disk M5.5

Trig. parallaxes: 1 - Henry+06, 2 - ESA97, 3 - Vrba+04, 4 - Ducourant+07, 5 - Burgasser+07

Table 1 lists 13 newly discovered objects (two of which were later resolved as binary systems). Compared to 73 previously known objects in the LHS catalogue (Luyten 1979a) with proper motions larger than 2 arcsec/yr, they represent a considerable increase in the number of the fastest stars on the sky. Except for two mid-M dwarfs and two white dwarfs all the new objects have masses at or below the substellar limit.

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4. The nearest BDs to the Sun

A very red and extreme HPM (∼4.7 arcsec/yr) object was discovered in an HPM survey of overlapping I band plates scanned in the SuperCOSMOS Sky Surveys (SSS). A very bright infrared counterpart was also detected at the expected position in the Two-Micron All Sky Survey (2MASS). The object was found to share its HPM with a well-known bright star separated by about 7 arcmin and consequently named ε Indi B (Scholz *et al.* 2003). With the given Hipparcos parallax of ε Indi A it was clear that the newly found object was the nearest BD to the Sun. Its proper motion was later improved by including additional epochs (Fig. 2). The final result (McCaughrean *et al.* 2004) agrees within 40 mas/yr with that of the primary star, which can be expected given the wide orbital motion.

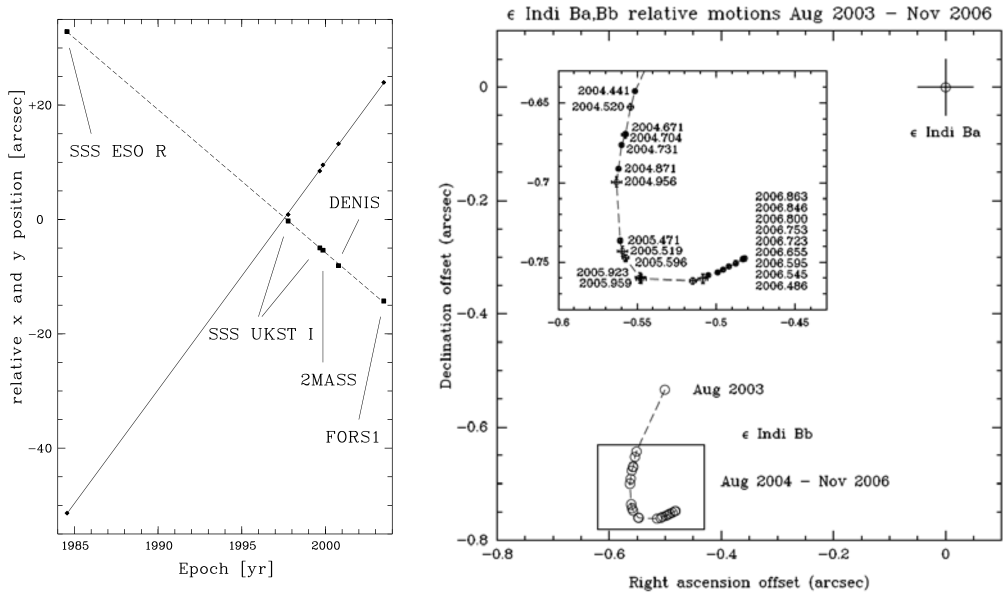

Figure 2. Left: Proper motion (x - solid line, y -dashed line) of ε Indi B (unresolved) from archival data, Right: Orbital motion of the resolved BD binary ε Indi Ba,Bb from the first 3 years of the adaptive optics monitoring program with NACO at the ESO VLT. The data are joined here with straight lines, not a fit.

McCaughrean *et al.* (2004) resolved ε Indi B as a close pair (sep. 0.7 arcsec) of two T-type BDs, ε Indi Ba,Bb, with an expected relative orbital period of only ∼15 years. This system provides the unique opportunity to measure the *individual* masses of both BDs by combining relative astrometry of the resolved pair (Fig. 2) with measurements of the absolute motion of the system barycenter against a network of field stars in wide-field CCD images. A corresponding long-term monitoring program (PI: M. McCaughrean) is currently being carried out.

Most of the known nearest BDs are T dwarfs. Among the 10 objects with measured parallaxes >100 mas in the compilation of Gelino *et al.* (2007), there are only two L dwarfs, discovered by Reid *et al.* (2000). Other bright L dwarfs discovered in HPM surveys (e.g. Scholz & Meusinger 2002; Salim *et al.* 2003) are still lacking parallaxes.

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5. Ultracool subdwarfs in the Solar neighborhood

Ultracool subdwarfs (hereafter USDs) with spectral types later than sdM7 represent a new class of metal-deficient low-mass stars and BDs which have typically Galactic halo kinematics. Compared to 600 L and T dwarfs, only <20 USDs have been discovered so far (mostly as HPM objects). A proper classification scheme is still under development. For an overview we refer the reader to Burgasser *et al.* (2007a) and references therein.

Table 2. Preliminary parallaxes of ultracool subdwarfs

Name	Spectral Type	Ref.	$\mu_\alpha \cos\delta$ [mas/yr]	μ_δ [mas/yr]	π [mas]	Ref.
SSSPM 1444−2019	sdM9 (sdL:)	(1)	-2901.5 ± 2.5	-1977.9 ± 2.2	55.1 ± 2.8	(4)
2MASS 0532+8246	sdL7	(2)	$+2047.7 \pm 1.8$	-1658.6 ± 1.5	40.8 ± 1.7	(4)
			$+2041.9 \pm 1.8$	-1648.2 ± 1.8	37.5 ± 1.7	(6)
2MASS 0937+2931	sdT6	(3)	$+952.2 \pm 1.6$	-1308.3 ± 1.7	161.6 ± 1.8	(4)
			$+973.0 \pm 7.1$	-1297.8 ± 7.1	162.8 ± 3.9	(5)

References: 1 - Scholz *et al.* (2004b), 2 - Burgasser *et al.* (2003), 3 - Burgasser *et al.* (2002), 4 - Röser *et al.* in prep., 5 - Vrba *et al.* (2004), 6 - Burgasser *et al.* (2007b)

Trigonometric parallaxes of USDs are urgently needed. We (Röser, Schilbach, & Scholz) are currently running a dedicated parallax program using Omega 2000 at the 3.5m telescope of the Calar Alto Observatory, targetting 10 USDs. Omega 2000 with its 15 by 15 arcmin field and 450 mas per pixel provides a much larger number of astrometric reference stars which makes the astrometric solutions more accurate than with other instruments. In Table 2 we present first results for SSSPM 1444 and two other USDs, for which comparison measurements are available. Although the preliminary Calar Alto parallax results are based on only 2.5 years of observations (and small ∼1-2 mas corrections to absolute parallaxes are not yet included) they are in good agreement with those from the USNO infrared astrometry program (Vrba *et al.* 2004; Burgasser *et al.* 2007b).

6. Concluding remarks

9 of the 13 discoveries of extreme HPM objects (Table 1) including the nearest BDs and USDs were made by using digitized photographic Schmidt plates. This underlines that these archival data are still important and by far not yet fully exploited. However, large area multi-epoch near-infrared surveys (e.g. Kirkpatrick *et al.* 2007) will have the best chances to uncover many more of the hidden BDs in the Solar neighborhood.

Considerable efforts are still needed to complete the astrometric characterization of a sufficient number of benchmark BDs and of the poorly understood class of USDs. Ground-based observations will continue to play a major role for high-accuracy astrometry of brown dwarfs, since most of them are too faint to be seen by Gaia.

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