Young T-Dwarf Candidates in IC 348*

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ABSTRACT

Context. The determination of the lower-end of the initial mass function (IMF) provides strong constraints on star formation theories.

Aims. We report here on a search for isolated planetary-mass objects in the 3 Myr-old star-forming region IC 348.

Methods. Deep, narrowband CH₄-off and CH₄-on images were obtained with CFHT/WIRCam over 0.11 sq.deg. in the central part of IC 348 to identify young T-dwarfs from their 1.6 μm methane absorption bands.

Results. We report three faint T-dwarf candidates with CH₄-on–CH₄-off colours >0.4 mag. Extinction was estimated for each candidate and lies in the range Aᵥ ∼ 5 – 12 mag. Comparisons with T-dwarf spectral models, and colour/colour and colour/magnitude diagrams, reject two of the three candidates because of their extreme z’ – J blueness. The one remaining object is not thought to be a foreground field dwarf because of a number density argument and also its strong extinction Aᵥ ∼ 12 mag, or thought to be a background field T-dwarf which would be expected to be much fainter. Models and diagrams give this object a preliminary T6 spectral type.

Conclusions. With a few Jupiter masses, the young T-dwarf candidate reported here is potentially amongst the youngest, lowest mass objects detected in a star-forming region so far. Its frequency is consistent with the extrapolation of current lognormal IMF estimates down to the planetary mass domain.

Key words. Stars: formation – Stars: low-mass, brown dwarfs – (Galaxy:) open clusters and associations: individual: IC 348 – Stars: luminosity function, mass function – Infrared: stars

1. Introduction

To date more than 500 L-dwarfs and about 150 T-dwarf candidates have been detected using a variety of optical and IR surveys. The vast majority of detected brown dwarfs are old (3–6 Gyr) field dwarfs (Faherty et al. 2009), having cooled over time. The first detection of a T-dwarf in a star-forming region was put forward by Zapatero Osorio et al. (2002), named S Orionis 70 and detected in σ Orionis. Burgasser et al. (2004) raises questions about the authenticity of the object as a cluster member and suggested that it was a field dwarf in the line of sight, which was backed up with a statistical analysis. Martin (2004) and Zapatero Osorio et al. (2008) undertook further confirmation of the object by follow-up membership and proper motion work. The population of these young, low-mass objects is critical to furthering our understanding of the very low-mass end of the initial mass function (IMF). Star-forming regions are well suited to search for the lowest mass brown dwarfs as young objects are hottest, and so brightest immediately after formation. Their temperature decreases over time, since by their very nature they are not massive enough to begin fusion via hydrogen or deuterium synthesis.

One ideal system in which to observe young brown dwarfs and constrain the IMF is IC 348, a star-forming region towards the direction of Perseus, centred at (J2000) 03h44m34s, +32°09′8″, and embedded in the foreground part of the Per OB2 association. The age of IC 348 has been determined to be ~1–3 Myr (Muench et al. 2003). This star-forming region is relatively nearby and whilst there is controversy surrounding its distance, IC 348 is located between 261±27 pc (Scholz et al. 1999) and 316 pc (Herbst 1998) from the Sun whilst the OB Per association, of which IC 348 is a member, is taken to be between 315 pc (Luhman et al. 2003) and 340 pc (Cernis 1993). An average value of 300 (±15) pc has been used for this work (Herbst 2008).

Extinction maps for IC 348, ranging from ~2<Aᵥ<20 mag depending on the cluster region, were derived by Cernis (1993), Muench et al. (2003), and Cambresy et al. (2006). Muench et al. (2003) derived the IMF of IC 348 down to 35 MJup and found it to be similar to the IMF of the Trapezium cluster, having a mode between 0.1–0.2 M⊙. Approximately 15–25% of the population of the cluster appear to be brown dwarfs and their spatial density is independent of the distance from the cluster centre. The lowest mass objects were not detected in their work because of the detection limits. Those objects with a mass of a few MJup are very faint and cool (~1200 K) enough that methane can form in their atmospheres. The presence of methane absorption bands in substellar objects defines the L/T dwarf boundary (Burrows et al. 2006). This was first exploited by Mainzer & McLean (2003) to look for very faint objects in IC 348 to a depth of H ~19.5 mag. Narrow-band 1.65 μm methane imaging of IC 348 was conducted in order to filter out the lower mass T-dwarfs from the L-dwarfs, by their H – CH₄...
Individual images were detrended using the ‘i’iwi pipeline (Albert et al., in prep.) at CFHT and sky subtraction, stacking, photometric and astrometric calibrations, and quality control were performed at Terapix\footnote{terapix.iap.fr} (Marmo 2007). The seeing (PSF FWHM) measured on the final images was between 0.55″ and 0.65″. The co-added JHK\_s images were photometrically calibrated using the 2MASS catalogue over the same area and renormalized to an arbitrary photometric zero-point of 30 mag. The methane images have no external photometric calibration and the \( CH_4 \) magnitudes are given here on an arbitrary albeit internally consistent scale, so that \( CH_4+CH_4\_off=0 \) for unreddened field dwarfs (see below). The Terapix pipeline additionally produced a catalogue of objects with aperture photometry for each filter.

### 2.2. MegaCam

MegaCam observations were obtained under programme 06BF28 in queue service mode on September 21-23, 2006. MegaCam consists of a grid of 36 2k×4k CCDs covering a 1°×1° footprint. The pixel size is 13.5 µm and the pixel scale is 0.185″. MegaCam was used to take 6 dithered \( \gamma \)-band images of 1500 s each, yielding a total integration time of 9000 s. After detrending the images at CFHT, sky-subtraction, stacking, and photometric and astrometric calibrations were done at Terapix. The images were photometrically calibrated using standard stars routinely observed by the Queue Service Observing team at CFHT. The seeing during the observations ranged from 0.65″ to 0.80″.

### 2.3. Photometric catalogues

A combination of SExtractor\footnote{http://svo.laeff.ina.es/theory/filters/index.php} (Bertin & Arnouts 1996) and PSF\_Ex (Bertin et al., in prep.) was used on each image to extract sources and build a photometric catalogue for each image. On a first step, SExtractor extracts well defined stellar-like objects, which are used by PSF\_Ex to compute a PSF model that is allowed to vary with position on the detector. Then, SExtractor uses this PSF model to more accurately extract and measure the photometry of all the sources detected on the image. Objects were detected at 3.5 \( \sigma \) above the background noise (see Section 2.4 for further details), most notably to avoid the high incidence of nebulous emission and reflected nebulosity in the region. This threshold is reasonably low because our interest lies in detecting the faintest possible objects in the region, the methane T-dwarfs. Unfortunately, this low threshold also increases the incidence of non-stellar-like detections because of nebulosities, and many misidentifications created via crosstalk in the detector (though this was only particularly problematic in the narrowband observations).

Further analysis was conducted using publicly-available 2MASS data for those detected objects that were bright enough to have a 2MASS counterpart. This was useful for two reasons: firstly that the photometric accuracy and pipeline reduction of the WIRCam images could be compared with those from 2MASS; and secondly that the difference in the photometric systems could be estimated from the photometric differences between the CFHT and 2MASS. The extracted \( J, H \) and \( K_s \) catalogues were matched with the \( J, H \) and \( K_s \) 2MASS catalogues in 206 stars that had overlapping magnitudes. Based on these, the dispersion between the extracted \( J, H \) and \( K_s \) catalogues and the 2MASS \( J, H \) and \( K_s \) catalogues was calculated. Good agreement was shown by mean magnitude differences of

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**Table 2. Filters and central, effective, wavelengths used in this work.**

| Filter | \( 
\delta^e \left( \mu m \right) \) | \( 
\Delta \lambda^e \left( \mu m \right) \) | \( \lambda/A_\nu \) |
|--------|-----------------|-----------------|-----------------|
| \( \gamma \) | 0.88 | 0.27 | 0.52 |
| \( J \) | 1.25 | 0.16 | 0.30 |
| \( CH_4\_off \) | 1.58 | 0.10 | 0.21 |
| \( H \) | 1.63 | 0.29 | 0.20 |
| \( CH_4\_on \) | 1.69 | 0.10 | 0.18 |
| \( K_s \) | 2.15 | 0.32 | 0.13 |

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2 www.cfht.hawaii.edu

3 http://svo.laeff.ina.es/theory/filters/index.php
Table 1. Instruments used with field of view (FOV), filters, and the central coordinates of the pointings. The J, H and Ks final WIRCam images are made up of four overlapping fields (A, B, C and D).

| Telescope          | FOV       | Filter       | Integration time (h) | Pointing coordinates (J2000) |
|--------------------|-----------|--------------|----------------------|------------------------------|
| CFHT MegaCam       | 0.96×0.94′| z′           | 2.5                  | 03°44′36.00 +32°01′50.00    |
| CFHT WIRCam        | 20′×20′   | CH4off, CH4on| 3.7, 1.4             | 03°44′14.80 +32°05′06.00    |
| CFHT WIRCam        | 20′×20′   | J, H, Ks     | 0.35, 0.16, 0.12     | A                            |
|                    |           |              |                      | B                            |
|                    |           |              |                      | C                            |
|                    |           |              |                      | D                            |

0.08 ± 0.02, 0.03 ± 0.05, and 0.04 ± 0.02 for J, H and Ks respectively. These values hold for the brightest stars in our images, since fainter ones are undetected in the 2MASS survey. In turn, this means that colour effects arising from CFHT filters are not taken into account in this calibration. Indeed, while the photometric zero-point used here is obtained from 2MASS, colour effects are not corrected for and our WIRCam J, H, Ks, CH4on and CH4off photometry is given in the CFHT Vega system and MegaCam z′ in the AB system.

Each waveband had a catalogue created which was then collated and cleaned of saturated objects, obvious artefacts, and a fraction of extended sources identified from their large PSF FWHM. An approximation of the completeness of the photometric catalogues was estimated from log(N_{obs}) vs. magnitude histograms, where N_{obs} is the number of stellar-like objects detected on the images. We thus derived completeness limits from Figure 1 (top) of ~23.5 (z′), 21.5 (J), 20.0 (H), 18.9 (Ks), 20.3 (CH4on), and 20.7 (CH4off). SExtractor photometric errors for each of the six bands are plotted in Figure 1 (bottom), highlighting the increasing photometric error for the faintening of the objects’ brightness. Uniquely, the CH4off error terminates at 0.06 magnitudes as the CH4off image was used for the detection of objects over all bands (see Section 2.4 for further details).

2.4. Methane photometry

The presence of methane absorption bands in the near-IR spectrum of T-dwarfs can be used to identify T-dwarf candidates photometrically (e.g. Tinney et al. 2005). Narrowband CH4off and CH4on data was taken in order to classify these objects. CH4off measures the pseudo-continuum at 1.58 μm while CH4on samples the methane absorption band at 1.69 μm. The passband of the two filters is overlain onto the spectra of a T0.5 and a T8 dwarfs in Figure 2. Note the greater methane absorption in the T8 dwarf spectrum compared to the T0.5 spectrum in the region around 1.69 μm.

Spectra of field dwarfs from L1 to T8 were convolved (Delorme et al. 2008) with the WIRCam CH4on and CH4off filters and the resulting methane colours plotted against spectral type in Figure 2. The methane colours are seen to smoothly increase towards later spectral types. Whilst L-dwarfs have CH4on–CH4off colours equal to zero, T-dwarfs have colours above 0.1 mag which rapidly increase towards later T-types. To date, no other types of objects in current knowledge has this sequence of methane colours. Thus, the CH4on–CH4off colour provides a useful means to separate L and T-dwarfs.

Additionally, as late-type T-dwarfs may remain undetected in the CH4on image, and due to strong CHa absorption, we first performed object detection at 3.5σ on the CH4on image, then performed PSF photometry at the location of these objects on both the CH4off and CH4on images. This ensures that all objects that could possibly be T-dwarfs are searched for in both filters.

Figure 2 provides an empirical calibration of the methane colours against spectral type for field dwarfs. For comparison, Figure 3 shows the CH4on–CH4off colour as a function of effective temperature (Teff) as predicted by COND and DUSTY 3 Myr and 5 Gyr models (Chabrier et al. 2000; Allard et al. 2001; Baraffe et al. 2003). While the DUSTY models are roughly similar at both ages, with CH4on–CH4off ~ 0 at Teff ≥ 1500 K, the COND models predict bluer colours for younger objects at Teff < 1500 K. According to the models, IC 348 T-dwarfs would then have a smaller Teff and thus a later spectral type than field T-dwarfs for the same CH4on–CH4off colour.

3. Results

Catalogues were obtained as described above for each of the MegaCam/WIRCam images. The COND and DUSTY 3 Myr and 5 Gyr models are also in the CFHT Vega system where the z′ band has been converted into AB magnitudes for our purposes. Similarly, the empirical field L-T dwarf sequence photometry has been adjusted to be consistent with the models and our data. In the colour/magnitude diagram presented the field dwarf sequence has been shifted to the distance of IC 348, taken to be at 300 pc.

3.1. T-dwarf candidate selection

Figure 4 shows CH4on–CH4off against CH4off for stellar-like objects detected on WIRCam methane images. An object was considered as a T-dwarf candidate if CH4on–CH4off ≥ 0.4 mag, which corresponds to ≥ 3.5 σ above the L/T transition (CH4on–CH4off = 0) for the faintest detected objects. Assuming that young T-dwarfs follow the field dwarf methane relation, the spectral type of those objects with CH4on–CH4off = 0.4 mag is close to T3 from Figure 2.

Objects with CH4on–CH4off ≥ 0.4 mag were initially all classified as T-dwarf candidates. The objects just below this limit could still be T-dwarfs from their CH4on–CH4off colours as shown in Figure 2 but would be more difficult to extract because of photometric errors. With this criterion 136 sources were selected. This sample was then visually scrutinised on both the...
**Fig. 1.** *top:* \(\log(N_{\text{Obj}})\) vs magnitude (where \(N_{\text{Obj}}\) is the number of detected objects in each band): The completeness limits are found from these plots for the six imaged bands, \(z\), \(J\), \(H\), \(K_s\), \(CH_4\) on and \(CH_4\) off. The line has been fitted to the histogram to find where the turning point occurs, thereby indicating our completeness limit. *bottom:* Photometric error, as measured by SExtractor, against magnitude. Note that the \(J\), \(H\), \(K_s\) images have multiple tracks as they are composed from 4 fields which were not acquired at the same time.

\(CH_4\) off and \(CH_4\) on images before being reduced to a shortlist of 12 possible candidates. Upon visual inspection, we found that the rejected 124 ‘objects’ were saturated stars, nebulous detections or ghosts. Of these 12 possible candidates, the shape of the PSF and the contours were further examined using IRAF, where

9 were identified as ghosts or detector cross-talk, so reducing this figure to 3 likely candidates. Thumbsized \(CH_4\) off images of the three candidates are shown in Figure 5.

The PSF photometry of the 3 candidates in \(z', J, H, K_s\) and \(CH_4\) on/\(CH_4\) off filters is listed in Table 3. Candidate IC348 CH4_2 was not detected in the \(z'\)-band. The \(z'\)-band detection limit was estimated by simulating a set of 1948 stars with magnitudes between 20 and 26 using Skymaker (Bertin 2008). These synthetic stars were then stacked onto the \(CH_4\) off footprint of the original \(z'\) image using Swarp (Marmo 2007). At the 3\(\sigma\) level, 1688 objects were detected where the faintest had an input magnitude of 25.7, which we take as being the detection limit in the \(z'\) filter.

Most of the objects detected on the WIRCam images lie along the line \(CH_4\) on−\(CH_4\) off = 0 in Figure 4 as expected for field dwarfs (Tinney et al. 2005), the photometric error increasing with magnitude. The 3 candidates are located in the faintest region of the plot, whilst also having increasing methane colours. The \(CH_4\) on−\(CH_4\) off rms photometric error at the magnitude of the candidates is \(\sigma \sim 0.12\) mag. The 3 candidates have \(CH_4\) on−\(CH_4\) off colours of 0.54, 0.78, and 0.49 mag, respectively, corresponding to a detection level of > 4\(\sigma\) (see Table 4).

Note that a number of objects in Figure 4 have strongly negative \(CH_4\) on−\(CH_4\) off colours, well beyond the rms photometric error. Upon inspection of the images, all these objects turn out to be young IC 348 members deeply embedded in bright compact
Fig. 5. Thumbsized $CH_4$off images of the three T-dwarf candidates, left to right, IC348\_CH4\_1, IC348\_CH4\_2 and IC348\_CH4\_3, respectively. Black circles highlight the location of the T-dwarf candidates. The images are 48$''$ to a side, where North is up and East is to the left.

Table 3. PSF photometry and photometric errors of the three T-dwarf candidates, in magnitudes.

| Object   | $z'$ | $\sigma_z'$ | J  | $\sigma_J$ | H   | $\sigma_H$ | Ks | $\sigma_Ks$ | $CH_4$off | $\sigma_{CH_4}$off | $CH_4$on | $\sigma_{CH_4}$on |
|----------|-----|-------------|----|------------|-----|------------|----|------------|------------|---------------------|----------|-------------------|
| IC348\_CH4\_1 | 23.32 | 0.07 | 21.62 | 0.04 | 20.95 | 0.07 | 20.22 | 0.06 | 20.32 | 0.04 | 21.06 | 0.08 |
| IC348\_CH4\_2 | $\geq$25.7 | - | 22.51 | 0.07 | 21.65 | 0.08 | 20.10 | 0.04 | 20.59 | 0.04 | 21.37 | 0.10 |
| IC348\_CH4\_3 | 23.85 | 0.10 | 22.02 | 0.07 | 21.02 | 0.07 | 19.94 | 0.05 | 20.17 | 0.03 | 20.66 | 0.06 |

Fig. 3. $CH_4$on$-CH_4$off colour vs. $T_{\text{eff}}$. 3 Myr COND (thick solid), 5 Gyr COND (thin solid) 3 Myr DUSTY (thick dashed) and 5 Gyr DUSTY (thin dashed) models are shown. The COND models predict later spectral types for 3 Myr IC 348 objects than for field dwarfs for given methane colours.

Finally, a cross-comparison was made with the study of Mainzer & McLean (2003). They classified 5 candidates as belonging possibly M, L or T-dwarfs, all of which are detected in our images but with $CH_4$on$-CH_4$off colours between -0.14 and 0.04 mag, placing them out of our T-dwarf candidate criteria.
3.2. Reddening and spectral type estimates

Estimation of the candidates’ extinction is required in order to be able to calculate their absolute magnitude and estimate their spectral type. Extinction has been estimated using colour/colour diagrams of CH$_{4}$on–CH$_{4}$off versus $J$–$H$, $J$–$K_s$ and $H$–$K_s$, as plotted in Figure 6. The extinction was computed for each candidate using the extinction vector and regressing the objects back towards the 3 Myr COND model. The final extinction value is the average of the 3 results obtained from each colour/colour diagram and is summarised in Table 4 along with CH$_{4}$on–CH$_{4}$off colour, detection level and spectral type for the three candidates. The estimated extinction is an upper limit if the candidates belong to the cluster as their true dereddened colours are probably intermediate between the 3 Myr COND and DUSTY models. If they are field dwarfs however, the given value is a lower limit as the objects should be dereddened towards the 5 Gyr field dwarf sequence that is bluer than the 3 Myr COND model.

We then used these results to compute the dereddened CH$_{4}$on–CH$_{4}$off colour for each candidate. We found these values to be 0.69 ± 0.16, 1.15 ± 0.24 and 0.76 ± 0.15 mag for IC348 CH4,1, IC348 CH4,2 and IC348 CH4,3, respectively. From Figure 2, these dereddened colours correspond to a spectral type of T5$^{0.5}$, T6$^{+0.5}$, and T5$^{0.5}$ for IC348 CH4,1, IC348 CH4,2 and IC348 CH4,3, respectively. As noted above, this may be a lower estimate as the models suggest that young T-dwarfs have a lower effective temperature than field T-dwarfs for the same CH$_{4}$on–CH$_{4}$off colour (see Fig. 3). Moreover, if the candidates were 5 Gyr field objects, they would have a larger extinction and therefore an even larger intrinsic CH$_{4}$on–CH$_{4}$off colour, which would also yield a later spectral type.

4. Discussion

We discuss here the likelihood that the methane candidates reported above are bona fide young, very low-mass members of the IC 348 star-forming region instead of being more evolved field T-dwarfs located on the line of sight to the young cluster. We also compare the number of T-dwarf candidates we identify in our survey to the number of expected planetary mass objects in IC 348, by extrapolating recent estimates of the substellar IMF to the planetary mass domain.

4.1. Membership

Further colour/colour and colour/magnitude diagrams (CMD) were plotted to constrain the candidates’ status. Figure 7 shows the J/$J$–$K_s$ CMD. Also plotted are the synthetic magnitudes and colours of the field T-dwarfs when shifted to the cluster distance. The 5 Gyr DUSTY and COND models are drawn to highlight the agreement between the models and the field dwarf sequence. The field T-dwarf sequence begins in between the 5 Gyr DUSTY and COND models, before sweeping towards the 5 Gyr COND model at ~1500 K that sharply increases in faintness with the late-T set.

In this diagram the three candidates appear to be confused with the late-L, early-T field dwarfs. However, once they are dereddened using the extinction values given in Table 4 they become bluer and brighter. All three candidates appear to follow the 3 Myr COND model quite closely. The fact that the dereddened candidates appear brighter than field T-dwarfs shifted to the cluster distance suggest that they are younger indeed. A young T-dwarf has a larger radius than a field T-dwarf for a given spectral type as it is still contracting. According to the COND models, the difference amounts to about a factor of 2 in radius between 3 Myr and 5 Gyr (for $T_{eff}$=1000-1500 K), which results in a 1.5 magnitude increase, consistent with the observed location of the candidates in Figure 7.

There is a possibility that the candidates are in fact field T-dwarfs located at a closer distance (between ~100 and 200 pc) along the line of sight to IC 348. The probability of one of the candidates being a field T-dwarf instead of an IC 348 cluster member can be estimated independently from extinction. According to Figure 2 the spectral type range T3-T5.5 corresponds to the measured CH$_{4}$on–CH$_{4}$off colours of our candidates at an age of 5 Gyr. Thusly, using the number density of T3-T5.5 field dwarfs in the solar neighbourhood, i.e. ~1 per 714 pc$^3$ according to Metchev et al. (2008) and the footprint of the CH$_{4}$ image of 0.11 sq.deg gives an estimate of 0.11 ± 0.06 T3-T5.5 foreground field dwarfs in the direction of IC 348. As we are concerned here with the probability of one of our candidates being a foreground field dwarf, this is a fairly robust method for determining the population density for field dwarfs in the direction of IC 348. However, this estimate is put into context when taking into account the large extinction values of the three candidates estimated from Figure 6. Even the least extincted candidate, IC348 CH4,1, has four magnitudes more extinction than expected for a foreground field dwarf (<1 mag), so all three objects must be near to or behind IC 348. However, the candidates cannot be background field T-dwarfs, seen through the IC 348 cloud, as their luminosity would then be much too high for their estimated spectral type. Finally, as indicated in Table 4 all three candidates are located within the cluster’s boundary (4′ core ra-
Fig. 6. CH₄ on–CH₄ off vs. J − H, J − Kₛ and H − Kₛ. T-dwarf candidates are plotted as (blue) squares. Photometric error bars are from SExtractor. Field T-dwarfs (red triangles) are shown for comparison. Lines show the 5 Gyr COND and DUSTY, and 3 Myr COND and DUSTY models as in Fig. 3. Candidates were dereddened towards the 3 Myr COND model using the extinction vector.

Table 4. Summary of values for the three candidates, where the cluster centre is taken to be at 03:44:34.5 +32°09′48.0″ (J2000).

| IAU name | CH₄(on-off) | Det. level | Aᵥ/mag | Est. sp. type | Distance from cluster centre | Object coordinates |
|----------|------------|------------|--------|--------------|-----------------------------|-------------------|
| CFHT J0344+3202 (IC348 CH₄ 1) | 0.54       | 4.3σ       | 5.0 ± 1.2 | T5 ±0.5       | 03:44:49.24 +32°02′48.4″   |
| CFHT J0344+3206 (IC348 CH₄ 2) | 0.78       | 6.2σ       | 12.4 ± 3.9 | T6 ±0.5       | 03:44:49.52 +32°06′35.4″   |
| CFHT J0344+3156 (IC348 CH₄ 3) | 0.49       | 4.3σ       | 9.0 ± 1.3  | T5 ±0.5       | 03:45:57.95 +31°56′43.3″   |

dius, 10-15′ halo; Herbig 1998, Herbst 2008) and are thus spatially consistent with being IC 348 members.

4.2. Contaminants

A further, useful diagram in defining these candidate objects is the \(z′ − J\) vs. \(J − H\) colour/colour diagram shown in Figure 8 (note that the \(z′\) is in the AB system). Here it can be seen that the two detected dereddened candidates are much bluer in \(z′ − J\) than both the field dwarf sequence and the COND 3Myr and 5Gyr models. There is mounting empirical evidence for young T-dwarfs to have bluer \(z′ − J\) colours than field T-dwarfs because of the effects reduced gravity has on the opacities (P. Delorme, priv. comm.). This effect stems from the strong potassium KI (7687&7701 µm) doublets, whose wings fall within the \(z′\) band. The lower the gravity the lesser the line broadening of these elements so less flux is lost by absorption in the \(z′\) band, resulting in the observed bluer \(z′ − J\) colours (F. Allard, priv. comm). However, these effects are unlikely to explain the extreme blueness of two of the three objects and suggests that candidates IC348 CH₄ 1 and IC348 CH₄ 3 are unlikely to be T-dwarfs. The final remaining candidate, IC348 CH₄ 2, remains a good T-dwarf candidate because of its non-detection in \(z′\).

If candidates IC348 CH₄ 1 and IC348 CH₄ 3 are not young T-dwarfs then what are they? We checked whether extragalactic objects could contaminate this region of the diagrams. To this end, galaxies from SWIRE, 2MASS and SDSS were found to have very different colours (\(z′ − J\) ~ 6-8mag) to our candidates. Similarly, quasars also have J-band magnitudes of ~ 24-25 mag, making them much fainter than our objects. Late-type (emission line) galaxies appear tightly in the region \(J − K\) ~ 0.95 mag and \(J − H\) ~ 0.88 mag and so again cannot be confused with our candidates (Chang et al. 2006). The status of the two rejected candidates continues to be unclear.

4.3. Comparison of IC348 CH₄ 2 with S Ori 70

Zapatero Osorio et al. (2002) found S Ori 70 to be a faint mid-T type object towards the direction of the young \(σ\) Orionis clus-
bands, except IC348_CH4_1 which falls out of the [4.5] band field of view. PSF photometry was performed using Starfinder (Diolaiti et al. 2001) and the fluxes were translated into magnitudes using the zeropoint fluxes provided by the Spitzer Science Center. Measurement uncertainties were tentatively estimated from the Poisson noise weighted by the coverage maps of the mosaics. The final photometry is given in Table 5 and the final errors include both measurement and zeropoint flux uncertainties.

In Figure 10, the $K_s - [3.6]$ vs $[3.6] - [4.5]$ colour/colour diagram is plotted with the two candidates, S Ori 70 and the IC 348 M6-M9 dwarf sequence from Luhman et al. (2005). The M, L and T IRAC field dwarf sequence from Patten et al. (2006) have also been plotted for comparison. The $[3.6] - [4.5]$ colour could be a good indicator of effective temperature, or spectral type, giving IC348_CH4_2 a spectral type of $\sim$T5, in line with our other estimates of T6. The $K_s - [3.6]$ colour, however, relates to a spectral type of L1, which is far too early for such a low-mass and cool object.

The $K_s - [3.6]$ colour of IC348_CH4_2 appears significantly bluer compared to the field sequence, which may be because of reduced gravity (Leggett et al. 2007). For mid-type and later T-dwarfs the reduced pressure broadening of H$_2$, as a gravity effect, makes the $K_s$ band brighter, whilst the [3.6] band faintens because of additional CH$_4$ absorption at $\sim$ 3 $\mu$m, resulting in a bluer $K_s - [3.6]$ colour. Another consequence of lower gravity is the faintening effect the CO abundances have on the [4.5] band for early T-types, thus balancing the [3.6] - [4.5] colour. These colour effects of low gravity are in agreement with this object being a young IC 348 T-dwarf.

Other effects such as strong sedimentation and little or no vertical mixing in the atmosphere could also contribute to the observed bluer $K_s - [3.6]$ colours (Leggett et al. 2007).

The possible existence of a hot inner dusty disc around S Ori 70, in keeping with other young members of S Orionis, can give rise to its redder $[3.6] - [4.5]$ colour.

4.4. The lower end of the IMF

Luhman et al. (2003) derived a nearly complete IMF for IC 348 down to 0.03 M$_\odot$ for $A_V \leq 4$ mag. They find a ratio of brown dwarfs (BDs, 0.02-0.08 M$_\odot$) to stars of about 12%. Muench et al. (2003) similarly derived an IMF for IC 348 down to 0.04 M$_\odot$, with a mode between 0.08 and 0.2 M$_\odot$, finding a ratio of BDs to stars of about 14%. From a deep J-band survey of the cluster, Preibisch et al. (2003) derived a BD to star ratio of 10%.

According to the COND and DUSTY models, the mass range of 3 Myr old T-dwarfs is between 0.001 M$_\odot$ and 0.005 M$_\odot$, corresponding to masses from $\sim$1 M$_{\text{Jup}}$ to $\sim$5 M$_{\text{Jup}}$. However, the models are somewhat uncertain at very low masses and young ages. Currently the models can have up to a 50% discrepancy in the masses for objects younger than 5 Myr (Chabrier, priv. comm). Still, the T-dwarf candidate IC348_CH4_2 is likely to be less massive than 10 M$_{\text{Jup}}$, if belonging to IC 348.

In order to obtain an estimate of the number of objects within this mass range that are expected to be in IC 348, we extrapolated current estimates of the IMF to the planetary mass regime. A lognormal estimate of the field IMF for unresolved systems was provided by Chabrier (2003), where the mode of the distribution, $m_0$, is 0.22 M$_\odot$ and its width, $\sigma$, is 0.57. This lognormal IMF would predict $\sim$1% objects in the mass range be-

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8 http://ssc.spitzer.caltech.edu/
Table 5. Spitzer PSF photometry and photometric errors of the three T-dwarf candidates. IC348\_CH4\_1 appeared outside the FOV in the [4.5]μm image.

| Object       | F[3.6]| Error | F[3.6]| Error | F[4.5]| Error | F[4.5]| Error | [3.6]| Error | [4.5]| Error |
|--------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| IC348\_CH4\_1| 0.0035| 0.0001| -      | -     | 19.75 | 0.03  | 17.80 | 0.03  | -      | -     | -      | -     |
| IC348\_CH4\_2| 0.0093| 0.0003| 0.0136| 0.0004| 18.70 | 0.03  | 17.80 | 0.03  | -      | -     | -      | -     |
| IC348\_CH4\_3| 0.0245| 0.0003| 0.0365| 0.0007| 17.65 | 0.02  | 16.73 | 0.02  | -      | -     | -      | -     |

Fig. 10. $K_\ast - [3.6]$ vs $[3.6] - [4.5]$. The field dwarf sequence from Patten et al. (2006) has been plotted (red crosses) for comparison. IC 348 M6-M9 dwarfs with disks (filled green squares) and those without (hollow green squares) are plotted (Luhman et al. 2005). IC348\_CH4\_2 and S Ori 70 appear significantly bluer in the $K_\ast - [3.6]$ colour than for field dwarfs. The extinction vector has also been plotted using values from the Spanish Virtual Observatory.

5. Conclusions

From a deep methane imaging survey of the star-forming region IC 348 we identified 3 T-dwarf candidates over the area of the cluster. After colour/colour and colour/magnitude diagram analysis two candidates have been rejected for being too bright at optical wavelengths. The remaining candidate, has an estimated spectral type of T6 and theoretical models suggest a mass of a few $M_{\text{Jup}}$ for this object at 3 Myr. From its luminosity, colour, extinction and spatial location, IC348\_CH4\_2 is a probable IC 348 T-dwarf member, and so is among the lowest mass objects observed so far in a star-forming region. The frequency of isolated planetary mass objects reported here for IC 348 is consistent with the extrapolation of current lognormal IMF estimates to the planetary mass domain.

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