L dwarfs in the Hyades

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ABSTRACT

We present the results of a proper motion survey of the Hyades to search for brown dwarfs, based on UKIRT Deep Sky Survey (UKIDSS) and Two-Micron All Sky Survey (2MASS) data. This survey covers ~275 deg² to a depth of K ~ 15 mag, equivalent to a mass of ~0.05 M⊙ assuming a cluster age of 625 Myr. The discovery of 12 L dwarf Hyades members is reported. These members are also brown dwarfs, with masses between 0.05 < M < 0.075 M⊙. A high proportion of these L dwarfs appear to be photometric binaries.

Key words: stars: low-mass, brown dwarfs – open clusters and associations: individual: Hyades

1 INTRODUCTION

The Hyades is the closest cluster to the Sun at a distance of 46.3 pc (Perryman et al. 1998), making it an ideal cluster to search for faint, low-mass objects such as brown dwarfs. However, due to its proximity, the Hyades covers a large area of the sky, requiring considerable amounts of telescope time to survey the entire cluster. In addition, there is a deficiency of very low-mass objects in the Hyades (Gizis, Reid & Monet 1999), which Bouvier et al. (2008) suggest is caused by the preferential evaporation of the lower mass cluster members.

The details of the most recent surveys of the Hyades are shown in Fig. 1 and Table 1. Many of these surveys have been specifically designed to be sensitive enough to detect brown dwarfs. However, only two brown dwarfs have been found so far (Bouvier et al. 2008). Bannister & Jameson (2007) used proper motions and the moving group method to find brown dwarfs that appear to belong to the Hyades moving group (HMG), with the possibility that they could also be escaped cluster members. Osorio et al. (2007) measured radial velocities for five of the Bannister & Jameson (2007) objects and confirmed that they have velocities lying in the 2σ ellipsoid of the HMG. However, only one T7.5 dwarf, 2MASS J12171110–031113 (2MJ1217–03; Burgasser et al. 1999), has a space velocity very close to that of the Hyades cluster, making it likely to be an escaped cluster member. The other four Bannister & Jameson (2007) objects with radial velocity measurements are probably members of the HMG but not escaped cluster members, so they may not be exactly coeval with the Hyades cluster.

Since the Hyades is located in front of the Taurus dark cloud star-forming region, it is dangerous to select members based purely on photometric criteria. Young, more distant objects can be readily confused with genuine Hyades members. As Hyades members have a moderate proper motion, candidates are selected if they have the correct photometric properties and proper motions.

This paper presents the results of a survey based on the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrance et al. 2007) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006). This survey covers ~275 deg² of the Hyades, corresponding to ~52 per cent of the total area of the cluster, assuming an area of π r² tidal, where r tidal is the tidal radius (10.5 pc; Perryman et al. 1998). Members are determined by selecting objects with suitable photometric properties and proper motions. Two ‘control clusters’, both within the ~275 deg² of the survey, are also considered to check for contaminants that may coincidentally have photometric properties and proper motions similar to that expected of Hyades members. A complete survey of all members will not be attempted, since suitably accurate photometry, used to separate the M dwarf cluster stars from the M dwarf field stars, does not currently exist. The completed UKIDSS Galactic Cluster Survey (GCS) of the Hyades will contain Z, Y, J, H and K magnitudes and second epoch K measurements. When complete, the GCS will provide adequate photometric measurements and proper motions of all objects in the region of the Hyades, allowing a complete census of members and an accurate determination of the Present Day Mass Function (PDMF) of the Hyades.

2 THE SURVEY

The GCS sub-survey of UKIDSS has so far covered ~275 deg² of the Hyades cluster in the K band to a magnitude of 18.2 mag, corresponding to a detection limit of 5σ. The UKIDSS data were acquired between 2005 August and 2007 March, 5–10 yr after 2MASS covered the same area of sky in J, H and K to a magnitude, K = 14.3 mag, corresponding to a detection limit of 10σ. The average epoch difference between the UKIDSS and the 2MASS data is

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covers the range $10 < K < 15$ mag, making this survey the largest, deep proper motion survey of the Hyades to date. Gizis et al. (1999) used 2MASS and a plate from the Second Palomar Observatory Sky Survey (POSSII) to survey the central 28 deg$^2$ of the Hyades (Fig. 1) but did not measure proper motions as the epoch difference between 2MASS and the POSSII plate was insufficient.

### 3 SELECTION OF HYADES MEMBERS

The large range of proper motions of Hyades members means it is not possible to use the method of characterizing the cluster and background stars by Gaussian distributions (see e.g. Deacon & Hambly 2004). Instead, the following method is applied. 2MASS and UKIDSS stars are first matched using a 2 arcsec matching radius. Proper motions are then measured simply as $\mu_x = \Delta \alpha \cos \delta / \Delta t$ and $\mu_y = \Delta \delta / \Delta t$, where $\Delta \alpha$ and $\Delta \delta$ are the difference between the RA and Dec., respectively, of the 2MASS and the UKIDSS coordinates, measured in arcsec, and $\Delta t$ is the epoch difference measured in yr.

Initially, all stars with proper motions within the range $50 < \mu_x < 180$ and $-160 < \mu_y < 80$ mas yr$^{-1}$ are selected from the stars matched between the UKIDSS and the 2MASS catalogues. This ensures complete coverage of the entire range of proper motions of members of the Hyades and both control clusters. Even though there is some variation in the proper motions of the Hyades members, they all appear to move towards a single point known as the ‘convergent point’ (CP; $\alpha_{CP} = 6^h 29.48^m$, $\delta_{CP} = 6^\circ 53' 4''$; Madsen, Dravins & Lindegren 2002). The angular distance, $D$, between the CP and each star, and the proper motion angle, $\theta$, measured as the angle between the line directly north and the line to the CP, is calculated for each star using spherical trigonometry:

$$\cos D = \sin \delta \sin \delta_{CP} + \cos \delta \cos \delta_{CP} \cos \alpha$$

$$\cos \theta = \frac{\sin \delta_{CP} - \sin \delta \cos D}{\cos \delta \sin D}$$

where $\delta$ and $\delta_{CP}$ are the Dec. of the star and the CP, respectively, and DA is the difference in RA between the star and the CP.

Cluster members should have a proper motion angle close to $\theta$. Assuming a mean Hyades proper motion of $\sim 100$ mas yr$^{-1}$, the typical error on the proper motions of $\pm 7$ mas yr$^{-1}$ corresponds to an error on $\theta_{obs}$ of $\tan^{-1} \frac{1}{25} \sim 4'$, where $\theta_{obs}$ is the observed proper motion angle. A range of $\pm 12'$ in $\theta_{obs}$ corresponds to $\pm 3\sigma$. Therefore, the requirement for a member to be selected is chosen to be $\theta - 12' < \theta_{obs} < \theta + 12'$, leading to a survey which is $\sim 99.7$ per cent complete.

Cluster members must also have proper motions with the correct magnitude. From the theory of moving clusters, it can be shown that the distance, $d$, measured in pc, of a member is given by

$$d = \frac{v \sin D}{4.74 \mu}$$

where $\mu$ is the proper motion of the member, measured in arcsec, and $v$ is the cluster velocity, which for the Hyades is equal to 46.7 km s$^{-1}$ (Dettweiler et al. 1984; Reid 1992). The distance of every potential member with a $\theta_{obs}$ within the required range is calculated. Then, a second membership condition is imposed; $32 < d < 60$ pc. This range is based on a cluster distance of 46.3 pc and a tidal radius of 10.5 pc and also includes an additional uncertainty of $\pm 3.2$ pc to allow for the 7 per cent $1\sigma$ uncertainties associated with the proper motion measurements. This additional $1\sigma$ error will still lead to a very complete survey, since very few members are expected to be

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**Table 1.** Previous surveys of the Hyades.

| Survey          | Area (deg$^2$) | Mag limit (mag) | Mass limit (M$_\odot$) |
|-----------------|---------------|----------------|------------------------|
| Bouvier et al.  | 16.0          | $I = 23$       | 0.05                   |
| Dobbie et al.   | 10.5          | $I = 20.3$     | 0.06                   |
| Gizis et al.    | 28.0          | $I = 16.3$     | 0.06                   |
| Reid (1992)     | 112.0         | $V = 19.5$     | 0.11                   |

$\sim 7.4$ yr. The moderate proper motions of Hyades members, which range between 74 and 140 mas yr$^{-1}$ (Bryja, Humphreys & Jones 1994), combined with the epoch difference of 5–10 yr, provide measurable proper motions between the two surveys. The astrometric accuracy of 2MASS for sources between the magnitude range $9 < K < 14$ mag is $\sim 70$–80 mas globally. However, multiply detected sources that fall in the overlap region between 2MASS tiles can be independently detected and measured to within $\sim 40$–50 mas. Since the UKIDSS data are astrometrically calibrated using 2MASS objects (Lawrence et al. 2007), the difference in the positions of the objects between the UKIDSS and the 2MASS data provides differential proper motion measurements. The error on these measurements can be estimated by combining the error on the positions of the objects in both catalogues with the average epoch difference, leading to a typical error of $50/7.4 \sim 7$ mas yr$^{-1}$. Since the UKIDSS data saturate at $K \sim 10$ mag, the combined survey...
located at the tidal radius. This second membership condition in effect selects the proper motions with the correct magnitude. Since the distance to each object is now known, their absolute magnitudes can be calculated.

The final step is to place the members passing the direction and distance tests into an HR diagram. Using the $K$ magnitude from UKIDSS and including the 7 per cent distance errors mentioned above associated with the error on the proper motion measurements, the errors on $M_K$ are calculated (Table 2 and Fig. 4). 2MASS provides $J$, $H$, and $K$ photometry, but UKIDSS $K$ is more accurate near the 2MASS survey limit. The errors on the $J$ magnitudes of the objects from 2MASS generally increase as the objects get fainter. As a result, the $J$ magnitudes dominate the errors on the $J - K$ colours near the 2MASS survey limit (Fig. 4). Since the $K$ magnitudes from UKIDSS are on the Mauna Kea Observatory (MKO) system (Tokunaga, Simons & Vacca 2002), the $J$ magnitudes from 2MASS are converted to the MKO system using the transformations supplied by Stephens & Leggett (2004), so that all $J$ and $K$ magnitudes are on the MKO system.

### 4 CONTAMINATION

Even though Hyades members are selected as those objects with the correct direction and magnitude of proper motion and the correct location in the $M_K$, $J - K$ colour–magnitude diagram (CMD), it is still possible that the sample will be contaminated by field objects. The proper motions, relative to the Sun, of all the stars in the region of the Hyades, with $J - K > 0.6$ mag, show the distribution of their proper motions is not symmetrical about 0,0 (Fig. 2). In order to estimate the contamination of true Hyades members due to objects that may coincidentally have photometric properties and proper motions similar to that expected of Hyades members, two control areas in proper motion space, which are called ‘control clusters’, are considered. These control clusters have the same spatial location as the Hyades but have slightly different proper motions.

The control clusters need to be as close as possible in proper motion space to the Hyades to provide a good estimate of the contamination, bearing in mind the asymmetric distribution of the proper motions of stars in the region of the Hyades (Fig. 2). Therefore, the CPs of the control clusters are chosen to be ±24° from the direction of the CP of the Hyades. This ensures that objects cannot be selected as candidates of both the Hyades and either control cluster, within the allowed uncertainty on $\theta$. Using the same $D$, calculated from the centre of the Hyades to its CP, the CPs of the two control clusters are calculated to be $\alpha_{\text{CP1}} = 6^h 36.1'6'', \delta_{\text{CP1}} = 19^\circ 07'2'', \alpha_{\text{CP2}} = 6^h 06.3'7'', \delta_{\text{CP2}} = 40'1.1''$. Members of the control clusters are then found by requiring $\theta_c - 12' < \theta_{\text{cp}} < \theta_c + 12'$, where $\theta_c$ may be the direction to either control cluster. The two membership conditions...
applied to the Hyades objects are also applied to the control cluster objects, i.e. the control clusters are treated exactly like the Hyades.

5 RESULTS

The $M_K$, $J - K$ CMDs for the Hyades and the two control clusters are shown in Fig. 3. It can be seen that control cluster 1 (CP1: $\alpha_{cp1} = 6^h 36^m 16^s$, $\delta_{cp1} = 19^\circ 07' 2$) has less M dwarf field stars ($J - K \sim 0.7$ mag) than control cluster 2. The number of stars in the Hyades M dwarf sequence is an approximate average of the number of stars in the M dwarf sequences of the two control clusters. This illustrates how difficult it is to separate the Hyades M dwarfs from the field M dwarfs. However, the Hyades CMD has a clear sequence of red dwarfs with $J - K > 1.0$ mag and $10.5 < M_K < 12.0$ mag. This sequence contains 12 Hyades red dwarfs (Table 2), while each control has two red dwarfs with similar colours and magnitudes. Since $1.1 < J - K < 2.0$ mag colours are characteristic of L dwarfs, our survey finds $12 - 2 = 10$ L dwarfs. However, which two are the field contaminants is unknown.

The Hyades CMD also shows 11 dwarfs with $9 < M_K < 10$ mag and $1.0 < J - K < 1.2$ mag, whereas control clusters 1 and 2 show three and two similar dwarfs, respectively. Therefore, the Hyades appears to have $12 - 3 = 9$ very late M dwarfs with $1.0 < J - K < 1.2$ mag. These are shown in Fig. 4 together with their redder counterparts, which may be contaminated by field dwarfs.

The comparison of the 2MASS $K$ photometry, converted to the MKO system, with the UKIDSS $K$ photometry shows no evidence of variability for the 12 brown dwarf candidates within the photometric errors.

6 DISCUSSION

The L dwarfs discovered in this work appear to have a horizontal sequence with $M_K \sim 10.7$ mag followed by a vertical drop at $J - K \sim 1.7$ mag, as seen in the $M_K$, $J - K$ CMD. However, we do not believe this can be the true sequence. Jameson et al. (2008) have used data from L dwarfs found in Upper Scorpius, $\alpha$ Per, the Pleiades, Ursa Major and the Hyades (Bannister & Jameson 2007) to make an empirical age determination for L dwarfs. They find gradients for these clusters in the $M_K$, $J - K$ CMD to be 1.95, 1.93, 1.81, 2.88 and 2.14, respectively. Ursa Major is clearly discrepant and the average gradient of the remainder is 1.96. Such a gradient would fit our L dwarf data if we regarded the bluest three L dwarfs and the faintest L dwarf to be single L dwarfs. The remaining L dwarfs would then have to be binary L dwarfs, which could sit up to 0.75 mag above the single star sequence. These single and equal-mass binary sequences are shown in Fig. 4. A large number of brown dwarf binaries might be expected in the Hyades, since tight L dwarf binaries are less likely to be lost than single L dwarfs due to their greater system mass. There are still three L dwarfs that remain above the equal-mass binary sequence. This could be
explained by experimental error, accepting that they are the expected contaminants or conceivably triple systems. If the apparent $K, J - K$ CMD is plotted, its shape is not significantly different the $M_K, J - K$ CMD.

The single L dwarf sequence must turn around at $J - K \sim 2.0$ mag, encompassing the two reddest Bannister & Jameson (2007) L dwarfs and continuing on through the T7.5 dwarf 2MJ1217−03. The T dwarf CFHT−Hy−21 ($J - K \sim 1.9$ mag; Bouvier et al. 2008) fits this interpretation quite well. CFHT−Hy−20 ($J - K \sim 0.9$ mag), on the other hand, sits $\sim 0.75$ mag above the proposed LT transition sequence. This object would therefore be a binary system, which is consistent with the belief that many LT transition objects are binaries (Tinney, Burgasser & Kirkpatrick 2003).

The single and equal-mass binary L dwarf sequences are continued to match the M dwarfs found by both Bouvier et al. (2008) and this work. Note there is a gap of $\sim 0.7$ mag between the late M dwarfs and the L dwarfs. This could be attributed to the ‘missing M dwarfs’, a deficit of M7–M8 dwarfs found in other clusters (Dobbie et al. 2004).

Using the NEXTGEN models (Baraffe et al. 1998), the bottom of the hydrogen burning main sequence ($0.075 M_\odot$) occurs at $M_K \sim 10.3$ mag, assuming a cluster age of 625 Myr. This almost exactly coincides with the brightest of the 12 L dwarfs. Therefore, the 12 L dwarfs are also brown dwarfs. Applying the DUSTY models (Chabrier et al. 2000), the masses for the 12 L dwarfs range between $0.05 < M < 0.075 M_\odot$. One of the 12 L dwarfs was previously known (2MASSW J0355419+225702; L3; Kirkpatrick et al. 1999) but not recognized as a Hyades member.

7 CONCLUSIONS AND FUTURE WORK

We have found 12 L dwarfs, which are also brown dwarfs, in our survey of the Hyades. The level of contamination by field L dwarfs is estimated to be 2 out of 12. Deciding the Hyades L dwarf sequence from these 12 objects is not straightforward, since there seem to be more binary L dwarfs than might be expected in a younger cluster. Many of the L dwarfs appear to be unresolved binaries. If these binaries could be spatially resolved using adaptive optics, they might prove to be a useful resource from which dynamical masses could be obtained for brown dwarfs of known age.

When the UKIDSS GCS is complete with Z, Y, J, H and K magnitudes and proper motions, it will be possible to make a survey of the Hyades $\sim 3$ mag deeper than this survey. The limit of the final survey will be $M_K \sim 15$ mag and should therefore find fainter L and T dwarfs in the Hyades. It will also be possible to make a good census of low-mass Hyades members and derive a precise PDMF of the Hyades.

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