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Measuring brown dwarf properties from deep surveys

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Abstract. We discuss brown dwarf properties that can be measured from current and future deep surveys, and how fundamental parameters, such as the mass function and formation history may be measured. As well as the possibility of finding new populations of benchmark objects that can be used to refine the calibration of ultra-cool models with new precisely measured properties. We also describe our ongoing searches for benchmark brown dwarfs, and discuss our first measurement of the formation history in the sub-stellar regime using data from the UKIDSS Large Area Survey.

Key words. Stars: Brown dwarfs – Surveys

1. Introduction

The rapid advancement of brown dwarf (BD) science in the last two decades can be largely attributed to the rise of large scale and deep optical and near infrared (NIR) surveys. They have identified over 1500 BDs across the L, T and Y dwarf spectral types. Pre year 2000 the most successful surveys were the DEep Near Infrared Survey (DENIS; Epchtein et al. 1997) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). These state of the art NIR surveys, and led the way in BD discovery, identifying over 450 L dwarfs and 50 T dwarfs (Burgasser et al. 2004; Tinney et al. 2005; Kirkpatrick et al. 2000; Martín et al. 2010; Artigau et al. 2010). Indeed these surveys continue to identify new BDs even today thanks to their combination with the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) survey. This ideal pairing is still revealing today some of the closest and coolest BDs in our galactic neighborhood e.g. Luhman 16 (Luhman 2013). Its success is owed to the filters in which it used to target observations. The 2MASS J, H and K_s filters are optimised for the detection of sub 2000K objects, ideally L dwarf types, and combined with an all sky coverage made for an impressive L dwarf hunting tool. Likewise in optical wavelengths the Sloan Digital Sky Survey (SDSS; York et al. 2000), and the Canada France Hawaii Telescope (CFHT) have contributed to the purely optical detection and identification of brown dwarfs that now equaling the numbers of BDs discovered as that of 2MASS and

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DENIS, with their high sensitivity and depth at the red end of the optical wavelengths.

The current, next generation of surveys including the UK Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007), the Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson & Sutherland 2002) and WISE, which probe deeper than 2MASS and SDSS are rapidly matching their discovery rates. UKIDSS has already identified as many L and T dwarfs as 2MASS, and only covers 10% of the sky, but probes 4 times fainter, covering 10 times the total volume of 2MASS. VISTA is set to exceed this also, which will go at least two magnitudes deeper and covers four times the volume of UKIDSS.

2. Brown dwarf properties from deep surveys

Deep surveys allow us to measure several observable properties of the galactic brown dwarf population. These include photometry and astrometry, allowing the accurate measurement of apparent magnitudes, proper motion, parallaxes and thus distances. Follow up spectroscopy can then measure their chemical composition, allowing the direct measurement of gravity and temperature. The unique mass-luminosity relation for brown dwarfs, such that it is strongly dependent on age, which in general can not be measured directly. This means that it is not usually possible to measure BD masses directly.

Other global fundamental BD properties, such as the initial mass function and the formation history come from statistics of large populations of objects, which can be measured for the first time with any accuracy thanks to the latest advent of deep surveys, like UKIDSS.

3. Individual properties- Benchmark brown dwarfs

The fundamental properties such as mass and age can not currently be measured directly from BD spectra as atmospheric ultra-cool models are not currently robust enough to make reliable measurements of these properties. However benchmarks brown dwarfs allow limits to be placed on these properties independently. In order to constrain the models one of the key points is knowing what stage of its evolution the object is in. Such ′age′ benchmarks are extremely valuable tools for this purpose. Age benchmarks can be identified as members of young clusters, moving groups (Gálvez-Ortiz et al. 2010; Clarke et al. 2010) and binary or multiple systems (Day-Jones et al. 2011; Zhang et al. 2010; Burningham et al. 2009, 2010). In general however good benchmark brown dwarfs are rare. As such this means that age benchmarks can essentially be split into two populations. The younger (<1 Gyr) and the older (>1Gyr) population.

Young benchmark BDs include members of young clusters, such as the Hyades (Bouvier et al. 2008; Seifaher et al. 2010), Pleiades (Martín et al. 1998; Bihain et al. 2006), Castor (Tinney 1998) and Ursa Major (Seifaher et al. 2010); and moving groups, since their kinematic signatures remain intact until ~1Gyr before they are disrupted by disk heating mechanisms (De Simone et al. 2004). BD members of these clusters are identified by their kinematics and radial velocities (Clarke et al. 2010; Gálvez-Ortiz et al. 2010). Such benchmarks allow not only an age but a metallicity constraint to be placed on the BD members of these clusters. The young benchmark BDs make up the largest contingent of the current benchmark BD population, but only probe a small area of the age population of BDs in the disc.

More evolved benchmarks are likely to be more useful in probing properties for the majority of the disc BD population. Such evolved benchmarks can be found as members of binary or multiple systems. The usefulness of these systems however is dependent on how accurate the age of can be measured from the host star. Such primary binary members as main-sequence stars and M dwarfs can provide good metallicity information but due to the convergence of model tracks on the main-sequence (Girardi et al. 2000; Yi et al. 2001), makes accurate age dating difficult, with error bars of several Gyrs. The later stages of evolution however may provide a better constraint on the age. Particularly from subgiant and white dwarf host stars. The subgiant phase is relatively short, but as it is pre-dredge up both metallicity and age information will be available, and ages could be as accurate as 10% (Thorén et al. 2004). The white dwarf phase can also have well constrained ages. Higher mass white dwarfs ($> 0.7M_{\odot}$) are likely to reveal ages with higher accuracy ($\sim$10%), as the ages of high mass white dwarfs are essentially the cooling age, as the main-sequence lifetime will be negligible compared to the cooling age. The cooling age for white dwarfs can be accurately determined from robust white dwarf models (Fontaine et al. 2001). These kinds of system are however quite rare, with only a handful of white dwarf + BD binaries thus far confirmed (Steele et al. 2013, 2009; Day-Jones et al. 2011; Maxted et al. 2006; Burleigh et al. 2006; Dobbie et al. 2005; Farihi & Christopher 2004; Zuckerman & Becklin 1992).

3.1. The current benchmark population

We have compiled a current list of age benchmark BDs (L and Ts only) from the literature which we present in Figure 1 as a function of spectral type. It can be seen that only one BD has an age estimate of over 6 Gyrs, and while there are a number of late T dwarf benchmarks, there are relatively few in the mid L-mid T dwarf spectral range. This is likely due to the bias of BD searches targeting later spectral types in more recent deep surveys (e.g. Pinfield et al. 2008; Burningham et al. 2010, 2013). We also use the BT Settl models (Allard et al. 2013) to estimate a mass for the benchmark BD population, which are presented in Figure 2. Again while we are now seeing a range of masses being probed, the younger BDs (<5Gyrs) are far more numerous than their older counterparts.

3.2. Our searches for benchmark brown dwarfs

We have made several searches to identify further age benchmark BDs, focusing on the the deep probing abilities of UKIDSS and SDSS to search for white dwarf + BD binary systems. Using UKIDSS DR8 to search independently for L and T dwarfs, and SDSS DR7 to search for white dwarfs. We used a custom written IDL code to search for likely binary pairings out to separations of 20,000AU based on the distance of the white dwarf, as estimated from its magnitude and colours, using previously confirmed spectroscopic white dwarfs with parallax as a guide. The paired BD would also have to be consistent with an L or T type at the same distance as the primary. We identified 380 candidate systems in this way, for which over 90% have thus far been followed up with second epoch imaging to measure proper motion and hence confirm binarity through a common proper motion measurement using several facilities, including the SPARTAN camera on the SOuthern Astrophysical Research telescope (SOAR), NEWFIRM and ISPI on the Blanco telescope and Fourstar on the Magellan telescopes in Chile. We have thus far confirmed the first T dwarf companion to a white dwarf (Day-Jones et al. 2011) and a new L dwarf + white dwarf widely separated system (Day-Jones et al. 2013, in prep.). A complete follow up of this sample will not only provide new highly valuable benchmark BDs, but will also allow a measurement of the wide binary fraction of BD + white dwarf binary systems, since this is the deepest, widest search for such systems (Day-Jones et al. 2013, in prep.).

4. Galactic population properties

Fundamental properties of the galactic population of BDs can only be measured from large populations of BDs, which has only been made possible with current deep surveys. Properties such as the initial mass function and the formation history have only recently been measured for BDs thanks to the likes of UKIDSS.

4.1. The brown dwarf formation history

The initial mass function is traditionally measured across the stellar mass regime by measuring the luminosity function for a population of stars, and applying a mass-luminosity relation (accounting for metallicity variation). Since BDs never reach the main sequence, this determination is complicated by the lack of

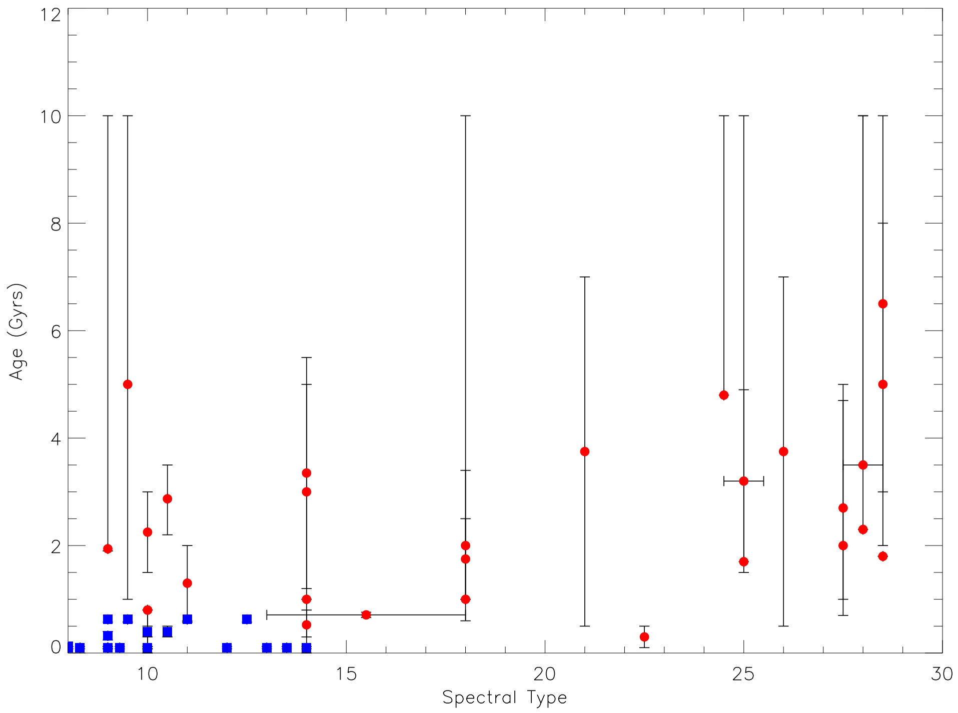

Fig. 1. Age of current benchmark L and T dwarfs compiled from the literature. Filled [blue] squares are young cluster objects. [Red,] filled circles are BDs in binary or multiple systems.

a unique mass-luminosity relationship. Instead the $T_{\rm eff}$ and luminosity are dependent on mass *and* age (Allard et al. 1997). This means that the luminosity function and $T_{\rm eff}$ distributions of field brown dwarfs depend not only on the mass function, but also on their formation history (Chabrier 2002).

There have been several simulations of the BD formation history. The first of these was performed by Chabrier (2002), who used just two formation histories, including a power law (as for main-sequence stars) and a time-decreasing exponential form. More recent simulations by Burgasser (2004) expanded on the simulations of (Allen et al. 1995) to explore other formation histories, including a cluster formation history, an empirical formation the same as (the same as Rocha-Pinto et al. 2000) for main-sequence stars, and a halo formation. Later Allen et al. (1995) made Monte-Carlo simulations using three different models, the same as Chabrier (2002) had previously used plus a segmented power law. These simulations, as with those of Burgasser (2004) were based on 2MASS data, which are largely incomplete in the L8-T5 region and thus a constraint could not be placed on the formation history using these simulations.

However, UKIDSS has given us the first opportunity for a real measurement of this formation history (FH) across the whole L and T temperature regime. Deacon & Hambly (2006) made simulations of the FH using the full coverage of UKIDSS Large Area Survey (LAS). These simulations, along with those of Allen et al. (1995) and Burgasser (2004) showed that the form of the FH is likely most sensitive in the L-T transition region, or the 1100-1500K range.

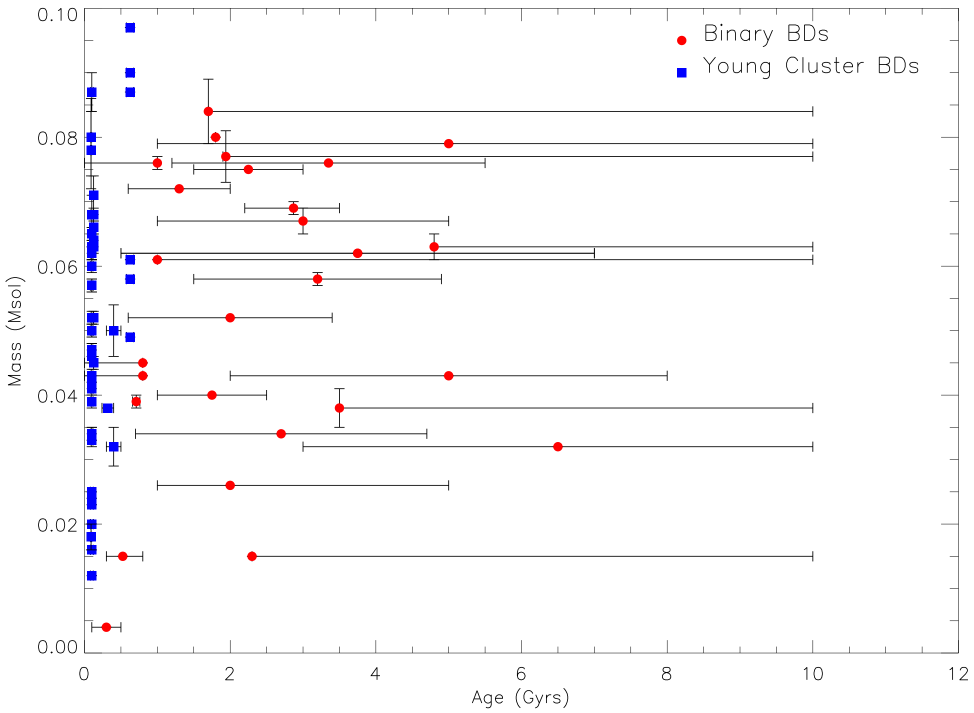

Fig. 2. Mass of current benchmark L and T dwarfs compiled from the literature. Filled [blue] squares are young cluster objects. [Red,] filled circles are BDs in binary or multiple systems.

We thus set to measure the FH by selected a sample of 260 mid L to mid T dwarfs from the UKIDSS LAS (DR7) based on the colours of spectroscopically confirmed L and T dwarfs from Schmidt et al. (2010). We embarked on a large spectroscopic follow up program on X-Shooter on the Very Large Telescope, and were able to make a first estimate of the FH from a small sub-sample of 76 L and T dwarfs for a magnitude limited complete sample over 450 sq degrees of sky (Day-Jones et al. 2013). The space densities we found, in comparison with other measured densities is shown in Figure 3, and in Table 1. We were not able to fully constrain the FH at this time, but our findings were in support of those for a negative form of α in the form of the IMF of BDs found for late T dwarfs alone (Pinfield et al. 2008; Burningham et al. 2010, 2013) We have since followed up more than 200 of our sample, and this new larger sample is currently being analysed (Day-Jones et al. 2014, in prep.). These BDs are also being explored for the possibility of being members of binary systems that may also contribute to the benchmark BD population.

5. Future deep surveys

There are several future and near future deep surveys/missions planned that will probe even deeper than we can currently observe. These include, in the optical, the Dark Energy Survey; Its main instrument DECam will act as a southern counterpart to the SDSS, surveying the whole of the southern sky in g',r',i',z' and Y filters. Similarly the VLT Survey Telescope Kilo Degree Survey (KIDS) will probe slightly

Table 1. Calculated space densities.

Ref.	Sp. Type range	Space density (no correction) ($\times 10^{-3}$ pc^{-3})	Malmquist and Eddington bias correction (%)	Binary corr. (%)	Space density ($\times 10^{-3}$ pc^{-3})
(1)	L4 - L6.5	0.345 ± 0.061	22	3-45	$0.176 \pm 0.031 - 0.295 \pm 0.052$
	L7 - T0.5	0.293 ± 0.050	22	3-45	$0.140 \pm 0.024 - 0.235 \pm 0.040$
	T1 - T4.5	0.235 ± 0.088	22	3-45	$0.106 \pm 0.040 - 0.178 \pm 0.067$
(2)	T6 - T6.5	-	12-16	3-45	$0.39 \pm 0.22 - 0.71 \pm 0.40$
	T7 - T7.5	-	12-16	3-45	$0.56 \pm 0.32 - 1.02 \pm 0.64$
	T8 - T8.5	-	12-16	3-45	$2.05 \pm 1.21 - 3.79 \pm 2.24$
(3)	L5 - L9.5	-	-	-	$2.0^{+0.8}_{-0.7}$
	T0 - T5.5	-	-	-	$1.4^{+0.3}_{-0.2}$
	T6 - T8	-	-	-	$5.3^{+3.1}_{-2.2}$
(4)	M7 - M9.5	-	-	-	4.9 ± 0.6
	L0 - L3	-	-	-	1.7 ± 0.4
	L3.5 - L8	-	-	-	2.2 ± 0.4
(5)	T0 - T2.5	-	-	~50	$0.86^{+0.48}_{-0.44}$
	T3 - T5.5	-	-	~22	$1.4^{+0.8}_{-0.8}$
	T6 - T8	-	-	~14	$4.7^{+3.1}_{-2.8}$
(6)	T6 - T6.5	-	-	30	1.1
	T7 - T7.5	-	-	30	0.93
	T8 - T8.5	-	-	30	1.4
	T9 - T9.5	-	-	30	1.6
	Y0 - Y0.5	-	-	30	1.9

References: (1) Day-Jones et al. (2013); (2) Burningham et al. (2013); (3) Reylé et al. (2010); (4) Cruz et al. (2007); (5) Metchev et al. (2008); (6) Kirkpatrick et al. (2012)

deeper across 1500sq degrees of sky in all of the SDSS filters. Both will provide many new BDs and new benchmark objects. Pannstars is already underway and will provide accurate parallaxes of thousands of stars, and reveal many new primary binary benchmark objects. The Large Synoptic survey Telescope (LSST) will cover half of the sky over the 0.3-1.1micron range, probing deeper than SDSS. Gaia, a space based mission, will also be set to provide accurate astrometry, radial velocities and photo-spectroscopy across the whole sky for V=6-20.

In the NIR regime there are several ground and space based missions that will provide important new populations of BDs in the near future. These include the Visible and Infrared Survey Telescope for Astronomy (VISTA), particularly the VISTA Hemisphere Survey (VHS) and the VISTA Kilo degree INfrared Galaxy survey (VIKING) will provide a deeper, southern counterpart to the UKIDSS LAS. The European (ESA) mission EUCLID will be a space based mission with four band (1 optical + 3 NIR) imaging and slitless low resolution spectroscopy across 15,000 sq degrees. The Japanese space mission SPICA will also provide a similar survey, with an additional mid Infrared (MIR) component and both imaging and spectroscopy. Finally the James Web Space Telescope (JWST) will also provide imaging and spectroscopy across the red-optical, NIR, and the MIR. These new surveys are set to discover thousands of new BDs, providing large new populations, which we will be able to constrain models to higher accuracy than is currently possible.

6. Conclusions

Just how deep can we keep going? As we probe further and fainter the main problem that will arise with these deeper surveys will come from the detection of such faint BDs

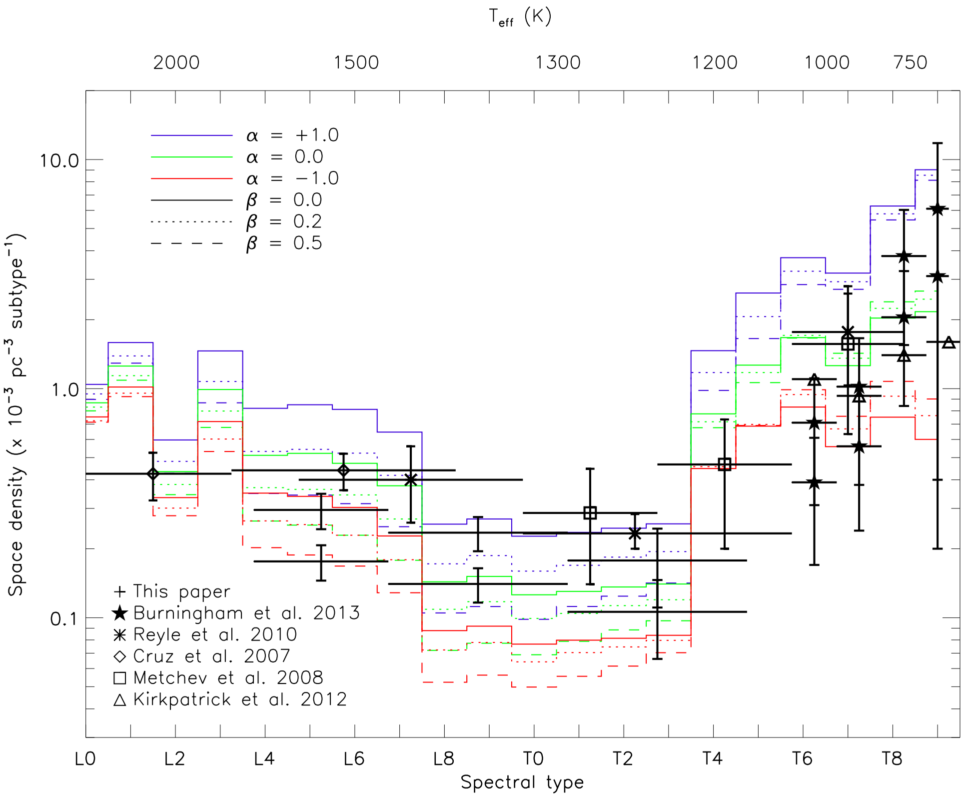

Fig. 3. Our sub-sample of mid L-mid T dwarfs are overplotted with simulations from (Deacon & Hambly 2006) with α **= +1.0, 0.0, -1.0** and β = 0.0, 0.2, 0.5 (where $\psi(M) \propto M^{-\alpha}$). Upper most points of the bins represent a binary fraction of 5% and the lower points are for a binary fraction of 45%.

and their increasing difficulty to follow them up with ground based spectroscopy. We are already finding it difficult to follow up faint objects detected in WISE. Even with the advent of next generation instruments on >30m class telescopes, e.g. E-ELT, GMT, TMT these fainter BDs will still be a challenge to measure high signal to noise spectroscopy. What will be needed is a way of measuring BD properties from their photometry alone (see e.g. Aberasturi et al. 2011), in a similar way we can currently do for main-sequence stars. This task can only be achieved with a large enough population of benchmark objects and a full understanding of the IMF and the FH, which looks promising with the currently under way and near future surveys.

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