Mon. Not. R. Astron. Soc. **385,** 1771–1778 (2008) doi:10.1111/j.1365-2966.2008.12973.x

The ages of L dwarfs*

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Accepted 2008 January 13. Received 2008 January 9; in original form 2007 November 23

ABSTRACT

We present a new method to derive the age of young ($<$0.7 Gyr) L dwarfs based on their near-infrared photometry, colours and distances. The method is based on samples of L dwarfs belonging to the Upper Sco association (5 Myr), the Alpha Per (85 Myr) and Pleiades (125 Myr) clusters, and the Ursa Major (400 Myr) and Hyades (625 Myr) moving groups. We apply our method to a number of interesting objects in the literature, including a known L dwarf binary, L dwarf companions and spectroscopic members of the young σ Orionis cluster.

Key words: stars: low-mass, brown dwarfs – open clusters and associations: general.

1 INTRODUCTION

Low-mass stars and brown dwarfs undergo a significant change in luminosity over the first hundred million years (hereafter Myr) of their life (Baraffe et al. 1998; Burrows et al. 2001). As brown dwarfs fade inexorably with time, estimating their age is important to infer fundamental parameters such as the mass. A large number of age diagnostics and methods exist, including the main-sequence turn-off (Mermilliod 1981), the lithium depletion boundary (Rebolo, Martin & Magazzu 1992), rotation and activity (Randich et al. 2001), kinematics (Dahn et al. 2002; Reid et al. 2002) and belonging to a moving group (Montes et al. 2001). However, uncertainties remain both on the observational and theoretical sides: for example, ages derived from the main-sequence turn-off method tend to be half those inferred from the lithium depletion boundary (Jeffries & Naylor 2001).

Large-scale sky surveys have uncovered a large population of ultracool dwarfs (defined as dwarfs with spectral types later than M7) (e.g. Delfosse et al. 1999; Kirkpatrick et al. 2000; Geballe et al. 2002). These discoveries required a new class of objects cooler than M dwarfs to be defined. L dwarfs were proposed by Kirkpatrick et al. (1999) and Martín et al. (1999) to describe the disappearance of titanium oxide and vanadium oxide and the onset of metal alkali at optical and infrared wavelengths. Old field L dwarfs represent a mixture of very-low-mass stars and brown dwarfs (Kirkpatrick et al. 2000). They have typical effective temperatures between 2200 and 1400 K (Basri et al. 2000; Leggett et al. 2000) and exhibit red optical and near-infrared colours (Knapp et al. 2004). There are currently about 500 L dwarfs[1] known, mainly uncovered by large-scale sky surveys (e.g. Kirkpatrick et al. 2000; Chiu et al. 2006) and proper motion studies (e.g. Cruz et al. 2003), including 76 with parallaxes (Perryman et al. 1997; Dahn et al. 2002; Vrba et al. 2004).

In this paper we present a scheme to infer the age of L dwarfs using their near-infrared photometry, assuming that they are single objects with a known distance. We have chosen five samples of young, intermediate-age and old late-type dwarfs in clusters and moving groups to derive an age–colour relationship independent of theoretical models. In the first part of this paper we describe the samples used in our study (Section 2), including field L dwarf members of the Hyades and Ursa Major moving groups, Pleiades proper motion members, α Per photometric candidates and Upper Sco spectroscopic members. In the second part we discuss the method to determine the age of L dwarfs (Section 3). Finally, we apply our method to several L dwarfs with known distance published to date (Section 4).

2 THE SAMPLES

2.1 Field L and T dwarfs with known distances

The full catalogue of field L and T dwarfs can be retrieved from the DwarfArchive.org webpage[1]. Among the 487 known L dwarfs as of 2006 November (starting date of this project), 76 had measured

*Based on observations made with the United Kingdom Infrared Telescope, operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council.

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[1] See http://spider.ipac.caltech.edu/staff/davy/ARCHIVE/, a webpage dedicated to L and T dwarfs maintained by C. Gelino, D. Kirkpatrick and A. Burgasser.

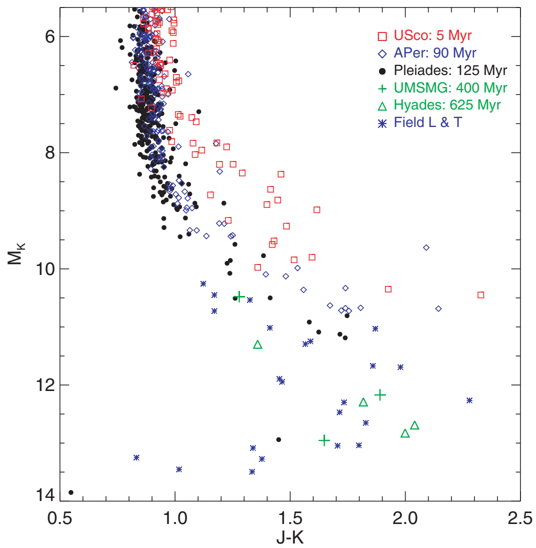

Figure 1. $(J-K, M_K)$ colour–magnitude diagram (CMD) for all the samples: Upper Sco (squares), α Per (diamonds), Pleiades (filled circles), Ursa Major (crosses), Hyades (triangles) and field dwarfs (star symbols). The photometry is on the MKO system.

parallaxes and proper motions (Perryman et al. 1997; Dahn et al. 2002; Vrba et al. 2004) but their age was, and remains for the large majority, unknown. We have used those parallaxes to infer the absolute K magnitudes (M_K) of each single L dwarf (star symbols in Fig. 1), i.e. L dwarfs not reported to date as belonging to multiple systems by high-resolution imaging surveys (see review by Burgasser et al. 2007b). The $J - K_s$ colours [on the Two Micron All Sky Survey (2MASS) system] taken from the L and T dwarf archive were transformed into the Mauna Kea Observatory system (MKO; Tokunaga, Simons & Vacca 2002) using equations detailed in Stephens & Leggett (2004) for direct comparison with photometric data on open clusters extracted from the WFCAM Science Archive (Hambly et al. 2008)[2] based on the UKIRT Infrared Deep Sky Survey (Lawrence et al. 2007).[3] All *JHK* photometry in this paper is on the MKO system unless otherwise stated.

2.2 The Hyades moving group

The Hyades galactic cluster is the nearest bound star cluster and has been extensively studied (Leggett & Hawkins 1989; Reid 1992, 1993; Reid & Hawley 1999). It has been found to be of approximate solar metallicity, Cayrel de Strobel et al. (1985) determine a value of [Fe/H] = +0.12, while Perryman et al. (1998) find 0.15. Recent age estimates range from 500 to 900 Myr (Barry et al. 1981; Kroupa 1995). The age estimate used in this paper was determined by Perryman et al. (1998) who fit theoretical isochrones which include the effects of convective overshoot to the *Hipparcos*-based cluster Hertzsprung–Russell diagram. They derive an age of 625 ± 50 Myr. The Hyades has a deficit of low-mass stars almost certainly due to dynamical mass loss, where the lower mass stars have escaped the cluster (Gizis, Reid & Monet 1999; Reid & Hawley 1999; Dobbie et al. 2002a; Moraux, Bouvier & Clarke 2005).

[2] The archive can be accessed at http://surveys.roe.ac.uk/wsa/index.html.
[3] More details on the project can be found at http://www.ukidss.org/.

Table 1. Summary of the four L dwarf members of the Hyades moving group. Magnitudes from 2MASS and infrared spectral types are listed for each object along with its distance derived from parallax measurement.

2MASS J	*J*	*H*	K_s	d_p	SpT
00361617+1821104	12.466	11.588	11.058	8.8 ± 0.1	L4
00325937+1410371	16.830	15.648	14.946	33.2 ± 6.9	L8
01075242+0041563	15.824	14.512	13.709	15.6 ± 1.2	L5.5
08251968+2115521	15.100	13.792	13.028	10.7 ± 0.1	L6
12171110−0311131	15.860	15.748	15.887	11.0 ± 0.3	T7.5

Bannister & Jameson (2007) have recently identified a number of known field L and T dwarfs with parallaxes as escaped Hyads and members of the Hyades moving group. This identification was made by requiring that the proper motions of these dwarfs pointed to the Hyades convergent point. These dwarfs also have a ‘moving group distance’ that agrees with their parallax determined distance. They found five L and two T dwarfs to be members of the Hyades moving group (Table 1). Osorio et al. (2007) measured radial velocities for five of the Bannister & Jameson (2007) Hyades moving group members. These radial velocities, together with the known proper motions, give all three components of the velocity. They confirm that these objects have velocity components lying in the 2σ velocity ellipsoid of the Hyades moving group. However, only one, 2MASS J121711.10−031113.1 (Burgasser et al. 1999), has space velocities close to those of the Hyades cluster, making it likely to be an escaped cluster member, although velocity dispersion will of course be larger for low-mass objects. It is therefore probably safer to assume the Bannister & Jameson (2007) objects, despite forming a tight sequence, are members of the moving group rather than escaped members of the cluster, and so may not be exactly coeval. 2MASS J020529.40−115929.6 (L7; Delfosse et al. 1997; Kirkpatrick et al. 1999) is not included in Table 1 since it is a known binary and possibly a triple system (Bouy et al. 2005) whose individual components are not accurately measured. Similarly, the T6 dwarf 2MASS J162414.36+002915.8 (Strauss et al. 1999) is not listed in Table 1 since if a member, it is also probably a binary. In addition, its velocity components are not as well defined as those of 2MASS J121711.10−031113.1.

2.3 The Ursa Major moving group

The principal members of the Ursa Major moving group are the stars that make up the ‘plough’, except for α UMa at a *Hipparcos* distance of 38 pc. Group members can be found all over the sky, for example Sirius, which may be a member, is only 2.65 pc from the Sun (distance from *Hipparcos*). Thus the Sun, while not a member, is actually situated inside the moving group. The convergent point of the Ursa Major moving group is located at $\alpha = 20^h18\overset{m}{.}83$, $\delta = -34°25\overset{\prime}{.}8$ (Madsen, Dravins & Lindegren 2002). The age of the group was determined as 300 Myr by Soderblom & Mayor (1993), although more recently, Castellani et al. (2002) found 400 Myr, while King et al. (2003) have reported an age of 500 ± 100 Myr for the group. We use 400 Myr as the age of the moving group. Using a similar method to that used for the Hyades moving group, Bannister & Jameson (2007) have found that three L dwarfs and one T dwarf with known distances belong to the Ursa Major moving group (Table 2). There is no evidence from the literature that any of these

Table 2. Summary of the one early-L dwarf, two transition objects and one T dwarf, members of the Ursa Major moving group. Magnitudes from 2MASS and infrared spectral types are listed for each object along with its distance (and its associated error) derived from parallax measurement.

2MASS J	J	H	K_s	d_p	SpT
03454316+2540233	13.997	13.211	12.672	27.0 ± 0.4	L1
14460061+0024519	15.894	14.514	13.935	22.0 ± 1.5	L/T
15232263+3014562	16.056	14.928	14.348	18.6 ± 0.4	L8
02431371−2453298	15.381	15.137	15.216	10.7 ± 0.4	T6

dwarfs are binaries from high-resolution imaging carried out from space or with ground-based adaptive optics. One L dwarf, 2MASS J152322.63+301456.2 (also known as Gl 584C; Kirkpatrick et al. 2000) has a spectral type of L8 and is on the LT transition, or the blueward part of the L dwarf sequence.

2.4 The Pleiades cluster

The Pleiades is arguably the best studied open cluster in the northern sky, mainly due to its proximity and richness. Its mean distance is estimated to be 132 ± 7 pc. This has been determined using various methods, including isochrone fitting (126 ± 6 pc; Johnson 1957), ground-based parallaxes (131 ± 7 pc; Gatewood, de Jonge & Han 2000) and a recent estimate from a detached eclipsing binary member of the Pleiades (139.1 ± 3.5 pc; Southworth, Maxted & Smalley 2005). The uncertainty on the distance is roughly half the tidal radius of the cluster (13 pc; Pinfield et al. 2000). The age of the Pleiades is 125 ± 8 Myr (Stauffer, Schultz & Kirkpatrick 1998) as derived by the lithium depletion boundary (Rebolo et al. 1992). The turn-off main-sequence age is, however, estimated to be ∼80 Myr (Mermilliod 1981), a difference also observed in other open clusters (Jeffries & Naylor 2001) including α Per (Barrado y Navascués et al. 2002). The large mean proper motion ($\mu \sim 50$ mas yr^{-1}) of the cluster makes the Pleiades an ideal place to identify members over a baseline of a few years.

Our sample of Pleiades brown dwarfs include photometric and proper motion members extracted from cross-correlations between optical and near-infrared data. The full selection procedure is detailed in Lodieu et al. (2007a). Briefly, we have cross-correlated optical data from the Issac Newton (Pinfield et al. 2000; Dobbie et al. 2002b) and Canada–France–Hawaii (Bouvier et al. 1998; Moraux et al. 2003) surveys with the UKIDSS Galactic Cluster Survey (GCS) Data Release 1 (DR1) available in the Pleiades to measure proper motions for about 60 brown dwarfs down to 0.03 $M_{\odot}$ thanks to a 5- to 7-yr baseline between the optical and infrared observations. Moreover, the stellar sequence originates from the work by Adams et al. (2001) using the 2MASS data base (Cutri et al. 2003). The subsample of low-mass stars and brown dwarf members fainter than an absolute magnitude $M_K = 6$ mag (MKO) is plotted as filled dots in Fig. 1.

In addition to the above sample, we have added two candidate members (filled dots in Fig. 1) with photometry in two optical filters from the Canada–France–Hawaii (Bouvier et al. 1998; Moraux et al. 2003) survey and in the *JHK* passbands as well as proper motion consistent with the Pleiades measured again over a 5-yr baseline (Casewell et al. 2007). The first one, PLZJ 23, is a transition object with $J - K$ (MKO) = 1.45 mag and a photometric spectral type estimated to be L8–T1.5. The second object, PLZJ 93, is a mid-T dwarf with $J - K$ (MKO) = 0.55 mag (Casewell et al. 2007).

2.5 The α Per cluster

The α Per cluster has been extensively studied using photometric, proper motion and spectroscopic criteria (Stauffer et al. 1985; Stauffer, Hartmann & Jones 1989; Prosser 1992, 1994). The cluster has a distinguishable proper motion of $\mu \sim 25$ mas yr^{-1} and is 182 ± 8 pc away from the Sun. This distance represents a compromise between the *Hipparcos* ($190.5^{+7.2}_{-6.7}$ pc; Robichon et al. 1999 and main-sequence fitting distances (176.2 ± 5.0 pc; Pinsonneault et al. 1998). The uncertainty in the distance does not affect the absolute magnitudes by more than ±0.1 mag and is smaller than the tidal radius of the cluster. The age of the cluster is 90 ± 10 Myr from the lithium depletion boundary (Stauffer et al. 1999), twice the age inferred from the turn-off main-sequence method (50 Myr; Mermilliod 1981). Barrado y Navascués, Stauffer & Jayawardhana (2004) revised the age to 85 ± 10 Myr, the value that we adopt here.

All α Per members down to the hydrogen-burning limit are photometric and proper motion members identified by Deacon & Hambly (2004) and confirmed as such by the GCS data. As for the Pleiades, the lowest mass members were extracted from the UKIDSS GCS DR1 over a 9-deg^2 area but remain photometric candidates only because we lack proper motions due to the small overlap between optical (Barrado y Navascués et al. 2002) and infrared (GCS DR1) observations. In that respect, this is the most uncertain sequence (diamonds in Fig. 1) among the five clusters/groups considered here, although we do have photometry in five passbands (*ZYJHK*). Moreover, the analysis of the control fields from the GCS (about 3 deg^2 located roughly four degrees away from the cluster centre) show that our sequence should suffer from a low level of contamination below K_s (2MASS) = 14.3 mag.

2.6 The Upper Sco association

Upper Sco is part of the nearest OB association, Scorpius–Centaurus (de Geus, de Zeeuw & Lub 1989) located at a distance of 145 pc from *Hipparcos* parallax measurements (de Bruijne et al. 1997; de Zeeuw et al. 1999). The cluster is 5-Myr old with a scatter of less than 2 Myr (Preibisch & Zinnecker 1999). This age estimate is derived from the nuclear age (5–6 Myr; de Geus et al. 1989) and the dynamical age (4.5 Myr; Blaauw 1991). Members with masses as low as 0.1 $M_{\odot}$ have been identified by various surveys at multiple wavelengths (Walter et al. 1994; Preibisch et al. 1998; Kunkel 1999; Preibisch, Guenther & Zinnecker 2001) and an estimate of the initial mass function (Salpeter 1955) over the 2.0–0.1 $M_{\odot}$ mass range was provided by Preibisch & Zinnecker (2002). Several additional optical surveys complemented by near-infrared photometry have been carried out in the region to find lower mass stellar members and brown dwarfs (Ardila, Martín & Basri 2000; Martín, Delfosse & Guieu 2004; Slesnick, Carpenter & Hillenbrand 2006).

We have extended the cluster mass function down to 0.01 $M_{\odot}$ and extracted 20 new brown dwarfs below 0.030 $M_{\odot}$ over 6.5 deg^2 surveyed during the science verification phase of the UKIDSS GCS (Lodieu et al. 2007b). All photometric candidates extracted from that survey are displayed as open squares in Fig. 1. We have recently confirmed 18 out of 20 photometric candidates (i.e. success rate of 90 per cent) fainter than K(MKO) ∼13.7 mag (or M_K(MKO) ∼7.9 mag) as spectroscopic members based on the their spectral shape and the presence of weak gravity-sensitive features (Lodieu et al. 2008). This limit in magnitude corresponds to effective temperatures cooler than 2700 K and masses below 0.030 $M_{\odot}$ according to theoretical models (Chabrier et al. 2000). All spectroscopic members have spectral types later than M8, the majority being L dwarfs.

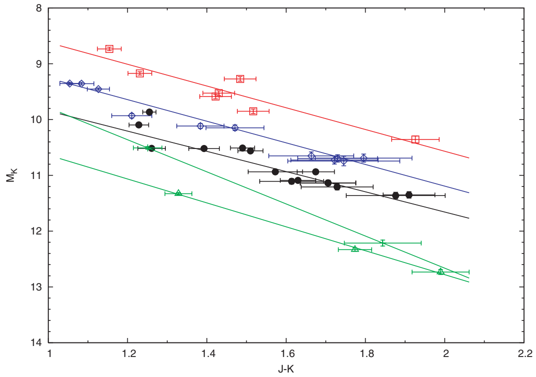

Figure 2. The ($J-K, M_K$) diagram for the members of all five clusters/groups under study, including Upper Sco in red (boxes), α Per in blue (diamonds), the Pleiades in black (filled circles), Ursa Major (crosses) and the Hyades in green (triangles). The photometry is on the MKO system.

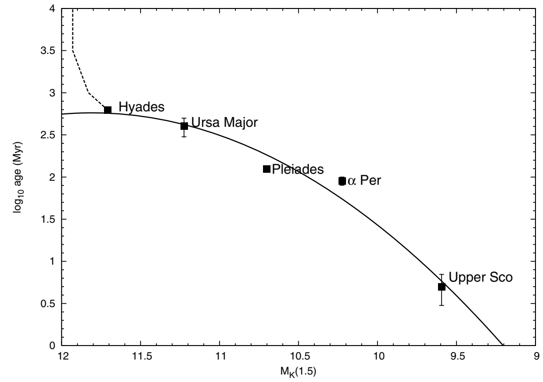

Figure 3. Age versus M_K for $J-K=1.5$ mag. The clusters are marked by filled squares with error bars corresponding to uncertainties quoted in Table 3. The dotted line represents the predicted deviation from the quadratic fit (solid line). The data for these points are found in Table 3. The photometry is on the MKO system.

3 THE DETERMINATION OF THE AGE

In this section we describe the method to derive the age of L dwarfs using their $J-K$ colours and absolute K magnitudes. Initially we consider only those L dwarfs on the redward sequence, i.e. dwarfs with spectral types from L0 up to approximately L8. We discuss the late-L and late-T dwarfs that lie on the L to T blueward sequence in Section 3.4. Fig. 2 shows an expanded simplified version of Fig. 1. Fig. 2 shows that the single L dwarfs for each cluster fit a well-defined sequence or isochrone. This is expected theoretically (Chabrier et al. 2000; Burrows et al. 2001; Burrows, Sudarsky & Hubeny 2006). For each cluster/isochrone there is a modest decrease ($\sim$ a factor of 2) in mass, but a smaller decrease ($\sim$25 per cent) in radius for the L dwarfs. $J-K$ increasing from 1.0 to 2.0 corresponds to a drop in $T_{\rm eff}$ from $\sim$2100 to $\sim$1700 K, which is approximately the same for all of the clusters. The separation of the cluster isochrones in M_K is caused by the different radii/surface areas at a given $J-K/T_{\rm eff}$.

3.1 Restrictions on the method

The first step is to remove known binaries or objects that clearly lie above the single-star sequence in each cluster/group, i.e. photometric multiple system candidates. Potential multiple systems in the Pleiades are listed in appendix F in Lodieu et al. (2007a). For the Hyades, we remove one known binary, 2MASS J0205293−115930 (L5.5) identified by Bouy et al. (2005). For α Per, we have excluded candidates lying clearly above the single-star sequence in a similar way as in the Pleiades. Finally, we have excluded the reddest dwarf in the Upper Sco sample [$J-K\sim 2.3$ mag and $M_K\sim 11$ mag (MKO magnitudes)].

The main restrictions on the method presented in Section 3.2 are as follows.

(i) The method is based on the MKO photometric system: corrections from the 2MASS into the MKO system are made using the transforms of Stephens & Leggett (2004).

(ii) A parallax or other distance determination is needed.

(iii) The object must not be a binary (see above). If it is, then the method can only be used if some further information is available to determine the photometry of each individual component.

(iv) Its metallicity must be approximately solar (see Section 3.3).

(v) The method is currently valid only for objects with spectral type earlier than L8, i.e. objects not on the L/T transition sequence, nor on the turning point to the L/T transition sequence (Section 3.4).

(vi) As can be seen from Fig. 3 the method will become inaccurate for ages $\geqslant$0.7 Gyr since the isochrones for older L dwarfs become progressively closer. This is expected theoretically, see Chabrier et al. (2000) for more details.

3.2 Method

First of all, we fit each dwarf sequence with a straight line of the form $M_K = \mathrm{A} + \mathrm{B}(J-K)$ (on the MKO system) as shown in Fig. 2. At the blue end of the sequence, we terminate the lines where they begin to curve up towards the M dwarf sequence. Values of the gradient B for each group are presented in Table 3 along with values of M_K at $J-K=1.5$ mag (MKO). We can see that the fit to the Ursa Major data points is clearly discrepant with the other groups. Its gradient of 2.88 is steeper than the mean values observed for the other clusters but is based on only two points.

It would probably be better to use a gradient of 1.98 around 400 Myr, the average of the ages of the Pleiades and Hyades. However, the value of M_K at $J-K=1.5$ mag (MKO) in Fig. 3 seems reasonable.

We suggest using the following method for determining the age of a dwarf with a known absolute magnitude M_K and $J-K$ colour.

Table 3. Name, age (in Myr), gradient B of the fit to M_K as a function of $J-K$ (MKO) and the value M_K for $J-K=1.5$ mag (MKO) obtained from the straight line fits for the five clusters/groups studied (Fig. 2).

Name	Age	Gradient	$M_K(1.5)$
Upper Sco	5 ± 2	1.95 ± 0.34	9.59 ± 0.03
α Per	85 ± 10	1.93 ± 0.12	10.22 ± 0.03
Pleiades	125 ± 8	1.81 ± 0.19	10.70 ± 0.04
Ursa Major	400 ± 100	2.88 ± 0.00^a	11.22 ± 0.00
Hyades	625 ± 50	2.14 ± 0.09	11.70 ± 0.03
–	1000	–	11.83
–	5000	–	11.93
–	10 000	–	11.93

[a] A gradient of 1.98 would be more adequate for Ursa Major (see discussion in Section 3.2).

First, plot the dwarf on Fig. 2, and determine which cluster/group it is nearest. Then use Table 3 to find the appropriate value of B for that cluster, hence the value of M_K can then be determined corresponding to $J - K = 1.5$ mag (MKO), i.e. $M_K(1.5) = M_K - \mathrm{B}\,(J - K - 1.5)$. The age in Myr for this value of M_K at $J - K = 1.5$ mag can then be read off the fit to the data in Fig. 3, given by a quadratic expression shown in equation (1),

$$\log(\mathrm{age}) = -53.9753 + 9.609\,44 M_K(1.5) - 0.406\,885 M_K(1.5)^2. \quad (1)$$

As can be seen from Fig. 3 it is possible to fit a smooth curve through the points that only just misses the Pleiades and α Per. There is no reason to believe that a smooth curve is the correct fit, but we will adopt this parabolic fit until more information is available. Indeed fig. 9 of Burrows et al. (2001) which plots dwarf masses versus age and T_{eff} has some kinks around 30 and 100 Myr due to deuterium burning which may explain the anomalous Pleiades and α Per points. A comparison with theoretical models is probably too premature. The Lyon group is in the process of revising the DUSTY models (F. Allard, personal communication; Chabrier et al. 2000) and the Arizona group (Burrows et al. 2006) do not calculate isochrones which makes it difficult to compare their L dwarf models with observations.

The polynomial equation (1) describing the smooth curve in Fig. 3 cannot be used for ages greater than the age of the Hyades. For ages ~1–10 Gyr, gravity will only change by very small amounts, hence one would expect the surface brightness to be constant for a given effective temperature (T_{eff}) and M_K would simply scale as 5 log (radius). Using the DUSTY models from Chabrier et al. (2000) to find radii at $T_{\mathrm{eff}} \sim 1800$ K (corresponding $J - K = 1.5$ mag) we can then calculate M_K relative to the Hyades. This is shown as the dashed line in Fig. 3. The associated M_K values at $J - K = 1.5$ mag are given in Table 3. Clearly this abrupt change of slope at the Hyades is unsatisfactory. It is tempting to suggest that the age of the Hyades is older than our adopted value of 625 Myr. This would make for a smoother gradient change.

Fig. 4 shows the $(J - K, J - H)$ colour–colour diagram for all the single stars used in determining the cluster fits on the MKO system. The line can be described by a linear regression like $J - H = \mathrm{a} + \mathrm{b}(J - K)$, where $\mathrm{a} = -0.11 \pm 0.07$ and $\mathrm{b} = 0.63 \pm 0.04$. This fit can be used to determine the K magnitude if for some reason only J and H photometry are available. One can then proceed as explained above to determine the age of the object.

3.3 Metallicity

It is clear that for a given spectral type, estimated from the spectrum over the 0.6–0.9 μm wavelength range, the $J - K$ colour is much bluer for metal-poor dwarfs (Burgasser et al. 2008). There is a similar effect seen in M dwarfs where the $J - K$ colour is bluer by less than 0.7 mag (Gizis 1997). This result is confirmed theoretically, i.e. $J - K$ gets bluer with decreasing metallicity at constant effective temperature (Burrows et al. 2006). All the clusters discussed here have approximately solar metallicity, implying that our age determination can only be valid for solar metallicity dwarfs. Only a few metal-poor dwarfs of L spectral type have been reported to date (Burgasser, Cruz & Kirkpatrick 2007a) so extending our method to low metallicity is currently impossible. To understand the effect of metallicity theoretical isochrones $(J - K, M_K)$ are needed for differing metallicities at cool temperatures and these are not yet available.

3.4 The L to T transition

The L dwarf sequence presents two parts. Up to a spectral type of ≈L8 the $J - K$ colour keeps increasing. It then turns over for cooler objects, yielding a decrease in the $J - K$ colour due to the loss of condensate grains from the photosphere and the strengthening methane absorption. Fig. 5 shows the change and the blueward transition region for the Pleiades (filled squares), Ursa Major (filled triangles) and the Hyades (filled diamonds). The Pleiades dwarfs are from Casewell et al. (2007) and the dwarfs for Ursa Major and the Hyades come from Bannister & Jameson (2007). As far as we are aware, no data exist for the LT transition region for α Per and Upper Scorpius. We have tentatively drawn sequences for the three clusters as displayed in Fig. 5. As expected, the Pleiades lies above Ursa Major, which is itself above the Hyades, suggesting that the trend observed for L dwarfs extends all the way down to T dwarfs. However, we feel that it would be too premature to claim an age relation for these transition L and T dwarfs, as data are currently limited to a small number of objects. Clearly, more members are required at cooler temperatures for all of the clusters to extend this

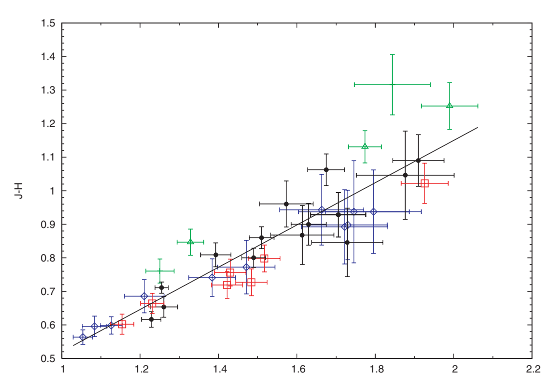

Figure 4. The $(J - K, J - H)$ colour–colour diagram for all members belonging to the five clusters/groups under study, including Upper Sco in red (boxes), α Per in blue (diamonds), the Pleiades in black (filled circles), Ursa Major (crosses) and the Hyades in green (triangles). The photometry is on the MKO system.

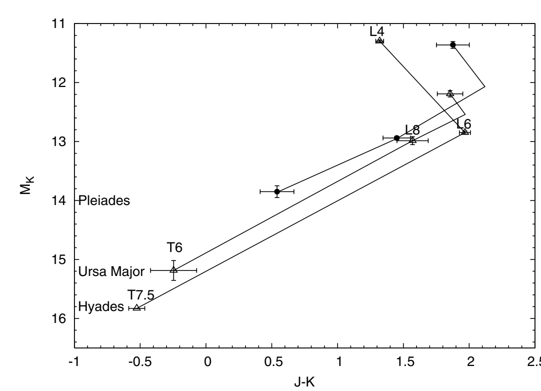

Figure 5. The $(J - K, M_K)$ CMD for the three clusters/groups studied with known L/T transition members. The Hyades and Ursa Major are plotted with triangles and the Pleiades objects are plotted with filled circles. The objects with known spectral types are marked (see Tables 1 and 2). No spectra have been observed for the Pleiades objects, and so no spectral types are available for them. The photometry is on the MKO system.

method around the maximum $J - K$ point (LT transition) and on to the T sequence (Fig. 5).

4 APPLICATION OF THE METHOD

In this section we apply our method to a number of interesting objects reported in the literature, assuming that they have solar-like metallicity and that they are single.

4.1 The L dwarf binary 2MASS J074642.5+200032.1

2MASS J0746425+2000321 is a resolved L0+L1.5 binary. Bouy et al. (2004) have measured the orbit of this binary and determine a total mass of 0.146 $M_{\odot}$. They estimate the individual masses as 0.085 and 0.066 $M_{\odot}$ with uncertainties smaller than 0.01 $M_{\odot}$. They estimate the age of this system to be 150–500 Myr based on its position in a Hertzsprung–Russell diagram using the DUSTY (Chabrier et al. 2000) isochrones. Gizis & Reid (2006) argue that it is an older system with an age of greater than 1 Gyr. They argue that the DUSTY models do not accurately model the complex molecular absorption and grains at this point, and so claim a better method is to compare the colours of 2MASS J074642.5+200032.1 with those of field objects, and so determine the system is older.

The system has a measured parallax of 81.9 ± 0.3 mas yr^{-1}, corresponding to a distance of 12.2 ± 0.1 pc and implying absolute K magnitudes of 10.61 ± 0.09 and 11.03 ± 0.17 for the primary and the secondary, respectively. Assuming $J - K$ colours of 1.12 and 1.3 mag (2MASSS), our method (using the transforms given in Stephens & Leggett 2004) gives ages of 574 and 575 Myr for the primary and the secondary, respectively. These results seem to favour the younger ages from previous studies. This system is important since with a known age and distance, it could be used to directly test theoretical models.

4.2 The 2MASS J120733.4−393254AB system

2MASS J120733.4−393254b (hereafter 2M1207b) is thought to be a planetary-mass (3–10$M_{\rm Jup}$; Chauvin et al. 2004, 2005) companion to 2M1207A (Gizis 2002) which belongs to the TW Hydrae association whose age is estimated to ∼8 Myr (Song, Zuckerman & Bessell 2003; Zuckerman & Song 2004). Recently, three independent trigonometric parallaxes yielding consistent values were reported, implying a distance of 52.4 ± 1.1 pc (Biller & Close 2007; Gizis et al. 2007; Ducourant et al. 2008). Hence, the absolute K magnitude of 2M1207b is $M_{K_s} = 13.33$ based on the latest near-infrared photometry ($J = 20.0 \pm 0.2$ mag, $K_s = 16.93 \pm 0.11$ mag in the 2MASS system) obtained by Mohanty et al. (2007).

Because 2M1207b has now an accurate age and distance, it would be a very interesting object to test our method. Unfortunately its red $J - K$ colour ($J - K = 3.07$ mag) possibly due to the presence of a disc seen edge-on (Mohanty et al. 2007) prevents us from comparing 2M1207b with our samples of L dwarfs whose $J - K$ colour are bluer than 2.0 mag. We can only put an upper limit on its age by extending the cluster sequences in Fig. 1 and argue that it is younger than α Per (85 Myr; Barrado y Navascués et al. 2004).

4.3 The HD 203030AB system

HD 203030B is a late-type (L7.5 ± 0.5) brown dwarf companion (Metchev & Hillenbrand 2006) to HD 203030A, a young G8 star at 40.8 ± 1.8 pc (Jaschek 1978; Perryman et al. 1997). The age of the primary is fairly well constrained, around 130–400 Myr, with a mean value of 250 Myr based on photometry, stellar rotation, chromospheric activity, lithium and space motion. The secondary has $M_{K_s} = 13.15 \pm 0.14$ and $J - K = 1.92$ (2MASS) (Metchev & Hillenbrand 2006) ($M_K = 13.13, J - K = 1.72$, MKO). Our method then yields an age of 401 Myr in agreement with the age range of the primary star.

4.4 The σ Orionis dwarfs

A large sample of brown dwarfs and planetary-mass objects (Zapatero Osorio et al. 2000) have been found in the σ Orionis cluster (age =3–7 Myr; $d = 360^{+70}_{-60}$ pc; Zapatero Osorio et al. 2002; Brown, de Geus & de Zeeuw 1994). Several of them have been confirmed as spectroscopic members of L spectral type based on their Hα emission and gravity features at optical wavelengths (Zapatero Osorio et al. 2000; Barrado y Navascués et al. 2001). The sample is divided into two groups: four sources whose $J - K$ colour and K magnitudes (SOri56, 58, 60 and 66; Table 4) are available from the UKIDSS GCS DR2 (Warren et al. 2007) and the remaining ones (Table 4) whose near-infrared photometry is available either from Zapatero Osorio et al. (2000) or Martín et al. (2001).

The M_K for each of these objects has been calculated for $J - K = 1.5$ mag using a slope of 1.95 from Fig. 2, i.e. the slope for Upper Sco, the cluster closest to σ Ori in terms of age. Table 4 shows a wide range of ages for these dwarfs. Our method confirms that using distances of 300–430 pc, some, but not all of these objects are young.

5 CONCLUSIONS AND OUTLOOK

We have presented a new method to infer the age of young (age ⩽0.7 Gyr) L dwarfs from their infrared photometry alone, assuming

Table 4. Name, absolute K magnitude (M_K), $J - K$ colour (MKO), and value of M_K at $J - K = 1.5$, and estimated ages assuming distances of 300, 360 and 440 pc for four spectroscopic L dwarfs member of the σ Ori cluster.

Name	RA	Dec.	M_K			$J - K$	$M_K(J - K = 1.5)$			Age (Myr)		
	J2000	J2000	300 pc	360 pc	430 pc		300 pc	360 pc	430 pc	300 pc	360 pc	430 pc
SOri 52	05 40 09.2	−02 26 32.0	8.884	8.488	8.103	1.090	9.683	9.287	8.902	8.5	1.5	0.2
SOri 56	05 39 00.9	−02 21 42.0	9.470	9.074	8.689	1.490	9.490	9.094	8.708	3.7	0.6	0.1
SOri 58	05 39 03.6	−02 25 36.0	9.658	9.262	8.877	1.280	10.087	9.691	9.306	35.9	8.6	1.6
SOri 60	05 39 37.5	−02 30 42.0	10.197	9.801	9.416	1.350	10.489	10.093	9.708	113.1	36.7	9.3
SOri 62	05 39 42.1	−02 30 31.0	10.474	10.078	9.693	1.590	10.299	9.903	9.517	68.2	19.2	4.2
SOri 65	05 38 26.1	−02 23 05.0	11.434	11.038	10.653	1.080	12.253	11.857	11.472	>580	576.1	519.2
SOri 66	05 37 24.7	−02 31 52.0	10.991	10.595	10.210	1.600	10.796	10.400	10.015	220.9	90.0	28.4
SOri 67	05 38 12.6	−02 21 38.0	11.234	10.838	10.453	1.300	11.624	11.228	10.843	559.2	421.0	241.1
SOri 68	05 38 39.1	−02 28 05.0	11.024	10.628	10.243	1.770	10.498	10.102	9.717	115.4	37.6	9.6

that their distance is known and they are single objects of solar like metallicity. Eggen (1996) finds that for a sample of nearby lower main-sequence stars 53 per cent have ages of less than 1 Gyr and we would expect a similar result for L dwarfs. Thus the technique will be useful for many L dwarfs.

Our method can only be as accurate as the calibrating clusters used and it is possible that differences in metallicity between the clusters could have a significant effect on the determination of the age. It would be very helpful to have some theoretical guidance on how the metallicity affects the isochrones which would involve running the structure and atmospheric models for different metallicities. At the very least the method is capable of saying whether a given dwarf is older or younger than the calibrating clusters with an accuracy of ±0.2 in log (age). However, relative ages can be measured more precisely. With a dynamic range $\sim$2.5 mag in absolute magnitude, it has the potential, with further observations and theoretical input, to become a very accurate and powerful method. Hence, we anticipate that this method will evolve and improve with the discovery of a larger number of L dwarfs with a wider range of ages as well as with updated theoretical models.

ACKNOWLEDGMENTS

NL, SLC and PDD are postdoctoral research associates that were funded for part of this work by PPARC and STFC. This research has made use of the Simbad data base of NASA's Astrophysics Data System Bibliographic Services (ADS). Research has benefited from the M, L and T dwarf compendium housed at DwarfArchives.org and maintained by Chris Gelino, Davy Kirkpatrick and Adam Burgasser.

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