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Proper motions of USco T-type candidates★†

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ABSTRACT

We present new *z*- and *H*-band photometry and proper motion measurements for the five candidate very-low-mass T-type objects we recently proposed to be members of the nearest OB association with the Sun, Upper Scorpius (USco). These new data fail to corroborate our prior conclusions regarding their spectral types and affiliation with the USco population. We conclude that we may be in presence of a turnover in the mass function of USco taking place below 10–4 $M_{\rm Jup}$, depending on the age assigned to USco and the models used.

Key words: techniques: photometric – surveys – stars: luminosity function, mass function – infrared: stars.

1 INTRODUCTION

The quest for young objects of spectral-type T remains an area of substantial interest as a way to address a fundamental question in our understanding of star formation: what is the lowest mass that this process can form? The earliest theoretical predictions by Kumar (1969), Low & Lynden-Bell (1976) and Rees (1976) suggested masses as low as ∼10 Jupiter ($M_{\rm Jup}$) but contemporary calculations reveal that in the presence of magnetic fields this limit could be much lower (Boss 2001; Stamatellos & Whitworth 2008).

Naturally, the searches for these objects have concentrated on the nearest young clusters and star-forming regions and these have led to the identification of several candidate infantile T-type objects. Crucially, none of these has been unambiguously confirmed astrometrically *and* spectroscopically. For example, Bihain et al. (2010) have detected a further candidate T-type member of the σ Ori cluster, adding to the previously known candidate mid-T, S Ori 70 (Zapatero Osorio et al. 2002, 2008; Burgasser et al. 2004; Luhman et al. 2008; Scholz & Jayawardhana 2008). However, proper motion measurements of both objects cast doubt on their association with this population (Peña Ramírez et al. 2011). More recently, Peña Ramírez et al. (2012) have identified another candidate T-type in this same region using photometry from the Visible and Infrared Survey Telescope for Astronomy (VISTA; Emerson et al. 2004) Orion survey.

Additionally, Marsh et al. (2010) have claimed the discovery of a T2 member of ρ Ophiuchus but this has since been refuted by Alves de Oliveira et al. (2010). Independently, Geers et al. (2011) have proposed several candidates as substellar members of this population through infrared spectroscopy, including one with a mass close to the deuterium burning limit. Another wide-field methane imaging survey of ρ Ophiuchus revealed 22 T-type dwarf candidate members down to 1–2 Jupiter (Haisch, Barsony & Tinney 2010). Burgess et al. (2009) identified a mid-T-type candidate from a deep methane survey of ∼0.11 square degree in IC 348 but neither spectroscopy nor astrometry is yet available to confirm membership. Spezzi et al. (2012) reported two potential T-type candidates in the core of the Serpens cloud although their nature remains uncertain with the sets of data available to the authors. Similarly, none of the faint Pleiades L/T dwarf candidates announced by Casewell et al. (2007) have been confirmed spectroscopically as members (Casewell et al. 2011). It is worth noting here that there are two spectroscopically and astrometrically confirmed T dwarf members of the Hyades cluster (Bouvier et al. 2008). However, these have significantly larger masses (∼50 $M_{\rm Jup}$) than the young T-types due to their substantially greater ages, $\tau \sim 600$ Myr.

Upper Scorpius (hereafter USco) is part of the Scorpius Centaurus OB association: it is located at 145 pc from the Sun (de Bruijne et al. 1997) and its age is estimated to 5 ± 2 Myr from isochrone fitting and dynamical studies (Preibisch & Zinnecker 1999) although a more recent study by Pecaut, Mamajek & Bubar (2012) suggests 11 ± 2 Myr (see also Song, Zuckerman & Bessell 2012). The association has been targeted in X rays (Walter et al. 1994; Preibisch et al. 1998; Kunkel 1999), astrometrically with *Hipparcos* (de Bruijne et al. 1997; de Zeeuw et al. 1999), and more recently at optical (Ardila, Martín & Basri 2000; Preibisch, Guenther & Zinnecker 2001; Preibisch & Zinnecker 2002; Martín, Delfosse & Guieu 2004; Slesnick, Carpenter & Hillenbrand 2006) and near–infrared (Lodieu, Hambly & Jameson 2006; Lodieu et al. 2007,

★ Based on observations collected with the ESO New Technology Telescope under programme number 089-C.0854(A).
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2011b; Dawson, Scholz & Ray 2011; Dawson et al. 2013) wavelengths. Tens of brown dwarfs have now been confirmed spectroscopically as members of USco (Martín et al. 2004, 2010; Lodieu et al. 2006, 2008; Slesnick et al. 2006; Slesnick, Hillenbrand & Carpenter 2008; Lodieu, Dobbie & Hambly 2011b) and the mass function of this population determined robustly, deep into the substellar regime (Preibisch et al. 2002; Slesnick et al. 2008; Lodieu et al. 2011b).

In a recent paper in our extensive series of publications relating to USco (Lodieu et al. 2011a), we identified five T-type candidate members with deep infrared photometry from the UK Infrared telescope wide-field camera (UKIRT/WFCAM; Casali et al. 2007). In the current work, we report proper motion measurements for these objects obtained from early deep WFCAM *J*-band observations and new *H*-band imaging that are separated in time by four years. In Section 2 and Section 3, we describe the new *H*-band observations carried out with the Son of Isaac (SofI) instrument installed on the European Southern Observatory (ESO) New Technology Telescope (NTT) in La Silla Observatory (Chile) and additional *z*-band imaging conducted with the Optical System for Imaging and low Resolution Integrated Spectroscopy (OSIRIS) installed on the Gran Telescopio de Canarias (GTC) in La Palma Observatory (Canary Islands). In Section 4, we use the new photometry and astrometry to examine the membership status of the five candidate T-type members. In Section 5, we place our new results into context and speculate about our (positive/negative) results.

2 NEAR-INFRARED PHOTOMETRY

2.1 *H*-band imaging

We performed near-infrared imaging of the five T-type candidates in USco listed in table 4 of Lodieu et al. (2011a) in the *H* filter with SofI on the 3.5-m NTT (Moorwood, Cuby & Lidman 1998). All five sources were observed on 2012 May 9.

SofI is equipped with a Hawaii HgCdTe 1024 × 1024 array with squared 18.5 μm pixels and has both imaging and spectroscopic capabilities. The pixel scale is 0.292 arcsec in the Large Field configuration, providing coverage of a 4.9 × 4.9 arcmin field of view. We employed a random dithering pattern within a 40 arcsec box using six on-source individual integrations of 20 s, repeating this 10 or 20 times for the two brightest and three faintest T-type candidates. This yielded total on-source exposures of 20 or 40 min for the bright and faint objects, respectively. At the time of the observations, the night was clear and the seeing was around 0.7–0.9 arcsec, allowing us to go deep enough to detect the T-type candidates with signal-to-noise ratios between 8 and 15. Dome flats and darks with the same on-source integrations were taken during the afternoon prior to our observing night. As our fields are within the footprint of the UKIRT Infrared Deep Sky Survey Galactic Clusters Survey (UKIDSS GCS; Lawrence et al. 2007), no photometric standard stars were observed.

2.2 Data reduction and astrometry

The data were reduced with the ESO European Southern Observatory Recipe Execution Tool (EXOREX) SofI pipeline recipes. These perform an automatic reduction of the target frames within an observing block, including flat-field correction, sky subtraction and cross-talk removal. The next step of the data analysis included photometric and astrometric calibrations using the WFCAM images as reference.

To astrometrically calibrate the SofI images we proceeded as follows: for a first guess we used the astrometry.net package[1] which requires the centre of image given by the (RA, Dec.) coordinates in the header, the pixel scale (0.292 arcsec pixel^{-1}), and a radius for the search (set to 12 arcmin, more than twice the field of view of the SofI images). The astrometric solution was satisfactory comparing with Two Micron All Sky Survey (2MASS) and the deep WFCAM images obtained as first epoch. However, it was not good enough for our purposes, i.e. to measure proper motions between the two epochs.

The second step made use of the GAIA software[2] which itself uses SExtractor (Bertin & Arnouts 1996). We ran the detection algorithm to extract all sources (pixel and world coordinates systems) in the SofI images. Then, we cross-correlated this SExtractor catalogue against the deep WFCAM data set and kept only the SofI (*x*,*y*) and WFCAM (RA, Dec.) coordinates in an output file for sources with *J*-band magnitudes in the 19–20 range. Next we used the IRAF task `ccmap` interactively with a polynomial of order 4. Using the faintest stars from the WFCAM images allowed us to exploit more than 100–170 point sources with a small intrinsic motion on the sky (i.e. about 21–25 per cent of all stars in the each SofI field), avoiding bright members of the association. We eliminated points whose astrometry was off by more than 5σ, yielding an rms of 44.8–51.1 mas and 33.2–45.1 mas in right ascension and declination, respectively (corresponding to about 1/6 of the SofI pixel scale or 11–13 mas yr^{-1}). The new image was saved and SExtractor ran again with a detection threshold of 3σ and an aperture twice the size of the full width at half-maximum (∼6 pixels or 2 arcsec) to detect all sources in the SofI field of view, including the targets.

2.3 Photometric calibration

We could not use point sources within the 2MASS data base to calibrate photometrically the SofI frames because most of these were saturated in our images. Instead, we cross-matched all objects detected by SExtractor (see Section 2.2) with the ninth data release of the UKIDSS GCS and retrieved all point sources detected in *H* with photometric error bars less than 0.1 mag for each individual field. The total numbers of matched sources within a matching radius of 2 arcsec was typically 200–240. We find a median offset of -0.799 ± 0.095 mag between the UKIDSS system (Vega system; Hewett et al. 2006) and the SofI photometry when we adopt the default zero-point of 25 mag in the SExtractor parameter field. We list the offsets for each of the five fields in Table 1. The final photometric uncertainties on the offsets corresponds to the root mean square of the dispersion between offsets and the individual errors. Table 2 lists the *H* magnitudes and their errors of our five USco targets, computed using the offsets from each individual frame.

3 OPTICAL PHOTOMETRY

3.1 *z*-band imaging

OSIRIS is the Optical System for Imaging and low Resolution Integrated Spectroscopy instrument (Cepa et al. 2000) on the 10.4-m GTC operating at the Observatory del Roque de Los

[1] More details at astrometry.net

[2] GAIA is a derivative of the SKYCAT catalogue and image display tool, developed as part of the VLT project at ESO. SKYCAT and GAIA are free software under the terms of the GNU copyright.

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Table 1. Offsets between the NTT/SofI and UKIRT/WFCAM *H*-band photometry using >100 point sources in each individual SofI field. The last row indicates the mean (Avg) value of the offset, taking into account the dispersion and errors on the individual offsets.

Field	RA (hh:mm:ss.ss)	Dec. (°:′:″)	Offset (*H*) (mag)	No. of stars
1	16:08:35.98	−22:29:11.1	−0.796 ± 0.082	210
2	16:08:45.73	−22:29:53.5	−0.784 ± 0.064	226
3	16:08:47.80	−22:29:04.5	−0.846 ± 0.070	243
4	16:09:55.91	−22:33:45.7	−0.807 ± 0.070	203
5	16:10:04.76	−22:32:30.6	−0.761 ± 0.080	197
Avg			−0.799 ± 0.095	

Muchachos (La Palma, Canary Islands). The OSIRIS instrument is equipped with two 2048 × 4096 Marconi CCD 42–82 with an 8 arcsec gap between them and operates at optical wavelengths, from 365 to 1000 nm. The unvignetted instrument field of view is about 7 arcmin × 7 arcmin with a pixel scale of 0.125 arcsec. We used the standard 2 × 2 binning mode.

We imaged the five T-type candidates in USco with the Sloan *z* filter available on OSIRIS during 2012 May. Bias and skyflats were observed on May 26 (evening) and May 28+30 (morning). On 2012 May 27, we obtained three series of 10 frames with 60 s on-source integrations covering the targets 16084780–2229045, 16084573–2229535 and 16083598–2229111. On 2012 May 29, we obtained three sets of 10 images with 20 s on-source integrations for 16095591–2233457 and 16100476–2232306 as well as nine images of 39 s for 16100476–2232306. We also repeated the observations of 16084780–2229045 and 16084573–2229535 obtaining four series of 10 images exposed 60 s.

All observations were conducted under average seeing of 1.1–1.3 arcsec, photometric or clear conditions, and airmass between 1.6 and 1.8. The sky was relatively dark during the observations made on May 27 because the moon was set whereas the 64 per cent-full moon was below 20° on 2012 May 29.

3.2 Data reduction and astrometry

We reduced the OSIRIS Sloan *z*-band images in a standard manner under the IRAF environment[3] (Tody 1986, 1993). First, we subtracted the mean bias and divided by the normalized averaged master skyflat to each individual science frame. Then, we combined each set of 10 images taken without dithering and finally combined those sets applying the offsets to create a master science frame. We note that our targets were located on CCD 2, thus, we only treated data from that chip throughout the reduction process.

We calibrated astrometrically the final combined science frames using IRAF and `ds9` (Joye & Mandel 2003). First, we saved in a file a list of point sources from the 2MASS catalogue (Cutri et al. 2003; Skrutskie et al. 2006) spread over the full OSIRIS field of view. Second, we ran the `daofind` task with the adequate detection and threshold parameters to identify (roughly) the same point sources to cross-match them in a subsequent step with the `ccxymatch` routine. The latter task required a reference star with pixel (*x*,*y*) and world coordinate system (RA, Dec.) coordinates to efficiently cross-match the 2MASS (*x*,*y*) and (RA,Dec.) catalogues. We typically found

[3] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation

Table 2. Photometry for the USco T-type candidates: the *Y*, *J* and methane photometry is from Lodieu et al. (2011a) to which we added the new *H*-band photometry from NTT/SofI and *z*-band magnitudes from GTC/OSIRIS. The $z - J$ and $J - H$ colours are given as well. The resulting proper motions measured between the first and second epoch images at near-infrared wavelengths are quoted in mas yr^{-1}.

RA (hh:mm:ss.ss)	Dec. (°:′:″)	*Y* (mag)	*J* (mag)	CH_{4off} (mag)	CH_{4on} (mag)	*H* (mag)	*z* (mag)	$J - H$ (mag)	$z - J$ (mag)	$\mu_\alpha \cos\delta$ (mas yr^{-1})	$\mu\delta$ (mas yr^{-1})	μ (mas yr^{-1})
16:08:35.98	−22:29:11.1	21.87 ± 0.14	20.96 ± 0.11	20.47 ± 0.20	21.11 ± 0.18	20.41 ± 0.15	22.59 ± 0.04	0.55 ± 0.18	1.63 ± 0.12	−3.6	+12.8	13.3
16:08:45.73	−22:29:53.5	21.47 ± 0.10	20.72 ± 0.09	20.29 ± 0.17	21.15 ± 0.13	20.20 ± 0.12	22.37 ± 0.07	0.52 ± 0.15	1.65 ± 0.11	−18.4	+6.9	19.7
16:08:47.80	−22:29:04.5	21.57 ± 0.11	20.72 ± 0.09	20.59 ± 0.24	21.45 ± 0.17	20.28 ± 0.13	22.48 ± 0.08	0.44 ± 0.16	1.76 ± 0.12	+12.9	−5.8	14.1
16:09:55.91	−22:33:45.7	21.10 ± 0.08	20.19 ± 0.06	19.81 ± 0.14	20.40 ± 0.08	19.87 ± 0.16	22.02 ± 0.07	0.32 ± 0.17	1.83 ± 0.09	+21.0	−12.7	24.5
16:10:04.76	−22:32:30.6	20.46 ± 0.05	19.69 ± 0.04	19.26 ± 0.11	19.75 ± 0.04	19.16 ± 0.12	21.50 ± 0.09	0.52 ± 0.12	1.81 ± 0.10	+35.4	+26.3	44.1

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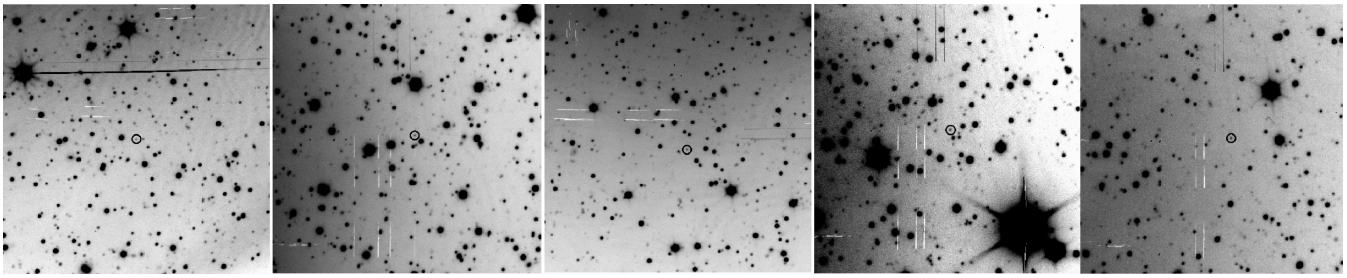

Figure 1. GTC/OSIRIS z-band images for the five candidates (circled and centred). North is up and East is left. Images are 1 arcmin × 1 arcmin.

80–100 stars in the field of view of CCD 2 running `ccmap` with a polynomial of order 4, resulting in an astrometric calibration better than 0.1–0.15 arcsec. The final reduced z-band images of the five candidates are shown in Fig. 1.

3.3 Photometric calibration

The GTC calibration plan provided us with only one observation of a photometric standard star (G 163-50) taken on the night of 2012 May 27 with a single on-source integration of 0.8 s at an airmass of 1.253. This DA3.2 white dwarf (Holberg, Oswalt & Barstow 2012) is a Sloan photometric standard (Adelman-McCarthy et al. 2011) and has a z-band magnitude of 13.809. We measured the instrumental magnitude using aperture photometry and applied a curve-of-growth analysis to allow for all the flux from the standard star.

We obtained a photometric zero-point of 28.028 ± 0.020 mag which is consistent within the error bars with both the values from the GTC OSIRIS daily monitoring of the zero-points[4] and our own previous measurement (28.038 ± 0.059) from data taken in Semester 12B (Lodieu et al. 2013). For the night of 2012 May 29, we use the average value from Semester 12B quoted above although data from the Carlsberg Meridian Telescope (http://www.ast.cam.ac.uk/ioa/research/cmt/data/camcext.12) suggest this night was similar in transparency to the first.

We performed aperture and point-spread function (PSF) photometry with `daophot` under IRAF because of the fairly crowded nature of this region (Fig. 1) and the faintness of our targets. We choose an aperture equal to 3× the full width at half-maximum and checked that our targets were all well subtracted without residuals by our PSF analysis. We corrected the instrumental magnitude for the z-band zero-point and the airmass. We did not take into account possible effects due to colour terms. We list in Table 2 the final magnitudes of the five T-type candidates in USco. We note that we quote the mean value of the magnitudes when two measurements were available (case of 16084573–2229535, 16084780–2229045 and 16100476–2232306), the uncertainty being the dispersion between both values to which we added in quadrature.

4 RE-EXAMINING MEMBERSHIP TO USco

4.1 New astrometric tests

To measure the relative proper motions for all common point sources, we cross-matched the catalogues from the five NTT pointings with the full catalogue of the deep WFCAM survey (Lodieu et al. 2011a) with a matching radius of two arcsec. We found about

[4] www.gtc.iac.es/en/media/osiris/zeropoints.html

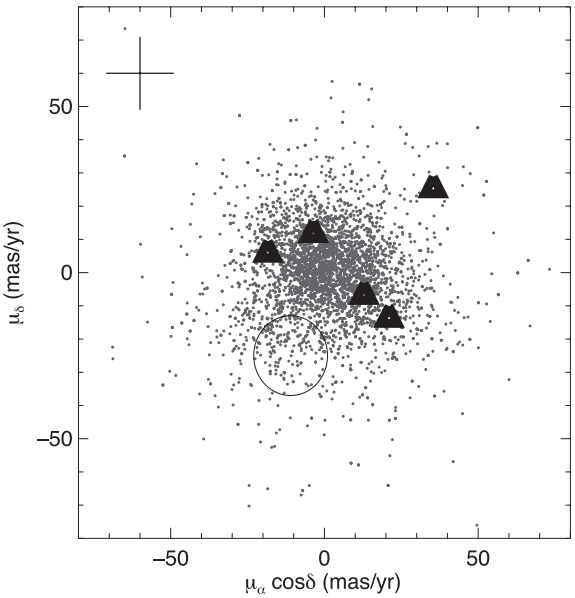

Figure 2. Proper motion vector point diagrams for the five T-type candidates in USco marked with thick black triangles. The large circle has a radius of 12 mas yr^{-1} and is centred on the USco mean proper motion. The small grey dots represent all point sources common to the deep WFCAM survey and the NTT fields.

3200 sources to compare with the proper motions measured for the five T-type candidates. We list the proper motion in the right ascension and declination as well as the total proper motion in Table 2. We show their positions in proper motion reduced vector point diagrams in Fig. 2 where our T-type candidates are highlighted with thick black triangles. All five candidates lie at least 2.5σ from the mean absolute proper motion of the association estimated as (−11, −25) mas yr^{-1} by *Hipparcos* (de Bruijne et al. 1997; de Zeeuw et al. 1999), arguing against their membership to the association.

We compiled a list of known spectroscopic members of USco from Ardila et al. (2000), Martín et al. (2004), Slesnick et al. (2006), Lodieu et al. (2006), Slesnick et al. (2008), Dawson et al. (2011), Lodieu et al. (2011b) and Dawson et al. (2013) to cross-match with the catalogue of point sources common to the NTT fields of view and the deep WFCAM survey (Lodieu et al. 2011a). Unfortunately, none of these known spectroscopic members lies within the NTT fields of view. This is not surprising considering that the total area covered by the five NTT pointings is of the order of 0.03 square degree. Lodieu et al. (2006) and Lodieu et al. (2007) found between 0.1 and 0.5 member candidates in 0.03 square degree down to the depth of the UKIDSS GCS, depending on the location in the association.

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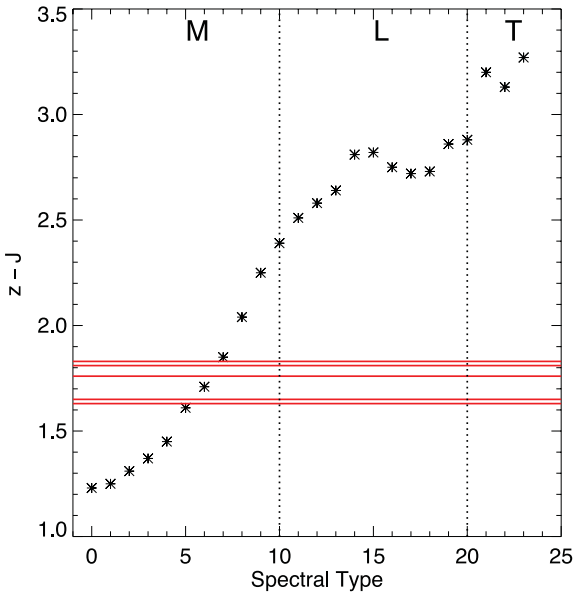

Figure 3. $z - J$ colours of the five T-type candidates as a function of spectral type (red solid lines). The typical colours of M, L and T dwarfs from Sloan (Hawley et al. 2002; West et al. 2008; Schmidt et al. 2010) are marked as asterisks. The M, L and T regions are delineated by vertical dotted lines.

4.2 New photometric tests

Using our new photometry, we have derived the $J - H$ colours of the five USco candidates so that we can further probe their nature (Table 2). We find that these lie in the range 0.32–0.55 with an upper limit on the photometric errors of 0.18 mag, implying that these sources could be either T2–T4 dwarfs or M dwarfs due to the degeneracy in the near-infrared colours (Hawley et al. 2002; West, Walkowicz & Hawley 2005; Hewett et al. 2006; Pinfield et al. 2008).

To break this degeneracy, we determined their $z - J$ colours and find these to be in the range 1.63–1.83 $\pm$ 0.12 mag (Fig. 3), typical of M4–M7 dwarfs (Hawley et al. 2002; West et al. 2005) but inconsistent with the expected much redder colours of L and T dwarfs (>2.5 mag; Pinfield et al. 2008; Zhang et al. 2009; Schmidt et al. 2010). Hence, on the basis of our new astrometric and photometric measurements we can rule out that these five candidates are young, 5-Myr old, planetary mass objects belonging to USco.

5 DISCUSSION AND OUTLOOK

Combining our new z and H photometry with our proper motion measurements, we conclude that the five candidates proposed by Lodieu et al. (2011a) as young, T-type candidates are not cool brown dwarf members of the USco association. Hence, up to now, no T-type brown dwarf has been confirmed astrometrically and spectroscopically in this region. Overall, there are no young T-types confirmed spectroscopically in young star-forming regions, except the object reported by Marsh et al. (2010) but questioned by Alves de Oliveira et al. (2010). No astrometric confirmation is available and it will remain hard in ρ Ophiuchus due to the small mean motion of members of this region.

We note the low success rate of wide-field surveys of young populations involving methane filters. For example, all of our five candidates are rejected after obtaining second epoch imaging and additional photometry. Burgess et al. (2009) reported three T-type candidates but later rejected two of them using optical imaging. Similarly, Spezzi et al. (2012) reported four T-type candidates from a methane imaging combined with *JHK* photometry and rejected two of them (the third may be a non-member too) from their positions in various colour–colour and colour–magnitude diagrams. We believe it is essential that additional photometry (e.g. deep optical i and z), spectroscopy or astrometry is obtained for the 22 candidate T-type members of ρ Oph identified by Haisch et al. (2010) so that their nature can be more rigorously examined.

So, after eliminating the five T-type candidates here, we have only one photometric candidate left (UGCS J16064645−2231238) in our one square degree survey in USco (Lodieu et al. 2011a). This candidate is the only object found in our survey with J fainter than ∼19 mag. We reach a 5σ limit of 21 mag, similar to the deep VISTA survey of 0.78 square degree in σ Orionis of Peña Ramírez et al. (2012) where three T-type candidates were identified, although proper motions indicate that two of them are likely to be non-members. Hence, our results are consistent with the main conclusions of Peña Ramírez et al. (2012) that we may see a turnover of the mass function below 10–4 $M_{\rm Jup}$ [depending on the isochrones (NextGen, DUSTY, BT-Settl) used and the age elected for USco (5 or 10 Myr) Baraffe et al. 1998; Chabrier et al. 2000; Allard, Homeier & Freytag 2012] unless young T-type brown dwarfs are fainter than predicted by state-of-the-art models.

The next step in our quest for the bottom of the stellar/substellar initial mass function in USco is to obtain deeper and wider imaging using a combination of Z, Y, J passbands where the USco sequence can be clearly de-lineated from the general field population (Lodieu et al. 2007). We have targeted over 10 square degree in USco with the largest infrared camera in the world, VIRCAM (Dalton et al. 2006), installed on VISTA to address this fundamental question regarding the fragmentation limit (Low & Lynden-Bell 1976; Rees 1976). Our results will be presented in a forthcoming paper.

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