A new free-floating planet in the Upper Scorpius association

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ABSTRACT

We report on a deep photometric survey covering an area of 1.17 deg² in the young Upper Scorpius stellar association using VIMOS IR and UKIDSS $ZJHK$ data taking several years apart. The search for the least massive population of Upper Scorpius (∼5–10 Myr, 145 pc) is performed on the basis of various optical and infrared color-color and color-magnitude diagrams, including WISE photometry, in the magnitude interval $J=14.5$–19 mag (completeness), which corresponds to substellar masses from 0.028 through 0.004 $M_\odot$ at the sky (Slesnick et al. 2008) and is located at a mean distance of 145±2 pc (de Zeeuw et al. 1999). We carried out a deep photometric survey in a zone of low foreground extinction ($A_v < 1$ mag; Preibisch et al. 1998 and references therein). Regarding the USco age, previous studies suggested that the association is ∼5 Myr old on the basis of the location of B-type stars in the Hertzsprung-Russell diagram and and their comparison with evolutionary tracks (de Geus et al. 1989; Preibisch & Zinnecker 1999; Preibisch et al. 2002). Recently, Herczeg & Hillenbrand (2015) estimated an age of ∼4 Myr for the low mass members of the USco association calculated from models that reproduce the lithium depletion boundary of various young star clusters and stellar moving groups. This is somehow younger than the USco age derived by Pecaut et al. (2012). These authors estimated an age of 11 ± 2 Myr for intermediate and high mass USco members, including the M-type supergiant star Antares. The newly discovered eclipsing binaries in USco (UScoCTIO 5 and EPIC 203868608, Kraus et al. 2015; David et al. 2015) also support ages close to the 10 Myr for the USco association. In addition, the high proper motion of the USco association ($\mu = 26.7 \pm 2.5$ mas yr$^{-1}$; Zacharias et al. 2004) is beneficial for the unambiguous identification of its true members once the astrometric and photometric studies are conveniently combined.

Here, we present an exploration extending over 1.17 deg² in the USco association. We used deep photometric data covering the wavelength range 0.8–3.4 μm. Our goal was to define the USco sequence of members with masses ranging from ∼0.025 through 0.004 $M_\odot$, within completeness. We also performed the spectroscopic follow-up of the faintest and least massive candidate found in our survey. The observational dataset is described in Section 2. The photometric and astrometric selection of USco member candidates and a discussion on possible field contaminants appear in Section 3. Section 4 introduces the spectroscopic data analysis of our faintest candidate. Mass values estimated from theoretical isochrones are presented in Section 5.1. In Section 5.2 we put our search in the context of other explorations carried out in the USco region, and we discuss the implications of our findings for understanding the USco mass function. Our conclusions are given in Section 6.

1. Introduction

The shape of the initial brown dwarf and planetary mass function and the minimum mass for the collapse and fragmentation of clouds are crucial topics to understand the dominant substellar formation process. Since substellar objects are significantly brighter and warmer at very young ages, e.g., less than 10 Myr (Chabrier et al. 2000), the detection of sources with a few Jupiter masses is possible by exploring nearby star-forming regions. Deep searches for the least massive population of these regions may shed light on the aforementioned topics.

The proximity and youth of the Upper Scorpius association (USco from now on) make this region more than suitable for performing searches for members in the substellar regime. The entire USco covers a vast area of more than 200 deg² in the sky (Slesnick et al. 2008) and is located at a mean distance of 145±2 pc (de Zeeuw et al. 1999). We carried out a deep photometric survey in a zone of low foreground extinction ($A_v < 1$ mag; Preibisch et al. 1998 and references therein). Regarding the USco age, previous studies suggested that the association is ∼5 Myr old on the basis of the location of B-type stars in the Hertzsprung-Russell diagram and and their comparison with evolutionary tracks (de Geus et al. 1989; Preibisch & Zinnecker 1999; Preibisch et al. 2002). Recently, Herczeg & Hillenbrand (2015) estimated an age of ∼4 Myr for the low mass members of the USco association calculated from models that reproduce the lithium depletion boundary of various young star clusters and stellar moving groups. This is somehow younger than the USco age derived by Pecaut et al. (2012). These authors estimated an age of 11 ± 2 Myr for intermediate and high mass USco members, including the M-type supergiant star Antares. The newly discovered eclipsing binaries in USco (UScoCTIO 5 and EPIC 203868608, Kraus et al. 2015; David et al. 2015) also support ages close to the 10 Myr for the USco association. In addition, the high proper motion of the USco association ($\mu = 26.7 \pm 2.5$ mas yr$^{-1}$; Zacharias et al. 2004) is beneficial for the unambiguous identification of its true members once the astrometric and photometric studies are conveniently combined.

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Key words. Galaxy: open clusters and associations: individual: Upper Scorpius, stars: low-mass, brown dwarfs.

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The four detectors of VIMOS were treated separately for a proper processing of the raw data. Raw images were reduced using the CCDRED routine within the IRAF environment. We applied a bias correction using the overscan regions. The flat-field correction was done by generating a super-flat image (one per filter) from the median combination of all VIMOS science images. With these super-flat frames we managed to reduce the fringing pattern, which is particularly strong for the $z$ band (Lagerholm et al. 2012). All science images were aligned and combined to produce deep frames per pointing and filter. Finally, we cut the vignetted areas from the processed image. The area of 1.17 deg$^2$ was determined from the cut images.

The photometric analysis was made using DAOPHOT routines within IRAF. First, we automatically identified unresolved sources in the reduced images using the DAOFIND routine. Aperture and point-spread-function (PSF) photometry was performed on the identified sources with an aperture radius of 4×FWHM. The stellar PSF was defined from the Gaussian fit to about 10–15 isolated stars homogeneously distributed across the frames. Instrumental magnitudes in the $I$-band were converted into observed magnitudes using data from the DENIS Near Infrared Survey of the Southern Sky (DENIS; Fachetti et al. 1994). We searched for common sources between DENIS and our data in the DENIS magnitude range $I = 17–18$ mag. Costado et al. (2005) found that the DENIS $I$ and VIMOS $I_{\text{Cousin}}$ magnitudes are quite alike with a negligible difference of $I_{\text{Cousin}} - I_{\text{DENIS}} = 0.03 \pm 0.04$ mag for M and L type sources, which is the spectral type domain of our interest. Therefore, we did not correct the VIMOS $I$-band magnitudes for any color term. Regarding the $z$-band photometry, the VIMOS instrumental magnitudes were calibrated using the $Z$-band data from the UKIDSS Eight Data Release (DR8) using sources in common that have UKIDSS magnitudes in the interval $Z = 16–17.5$ mag. The VIMOS $z$ filter is centered at a redder wavelength than the UKIDSS $Z$-band; however, after multiplying the VIMOS $z$ filter by the response function of the detectors, the bandpasses of the two filters become very similar. To further test whether there is a color term between VIMOS $z$ and UKIDSS $Z$ magnitudes, we retrieved the near-infrared spectra of L-type field dwarfs from the catalog by Rayner et al. (2009). All spectra were conveniently convolved with the filter transmission profiles and corresponding detectors response functions and integrated to the $z$ and $Z$ magnitudes. We found that the resulting magnitudes are alike with negligible differences confirming that no color term is required for calibrating the VIMOS $z$-band. The dispersion of the photometric calibration was determined at $\pm 0.09$ mag for the $I$-band and $\pm 0.04$ mag for the $z$-band. These quantities were quadratically added to the instrumental PSF magnitude errors provided by IRAF.

We estimated the completeness magnitudes of the VIMOS survey ($Iz$-bands) and the combined VIMOS–UKIDSS exploration ($Iz+ZHK$ bands, see Section 3.1) from the comparison of the total number of identified sources per magnitude interval with an exponential distribution of stars. The exponential fit was obtained for each filter independently using bright to intermediate magnitude sources. The completeness magnitude is

1 Central wavelengths and bandwidths (µm) as follows: $L = 0.823$, $\Delta L = 0.0914$; $z = 0.914$, $\Delta z = 0.185$. The transmission of the VIMOS filters slightly changes from detector to detector. The values above correspond to the average of the four detectors. In this paper, all quoted magnitudes are given in the Vega system.

2 UKIDSS uses the UKIRT Wide Field Camera (WFCAM; Casali et al. 2007) and a photometric system described in Hewett et al. (2006). The pipeline processing and science archive are described in Hambly et al. (2008). The UKIDSS broadband $ZHK$ data are directly calibrated from 2MASS point sources (Hodgkin et al. 2009).

3 The Image Reduction and Analysis Facility (IRAF) is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for research in Astronomy, Inc., under contract to the National Science Foundation.

4 In imaging mode, the VIMOS illuminated area is $1970 \times 2300$ pix$^2$. Exact values per detector were taken from VLT–MAN–ESO–14610–3509v861.pdf as of May 2015.
defined as the magnitude interval that immediately precedes the magnitude bins displaying a continuous deficit of stars with respect to the exponential prediction. The limiting magnitude is calculated as the magnitude bin at which the total number of sources deviates by ≥50% from the counts of the completeness magnitude bin. Our determined completeness and limiting magnitudes are given in Table 1 and roughly correspond to source detections around the 10σ and 4σ levels, respectively (σ is the sky background noise). In short, the USco VIMOS survey is complete down to $z = 21.7$ and $I = 22.0$ mag. These values correspond to the shallowest images of VIMOS pointing number 5, whose source counts versus observed magnitudes are illustrated in Figure 2. The deepest VIMOS pointing (number 11) has images that are ∼1.1 mag fainter in both bands. Regarding the UKIDSS data and following the same approach, we determined the following completeness and limiting magnitudes: $Z = 20.8$, $Y = 20.5$, $J = 19.0$, $H = 18.7$, and $K = 18.0$ mag (completeness), and $Z = 21.5$, $Y = 21.2$, $J = 20.0$, $H = 19.4$, and $K = 18.7$ mag (limiting magnitudes). These quantities agree with the values given by other groups (Lodieu et al. 2006) and with the information provided on the UKIDSS webpage. In view of these numbers, our VIMOS survey is 2 mag deeper than the UKIDSS data.

The VIMOS data were astrometrically calibrated using the right ascension and declination coordinates of the 2MASS catalog (Skrutskie et al. 2006). The internal precision of the astrometric calibration is ±0.2′.

2.2. Near-infrared spectroscopy

Near-infrared JHK spectroscopy of USco J155150.2−213457 (hereafter J1551−2134, see Section 3) was obtained using the Folded-port InfraRed Echellette (FIRE; Simcoe et al. 2008) 2013) instrument installed at the 6.5-m Baade Telescope, one of the Magellan telescopes sited on Las Campanas Observatory (Chile). FIRE is a near-infrared dual-mode spectrometer (de-
Table 1. VIMOS observing log, completeness and limiting magnitudes.

| Pointing | RA (J2000) | DEC (J2000) | Filter | Date | Te xp  (s) | Seeing (") | Comp. Lim. (mag) |
|----------|------------|-------------|--------|------|-----------|------------|-----------------|
| 1        | 15:53:30.0 | −21:19:59.9 | I      | 2009 Apr 02 | 3x160 | 0.57 | 23.1 | 23.8 |
| 2        | 15:54:38.8 | −21:55:99  | I      | 2009 Apr 02 | 3x105 | 0.53 | 22.8 | 23.5 |
| 3        | 15:54:38.8 | −21:37:59.9 | I      | 2009 Apr 02 | 3x160 | 0.66 | 22.8 | 23.8 |
| 4        | 15:54:38.8 | −21:19:59.9 | I      | 2009 Apr 02 | 3x105 | 0.55 | 22.4 | 23.3 |
| 5        | 15:47:46.0 | −21:55:99  | I      | 2009 Apr 20 | 3x160 | 0.86 | 22.0 | 23.0 |
| 6        | 15:47:46.0 | −21:37:59.9 | I      | 2009 Apr 20 | 3x105 | 0.60 | 22.0 | 23.3 |
| 7        | 15:47:46.0 | −21:19:59.9 | I      | 2009 Apr 20 | 3x105 | 0.78 | 21.7 | 22.6 |
| 8        | 15:48:54.7 | −21:55:99  | I      | 2009 Apr 20 | 3x105 | 0.74 | 22.0 | 22.7 |
| 9        | 15:48:54.7 | −21:37:59.9 | I      | 2009 Apr 20 | 3x105 | 0.66 | 22.0 | 23.3 |
| 10       | 15:48:54.7 | −21:19:59.9 | I      | 2009 Apr 20 | 3x105 | 0.66 | 21.9 | 22.6 |

The other line separator was employed for the interval $J = 14.5$–16.5 mag and runs parallel to the USco sequence of known objects shifted by $\sim 4\sigma$ towards blue $z - J$ colors, where $\sigma$ represents the color dispersion of the USco photometric sequence. The other line separator was employed for the interval $J = 16.5$–19.0 mag and was based on the separator proposed by Lodieu et al. (2007): it goes from $(z - J) = (1.7, 16.5)$ to $(2.0, 19.0)$ mag. The defined field–USco separator is shown with a solid line in Figure 3. USco member candidates must fall to the red of the separator line. This is a rather conservative selection criterion intended to identify all possible candidates. We acknowledge that additional criteria were required to clean the list of photometric candidates and avoid contaminants.

Within the VIMOS–UKIDSS survey completeness ($J = 14.5$–19 mag), a total of 92 sources were found populating the red side of the defined separator in Figure 3. Of them, 65 are resolved (their FWHMs are at least 1.5 times higher than the width provided by the average seeing), and 27 sources appear to be point-like objects. We did not consider the 65 resolved objects in our list of USco candidates (see next). We checked the catalogued aperture UKIDSS photometry by obtaining the PSF photometry of the 27 unresolved objects, the majority of which are quite faint and close to the completeness magnitude of the survey. The new PSF photometry located 16 out of 27 sources to the blue of our $zJ$ selection criterion (many of these objects have aperture photometry contaminated by nearby bright stars), and they were rejected. Only 11 unresolved sources remained as $zJ$ USco member candidates. They are depicted with red symbols and are labelled with their abridged names in Figure 3. In Table 2 we provide their photometry. With the exception of three objects, most lie rather close to the artificial boundary defined to separate USco candidates from field sources.
We used the VIMOS data only. We combined the previous magnitude brightness within the dynamic range or lies within none of the USco candidates published by other groups has a cross-correlation of UKIDSS and 2MASS catalogs by Deacon et al. (2009). See also Section 3.5. Except for these two sources, the former object was first identified from an UKIDSS-only survey as an M8.0 bonafide member of the USco association. The latter by Lodieu et al. (2006). In Lodieu et al. (2008) it was confirmed by Lodieu et al. (2006) for a similar diagram. These authors dealt with candidates in the magnitude interval imposed by Ardila et al. (2000) for a similar diagram. These authors dealt with candidates in the magnitude interval $I = 13-19$ mag, which includes the late-M types. Our survey is deeper than theirs; we thus linearly extrapolated the proposed criterion towards fainter magnitudes and the L types as shown by the solid line in Figure 3. This extrapolation falls to the blue of the photometric sequence of field L dwarfs down to the completeness of the VIMOS data. The field sequence displayed in Figures 3 and 4 was built by using data from Hewett et al. (2006), Patten et al. (2006), and Leggett et al. (2007) as described in Section 3.3.

Nine candidates from the VIMOS–UKIDSS $J$ search were found to fulfil the $I_J$ criterion, i.e., they lie to the red of the field–cluster photometric separator. The nine sources are included in the top panel of Table 2. Only two $I_J$ candidates failed the $I_J$ selection process (bottom panel of Table 2) because they display blue $I - z$ colors despite having the faintest $I$ magnitudes in our list of candidates. Surprisingly, they were the two reddest candidates in the $J$ search. Next, we investigated these two candidates in detail.

In order to confirm the photometry of J1554–2145, we collected J-band images with the Long-slit Intermediate Resolution Infrared Spectrograph (LIRIS, Manchado et al. 2004) on the William Herschel Telescope (WHT) on 2012 June 15. LIRIS has a HAWAII detector of 1024 $\times$ 1024 px$^2$ with a plate scale of 0′′.25 per pixel. In imaging mode, LIRIS has a field of view of 4.27 $\times$ 4.27 arcmin$^2$. The LIRIS image provided us with a time baseline of 7 yr with respect to the older UKIDSS data, and of 5.2 yr with respect to the VIMOS images. The LIRIS $J$-band data were acquired with a dithering pattern of nine positions.
over the detector; individual exposure time was 50 s per dither, and the total exposure time was 2250 s. Observing conditions were photometric with a seeing of 1.4". Data reduction included flat field correction and sky subtraction using routines within the IRAF environment. Individual images were aligned and combined to produce deep data in the J band. The final LIRIS image has a limiting magnitude of $J = 20.7$ mag at the 4-$\sigma$ level. This photon depth would have been sufficient to guarantee the detection of J1554−2145 with an excellent signal-to-noise ratio (S/N) if the object’s brightness were that of the UKIDSS catalog ($J = 18.483$ mag). However, this particular source was not detected in the LIRIS image, indicating that at the time of the LIRIS observations, J1554−2145 had $J \geq 20.7$ mag, in highly contrast with the UKIDSS J band measurement. Based on this result, we concluded that J1554−2145 is a variable source whose nature cannot be unveiled with our current data. It might actually be an USco member; there are known young sources with strong photometric variations due to circumbinary disks in Orion, or stars like KH 15D (Johnson et al. 2004) and CHS 7797 (Rodríguez-Ledesma et al. 2012). To the best of our knowledge, J1554−2145 has not been previously identified in any variable or extragalactic source catalog or in supernovae databases.

The VIMOS $z$ and UKIDSS $J$ equatorial coordinates of J1552−2133 differ by 1°.5. This suggests that either we identified two different sources at optical and near-infrared wavelengths or the source has a high proper motion of $\approx 0.4$ arcsec yr$^{-1}$. We were convinced that the VIMOS $z$ and $I$ identifications correspond to one source because both data were taken at the same time and both $z$ and $I$ coordinates agree within the astrometric error bars. We thus relied on the $I−z$ color. Unfortunately, we cannot confirm whether the UKIDSS detection corresponds to the VIMOS object. In any scenario, this source does not appear to be a member of USco according to our selection criteria: either its $I−z$ color is too blue or it has a high proper motion inconsistent with the stellar association. From now on, neither J1554−2145 nor J1552−2133 (bottom panel of Table 2) are considered as USco photometric candidates. Therefore, we were left with 9 candidates (two of which are known in the literature, that successfully pass the $zJ$ and $IZ$ photometric criteria down to the completeness magnitude of the VIMOS–UKIDSS survey.

To fully exploit the combined VIMOS–UKIDSS survey between completeness and limiting magnitudes, we searched for sources with the following photometric criteria, which are valid to identify cool dwarfs with spectral types later than early-L in USco: $J > 19.0$, $I > 22.0$, $z > J > 2$, and $I − z > 1$ mag, or $J$-band non-detections. Ten objects were found with colors redder than the $zJ$ field–USco boundary in Figure 5, seven of which turned out to be false detections close to the spikes of very bright stars. One showed an extended profile with 3.2 times the stellar FWHM, and the remaining two unresolved sources lied near bright stars. We carried out their PSF photometry using the UKIDSS images and obtained that their new colors were not compatible with our criteria (they moved to the cloud of field objects, i.e., to the blue side of the separator in Figure 5). In short, the search for new USco member candidates with VIMOS and UKIDSS magnitudes beyond completeness yielded no new objects of interest. Therefore, our USco candidates are those listed in the top panel of Table 2.

3.3. Additional photometric criteria

To provide further robustness to our list of USco member candidates, we built additional color–magnitude and color–color diagrams. Figure 5 depicts various of these diagrams using the VIMOS, UKIDSS and WISE photometry, thus covering the wavelength interval between 0.8 and 3.4 $\mu$m. The nine candidates from the top panel of Table 2 are indicated with red symbols and are labelled in all panels of the Figure. We also included the known USco confirmed members and photometric candidates published by Ardila et al. (2000), Lodieu et al. (2011), and Lodieu et al. (2013).

The $J−J$ versus $J−K$ color–color panel of Figure 5 is useful to discriminate extragalactic sources from very red dwarfs (see the discussion by Bihain et al. 2009). In this panel, we added those resolved objects found in Section 3.1 whose FWHMs were 1.5 times higher than the stellar PSF. All of these objects occupy a particular region of the color–color diagram: they tend to have $J−K$ values while their $I−J$ colors do not exceed the 3 mag boundary. These colors, where the $K$ band is particularly red, are typical of galaxies (Franx et al. 2003). None of the nine USco photometric candidates fall within this region; on the contrary, they follow, and actually extrapolate, the color–color sequence defined by the previously confirmed USco members. This adds consistency to our photometric selection of unresolved objects described in previous Sections.

The USco candidates J1552−2124 and J1549−2115, which have the faintest $J$-band magnitudes in Table 2, display $J − H$, $J − K$, and $J − W1$ colors bluer than other USco objects. As shown in Figure 5 and from comparison with the field sequence, these two objects might have early-T spectral types if they were USco members and if the USco sequence were described by the field sequence of red dwarfs. The average location of field dwarfs between the mid-M types and the late-T types shown in Figures 3–5 was constructed by calculating the mean magnitudes and colors for each spectral type (Hewett et al. 2009) and by using the equations published by Dupuy & Liu (2012). It was normalized to the location of thirteen USco M5–5.5-type dwarfs taken from Slesnick et al. (2008). However, J1552−2124 and J1549−2115 do not display $I−z$ and $z−J$ colors fully compatible with T0–T5 dwarfs and their blue deviation from the trend delineated by other USco candidates in the color–magnitude diagrams of Figure 5 was interpreted as a likely non-membership signature.

From the combined 1.17-deg$^2$ VIMOS–UKIDSS USco survey exploring the magnitude interval $J = 14.5 − 19$ mag, we identified a total of 7 photometric member candidates with colors covering the broad 0.8–3.4 $\mu$m wavelength range consistent with membership in the young stellar association. They likely have spectral types between late-M and mid-L as it is inferred from the direct comparison of their colors with the indices of field, high gravity dwarfs.

3.4. Contamination

Our photometric search may suffer from some contamination, which we studied next. The main source of contaminants was expected to be due to Galactic field sources of M, L, and T spectral types, and reddened galaxies. We derived the Galactic contamination contribution following the prescription given in Caballero et al. (2008) and references therein). In the range of magnitudes $J = 14.5−19$ mag (the $zJ$ search), a total of $\sim$4.5 field M-, L-, and T-dwarfs are expected to pollute the explored regions of the color–magnitude diagrams of previous Sections. These contaminant objects are likely interlopers distributed in spectral types and magnitude intervals as follows: $\sim$2.7 field M dwarfs would appear in the range $J = 14.5−16.0$ mag, and $\sim$1.6 field L dwarfs would be contaminating the faintest magnitude bin $J = 16−19$ mag. As for the field T dwarfs, the expected pollution was small with roughly $\sim$0.2 T-type objects at the faintest mag-
Fig. 5. Color–color (top left panel) and color–magnitude diagrams (top right and bottom panels) combining VIMOS, UKDISS, and WISE photometry. The nine \( z \) USco candidates are plotted as red symbols and are labelled. Confirmed USco members from [Ardila et al. (2000) and Lodieu et al. (2011)] are shown with blue solid circles, and USco candidates from [Lodieu et al. (2013)] are illustrated with blue open circles. Other symbols as in Figure 3.
nitudes of $J = 18$–19 mag. The contamination due to background giant red stars of M spectral types was expected to be negligible since the USco stellar association is located at latitudes above the Galactic plane ($b \sim +20$ deg). The derived contamination by field cool dwarfs with spectral types similar to those we were seeking in USco suggested that, out of the 7 photometric candidates, only 2–3 would remain as USco members.

Regarding the extragalactic contamination, the good seeing of the VIMOS data and the small size of the VIMOS pixel allowed us to easily distinguish extended sources down to $J = 19$ mag as described in Section 3.1. The location of these objects in the $I - J$ versus $J - K$ color-color diagram of Figure 5 diverges from that of USco members as discussed in Section 3.3. We checked the FWHM of our USco candidates in all the available UKIDSS images confirming that they were consistent with the stellar PSFs at various explored wavelengths. To estimate the number of unresolved red galaxies that may be contaminating our VIMOS–UKIDSS survey, we used the multicolor GOODS–MUSIC V2.0 catalog (Grazian et al. 2006; Santini et al. 2009) in a similar manner as in Bihain et al. (2009). In the magnitude range $J = 14.5$–20.0 mag, i.e., down to the UKIDSS $J$-band limiting magnitude, we searched for GOOD–MUSIC sources that comply with the photometric selection criteria described in Sections 3.1 and 3.2 and found none. Furthermore, a list of USco member candidates free of extragalactic unresolved red contaminants can be produced by performing a proper motion analysis of the candidates (see Section 3.5), since very distant sources do not show significant motion at all while USco has a distinctive proper motion.

### 3.5. Proper motion analysis

The proper motion of the young USco stellar association is $\mu_\alpha \cos \delta = -12.1 \pm 1.6$ and $\mu_\delta = -23.8 \pm 1.9$ mas yr$^{-1}$ (Zacharias et al. 2004), which is measurable using our data and data from the UKIDSS archive. The final assessment of membership in USco is done by deriving the proper motions of the 7 photometric candidates. We employed various combinations of optical and near-infrared images separated in time by several years for this purpose. One collection of images was formed by UKIDSS $J$ and $K$ data (2005 June 05) and VIMOS $f$ and $z$ images (this paper), which were taken $\approx 3.8$ yr apart. Another collection of images comprised the UKIDSS $K$-band first and second epoch data (2005 June 05, 2011 March 16), providing a time baseline of $\approx 5.8$ yr. For those photometric candidates fainter than $J = 18.0$ mag, we also used the UKIDSS $H$-band images (2005 June 05) to improve the S/N of the astrometric measurements. The UKIDSS and VIMOS data had an average seeing of 0″8 and 0″6, respectively.

Proper motions were obtained from the comparison of the target coordinates (in pixels) with the positions of $\sim 20$–30 unresolved sources within the area of $3 \times 3$ arcmin$^2$, except for except for J1551–2134, for which a larger area of $4 \times 4$ arcmin$^2$ was analyzed. Pixel transformations were derived employing third/fourth order polynomials and the GEOMAP routine within IRAF. The typical dispersion of the polynomial transformations was $\pm 0.1$ pix for the right ascension and declination axis after rejecting reference sources that deviated by more than $2.3 \sigma$ from null motion, where $\sigma$ denoted the dispersion of the astrometric transformations. All of the unresolved reference sources defining the null motion were selected to have S/N higher than 15 in the flux peak with respect to the background noise. By considering the temporal difference between images, and the pixel scales and north–east orientation of the detectors, displacements in pixels were converted into the proper motion measurements provided in Table 3. The quoted astrometric uncertainties were obtained by quadratically adding the dispersions of the polynomial transformations and the errors of the targets’ centroids as provided by the automatic identification algorithms; the latter oscillated between $\pm 0.01$ pix for the brightest photometric candidates and $\pm 0.3$ pix for the faintest candidates. The astrometric error bars of the faintest targets are clearly dominated by the UKIDSS centroid errors. Table 3 also contains the time baselines, the filters, and the S/N of the targets as measured on the corresponding images.

As shown in Table 3, for each USco candidate we managed to obtain a minimum of five proper motion measurements; all individual derivations are consistent with each other within the quoted uncertainties, except for a few cases where the S/N of the target is close to the detection limit. We adopted the weighted mean motions as the final values.

Conservatively, the proper motion errors associated with the adopted motions for a given photometric candidate correspond to the largest uncertainty of the individual measurements where the target is detected with S/N greater than 10. Figure 6 shows the proper motion diagram where the seven USco photometric candidates are depicted in red color. The expected location of USco members is given by the ellipse of semi-major axis of 13.8 mas yr$^{-1}$ and semi-minor axis of 13.5 mas yr centered at the motion of the young stellar association. The size of the ellipse was computed as twice the proper motion dispersions ($\pm 6.9$ mas yr$^{-1}$ in $\mu_\alpha$, and $\pm 6.7$ mas yr$^{-1}$ in $\mu_\delta$) observed among the USco low-mass members confirmed by Lodieu et al. (2008); this is, the ellipse defines a 2-$\sigma$ criterion for the astrometric assessment of membership in USco. Five out 7 photometric can-
Table 3. Proper motion measurements.

| Abbrd. name | \( \Delta \) (yr) | \( \Delta \) (mas/yr) | Images | \( \mu_\alpha \cos \delta \) (mas yr\(^{-1}\)) | \( \mu_\delta \) (mas yr\(^{-1}\)) |
|------------|----------------|----------------|--------|----------------|----------------|
| J1554−2135 | >15 / >15 | J / z | -10.61 ± 3.69 | -20.33 ± 3.83 |
|            | >15 / >15 | K / z | -14.01 ± 2.89 | -21.76 ± 3.72 |
|            | >15 / >15 | K / I | -11.19 ± 3.73 | -17.49 ± 3.58 |
|            | >15 / >15 | K / I | -19.79 ± 2.22 | -13.88 ± 2.26 |
|            | >15 / >15 | K / K | -13.03 ± 3.07 | -22.81 ± 3.23 |
| Weighted value |                |                |        | -20.50 ± 3.83 |
| J1548−2142 | >15 / >15 | J / z | 5.56 ± 3.88 | -14.60 ± 4.23 |
|            | >15 / >15 | K / z | 5.53 ± 3.11 | -17.31 ± 3.70 |
|            | >15 / >15 | K / I | 5.25 ± 4.15 | -14.87 ± 4.65 |
|            | >15 / >15 | K / I | 5.42 ± 3.73 | -15.77 ± 3.86 |
|            | >15 / >15 | K / K | 4.28 ± 4.37 | -16.93 ± 3.90 |
| Weighted value |                |                |        | -18.46 ± 4.65 |
| J1550−2201\(^a\) | >15 / >15 | J / z | 4.69 ± 4.80 | -84.60 ± 4.45 |
|            | >15 / >15 | K / z | -3.04 ± 4.74 | -88.24 ± 4.87 |
|            | >15 / >15 | K / I | 13.70 ± 5.24 | -83.01 ± 3.99 |
|            | >15 / >15 | K / K | 8.21 ± 5.34 | -85.76 ± 4.72 |
|            | >15 / >15 | K / K | 2.76 ± 3.46 | -82.87 ± 3.29 |
| Weighted value |                |                |        | -85.21 ± 4.87 |
| J1551−2142 | >15 / >15 | J / z | 4.81 ± 5.42 | -22.79 ± 5.35 |
|            | >15 / >15 | K / z | 8.67 ± 4.21 | -22.21 ± 4.18 |
|            | >15 / >15 | K / I | 7.76 ± 5.27 | -17.51 ± 5.09 |
|            | >15 / >15 | K / K | 11.95 ± 3.86 | -20.41 ± 4.06 |
|            | >15 / >15 | K / K | 7.15 ± 3.69 | -27.46 ± 3.37 |
| Weighted value |                |                |        | -24.78 ± 5.35 |
| J1554−2142 | >15 / >15 | J / z | -17.30 ± 6.37 | 10.50 ± 6.07 |
|            | >15 / >15 | K / z | -21.07 ± 5.71 | 9.06 ± 5.03 |
|            | >15 / >15 | K / I | -18.27 ± 6.54 | 9.48 ± 6.47 |
|            | >15 / >15 | K / K | -21.90 ± 7.56 | 11.25 ± 4.75 |
|            | >15 / >15 | K / K | -23.97 ± 5.10 | 10.81 ± 4.43 |
| Weighted value |                |                |        | -20.33 ± 6.54 |
| J1555−2126 | >14.7 / >15 | J / z | -30.17 ± 7.32 | -2.12 ± 7.02 |
|            | >15 / >15 | K / z | -21.60 ± 4.50 | 4.27 ± 5.34 |
|            | >14.7 / >15 | J / I | -4.03 ± 7.13 | 8.07 ± 7.01 |
|            | >15 / >15 | K / I | -20.90 ± 4.52 | -3.93 ± 5.20 |
|            | >15 / >15 | K / K | -30.42 ± 4.92 | -1.25 ± 4.69 |
| Weighted value |                |                |        | -28.37 ± 7.32 |
| J1551−2134 | 7.1 / >15 | J / z | 1.66 ± 10.82 | -26.60 ± 11.15 |
|            | 10.5 / >15 | H / z | -15.07 ± 7.07 | -9.21 ± 6.37 |
|            | 14.5 / >15 | K / z | -8.73 ± 4.68 | -13.95 ± 4.74 |
|            | 7.1 / >15 | J / J | -3.22 ± 10.90 | -27.97 ± 11.24 |
|            | 10.85 / >15 | H / J | -18.88 ± 7.03 | -12.87 ± 6.55 |
|            | 14.85 / >15 | K / J | -10.84 ± 4.27 | -16.02 ± 4.37 |
|            | 14.6 / >15 | K / K | -5.68 ± 4.85 | -22.85 ± 5.00 |
| Weighted value |                |                |        | -7.76 ± 7.07 |
| J1552−2124\(^a\) | 6.0 / >15 | H / z | -6.69 ± 12.41 | 0.37 ± 11.16 |
|            | 7.9 / >15 | H / z | -3.78 ± 6.97 | -23.15 ± 6.68 |
|            | 8.0 / >15 | K / z | -9.02 ± 6.10 | 8.93 ± 7.04 |
|            | 6.0 / >15 | K / J | -5.10 ± 12.13 | -2.06 ± 10.97 |
|            | 7.9 / >15 | H / I | -5.22 ± 6.71 | -23.73 ± 6.63 |
|            | 8.0 / >15 | K / I | 10.48 ± 5.46 | 9.09 ± 6.93 |
|            | 8.0 / >15 | K / K | 5.23 ± 5.38 | -0.88 ± 6.14 |
| Weighted value |                |                |        | 4.24 ± 10.90 |
| J1549−2115\(^a\) | 6.4 / >15 | J / z | -20.01 ± 12.11 | -12.04 ± 10.70 |
|            | 6.2 / >15 | H / z | 12.09 ± 9.43 | -9.29 ± 9.50 |
|            | 8.3 / >15 | K / z | -2.99 ± 8.06 | -0.95 ± 8.30 |
|            | 6.4 / >15 | J / J | -24.98 ± 11.81 | -14.31 ± 10.75 |
|            | 6.2 / >15 | H / J | 10.82 ± 9.31 | -10.19 ± 8.88 |
|            | 8.3 / >15 | K / J | -4.75 ± 7.96 | -7.39 ± 7.69 |
|            | 7.6 / 8.1 | K / K | -0.11 ± 6.22 | -3.00 ± 6.26 |
| Weighted value |                |                |        | -1.10 ± 12.11 |

Notes. \((a)\) Signal-to-noise ratio of the photometric candidates on the corresponding UKIDSS and VIMOS images. \((b)\) Known high proper motion source (2MASS J15501151−2201213). Our proper motion measurement agrees within 1-\(\sigma\) with the value reported by Deacon et al. (2009) \((c)\) Candidates discarded in Section 3.3.

Fig. 7. Finding chart of the new USco member candidate J1551−2134. VIMOS \(\delta\) band, 2 \(\times\) 2\’ in size.

4. Spectroscopic follow-up of J1551−2134

The FIRE spectrum of the new photometric and astrometric likely member, J1551−2134, is presented in Figure 8. It is compared with field, high gravity field L dwarfs in the top panel of the Figure, and with young, low gravity L dwarfs in the middle panel of the Figure. The comparison spectra were collected from different works: SDSS J053951.99−005902.0 and 2MASS J15150083+4847416 from Rayner et al. (2009), SIMP J2154−1055 from Gagné et al. (2014), 2MASS J22443167+2043433, GD 163B, and DENIS J0205−11AB from...
McLean et al. (2003), and VHS J1256–1257b from Gauza et al. (2015). These data share a spectral resolution similar to the FIRE spectrum. As inferred from the top panel of Figure 8 J1551–2134 displays a red slope compatible with a spectral classification of L6 with an uncertainty of one subtype. This typing agrees with the optical and infrared colors of J1551–2134.

At the age of the USco stellar association, substellar objects like J1551–2134 are expected to be undergoing gravitational self-contraction. Therefore, their atmospheres are governed by conditions of low pressure and low gravity. This impacts the fine details of the output flux at cool temperatures like those of the L types, particularly the atomic features: the lower the surface gravity, the weaker the atomic lines become (e.g., the NaI doublet at 1.14 µm, the two KI doublets at 1.17 and 1.25 µm). Also, the molecular features due to FeH (like the one at 1.19 µm, which persists down to spectral type ~L5) are affected. These and other signatures caused by low-pressure atmospheres are noticed in the J-band spectrum of J1551–2134. As illustrated in the bottom panel of Figure 8, the KI lines are not detected in J1551–2134 at the resolution of our data. We determined an upper limit on the pseudo-equivalent widths of the J-band KI lines of ≤6 Å. On the contrary, the comparison field, high-gravity dwarf (GD 165B) has strong KI absorptions. Furthermore, the 1.4–1.65 µm H2O features of the H-band adopt a “triangular” shape due to low gravity atmospheres (Lucas et al. 2001, Kirkpatrick et al. 2006), a feature that is also seen in J1551–2134. Complementary, we also measured the gravity-sensitive indices defined for low-to-intermediate resolution spectra by Allers & Liu (2013), finding FeH = 1.22 ± 0.02, FeH2 = 1.16 ± 0.03, KI = 0.94 ± 0.01 and H-cont = 0.93 ± 0.03 for J1551–2134. All indices are compatible with low-to-intermediate gravity scores. This result together with the upper limit on the strength of the J-band KI lines and the “triangular” shape of the H-band pseudo-continuum confirm the very low gravity nature of this object. The FIRE spectrum thus supports its membership in USco. J1551–2134 becomes a genuine young L6 ± 1 object.

Although J1551–2134 displays clear spectral features of youth, the overall near-infrared spectral energy distribution is not similar to other low gravity L dwarfs of intermediate age (10–500 Myr), which show very red J − K colors, like those shown in the middle panel of Figure 8. On the contrary, the near-infrared colors and spectral slope of J1551–2134 resemble older (high gravity) field dwarfs and other similarly young mid-L dwarfs found in σ Orionis (3 Myr) and USco (Martín et al. 2001, Lodieu et al. 2008, Peña Ramírez et al. 2012, Lodieu et al. 2013, Zapatero Osorio et al. 2015). This suggests that the very red J − K colors observed from low gravity L dwarfs of intermediate age (typically ≥10 Myr) cannot be explained by the effects of low gravity atmospheres only, or at least the reddening of the J − K color may depend nonlinearly on the low gravity. Alternative explanations such as scenarios based on warm dusty disks/envelopes have been proposed to reproduce the spectral behavior of very red L-type objects of intermediate age (Zapatero Osorio et al. 2010, Zakhozhay et al. 2015).

5. Discussion

5.1. Masses of USco member candidates

To estimate the masses covered by our VIMOS–UKIDSS survey, we compared the J-band magnitudes of our photometric candidates with the evolutionary models by the Lyon group (Baraffe et al. 1998, Chabrier et al. 2000, Baraffe et al. 2003). Theoretical luminosities and effective temperatures were con-

Fig. 8. FIRE low resolution near-infrared spectrum of J1551–2134 (solid red line) compared with field high-gravity dwarf templates (top panel) and with young low- (VL–G) and intermediate-gravity (INT–G) L dwarfs (middle panel). The comparison spectra are labelled and plotted with solid gray lines (see text for proper references to the data). Red dotted lines depict the wavelength regions strongly affected by telluric absorption. The bottom panel illustrates the enlargement of J1551–2134’s FIRE spectrum at around the KI lines (J-band). All spectra are normalized to unity at 1.32 µm and are shifted by a constant in the vertical direction. Some molecular and atomic features are identified.
The VIMOS–UKIDSS survey is complete in the mass interval 0.005–0.028 $\odot$ in the USco region studied by us. The completeness of this young stellar association. Béjar et al. (2009) and Lodieu et al. 2009; Dawson et al. 2013, 2014) also covered the same area, which represents a modest 0.6% of the wide USco extension. These authors mainly employed data from the catalogs DENIS, 2MASS, and UKIDSS and uncovered vast extensions of this young stellar association. Béjar et al. 2009 and Lodieu et al. 2011 searched for the USco population within the mass interval $0.025$–$0.025$ $M_\odot$, while Dawson et al. 2013 (2013) and Lodieu et al. 2011 (2012) identified and studied spectroscopically USco members with masses ranging from 0.9 $M_\odot$ to 0.01 $M_\odot$ and spectral types M5–L1. Our VIMOS–UKIDSS survey, although smaller in area coverage, represents the extension towards lower planetary masses and later spectral types. The recent work by Lodieu et al. 2013, with magnitude and mass sensitivities similar to our search, is the widest and deepest search for USco photometric candidates performed to date; however, it does not include the USco region studied by us.

As for the two photometrically, astrometrically, and spectroscopically confirmed USco members found in this work, we derived the following masses (5 Myr, 145 pc): $\approx 0.021 M_\odot$ (J1554–2135) and $\approx 0.8 M_\odot$ (J1551–2134, new discovery). For an older age of 10 Myr (see Section 5.2), the masses of the new USco member would turn to be $0.025 M_\odot$ and 1.8 $M_\odot$, respectively. For an older age of 10 Myr (see Section 5.2), the mass of Peña Ramírez et al. (2012) predicted the presence of 3.5$^{+1.4}_{-1.0}$ USco members (using an age of 5 Myr) with masses of 0.025–0.004 $M_\odot$ equally distributed as follows: 1.7 $\pm$ 0.4 objects for the mass bin 0.025–0.012 $M_\odot$ and 1.8$^{+6}_{-5}$ sources populating the least massive interval 0.012–0.004 $M_\odot$. A similar number and distribution of objects would be expected if the USco age were 10 Myr. Despite being consistent with the expectations, the finding of two USco members in our survey favours the low values of the $\alpha$ exponent of the power law mass function better than the high values. What we indeed found was one USco member at each side of the brown dwarf—planetary-mass classical boundary.

As seen from the comparison of the USco string of members with the location of the field sequence of M, L, and T-type dwarfs shown in Figures 3–5, our VIMOS–UKIDSS survey was designed deep enough to detect early-T and possibly mid-T type USco objects (this comparison did not account for the impact of low gravities on the spectral behaviour of the methane atmospheres). The evolutionary models suggest that USco potential members with temperatures below 1300 K (the L T transition) and within the completeness magnitude of our survey would have masses in the interval 0.007–0.004 $M_\odot$ ($J = 18.57$–19.00 mag) The mass function of Peña Ramírez et al. 2012 predicts $-0.8$ objects of this kind. We found no candidates displaying colors typical of field T dwarfs, which is compatible with the predictions and allowed us to discard mass functions with $\alpha \geq 1.0$, 1.1, and 1.2 with confidence levels of 90%, 95%, and 98%, respectively.

### 6. Summary and conclusions

We used deep photometric $I$- and $z$-band data collected with the VIMOS instrument to perform a search for the least massive population of the young USco stellar association (~5–10 Myr, 145 pc). Combined with the UKIDSS catalog, the survey explored an area of 1.17 deg$^2$ (northeast of the extent USco region) in the magnitude and mass ranges $J = 14.5$–19 mag and 0.028–0.004 $M_\odot$ (completeness). We also employed the WISE catalog (W1 and W2 magnitudes) for the analysis of the photometric candidates. We found an initial list of 11 photometric $z$-$J$ candidates, which was later reduced to 7 after evaluation of the plethora of colors covering the wavelength interval 0.8–3.4 $\mu$m. The proper motion study confirmed only 2 USco members, one of which has a brown dwarf mass of $0.020–0.022 M_\odot$ and was previously known, and the second object, J1551–2134, is a new discovery that has a planetary-mass of $0.008–0.010 M_\odot$ and no apparent infrared flux excesses up to 4.5 $\mu$m. The near-infrared spectroscopic follow-up of J1551–2134 (JHK FIRE spectrum of resolution 450 at 1.66 $\mu$m) confirmed the low-gravity nature of its atmosphere (weak alkaline lines, strong VO absorption, peaked H-band pseudoccontinuum), as expected for a young cool source, and yielded a spectral type of L6 $\pm$ 1. J1551–2134 shows optical and infrared colors resembling those of field, high gravity...
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dwarfs and very young (<10Myr) members of similar classification in marked contrast with the very red indices of field, low-gravity L dwarfs of intermediate age. This suggests that gravity alone is not the key factor to account for the very red nature of some young L dwarfs and/or that the colors do not depend linearly on gravity. The finding of two USco substellar members in our VIMOS-UKIDSS survey is consistent with the low values of the exponent in the mass spectrum of σ Orionis found by Peña Ramírez et al.[2012]. The non detection of T-type candidates in our survey allowed to constrain a mass spectrum in the interval 0.007–0.004 M⊙/M ∼ M−5, where α < 1.2 with a confidence level of 98%.

11515–2134 is one of the least massive and latest type members of the USco stellar association.

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