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Who wants a million brown dwarfs?

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Abstract. I review the history of using large surveys to study brown dwarfs in the solar neighbourhood, and highlight opportunities and hurdles as we for the first time become capable of detecting millions of L and T dwarfs.

Key words. Brown dwarfs

1. Introduction

The number of astronomically catalogued stars has increased by six orders of magnitude since the first visual star catalogues were produced by ancient astronomers such as Timocharis & Aristillus (c 300BCE), and Hipparchus (c 135 BCE), with several billions now described in the current generation of astronomical databases. This growth has been driven by technological advances from the invention of the telescope to the advent of large scale digitised multiwavelength surveys over the last couple of decades. Whereas early visual catalogues were limited to 1000s of stars, the telescope allowed the first million stars to be catalogued in three great non-photographic surveys of the 19th century: Bonner Durchmusterung (BD; 1852 - 1859), 320K stars; Cordoba Durchmusterung (CD; 1892) 580K stars; and Cape Photographic Durchmusterung (CPD; 450K stars, 1896). Brown dwarfs are now on the same cusp, as the new generation of astronomical surveys probe sufficiently large volumes that for the first time, millions of brown dwarfs will be detectable. With this in mind, I will briefly review the history of brown dwarf discovery in large scale surveys, outline the current state-of-the-art, and finally examine the possibility of pursuing substellar science goals with samples sizes of 10^6 with future surveys.

2. A brief history of brown dwarfs in large surveys

Efforts to identify brown dwarfs in large astronomical surveys have typically followed one of two routes, depending on the diversity of photometric information contained in survey data, and on the extent of our knowledge of the photometric properties of the targeted population. For example, the photographic surveys of the 20th Century were typically limited to 2 or 3 photometric bands (e.g. B, R, I), and few empirical constraints were yet available for the colours of brown dwarfs in the field. As a result, searches for objects beyond the M dwarf sequence focused on identifying faint objects with high proper motions. Ruiz et al. (1997) identified the first free-floating brown dwarf in the Solar neighbourhood, the L dwarf Kelu 1, in a 400 deg^2 proper motion survey. Such a method is sensitive to all intrinsically faint nearby objects detected in the survey regardless of their SED, and consequently this search also turned up a variety of very faint stars and cool white dwarfs (e.g. Ruiz & Takamiya 1995).

Whilst photometrically unbiased proper motion searches have significant advantages when the spectral energy distribution (SED) of targeted sources is poorly known, or insufficient photometry is available to distinguish contaminants, they introduce biases in favour of fast moving populations (e.g. thick disk and halo sources) and are only sensitive to the most nearby objects. To efficiently select large numbers of brown dwarfs from a wider volume and without kinematic bias, multicolour photometric selection is necessary. The advent of large multiband digital surveys, and the prior discovery and characterisation of the prototypical T dwarf, Gl 229B (Nakajima et al. 1995), and prototype L dwarfs, GD 165B (Becklin & Zuckerman 1988) and Kelu-1 (Ruiz et al. 1997), allowed the first substantial samples of field brown dwarfs to be assembled using photometric selection methods.

Three surveys can be credited with facilitating the rapid development of brown dwarf science that took place in the late 1990s and early 2000s: the DEep Near Infrared Survey of the southern sky (DENIS; Epchtein et al. 1997), the 2 Micron All Sky Survey (2MASS; Skrutskie et al. 2006) and the Sloan Digital Sky Survey (SDSS; York et al. 2000). Their attributes and their contributions to the known L and T dwarf samples are summarised in Table 1. The bulk of discoveries in these surveys have been made using photometric selections that relied on the steep red slope of the 0.8–1.3μm SED of LT dwarfs to distinguish them from warmer stars. In the case of DENIS and SDSS suitable colours were available internally, however for the case of 2MASS crossmatching against the USNO photographic survey data to identify objects that were undetected in the B and R bands was required. This technique of using non-detections in certain bands to constrain the SED of candidates continues to be standard selection method for finding cool brown dwarfs, and is often to referred to as a "drop-out" method. As a result of 2MASS, SDSS and DENIS datasets, the study of brown dwarfs in the local field developed rapidly in the early 2000s. An excellent and complete review of the state of play following these surveys may be found in Kirkpatrick (2005). Despite the success of photometric selection, proper motion selection continues to be a useful alternative, both for identifying photometric outliers and for probing to the full depth of the survey where photometric contaminants become more problematic due to underconstrained colours (e.g single band detections etc) and large photometric uncertainties (e.g. Sheppard & Cushing 2009; Looper et al. 2007; Kirkpatrick et al. 2010b).

3. The state of the art

The current generation of near-infrared surveys have increased the searchable volume for brown dwarfs by factors of 10 over that available through e.g. 2MASS. The UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) Large Area Survey (LAS) was designed to overlap with SDSS covered sky with $YJHK$ photometry, and this complementarity has facilitated robust searches of LAS data to within 0.5 mags the maximum J band depth of the survey ($J \approx 19.6$), probing nearly a factor ten larger volume that 2MASS. This has led to the identification of some 230 T dwarfs, doubling the pre-UKIDSS sample (see Table 1), and provided the first extension of the T sequence beyond T8 (Warren et al. 2007; Burningham et al. 2008). Rare objects, such as one of the first T subdwarfs (Burningham et al. 2013) and a planetary-mass T8 companion to a young star (Goldman et al. 2010; Burgasser et al. 2010; Burningham et al. 2011) have also been identified. It has also allowed the discovery of several wide binary substellar companions to stars, which can be used as benchmarks for testing model atmospheres (Day-Jones et al. 2011; Burningham et al. 2009; Pinfield et al. 2012; Burningham et al. 2013). At warmer types, the UKIDSS LAS-SDSS crossmatch has allowed for uniform selection brown dwarfs spanning the late-M to early T regime for the purpose of characterising the luminosity function across the LT transition, the region most sensitive to the Galactic brown dwarf formation history (e.g. Burgasser 2004a). This project has resulted in the discovery of nearly

Table 1. The numbers of published L and T dwarfs by survey, discovery references and the potential numbers detectable based on the surveys' depths and current estimates of the L and T dwarf space densities. Space densities were compiled from data in Cruz et al. (2007), Day-Jones et al. (2013) and Kirkpatrick et al. (2012). SDSS potential yields are not projected due to poor availability of mean z' magnitudes for LT dwarfs. The CFBDS(IR) yields are based on the region with J band overlap.

Survey	Bands	Area / deg^2	Depth	N_{pub} L, T	Refs	N_{det} L, T
DENIS	iJH	20000	J = 16.5	49, 1	1–7	1400, 56
2MASS	JHK	all sky	J16.5	403, 57	8 – 39	2800, 110
SDSS (I & II)	$ugriz$	16000	z' = 20.5	381, 55	40 – 50	
UKIDSS-LAS	$YJHK$	3600	J = 19.6	142, 263	50–59	22000, 1100
CFDBS	iz	1000	z'_{AB} = 24.0	170, 45	60–64	
	J	355	J = 20.0			3800,180
WISE	$W1W2W3W4$	all sky	$W2$ = 15.6	10, 176	64–67	19000, 1200
VISTA-VHS	$(Y)J(H)K_s$	20000	J = 19.6	0, 5	68	120000, 6000
VISTA-VIKING	$ZYJHK_s$	1500	J = 21.0	0, 0	-	65000, 3100

References: 1) Delfosse et al. (1997); 2) Martín et al. (1999); 3) Martín et al. (2010); 4) Bouy et al. (2003); 5) Kendall et al. (2004); 6) Phan-Bao et al. (2008); 7) Artigau et al. (2010) ; 8) Kirkpatrick et al. (1999) ;9)Kirkpatrick et al. (2000); 10) Kirkpatrick et al. (2008); 11) Kirkpatrick et al. (2010a); 12) Burgasser et al. (1999) ; 13) Burgasser et al. (2000);14) Burgasser et al. (2002); 15) Burgasser et al. (2003a) ; 16) Burgasser et al. (2003b) ; 17) Burgasser et al. (2003c); 18) Burgasser et al. (2004);19) Burgasser (2004b) ; 20) Kirkpatrick et al. (2010b) ; 21) Reid et al. (2008); 22) Gizis (2002); 23) Gizis et al. (2000); 24) Gizis et al. (2003); 25) Kendall et al. (2003); 26) Kendall et al. (2007); 28) Cruz et al. (2003); 29) Cruz et al. (2004); 30) Cruz et al. (2007); 31) Wilson et al. (2003) ; 32) Folkes et al. (2007); 33) Metchev et al. (2008); 34) Looper et al. (2007); 35) Looper et al. (2008); 36) Sheppard & Cushing (2009); 37) Scholz et al. (2009); 38) Geißler et al. (2011); 39) Tinney et al. (2005); 40) Fan et al. (2000); 41) Hawley et al. (2002); 42) Geballe et al. (2002); 43) Schneider et al. (2002); 44) Knapp et al. (2004); 45) Chiu et al. (2006); 46) Zhang et al. (2009); 47) Scholz et al. (2009); 48) Schmidt et al. (2010); 49) Leggett et al. (2000); 50) Lodieu et al. (2007); 51) Pinfield et al. (2008); 52) Burningham et al. (2008); 53) Burningham et al. (2009); 54) Burningham et al. (2010a); 55) Burningham et al. (2010b); 56) Burningham et al. (2013); 57) Cardoso submitted; 58) Day-Jones et al. (2013); 59) Marocco submitted; 60) Delorme et al. (2008b) 61) Reylé et al. (2010); 62) Delorme et al. (2010); 63) Albert et al. (2011); 64) Kirkpatrick et al. (2011); 65) Kirkpatrick et al. (2012); 66) Mace et al. (2013); 67) Pinfield et al. (2014); 68) Lodieu et al. (2012)

200 new ultra cool dwarfs with types M8 – T4 (Day-Jones et al. 2013, , Marocco et al in prep).

The Canada-France Brown Dwarf Survey (CFBDS; Delorme et al. 2008b) covers 1000 deg^2 in the iz bands, with a J band near-infrared extension (CFBDIR; Delorme et al. 2010), and has also made significant contributions. For example, spectroscopically guided photometric selection has been employed to constrain the L5–T8 luminosity function (Reylé et al. 2010), along with early additions to the T8+ sample (Delorme et al. 2008a). It also identified a close binary system CFBDIR 1458+1013, which was resolved as a T8+Y0 pair with Keck laser guide star adaptive optics (Liu et al. 2011), representing the first Y dwarf to be discovered (though it was not classified as such until Cushing et al. 2011). More recently, the CFBDIR has also been responsible for the identification of a planetary mass T dwarf CFBDSIR 2149-0403 (Delorme et al. 2012).

The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) spacecraft has provided one of the most significant steps forward in recent years. The most prominent impact of the WISE mission has been in the coolest regime of the brown dwarf population, with a new "Y" spectra class defined to classify the coolest brown dwarfs it has found (Cushing et al. 2011; Kirkpatrick et al. 2012). In addition to uncovering 17 Y dwarfs, over 180 T dwarfs have been identified (see Table 1) including the prototypical T subdwarf, Wolf 1130B (Mace et al. 2013).

Multicolour photometric selections have been responsible for the bulk of WISE discoveries, but probing its full depth has relied on proper motion searches drawing on its multiple epochs of observations. Of particular note are the searches carried out by Luhman that have been responsible for identifying the nearest and coolest known brown dwarf (Luhman 2014a); a hitherto unidentified nearby LT binary pair (Luhman 16AB; Luhman 2013); and for largely ruling out the existent of a wide orbit substellar companion to the Sun (Luhman 2014b). Single band $W2$ high motion searches have also identified new T subdwarfs (Pinfield et al. 2014).

Table 1 reveals that already, with a few exceptions, the number of published L and T dwarf discoveries consistently lag far behind the maximum possible number of detections in a given survey. This is for several reasons. Firstly, reliable photometric selection of L and T dwarfs relies on having measured colours, or useful constraints from drop-outs, that effectively remove contaminants e.g. $i' - z'$, $z' - J$ or $W1 - W2$; and the more the better. As such, the true depth to which targets may be selected depends strongly the complementarity of the respective depths of differing bands and surveys. For example, z' should be 2 mags deeper than J to allow M dwarfs to be excluded, and it is this that limited the effective depth to which the UKIDSS-LAS could be mined for late-T dwarfs.

The other significant hurdle is the observational expense of obtaining spectroscopy for large numbers of objects at ever fainter magnitudes. There are some persuasive cases for obtaining large samples of L and T dwarfs. For example distinguishing differing brown dwarf formation histories at any significance will require substantially larger samples than currently held. Similarly measuring the substellar halo luminosity function to test for variations of the IMF at extreme metallicity, or to test for the metallicity dependence of the substellar limit will require selecting large numbers of rare halo brown dwarfs from much larger samples of LT dwarfs. Leveraging the potential of Gaia to provide well characterised benchmark primary stars in targeted parameter space (e.g. low-gravity, high-metallicity etc) will also require effective classification of large numbers of substellar companions prior to spectroscopic follow-up.

It is important to note the benefit that WISE has brought to exploiting other surveys in this context. For example, by matching the SDSS, UKIDSS LAS and WISE datasets, Skrzypek & Warren (2013) have developed a novel method for estimate L and T dwarf spectral types without the need for spectroscopy using the $izYJHKW1W2$ colours. Photometric classification methods such as this and those being developed by other groups will prove essential for exploiting the potential of deeper future surveys for which spectroscopy of many 1000s of objects will be unfeasible.

In the coming years, two surveys within the VISTA program are likely to be at the forefront of brown dwarf science, the VISTA Kilo Degree Survey (VIKING) and the VISTA Hemisphere Survey (VHS), the latter of which will probe 5 times the volume that the UKIDSS LAS probed. However, the current lack of deep optical survey covering the entire hemisphere (the Dark Energy Survey overlaps with 4000 deg^2) will hinder it reaching its full potential in the near-term. None-the-less, these surveys provide the opportunity to extend the samples of rare objects such as benchmarks and halo brown dwarfs from 10s of objects up to 100s.

The 3π survey being carried out using the Pan-STARRS 1 telescope effectively mixes the techniques of astrometric and photometric selection, allowing it to target brown dwarfs that overlap with contaminant populations in near-infrared colour space. It has proven particularly useful for selecting L and T dwarf benchmarks as wide binary companions to stars (e.g. Deacon et al. 2012a,b, 2014). This survey will also obtain parallaxes for many objects, and opens the possibility of selecting nearby brown dwarfs purely on the basis of their absolute photometry.

4. The future

The next decade will see two survey projects come on-line which will for the first time allow the detection of millions of brown dwarfs. The 20000 deg^2 imaging survey carried out as part of the Euclid mission (Refregier et al. 2010) will reach a depth of $J_{vega} \approx 23$, with similar depths in HK. It will also obtain riz imaging to complementary depths (e.g. $z_{vega} \approx 24.0$). This will allow the selection, and potentially photometric typing of objects down $J \approx 20.0$. The Large Synoptic Survey Telescope, meanwhile, will reach a depth of $z \approx 28$ in its deep stacks by the end of its first decade (LSST Science Collaboration et al. 2009). This will allow exploitation of Euclid to its full J band depth, representing a factor of 4000–8000 increase in searchable volume over 2MASS, depending on the amount of overlap sky. This will make million brown dwarf (mega-BD) catalogues a real possibility, but will depend strongly on the ability to photometrically classify L and T dwarfs. Current efforts in this vein have relied on using the WISE bands to fully characterise the SEDs of selected L and T dwarfs (e.g. Skrzypek & Warren 2013). If the next generation of surveys is to achieve its potential in revolutionising substellar science, it is highly desirable that a successor to WISE be launched that will match the depths of LSST and Euclid in the coming decades.

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