L and T dwarfs in the Hyades and Ursa Major moving groups

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ABSTRACT

We have used the moving cluster method to identify three L dwarfs and one T dwarf in the Ursa Major/Sirius moving group (age 400 Myr). Five L dwarfs and two T dwarfs are found to belong to the Hyades moving group (age 625 Myr). These L and T dwarfs define 400- and 625-Myr empirical isochrones, assuming that they have the same age. Moving group membership does not guarantee coevality.

Key words: stars: kinematics – stars: low-mass, brown dwarfs – open clusters and associations: individual: Ursa Major – open clusters and associations: individual: Hyades – galaxies: star clusters.

1 INTRODUCTION

Apart from a brief phase of lithium burning, brown dwarfs cool continuously. Thus any meaningful comparison with theory requires a knowledge of the age of the brown dwarf. For this reason much effort has been devoted to finding brown dwarfs in clusters whose age is known. The three closest clusters are the Hyades (d = 46 pc), Coma (d = 90 pc) and the Pleiades (d = 130 pc). The Hyades and Coma are old clusters with ages of 625 Myr (Perryman et al. 1998) and 500 Myr (Odenkirchen, Soubiran & Colin 1998) respectively, and were not thought to have any brown dwarfs. More recently, Moraux et al. (2003) have found two brown dwarfs in the Hyades and Casewell, Jameson & Dobbie (2005) have found 13 brown dwarf candidates in the Coma cluster. The Pleiades (age 125 Myr) has some 50 known brown dwarfs (Jameson et al. 2002), with some more recently discovered by Moraux et al. (2003). Thus the nearest cluster with a significant number of known brown dwarfs is the Pleiades at a distance of 130 pc. This distance, together with the intrinsic faintness of brown dwarfs, naturally makes it difficult to study cluster brown dwarfs. By contrast, field brown dwarfs are close (∼10–40 pc) and easier to study but usually have unknown ages. However, some field star ages have been measured [see for example Kirkpatrick et al. (2001) or Burgasser, Burrows & Kirkpatrick (2006)]. Field brown dwarfs are found by surveys such as 2MASS (Skrutskie et al. 1997), DENIS (Epchtein et al. 2002) and the SDSS (York et al. 2003). A compilation of the known L and T dwarfs can be found in the L and T Dwarf Archive (Kirkpatrick 2003).

One possible way of finding the ages of field brown dwarfs would be to see if they are members of a moving group. A moving group is a group of stars with the same velocity, magnitude and direction, and the same age [see Zuckermann & Song (2004) for a recent review]. One of the closest moving groups is the Ursa Major/Sirius moving group (hereafter UMSMG). The core of the moving group, possibly a bound cluster, is in the direction of Ursa Major. Indeed, the stars of the ‘Plough’ (except UMa) are all members, as also is Sirius (see Fig. 1). Thus the Sun is actually inside the UMSMG. Group members can be found all around the sky, and may be very close: for example, Sirius is only 2.65 pc from the Sun. The age of the UMSMG has been determined as 300 Myr by Soderblom & Mayor (1993). More recently, Castellani et al. (2002) found 400 Myr while King et al. (2003) found 500 ± 100 Myr for the group age. We will adopt an age of 400 ± 100 Myr.

Since moving group stars have a common velocity, they appear to be moving towards the same place in the sky; this is called the ‘convergent point’. The UMSMG convergent point is located at \( \alpha_{2000} = 20^h18^m38.3, \delta_{2000} = -34^\circ25'8" \) (Madsen, Dravens & Lindegren 2002). Thus if a field brown dwarf has a proper motion directed towards the UMSMG convergent point, it is a potential member of the UMSMG. This, coupled with two distance tests (see below), allows us to identify members with considerable confidence.

The Hyades is discussed in a thorough paper by Perryman et al. (1998). The cluster lies at a distance of \( d = 46 \) pc, and has an extent in the sky of approximately 20'. Madsen et al. (2002) give the position of the cluster centroid as \( \alpha_{2000} = 4^h26^m58, \delta_{2000} = +16^\circ54' \). The Hyades is known to be deficient in low-mass members (Gizis, Reid & Monet 1999). These have probably evaporated from the cluster. Indeed, Chereul, Creze & Bienayme (1998) have identified escaped Hyads and these may be thought of as part of the Hyades Moving Group (HMG). The convergent point of the Hyades is located at \( \alpha_{2000} = 6^h29^m48, \delta_{2000} = -6^\circ53'4 "\), and their total space velocity is 46 km s\(^{-1}\) (Madsen et al. 2002). The most recent and generally quoted Hyades age is 625 ± 50 Myr by Perryman et al. (1998), and we will adopt this age.

2 IDENTIFYING GROUP MEMBERS

For the 70 members of the L and T Dwarf Archive (Kirkpatrick 2003) (available at http://www.dwarfarchives.org) with a measured proper motion, we first calculate the angular distance, \( D \), of the

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dwarf from the UMSMG or HMG convergent point, where $D$ is given by

$$\cos D = \sin \delta \sin \delta_p + \cos \delta \cos \delta_p \cos DA.$$  \hspace{1cm} (1)

Here $\delta$ and $\delta_p$ are the dwarf declination and convergent point declination, and $DA$ is the difference of their respective right ascensions.

Next we find the direction, $\theta$, from north of the convergent point, where

$$\cos \theta = \frac{\sin \delta_p - \sin \delta \cos D}{\cos \delta \sin D}.$$  \hspace{1cm} (2)

A group member should have a proper motion direction equal to $\theta$. However, there is some velocity dispersion amongst group members, otherwise all group members would appear to be very close together, as if in a bound cluster. For the UMSMG the velocity $v$ is 17.98 km s$^{-1}$ and $\sigma_v = 2.82$ km s$^{-1}$ (Madsen et al. 2002). We adopt the same $\sigma_v$ for the Hyades' recent escapers, even though this value is considerably less than the $\sqrt{3.6^2+3.2^2+5.2^2} = 7.09$ km s$^{-1}$ given by Chereul, Creze & Bienayme (1999). Thus we impose the same membership conditions for both the UMSMG and the HMG.

We find that members have a proper motion direction within $\sim 13^{\circ}$ of $\theta$. This corresponds to $1.5\sigma_p$, or 87 per cent completeness, which seems reasonable. This constraint is our first criterion for membership, and the random chance of passing this first test is clearly $4 \times 2 \times 13/360 = 0.28$. The extra factor of 4 is because proper motion directions are not randomly oriented (see Section 7).

It may readily be shown (Carroll & Ostlie 1996) that for a moving group the distance $d_{\text{arc}}$ (in parsecs) of any member is given by

$$d_{\text{arc}} = \frac{v \sin D}{4.74 \mu}.$$  \hspace{1cm} (3)

where $\mu$ is the proper motion in arcsec per year. If the star is not a moving group member then the above formula does not apply.

Our second test is to compare this moving cluster distance with the distance measured by parallax, $d_p$. Once again, 1.5 times the velocity dispersion leading to a 28 per cent error compared with the parallax distance seems to cover all the members that we find. As in the first test, we estimate the random chance of a star passing this test. Using the 70 dwarfs with parallaxes, minus the four dwarfs that we ultimately identify as UMSMG members (as discussed in the next section), we calculate $d_{\text{arc}}/d_p$ and find that nine dwarfs have $0.72 < d_{\text{arc}}/d_p < 1.28$, i.e. within $1.5\sigma_p$, or 28 per cent. If nine out of 66 dwarfs pass this test by chance, the probability is $9/66 = 0.14$. A similar test for the HMG yields $14/63 = 0.22$. We adopt this higher probability for both the UMSMG and the HMG to avoid over-estimating the significance of the test outcomes.

Finally we calculate the absolute magnitude at any wavelength using the parallax, and our last test is to place the objects in a colour–absolute magnitude diagram. This third check requires that the object lies in a ‘correct’ or sensible position in the colour–magnitude diagram. By that we mean that there is some evident sequence. We do not require that the objects fit the theoretical isochrones [see point (v) under Section 6].

The entire L dwarf sequence for the 70 field stars is approximately 3.5 mag wide, a factor of 25 in intensity. Allowing for binaries, an isochrone can vary in intensity at any colour by a factor of 2. This gives $2/25 = 0.08$ as the random chance of passing the third test.

Thus the total probability of passing all three independent tests by chance is $0.28 \times 0.22 \times 0.08 = 0.005$ per cent, suggesting that passing all three tests gives 99.95 per cent confidence of membership.

The Dwarf Archive has some 459 entries but unfortunately only 70 of these have measured proper motions. Those with proper motions also have accurate parallaxes.

### 3 L AND T DWARFS IN THE UMSMG

Of the 70 objects in the archives with proper motions, we find four to be members of the UMSMG. Three are L dwarfs and there is one T dwarf. Table 1 lists their spectral type, magnitude and distance as determined from the moving cluster and parallax methods. Also in Table 1 we give $\Delta \theta$, the difference between the convergent point direction and measured proper motion direction. As mentioned above, due to velocity dispersion and errors in the moving group we do not expect $\Delta \theta$ to be zero or $d_{\text{arc}}/d_p = 1$. Velocity dispersion dominates over measurement errors. As can be seen from Table 1, $\Delta \theta$ varies from 1:6 to 13:5 and $d_{\text{arc}}/d_p$ differs from unity by 1–18 per cent. With these two parameters the group members effectively pick themselves. Thus if $\Delta \theta$ is allowed to increase above $13^\circ$ to (say) $25^\circ$, no candidates have $d_{\text{arc}}/d_p$ close to unity.

However, in the interests of scientific integrity, we point out that a fifth star, 2M 1228–15, passed the first two tests and apparently passed the third. However 2M 1228–15 is a known near-equality binary (Brandner et al. 2004). Thus its two components lie $\sim 0.75$ mag below their combined magnitude and do not fit the UMSMG sequence, hence failing the third test. This does not fit very well with our estimate of $\sim 3$ per cent chance of passing the first two tests by random chance.

### 4 L AND T DWARFS IN THE HMG

For the HMG we find that five L dwarfs and two T dwarfs pass all three tests. Again relaxing the constraints on $\Delta \theta$ and $d_{\text{arc}}/d_p$ would find no further members. However, 2M 0205–11 (also known as DENIS-P J020529.0–115925) was found to be a binary by Koerner et al. (1999) who measured $K$-band flux ratios of $1.00 \pm 0.26$ and $0.99 \pm 0.08$. More recently, Bouy et al. (2005) claim that it is a triple system with $I$ magnitudes of 17.30, 18.38 and 18.80, and spectral types of L5.5, L8 and T0. These parameters suggest that the primary would have more than half of the $K$ flux and so should not be moved down 0.75 mag in the colour–magnitude diagram. We mark 2M 0205–11 with a downward-pointing arrow in Figs 3 and 4 (later) and regard its membership of the HMG as uncertain.

Fig. 2 shows the location of the HMG in the Galactic radial direction ($x$-axis) and perpendicular to the plane ($y$-axis). The Sun is at $(0, 0)$. The cluster is obvious and most of the moving group...
Table 1. Summary of the four brown dwarf members of the UMSMG and seven brown dwarf members of the HMG identified in this work. Infrared spectral types and magnitudes are listed, along with distances obtained from parallax measurements ($d_p$) and the moving cluster method ($d_{mc}$), and the difference between predicted and observed proper motion directions ($\Delta\theta$).

| 2MASS ID         | IR spectral type | $m_J$    | $m_H$    | $m_K$    | $d_p$ (pc) | $d_{mc}$ (pc) | $\Delta\theta$ (°) |
|------------------|------------------|----------|----------|----------|------------|---------------|---------------------|
| 2M J02431371–2453298 | T6              | 15.381 ± 0.050 | 15.137 ± 0.109 | 15.216 ± 0.168 | 10.7 ± 0.4 | 10.6 ± 0.5 | 1.64               |
| 2M J03454316+2540233  | L1 ± 1          | 13.987 ± 0.027 | 13.211 ± 0.030 | 12.672 ± 0.024 | 27.0 ± 0.4 | 31.7 ± 1.2 | 5.62               |
| 2M J14460601+0024519  | L6              | 15.894 ± 0.082 | 14.514 ± 0.035 | 13.935 ± 0.053 | 22.0 ± 1.5 | 19.7 ± 1.5 | 13.54              |
| 2M J15232263+3014563  | L8              | 16.056 ± 0.099 | 14.928 ± 0.081 | 14.348 ± 0.067 | 18.6 ± 0.4 | 17.1 ± 1.1 | 11.70              |

*Also known as Gl 584C.

5 NOTES ON INDIVIDUAL STARS

2M 0243–24. Burgasser et al. (2006) listed the effective temperature of this star as $1040 \leq T_{\text{eff}} \leq 1100$ K, with $\log g$ in the range 4.8–5.1 and an age of between 0.4 and 1.7 Gyr. This age range just fits to our adopted age for the UMSMG.

2M 1523 + 30. Also known as Gl 584C, this star, which we include as a member of the UMSMG, was considered extensively by Kirkpatrick et al. (2001) who estimated its age to be between 1.0 and 2.5 Gyr. This age is the average of several methods which have a total range of 0.3–2.5 Gyr, and thus encompasses the UMSMG age of 400 Myr.

2M 1624 + 00. Burgasser et al. (2006) listed the effective temperature of this star as $980 \leq T_{\text{eff}} \leq 1040$ K, with $\log g$ in the range 5.3–5.4 and an age of between 4.3 and 5.8 Gyr. This age is in clear conflict with the HMG age of 625 Myr. The method used by Burgasser et al. (2006) was to find $g$ and $T_{\text{eff}}$ from spectral indices, and compare these values with the model of Burrows et al. (1997) which yields masses and ages directly. They also used measured luminosities to obtain masses and radii and then the models again to find the ages. This alternative method gives an age of 0.6 to 10 Gyr, just consistent with the Hyades age.

2M 0036+18. Berger et al. (2005) presented a study of the magnetic properties and summarized current research on this object, citing $T_{\text{eff}} = 1923^{+195}_{-180}$ K (Vrba et al. 2004), $\log g \approx 5.4$ (Schweitzer et al. 2001), and an inferred age of at least 1 Gyr from the work of Burrows et al. (2001).

2M 0205–11. This object is a known binary (Koerner et al. 1999); Bouy et al. (2003) assumed an age ‘greater than 0.5 Gyr’ but in later work, Bouy et al. (2005) presented evidence to suggest that 2M 0205–11 is possibly a triple system and they assumed an age of between 1 and 10 Gyr.

2M 1217–03. Burgasser et al. (2003) suggested the possibility of a faint companion to this object in Hubble WFPC-2 data. However, the putative companion is close to the detection limits of the image.

6 DISCUSSION

Fig. 3 plots the $J - K, M_K$ colour–magnitude diagram for both the UMSMG and the HMG members. Also shown are the 60 other L and T dwarfs from the archive with known parallaxes (2M 1228–15 A and B are plotted). These show a rather scattered distribution which is to be expected since they presumably have a range of ages. In addition, we have plotted the 500-Myr DUSTY model of Chabrier et al. (2000) and the same age COND models (Baraffe et al. 2003). We draw the following conclusions.
Moving groups may arise from a dispersing cluster or from a star formation event in a particular region of a molecular cloud; in either case, the members of the group will be coeval. Alternatively, a moving group may be the consequence of a dynamical process where, for example, the Galactic bar drives some resonance to produce a group of stars with a common velocity. In this case the stars will not lie on a moving group. In this case the stars will not lie on a moving group.

For the lack of near-equal-mass binaries is that these are of course more massive entities and therefore less likely to have been ejected from their parent clusters.

So far we have implied that the membership of a moving group guarantees objects have the same age. This is not necessarily true. Moving groups may arise from a dispersing cluster or from a star formation event in a particular region of a molecular cloud; in either case, the members of the group will be coeval. Alternatively, a moving group may be the consequence of a dynamical process where, for example, the Galactic bar drives some resonance to produce a group of stars with a common velocity. In this case the stars will not be coeval (see, for example, Dehnen 1998). The Pleiades moving group, sometimes called the local group, and other groups have stars of differing ages (Chereul et al. 1998, 1999). Also, the core stars of the UMSMG clearly fit a good sequence in the Hertzsprung–Russell diagram and are coeval (King et al. 2005). It is possible that these stars are part of a moving group with a common velocity. In this case the stars will not lie on a moving group. In this case the stars will not lie on a moving group.
Resonance-driven stars tend to favour particular V (Galactic azimuthal direction) velocities. These favoured velocities coincide with both the UMSMG and HMG V velocities [see, for example, Dehnen (1998) or Skuljan, Hearnshear & Cottrell (1999)]. Thus there is a greater than random chance that stars will have proper motions pointing to the convergent point of these groups. This effect is rather difficult to quantify over the whole sky, so we have added an estimated factor of 4 in Section 2 for calculating the chance of a proper motion being directed towards the UMSMG or HMG convergent point. However, if an object has the UMSMG or HMG velocity by virtue of a dynamical resonance rather than from being a genuine member of the group, its moving group distance (see Section 2) will not be the same as its parallax distance and it will fail our second test. Perhaps fortuitously, all our objects pass the second test.

Of course our third test, that the dwarfs fit a ‘sensible’ sequence, should select coeval objects. However, we do not know exactly where this sequence is and the sceptic might argue that we have simply got the wrong sequence. Indeed, with 2M 1228–15 the first two tests produced an object that did not fit the UMSMG sequence (see above). On the positive side the five HMG L dwarfs do seem to form a very good sequence, and the two HMG T dwarfs have very similar absolute K magnitudes. The results for the UMSMG are not so compelling, but two L dwarfs lie on a line parallel and above the Hyades sequence as expected for a younger group.

The results described in this paper should perhaps be treated with some caution. Nevertheless, the kinematic data exist and should be used. As more proper motion and parallax data become available, these and other sequences may become better established.

Summarizing, we can say that some moving group members are undoubtedly coeval, but membership of a moving group based on the criteria described in this paper does not guarantee coevality.

8 CONCLUSIONS

We find one T dwarf and three L dwarfs that belong to the UMSMG, whose age is 400 Myr. We find a further two T dwarfs and five L dwarfs, one rather dubious, that are members of the HMG. These stars provide preliminary empirical isochrones for these ages.

We plan to extend this technique to other moving groups. Only 70 of the 459 archived dwarfs have the proper motions and parallaxes needed to identify them with moving groups. We believe that many more L and T dwarfs could be identified with moving groups if more proper motions and parallaxes were available. This would allow them to be assigned an age, although it should be remembered that moving group ages can never be totally secure.

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