

# A Population of Very Young Brown Dwarfs and Free-floating Planets in Orion

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Accepted by Monthly Notices of the Royal Astronomical Society

## Abstract

We describe the results of a very deep imaging survey of the Trapezium Cluster in the  $IJH$  bands, using the UKIRT high resolution camera UFTI. Approximately 32% of the 515 point sources detected are brown dwarf candidates, including several free floating objects with masses below the Deuterium burning (planetary) threshold at 0.013 solar masses, which are detectable because of their extreme youth. We have confidence that almost all the sources detected are cluster members, since foreground contamination is minimal in the 33 arcmin<sup>2</sup> area surveyed and the dense backdrop of OMC-1 obscures all background stars at these wavelengths. Extinction is calculated from the  $(J-H)$  colours, permitting accurate luminosity estimates and temperatures are derived from the dereddened  $(I-J)$  colours. There is some evidence for a cut-off in the luminosity function below the level corresponding to several Jupiter masses, which may represent the bottom end of the IMF. Since star formation is complete in the Trapezium this limit could have wide significance, if confirmed. However, it could well be an effect of the dispersal of the molecular cloud by the central O-type stars, a process whose timescale will vary between star formation regions.

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## 1 Introduction

The last five years have seen great progress in the detection of brown dwarfs in the Local Neighborhood, young Galactic Clusters and star formation regions, starting with the near simultaneous discovery of the first clearly confirmed brown dwarfs, Teide 1 in the Pleiades (Rebolo, Zapatero-Osorio & Martin 1995) and Gl229b in the Local Neighborhood (Nakajima et al.1995). Star formation regions offer the advantage that substellar objects are 3 orders of magnitude more luminous at an age of a few Myr than at an age of a few Gyr. Early photometric and spectroscopic work (Comeron et al.1993,1996; Williams et al.1995) indicated that brown dwarfs are probably very common in star formation regions. However, confirmation of substellar status is problematic in star formation regions, owing to the ubiquity of Lithium in young objects and the complicating effects of extinction on both photometry and spectroscopy.

Recently, high quality spectroscopy (Luhman & Rieke 1998; Luhman et al. 1998, Wilking, Greene & Meyer 1999) and the publication of theoretical

evolutionary models for young substellar objects (Burrows 1997; D'Antona & Mazzitelli 1998, hereafter B97 and DM98) have provided convincing evidence that photometric identification of young brown dwarf candidates is reliable. In photometric studies, masses of candidate objects are derived by comparison of the observables (luminosity and temperature) with the evolutionary tracks. The isochrones of B97 and DM98 are in fairly good agreement in regard to the mass-luminosity relation at an age of about 1 Myr but there is some disagreement about the mass-temperature relation (HR diagrams are compared by Luhman & Rieke 1998). Even if the theoretical effective temperatures were without flaw, there is considerable uncertainty in the derivation of temperatures from photometry or spectroscopy, at the level of  $\pm 200$  K in M and L dwarfs. Hence, we use luminosity, which is more easily measured, to derive masses for our sources.

In this paper we report the results of a deep infrared photometric survey of the Trapezium Cluster in Orion. A large population of substellar objects is discovered, including the first free-floating objects of planetary mass. We note that the IAC group (Bejar et al. 1999, not yet published) has simultaneously reported a similar discovery of planetary mass objects in the adjacent  $\sigma$  Orionis cluster. The Trapezium has been intensively studied for many years and we have been able to draw upon a large body of publications to aid in our work. We selected the Trapezium for several reasons. (1) Its very high stellar density allowed photometry of several hundred sources in a fairly small survey. (2) False positive detections are essentially eliminated because the dense backdrop of OMC-1 obscures all background stars even at K band, as shown by Hillenbrand & Hartmann (1998) through optical-infrared comparison of the cluster stellar density profile. (3) The extinction within the cluster is relatively low ( $0 < A_V < 15$  for most sources), permitting reasonably precise dereddening. (4) Star formation is essentially complete in the cluster and the age range is thought to be 0.3-2 Myr, so the age-luminosity degeneracy is not large.

## 2 Observations

Deep Imaging of the Trapezium cluster was carried out at United Kingdom Infrared Telescope (UKIRT) on 14-16 December and 22-23 December 1998, using UFTI, the UKIRT Fast Track Imager. The observations of 22-23 Dec were made by observatory staff to compensate for time lost to poor weather and equipment failures on 15-16 Dec. UFTI is a high resolution camera constructed by the authors at Oxford University with assistance from several other UK institutions (Roche & Lucas 1998). It has a  $1024 \times 1024$  HAWAII array sensitive between 0.78 and 2.5 microns. The image scale is 0.091 arcsec/pixel, yielding a field of view of 92.6 arcsec. Observations of 15 contiguous fields were made in the  $I$ ,  $J$  and  $H$  filters, with 900s exposures in each filter. Twilight flatfields were taken to reduce the data. Seeing conditions were typically 0.6 arcsec FWHM in all 3 filters, with only slightly poorer image quality at  $I$  band. The fine pixel scale led to a high degree of over-sampling, which was very useful for distinguishing

stars from small knots of nebulosity and in permitting reliable photometry of low signal to noise detections.

## 2.1 Filter Selection

Taking advantage of the short wavelength sensitivity of the HAWAII array UFTI contains  $I_U$  (0.786-0.929  $\mu\text{m}$ ) and  $Z_U$  (0.85-1.05  $\mu\text{m}$ ) band filters. These filters sample the steeply rising part of brown dwarf spectra from the optical to the near infrared flux peak. The  $I_U$  filter was selected because the  $Z_U$  band contains a very strong [SIII] emission line which might have contaminated the photospheric flux in “proplyd” sources and because the  $(I-J)$  colour is a more reliable temperature indicator than the smaller  $(Z-J)$  colour given that fluxes have to be dereddened. The  $J$  and  $H$  filters were chosen to measure extinction using the temperature insensitive  $(J-H)$  colour. The  $K$  filter was not selected because a significant fraction of the flux comes from hot circumstellar dust at 2.2  $\mu\text{m}$ , making it unreliable for determining extinction or luminosity and because it contains fairly strong low-excitation emission lines.

The UFTI  $I_U$  band calibration (equ.1) relative to Cousins  $I$  was made by observation of 8 faint red standards of approximately solar metallicity taken from Leggett et al.(1998). The calibration has been confirmed by observatory staff, including observations of blue standards, and can be fit remarkably well by a linear equation. The  $I_U$  bandpass is somewhat redder than  $I_C$ , which compensates for the low quantum efficiency of the HAWAII array at these wavelengths ( $\sim 23\%$ ) when observing cool stars. The  $J$  and  $H$  filters are of the new type commissioned by the Mauna Kea Consortium. The transformation to the CIT colour system (equ.2,3) was determined by combining the transformations of S.Leggett for CIT to UKIRT( $IRCAM$ ) with that for UKIRT( $IRCAM$ ) to UKIRT( $UFTI$ ). We use the UFTI  $J$  and  $H$  magnitudes in this paper but use Cousins  $I$  for ease of comparison with other studies. This is possible because fortuitously the net effect of extinction on equ.1 is much less than the measurement errors.

$$I_C = I_U + 0.273(I_U - J_U) \quad (1)$$

$$(J - H)_U = 1.03(J - H)_{CIT} \quad (2)$$

$$J_U = K_{CIT} + 1.132(J_{CIT} - K_{CIT}) \quad (3)$$

## 2.2 Data Reduction and Photometry

The data were reduced using IRAF and the Starlink package CCDPACK for image mosaicing. Photometry was carried out using the DAOPHOT package in IRAF. Photometry in the core of the Trapezium cluster is complicated by the pervasive nebulosity, which has structure on all the observed spatial scales. This often leads to inaccurate measurement of sky background when doing automated photometry, and causes the DAOFIND algorithm to misidentify many small-scale nebular flux variations as stars. To overcome these problems, we

cross correlated the stars found in each filter to remove most of the nebulous sources and also rejected all very blue sources ( $(J - H) < 0.2$ ), which inspection indicated were all spurious. Every source was then visually inspected and photometry was performed manually in order to select the best appropriate sky annulus in each case. The results of manual photometry were generally used in preference to the results of automated crowded-field photometry, with a few exceptions where the ALLSTAR routine was needed for photometry of close binaries. The final photometric precision is  $\sim 5\%$  in the outlying regions of the survey where the nebulosity is faint, limited by temporal variations in the image profile. Precision in the bright nebulous core (in which the majority of sources lie) is between 5% and 20% (for the worst cases), depending on the degree of spatial variation of surface brightness and the source magnitude. Since a large fraction of young stars are variable, more precise photometry at one epoch would not have had much greater value.

### 3 Results

The main results of the survey are presented graphically in Figure 1(a-b). 515 unsaturated point sources were detected in both the  $J$  and  $H$  bands, of which 313 were also detected at  $I$  band. An additional 48 sources were detected at greater than  $5\text{-}\sigma$  in the  $H$  band alone, and appear as upper limits in Figure 1(b). An approximate colour-magnitude sequence for zero extinction is indicated by the dotted line. The value of the nearly temperature independent intrinsic ( $J-H$ ) colour over the range  $\sim 2200\text{-}4000$  K is clear, since nearly all low mass stars and substellar sources will deredden to a colour near  $(J-H) = 0.6$ . However, we prefer to use a two-colour sequence for formal dereddening where possible (see Section 3.2). The empty region to the upper right of the diagram represents the saturation limit near  $m_H = 11.7$ .

A large fraction ( $\approx 32\%$ ) of the  $JH$  sources are brown dwarf candidates, lying below the reddening track for a  $0.08 M_\odot$  star at an age of 1 Myr, as calculated from the B97 isochrones. Approximately 13 sources appear to lie below the 1 Myr track for an object with the minimum mass to burn Deuterium ( $\approx 0.013 M_\odot$ ). Following the definition suggested by Burrows (1997) it is convenient to call such objects free-floating planets, even though they are likely to have formed by cloud core fragmentation in the same manner as stars and brown dwarfs. A definition by mass has the advantage that it can be applied before all the formation mechanisms are known. An interesting feature of Figure 1(a) is the paucity of very faint blue sources with  $m_J > 19$ , given that several fairly red sources are seen below this limit. This observation is based on a small number of objects but it is supported by the upper limits in Figure 1(b), which show that many very faint red sources are detected at  $H$  band only, but none with  $(J-H) < 1.3$ . This appears to indicate a sharp drop in the cluster Luminosity Function, at a level corresponding to about  $8 M_{Jup}$ . The significance of this is discussed in Section 4.2.

$IJH$  photometry of the observed point sources is presented in Table 1<sup>1</sup> together with astrometry, dereddened magnitudes, luminosities, derived masses (using both the B97 and DM98 isochrones) and temperatures. We have surveyed the inner regions of the Orion Nebula cluster, in which most star formation is thought to have occurred over the period between 0.3 and 2 Myrs ago (Ali & Depoy 1995, Hillenbrand 1997), which leads to a small uncertainty in the derived masses, which we have indicated on Figure 1(a) by plotting the brown dwarf threshold for three different ages. A small proportion of younger sources is undoubtedly present, whose masses will be less than we have estimated, but we have excluded the 18 sources which exhibited extended (non-stellar) profiles from our photometry and performed a further colour selection against proplyds (see Section 3.2) so only a few extremely young sources should remain in Table 1.

The  $I$  vs.  $(I-J)$  data in Figure 2 show that nearly 90% of the sources follow a well defined sequence which is almost parallel to the reddening line. However, 41/313 of the sources (13%) have much bluer  $(I-J)$  colours and lie to the left of the arbitrary line, parallel to the reddening line, which is plotted in Figure 2. An initial suspicion that this might be due to poor photometry was disproved by observing that the same two sequences are followed in a subset of 92 sources located more than  $\sim 2$  arcminutes away from the cluster core, where photometry is not compromised by bright nebulosity (not shown). Since we have selected filters with no strong low-excitation emission lines the obvious interpretation is that the blue colours are due to scattered light from those objects which are very young or are viewed close to the plane of the accretion disk. This interpretation is confirmed by comparison with the list of proplyds detected via emission line imaging with the *Hubble Space Telescope (HST)* in O’Dell & Wong (1996). Only 11/41 were detected in their relatively shallow optical surveys, which suffer from greater extinction and do not overlap precisely with our survey. However, 10/11 are listed as proplyds, and 1/11 is listed as a star. The star is presumed to illuminate circumstellar matter which was not detected by *HST* because it does not receive sufficient UV radiation from the central O-type stars, or because the proplyd “tail” lies too close to the line of sight. These 10 proplyds are marked with crosses in Figure 2.

The 41 blue sources are widely distributed throughout the survey region and do not display obviously unusual (J-H) colours, only a weak tendency to be bluer than the rest. The  $I$  vs.  $I-J$  diagram appears to be an efficient way of detecting proplyds at large distances from the photoionising O stars. However, the effect of circumstellar matter on infrared colours is not obvious, since it depends on the orientation of the system and distribution of matter in a complicated way (eg. Kenyon et al.1993). The observed (J-H) colours may well be different from the photospheric colours in these systems so we have excluded all the blue sources from our dereddening analysis. It is likely that some sources in the red group also have slightly modified colours due to anomalous extinction (i.e. both absorption and scattering) but this is not expected to be significant for most

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<sup>1</sup> Table 1 is available electronically by FTP to star.herts.ac.uk, in pub/Lucas/Orion.

sources of age  $\sim 1$  Myr, since the spectral energy distributions of T Tauri stars are usually well fitted by a Planckian (photospheric) function at wavelengths between the visible and the thermal infrared (eg. Rydgren et al. 1976, Wilking et al. 1989). The 202 faint sources detected only at  $J$  and  $H$  cannot be probed for anomalous colours in this way and probably include some sources which are therefore inaccurately dereddened. However, the proportion of anomalous sources will be lower than 13% in this group because the blue sources are easier to detect at  $I$  band. Those sources in Figure 1(a) with  $m_J > 16.2$  which are detected in all 3 filters are almost exclusively members of the blue group. Hence, blue sources detected only at  $J$  and  $H$  will be very few except below the  $I$  band detection limit which corresponds to  $m_J \approx 18$ . A likely example of one such faint source at lower left in Figure 1(a-b) is Orion 131-047 (adopting the O’Dell & Wen (1994) naming convention), for which  $m_J = 18.22$  and  $(J-H) = 0.39$ . This is an unrealistically blue colour for such a low luminosity source (which has accurately measured fluxes) so it is likely that the  $(J-H)$  colour has been reduced by at least 0.2 magnitudes by scattering effects.

### 3.1 Extinction Law

Many observers have found evidence for an anomalous extinction law in the Trapezium at optical and infrared wavelengths (eg. Davis et al.1986; Cardelli, Clayton and Mathis 1989, hereafter CCM). We adopt the  $R_V = 5.5$  extinction law of CCM, calculated for  $\theta_1$ C Ori using data at similar wavelengths to those observed here. The infrared extinctions for this law are  $A(I_C)=0.643$ ,  $A(I_U)=0.583$ ,  $A(J)=0.334$ ,  $A(H)=0.214$  for  $A(V)=1$ . The effect of the unusually high  $R_V$  is to increase the slope of the reddening lines, resulting in higher derived luminosities and masses for sources with significant extinction. However, the change in near infrared reddening is quite small because, as showed by CCM, all extinction laws converge at wavelengths  $\gtrsim 0.9 \mu\text{m}$ , such that  $A(\lambda)/A(I)$  is similar in all known clusters. Only the optical extinction is greatly modified and we are not concerned with this. Hence, we use  $A(J) = 2.783E(J - H)$ , which compares with  $A(J) = 2.364E(J - H)$  for the  $R=3.05$  interstellar extinction law derived from Whittet (1990) and  $A(J) = 2.543E(J - H)$  which follows from the oft-quoted  $\lambda^{-1.8}$  law for near infrared interstellar extinction. This convergence of extinction laws in the near infrared is fortunate, since we doubt whether a common extinction law will apply to all the stars in a given star formation region, especially in Orion where the nebulosity has such complex spatial structure.

### 3.2 Dereddening Procedure

For the  $IJH$  detections, we have used the unusual procedure of dereddening to an empirically derived curve in the  $(I-J)$  vs.  $(J-H)$  two-colour diagram, rather than to a theoretical curve in a colour-magnitude diagram. This was for two reasons: firstly, theoretical models are at an early stage of development for such young substellar sources and appropriate colour predictions have yet to

be published at the time of writing; secondly, theoretical colour predictions are subject to the significant uncertainty in the absolute temperature-colour calibration which we referred to in Section 1. The empirical curve (Figure 3(a)) was derived from a fit to observations of M and L dwarfs of near solar metallicity from Leggett et al.(1998) and UKIRT stellar standards of unknown metallicity for  $(I-J) < 1$ , where there is no known metallicity dependence. A possible flaw in this approach is that young stars and brown dwarfs have lower surface gravities than main sequence objects of the same effective temperature. However, the colour predictions by Baraffe et al.(1998) for young low mass stars indicate that much larger changes in  $\log(g)$  ( $> 1$  dex) have a negligible effect on these colours. The B97 models also indicate that  $\log(g)$  at 1 Myr does not approach red giant values for the masses considered here, so the empirical curve is not likely to be far in error. A cubic polynomial was used, with a Gaussian addition to fit the peak at  $(I-J) \approx 1.0$ . The form of the relation is a good match to the plots of Bessell & Brett (1988) and Leggett (1992).

The results for the 272  $IJH$  sources which are not anomalously blue in  $(I-J)$  are plotted in Figure 3(b). 95 sources have double valued solutions but only 1 solution has a plausible colour and flux in nearly every case. The handful of uncertain choices are low mass stars near the bump in the curve at  $(I-J) \approx 1.0$ , where the two solutions lie close together in  $(J-H)$  and derived luminosity but differ substantially in  $(I-J)$  and hence derived temperature. These ambiguous sources are listed as such in Table 1. We are confident that the dereddened  $(J-H)$  colours are accurate to  $\pm 0.1$  mag in nearly every case, given the weak temperature dependence of this colour; a standard error of 0.05 mag is estimated, due to measurement error and uncertainties in the empirical curve and dereddening law. The  $J$  band extinction correction should therefore have typical uncertainties of  $\pm 0.14$  mag, which is small enough to produce a useful Luminosity Function. The dereddened  $(I-J)$  colours are more sensitive to any errors in the process, such that the standard error is approximately 0.25 mag. However, the very strong temperature dependence of the  $(I-J)$  colour means that this leads to only a modest uncertainty in derived values of  $T_{eff}$  (q.v Section 4.3).

The 202  $JH$ -only detections were dereddened to the theoretical track shown in the colour-magnitude diagrams (Figure 1(a-b), which is a simple linear fit to an  $L-T_{eff}$  relation (taking the average of the DM98 and B97 predictions at 1 Myr), and a  $T_{eff}$ - $(J-H)$  relation (taking the average of the Wilking et al (1999) and Baraffe et al.(1998) relations for main sequence stars, which agree to 0.02 mag). Only the B97 and Baraffe predictions extend to the faintest magnitudes and lowest temperatures ( $(I-J) > 3.3$ ). In this region the  $(J-H)$  colour changes more rapidly with  $T_{eff}$  and the uncertainties increase.

## 4 Interpretation

## 4.1 Luminosity Function and IMF

The Luminosity Function (LF) is plotted for all sources detected at  $H$  band with  $m_H > 12.25$  in Figure 4(a). The function declines from a strong peak at  $m_H \leq 12.5$ , which is not well measured here due to saturation. Zinnecker, McCaughrean & Wilking (1993) and Ali & Depoy (1995) observed the equivalent K band function and found a peak at  $m_K=11-12$ , the function declining to fainter magnitudes but flattening off and possibly rising beyond  $m_K=14$ . In our data a strong peak at  $H=16.5$  is apparent, which probably has physical significance given that the function is based on more than 500 sources, and any real features are blurred by extinction of typically 1 magnitude at H band. The peak exists independently of the magnitude binning and is seen in Figure 1(b) as a clump of sources with  $16 < m_H < 17$ . A corresponding feature exists in the J band LF at  $J=17.5$ . The completeness falls gradually, due to the variable nebular surface brightness but is estimated at  $> 90\%$  to  $m_H=18.0$ , as evidenced by the small secondary peak there.

The observed function is converted to the absolute Luminosity Function shown in Figure 4(b), including only the dereddened sources (i.e. excluding H band only detections and blue  $IJH$  sources).  $M_{bol}$  is determined for each source using  $J$  band magnitudes and bolometric corrections (these being well established at  $J$ ) and a distance modulus of 8.22. The bias due to necessarily retaining some faint, anomalously blue sources due to lack of  $I$  band data is only significant below  $m_J=18$ , which is approximately the completeness limit (the nebulosity reduces sensitivity more in the  $I$  and  $J$  bands than at  $H$ .) We adopted the following bolometric corrections, derived from a simple fit to the relations between  $T_{eff}$ ,  $J-H$  and  $BC_J$  of Wilking et al.(1999) (and Baraffe et al.(1998) for  $T_{eff} > 3500$  K) and using the DM98 1 Myr isochrone to connect  $T_{eff}$  to Luminosity:

$$BC_J = 1.955; J_{dr} > 13.77 \quad (4)$$

$$BC_J = 0.1583J_{dr} - 0.2248; J_{dr} < 13.77 \quad (5)$$

where  $J_{dr}$  is the dereddened  $J$  magnitude and the  $BC_J$  refers to the UFTI filter, which has smaller bolometric corrections than the CIT filter.

Figure 4(b) shows a primary peak at  $M_{bol} = 6$  and a small secondary peak at  $M_{bol} = 10.5$ . Incompleteness is significant for  $M_{bol} < 6.2$ , due to saturation of bright sources, and for  $M_{bol} > 11.75$ , which corresponds to  $J > 18$ . The secondary peak corresponds roughly to the peak at  $H = 16.5$  in Figure 4(a). We convert the LF to the IMF using the tracks of B97 and DM98. To remove bias due to non-detection of highly reddened sources we include only sources with  $(J - H)_{obs} < 1.5$ . The results in Figure 5 therefore represent an unbiased sample of the IMF complete to  $\log(M/M_\odot) = -1.5$ . In a log-log plot, both IMF's show a fairly flat stellar function which has a tendency to fall slightly into the brown dwarf regime. Both IMF's also show some indication of a rise beyond the completeness limit but deeper observations will be needed to quantify this.

The discovery of a large population of brown dwarf candidates contrasts with previous surveys (eg. Hillenbrand & Hartmann 1998) which have concluded that



few substellar objects exist. This conclusion appears to have been based on the well-established decline in the LF beyond the principal peak at  $m_K \approx 11.5$ . This survey is the first to go deep enough at infrared wavelengths to detect the secondary peak in the LF.

## 4.2 A Cut-off in the Luminosity Function ?

The absence of faint blue sources (see Section 3.1) is well established by the inclusion of the  $H$  band upper limits. This may indicate a sharp turn-down in the LF, and perhaps a cut-off, at a level corresponding to about 8 Jupiter masses. However, such sources would be close to the survey sensitivity limit (which we believe to lie just below  $5 M_{Jup}$ ) particularly if their intrinsic ( $J-H$ ) colours are redder than we expect. Moreover, the B97 mass-luminosity relation becomes steeper below about  $8 M_{Jup}$ , so a turn down in the LF would occur even for a flat IMF. Hence a deeper survey will be needed to confirm the reality of the fall in the IMF. The least massive detection with good photometry is Orion 023-115, which has  $J=19.38$ ,  $(J-H)=0.97$  and a derived mass of  $8.4_{-2.7}^{+1.4} M_{Jup}$  ( $8.0_{-2.6}^{+1.3} \times 10^{-3} M_{\odot}$ ) for an age of 1 Myr, using the B97 tracks. The quoted  $+/-$  uncertainties refer to alternative ages of 2 Myr and 0.3 Myr respectively. None of the faint sources in Figure 1(a) with highly uncertain  $J$  band fluxes have a lower derived mass. If real, the turn-down might be attributed to a minimum Jeans mass for gravitational cloud core collapse, below which star formation cannot occur. Alternatively, it may be due to the ending of star formation in the cluster before extremely low mass cloud cores had time to collapse, since this process is believed to take longer in less massive cores. This may be attributable to dispersal of dense molecular gas by the photoionising O-type stars at the centre of the cluster. The IAC group apparently find no sign of the turn down in the LF at planetary masses in the neighboring  $\sigma$  Orionis cluster, so we favour the second explanation. If correct, this explanation may still be significant with regard to any galactic population of free-floating planets: most star formation is believed to occur in high mass star formation regions like the Trapezium or M16, with the consequence that free-floating planets may be relatively rare. However, the effectiveness of this mechanism for reducing planet formation efficiency will vary depending on local conditions.

## 4.3 Effective Temperatures

The dereddened  $I-J$  colours are converted to the effective temperatures in Table 1 using the models of Baraffe et al.(1998). The derived values of  $T_{eff}$  are in reasonable agreement with the predictions of B97 and DM98, in which  $2600 < T_{eff} < 2900 K$  for objects of brown dwarf mass at 1 Myr. However a few sources in this mass range are detected with dereddened  $(I - J) \geq 3$ , which implies  $T_{eff} \leq 2500 K$ , at least for main sequence objects. We estimate that our derived temperatures are accurate to  $\pm 200 K$ , leaving aside the uncertainty in the absolute  $T_{eff}$  vs.  $I-J$  relation and assuming this is not altered significantly

by the youth of the sources. In any case the  $I$ - $J$  colours should provide a useful guide to relative temperatures.

#### 4.4 Potential Problems

We have carefully avoided several potential problems in studies of young clusters, such as cluster membership, infrared excess and line emission but some serious issues remain. We consider each in turn. (1) Foreground contamination is minimal in the tiny area surveyed, introducing perhaps 5 red dwarfs into the sample over a range of about 3 magnitudes, using the stellar space densities of Tinney (1993). (2) Background contamination is removed by the dark backdrop of OMC-1 (see Hillenbrand & Hartmann 1998). Our avoidance of the K band filter removes any chance of seeing through OMC-1 at the faint limits. (3) Infrared excess due to hot dust is not believed to be significant at H band, since the spectra of T Tauri stars are well fitted by black bodies at this wavelength. (4) Line emission was minimised by the choice of filters. (5) Variation in the infrared extinction law will probably be small (see Section 3.4) and the effect on the derived IMFs is minimised by excluding highly reddened sources. (6) Scattering is a potentially serious problem. Even sources without anomalous colours in the  $I$  vs.  $(I-J)$  diagram may have distorted  $(J-H)$  colours and fluxes. As noted in Section 3 however, photospheric flux dominates the spectral energy distributions of most T Tauri stars for  $0.6 \mu\text{m} < \lambda < 2 \mu\text{m}$ ) so significant distortion of broad band colours and fluxes is unlikely to be common. This should be investigated in future by searching for the polarisation signature of scattered light. (7) The evolutionary tracks for substellar objects are in an early stage of development, which leads to a significant uncertainty in derived masses. However the fairly close similarity of the B97 and DM 98 tracks, for luminosity and  $T_{eff}$ , is encouraging.

## 5 Conclusions

A large population of brown dwarf candidates is detected in the Trapezium Cluster and a small population of objects with planetary masses. We have confidence that these are true cluster members and, though many uncertainties exist in deriving the masses, they are not likely to be large enough to cause misclassification of low mass stars as low mass brown dwarfs or free-floating planets. The derived IMF is fairly flat on a log-log plot at low stellar masses but declines slightly at brown dwarf masses, indicating that brown dwarfs are a little less numerous than stars. There is a possible small peak near  $\sim 0.02M_{\odot}$ , which is below the completeness limit. Approximately 13 planetary mass objects are detected but none with  $M < 8 \times 10^{-3}M_{\odot}$ . We suggest that this is due to dispersal of the star-forming cloud by the photoionising O-stars before such objects had time to form.

Approximately 13% of sources have anomalously blue  $(I-J)$  colours, which we attribute to scattering from circumstellar material. These blue excesses are

strongly correlated with detection as 'proplyds' by *HST*, so this colour selection may prove to be a powerful new tool for detecting sources with circumstellar envelopes. The effect of scattering on the colours of the general population should be investigated via polarimetry and spectroscopy.

### Acknowledgements

We wish to thank the staff of UKIRT, which is operated by the Joint Astronomy Centre on behalf of the UK Particle Physics and Astronomy Research Council (PPARC). Particular thanks are due to Sandy Leggett and Andy Adamson for providing information on the colours of cool stars and for carrying out reactive observations for us. We also thank the Panel for the Allocation of Telescope Time for providing us with reactively rescheduled observing time. We thank Juliette White for helping us with the dereddening procedure and we are grateful to the referee, Richard Jameson, for useful and timely comments. PWL is grateful for support by PPARC via a Post Doctoral Fellowship at the University of Hertfordshire.

### References

- Ali B., & Depoy D.L. 1995, *AJ*, 109,709
- Baraffe I., Chabrier G., Allard F., & Hauschildt P.H. 1998, *A&A*, 337,403
- Bessell M.S., & Brett J.M., *PASP*, 100,1134
- Burrows A. 1997, *ApJ*, 491,856
- Cardelli J.A., Clayton G.C., & Mathis J.S. 1989, *ApJ*, 345,245
- Comeron F., Rieke G.H., Burrows A., Rieke M.J. 1993, *ApJ* 416,185
- Comeron F., Rieke G.H., & Rieke M.J., *ApJ* 473,294
- D'Antona F., & Mazzitelli 1997, *MmSAI*, 68,607
- Davis D.S., Larson H.P., & Hofmann R., 1986, *ApJ*, 304,481
- Hillenbrand L.A. 1997, *AJ* 113,1733
- Hillenbrand L.A., & Hartmann L.W. 1998, *ApJ*, 492,540
- Kenyon S.J., Whitney B.A., Gomez M., & Hartmann, L., 1993, *ApJ* 414,773
- Leggett S.K., Allard F., & Hauschildt P.H. 1998, *ApJ* 509,836
- Luhman K.L., & Rieke G.H., 1998, *ApJ* 497,354
- Luhman K.L., Rieke G.H., Lada C.J., & Lada E.J., 1998, *ApJ* 508,347
- Nakajima T., Oppenheimer B.R., Kulkarni S.R., Golimowski D.A., Mathews K., & Durrance S.T., 1995, *Nature* 378,463
- O'Dell C.R., & Wong K. 1996, *AJ* 111,846

- Rebolo R, Zapatero-Osorio M.R., & Martin E.L., 1995, *Nature* 377,129
- Roche P.F., & Lucas P.W., 1998, on-line, [www-astro.physics.ox.ac.uk/pwl/camera.html](http://www-astro.physics.ox.ac.uk/pwl/camera.html)
- Rydgren A.E., Strom S.E., & Strom K.M., *ApJS* 30,307
- Tinney C.G. 1993, *ApJ*, 414, 279
- Whittet D.C.B., 1992, *Dust in the Galactic Environment*. Institute of Physics, Bristol.
- Wilking B.A., Greene T.P., & Meyer M.R. 1999, *AJ* 117,469
- Wilking B.A., Lada C.J., & Young E.T. 1989, *ApJ* 340,823
- Williams D.M., Comeron F., Rieke G.H., & Rieke M.J., 1995, *ApJ* 454,144
- Zinnecker H., McCaughrean M.J., & Wilking B.A. 1993, in "Protostars and Planets III", p429, edited by E.H.Levy & J.I.Lunine, pub. Tucson: University of Arizona Press.

Figure 1: (a)  $J$  vs.  $(J-H)$  plot. Open circles are highly uncertain data points. The dotted line is an approximate zero reddening track (see text). The solid lines are parallel to the  $A(V)=7$  reddening vector and divide the population into stars, brown dwarfs and planets, using the B97 prediction and an age of 1 Myr. The dashed lines correspond to the 0.3 Myr and 2 Myr predictions, indicating the effect of the age spread on the classification. The effect is similar at the planetary boundary.

(b)  $H$  vs  $(J-H)$  plot. This includes upper limits for sources with  $J > 20$ , which confirms the paucity of faint blue sources.

Figure 2:  $I$  vs  $(I-J)$  plot. Anomalously blue sources lie to the left of the arbitrary line parallel to the reddening track. Of the 11 blue sources detected by HST, 10 are proplyds, plotted as crosses.

Figure 3: (a) Empirical 2-colour curve fitted to the plotted observations. Two example dereddening tracks are also shown, indicating the possibility of double-valued solutions.

(b) results of dereddening Orion data.

Figure 4: (a) Observed  $H$  band luminosity Function. The equivalent  $J$  band function is overplotted as a dashed line. Both functions are complete to approximately magnitude 18.

(b) Dereddened Luminosity Function, complete between magnitudes 6.2 and 11.75.

Figure 5: IMFs for Burrows 1997 and DM98 tracks, complete to  $\log(M/M_{\odot}) = -1.5$ . Errorbars are plotted assuming Poisson statistics. The IMF appears to fall slowly into the Brown Dwarf regime, but rises again below the completeness limit.











