Candidate free-floating super-Jupiters in the young σ Orionis open cluster

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ABSTRACT

Context. Free-floating substellar candidates with estimated theoretical masses of as low as ~5 Jupiter masses have been found in the ~3 Myr old σ Orionis open cluster. As the overlap with the planetary mass domain increases, the question of how these objects form becomes important. The determination of their number density and whether a mass cut-off limit exists is crucial to understanding their formation.

Aims. We propose to search for objects of yet lower masses in the cluster and determine the shape of the mass function at low mass.

Methods. Using new- and (re-analysed) published IZJHK,[3.6]–[8.0]-band data of an area of 840 arcmin², we performed a search for L/T-type cluster member candidates in the magnitude range J ~ 19.5–21.5 mag, based on their expected magnitudes and colours.

Results. Besides recovering the T type object S Ori 70 and two other known objects, we find three new cluster member candidates, S Ori 72–74, with J ~ 21 mag and within 12 arcmin of the cluster centre. They have theoretical masses of 4–5 M_Jup and are among the least massive free-floating objects detected by direct imaging outside the Solar System. The photometry in archival Spitzer [3.6]–[5.8]-band images infers that S Ori 72 is an L/T transition candidate and S Ori 73 a T-type candidate, following the expected cluster sequence in the mid-infrared. Finally, the L-type candidate S Ori 74 with lower quality photometry is located at 11.8 arcsec (~4250 AU) of a stellar member of σ Orionis and could be a companion. After contaminant correction in the area complete to J ~ 21.1 mag, we estimate that there remain between zero and two cluster members in the mass interval 6–4 M_Jup.

Conclusions. We present S Ori 73, a new candidate T type and candidate σ Orionis member of a few Jupiter masses. Our result suggests a possible turnover in the substellar mass spectrum below ~6 Jupiter masses, which could be investigated further by wider and deeper photometric surveys.

Key words. stars: luminosity function, mass function – Galaxy: open clusters and associations: individual: σ Orionis – stars: low-mass, brown dwarfs

1. Introduction

Free-floating objects with masses of several to a few times the mass of Jupiter appear to populate young open clusters (see Lucas & Roche 2000; Zapatero Osorio et al. 2000). They could form in a similar way to stars, by gravitational fragmentation above an opacity mass limit (Hoyle 1953; Larson 1973; Low & Lynden-Bell 1976; Rees 1976; Silk 1977) or by turbulent fragmentation (Padoan & Nordlund 2002, 2004; Padoan et al. 2007) of collapsing molecular clouds, or as stellar embryos that are fragmented, photo-eroded, or ejected before they can accrete sufficient mass to become stars (see Whitworth & Goodwin 2005, and references therein). They could also form by gravitational instability in circumstellar disks (Boss 1997; Whitworth & Stamatellos 2006), then have their orbits disrupted and be ejected (Stamatellos & Whitworth 2009; Veras et al. 2009). A better knowledge of the cluster mass function (MF; number of objects per unit mass) at these low masses will help us to determine the main formation process for these objects. Indeed, numerical simulations of opacity-limited fragmentation show a cutoff in the mass function at ~4 Jupiter masses (Bate & Bonnell 2005; Bate 2005, 2009), whereas numerical simulations of turbulent fragmentation show an approximately log-normal, shallower drop at substellar masses (Padoan & Nordlund 2004). A detailed comparison with planets (e.g., spectral emission and chemical composition) will also provide complementary information about their origin and evolution (Fortney et al. 2008).

The σ Orionis open cluster in the Ob 1b association, together with other star-forming regions in the Orion and...
Scorpius-Centaurus complexes, is well-suited to the search for free-floating planetary-mass objects. It is young (3 ± 2 Myr; Zapatero Osorio et al. 2002b), relatively nearby (360 ± 60 pc, Brown et al. 1994; 444 ± 20 pc, Sherry et al. 2008), affected by very low extinction (A_V < 1 mag; Sherry et al. 2008), and of solar metallicty (González Hernández et al. 2008). A revision of published, basic parameters of the cluster was provided by Caballero (2007). Caballero et al. (2007) found a smoothly continuous MF down to ~6 Jupiter masses (M_Jup) and that the brown dwarfs appear to harbour disks with a frequency similar to that of low-mass stars. This suggests that low-mass stars and substellar objects share the same formation mechanism. Also, S Ori 70, of spectral type T6, has been proposed to be a cluster member with an estimated mass of 2–7 M_Jup (Zapatero Osorio et al. 2002a, 2008; Martin & Zapatero Osorio 2003; Burgasser et al. 2004; Scholz & Jayawardhana 2008; Luhman et al. 2008).

In this paper, we present new IZHK-band photometry and a re-analysis of previous data of the σ Orionis cluster, allowing us to search for faint candidates in an area of ~790 arcmin^2, to the completeness magnitude I ~ 21.1 mag. Our search area overlaps with those of Caballero et al. (2007) and Lodieu et al. (2009b), and its J-band completeness magnitude is about 1.5 and 2 mag fainter, respectively. We report the detection of three new cluster member candidates with theoretical masses of ~4 M_Jup.

2. Observations and data reduction

We discuss the new data obtained for this study and the data from Caballero et al. (2007) and Zapatero Osorio et al. (2008) that were reduced or analysed again in an attempt to increase the sensitivity to faint sources.

2.1. Optical data

The I-band imaging data presented in Caballero et al. (2007) were obtained with the Wide Field Camera (WFC) mounted at the Isaac Newton Telescope (INT). The WFC contains four CCDs of 2k × 4k pixels and 0.33 arcsec/pixel. Figure 2 shows the area of the corresponding frame, limited to their overlap with the near-infrared data (solid and dashed lines). A new automatic search for sources was performed with the IRAF routine FINDSTAR (Almoznino), which led to a substantial increase in the number of sources at faint magnitudes with respect to those considered by Caballero et al. (2007). FINDSTAR is especially useful for detecting sources in combined dithered images (or in images with background gradients), where the standard deviation varies from centre to border. We then carried out the aperture and point-spread-function (PSF) photometry using routines within the DAOPHOT package. Objects missed by the automatic search routine but easily detected by eye in the PSF-subtracted images (e.g., sources partially hidden in the wings of bright stars) were added to the list of sources. Finally, for each of the four CCD images, the new photometry was calibrated using ~1850 objects in common with the Caballero et al. (2007) photometry in the Cousins system. We found average completeness and limiting magnitudes of I_{cmp} = 23.0 mag and I_{lim} = 23.9 mag, respectively.

To determine these completeness and limiting magnitudes, we compiled the distribution of the instrumental magnitude error versus the calibrated magnitude for each image. In the bottom panel of Fig. 1, we present this with the source catalogue of one of the WFC CCD images. The completeness and limiting magnitudes were defined to be the faintest magnitude bins where the average errors are ≤0.10 and 0.20 mag, respectively.

These errors correspond to signal-to-noise ratios of S/N = 10 and S/N = 5, respectively (see e.g., Newberry 1991). The average error per magnitude bin is overplotted as a red solid line. The magnitudes of the bins just below errors of 0.1 mag (blue lower line) and 0.2 mag (blue upper line) were defined here as the completeness and limiting magnitudes, respectively.

Fig. 1. Upper panel. Histogram in logarithmic scale of the I-band sources as a function of the calibrated magnitude (see text for details about the dotted lines). Lower panel. Instrumental magnitude error versus the calibrated magnitude of these sources (dots). The average error per magnitude bin is overplotted as a red solid line. The magnitudes of the bins just below errors of 0.1 mag (blue lower line) and 0.2 mag (blue upper line) were defined here as the completeness and limiting magnitudes, respectively.

These errors correspond to signal-to-noise ratios of S/N = 10 and S/N = 5, respectively (see e.g., Newberry 1991). The average error per magnitude bin is overplotted as a red solid line. The upper panel shows the histogram of all sources on a logarithmic scale as a function of the calibrated magnitude. The inclined dotted line represents a power law fit to the histogram in the range [mag_{cmp} - 2.5, mag_{cmp}], where mag_{cmp} is the completeness magnitude (vertical dotted line). At mag > mag_{cmp}, the histogram’s deviation from the fit is most probably caused by sources affected by random upward or downward fluctuations of the background, the upward ones being preferentially detected above the detection threshold (Malmquist bias; see also Beichman et al. 2003). Comparing the counts of the histogram of sources having errors smaller than 0.1 mag with the counts of the linear extrapolation of its power law fit at the completeness magnitude, we estimated a level of completeness of ≥90%. This method was also applied to the other data sets.

We used broad IZ-band images from the Keck II Low Resolution Imaging Spectrograph (LRIS), associated with the discovery of S Ori 70 (see Zapatero Osorio et al. 2002a), as well as unpublished I-band images obtained with the same
Fig. 2. Main search area: WFC-ISAAC I-band data (dashed line) together with follow-up H- or K-band data (solid line). Additional search areas: WFC I-, LRIS I-, and Omega2000 H/K-band data (shaded regions delimited by dotted lines). Individual fields are not represented for clarity (see Fig. A.1). These areas have a completeness $J > 21.1$ mag, except the upper corner in the main area (indicated by the dot-dot line) and the shaded regions on the left side. S Ori 72 and S Ori 73 are represented by filled squares, S Ori 74 by an open square, and S Ori J053840.8−020422 and S Ori J053811.0−023601 by open triangles (see finding charts of Figs. B.1–B.4). Circular symbols are cluster members and candidates (Zapatero Osorio et al. 2000; Caballero et al. 2007; Caballero 2008b); their size increases with fainter $I$-band magnitude, to highlight the location of the least massive objects. Filled circles are planetary-mass candidates with $M < 0.013 M_{\odot}$, including S Ori 70 (Zapatero Osorio et al. 2002a). Crosses are $\sigma$ Ori AB and E, at the centre of the cluster.

Table 1. Coordinates and depth of the LRIS images.

| ID   | $\alpha$ (J2000) | $\delta$ (J2000) | Filter | $m_{\text{cmp}}$ | $m_{\text{lim}}$ |
|------|------------------|------------------|--------|------------------|------------------|
| 1998i1 | 05 38 16.6       | −02 37 53       | I      | 23.6, 24.5       |
| 1998i2 | 05 38 21.0       | −02 37 59       | I      | 23.5, 24.4       |
| 1998i3 | 05 38 56.4       | −02 38 57       | I      | 23.5, 24.1       |
| 1998i4 | 05 39 21.2       | −02 37 54       | I      | 23.5, 24.4       |
| 1998i5 | 05 39 56.4       | −02 34 00       | I      | 23.6, 24.4       |
| 1998i6 | 05 38 16.6       | −02 37 53       | Z      | 22.1, 22.9       |
| 1998i7 | 05 38 21.0       | −02 47 59       | Z      | 22.4, 23.3       |
| 1998i8 | 05 38 56.4       | −02 38 57       | Z      | 22.4, 23.3       |
| 1998i9 | 05 39 21.2       | −02 37 54       | Z      | 22.5, 23.4       |
| 1998i10| 05 39 56.4       | −02 34 00       | Z      | 22.4, 23.3       |
| 2000i1 | 05 38 17.4       | −02 37 48       | I      | 23.8, 24.6       |
| 2000i2 | 05 38 21.4       | −02 48 03       | I      | 23.5, 24.5       |
| 2000i3 | 05 38 55.2       | −02 38 52       | I      | 23.3, 24.3       |
| 2000i4 | 05 39 20.3       | −02 37 58       | I      | 23.7, 24.5       |
| 2000i5 | 05 39 57.2       | −02 34 04       | I      | 23.6, 24.7       |

The pixel scale is 0.210 arcsec pixel$^{-1}$ and the field of view in the $\alpha-\delta$ frame is $5.8 \times 7.2$ arcmin$^2$. For the images 1998i, x1, 2000i[1, 2, 4, 5], and 2000i3, this field of view is rotated $16, 90$, and 105 deg counterclockwise, respectively.

2.2. Near- and mid-infrared data

The J-band imaging data from Caballero et al. (2007) were obtained with the Infrared Spectrometer And Array Camera (ISAAC), mounted at the Very Large Telescope (VLT) and containing a Rockwell Hawaii detector of $1 k \times 1 k$ pixels and 0.148 arcsec/pixel. We re-reduced these data to obtain a clean sky subtraction, remove bad pixel values, and identify more reliably charge persistencies of bright sources in the detector. The raw images were dark subtracted, superflat divided, sky subtracted (with the routine LIRISDR.LIMAGE.LRUNSKY from Acosta-Pulido, which includes object masking and vertical gradient correction), their elements flagged for bad pixel (at extreme values for thresholding) using bad pixel masks from superflats, related by pixel shifts (computed from clearly defined sources in common), and combined all at once in strips along right ascension or declination (16 strips in total). The photometry of each strip was performed similarly as for the WFC data. We ensured that all the sources remaining in the PSF-subtracted images were recovered, as we did for the Omega2000 J-band images (see below). The photometry was calibrated using an average number of 12 point sources from the 2MASS catalogue (Skrutskie et al. 2006) of quality flags AAA or AAB. The average calibration environment, including bias and zero image subtraction and flat-field correction. Observations were done using a dithering pattern. Science images were combined to obtain flat-field images to correct for fringing. Individual images were aligned and combined to obtain final images. Aperture and PSF photometry was performed for one of the CCDs. Its photometric calibration was done using about 400 stellar sources from GCS-UKIDSS of $\sigma_{Z, \text{UKIDSS}} < 0.1$ mag, implying a relative calibration error of 0.02 mag. We caution that the UKIDSS Z-band filter is different from that of the WFC images. We estimated completeness and limiting magnitudes of 22.4 and 23.1 mag, respectively. Astrometry was obtained for all the optical images with an accuracy of $-0.2$–0.05 arcsec, using 2MASS as reference and an adaptation of the IRAF MYASTROM procedure (Puddu, see also Bihain et al. 2006). A representation of the individual fields is provided in Fig. A.1 (top left and right panels).
Table 2. New near-infrared observations.

| ID | α (J2000) | δ (J2000) | Instr. | Filter | Area (arcmin²) | Date(s) | £exp | mexp | mlim |
|----|--------|--------|--------|--------|----------------|--------|------|-----|------|
| 1-k | 05 39 39.9 | −02 30 26 | Omega2000 | $K_s$ | 197 (279) | 2005 Jan. 31, Feb. 1, Oct. 26 | 326 | 20.5 | 21.2 |
| 2-j | 05 39 35.1 | −02 34 44 | Omega2000 | $J$ | 214 (259) | 2006 Oct. 07 | 63 | 20.9 | 21.9 |
| 2-h | 05 39 19.3 | −02 33 36 | Omega2000 | $H$ | 181 (295) | 2005 Oct. 19 | 186 | 21.2 | 21.9 |
| 2-k | 05 39 21.2 | −02 35 14 | Omega2000 | $K_s$ | 194 (282) | 2005 Oct. 24−25 | 139.5 | 20.1 | 21.0 |
| 3-h | 05 38 40.1 | −02 48 09 | SofI | $H$ | 21 (27) | 2006 Dec. 27 | 147 | 20.3 | 20.9 |
| 4-h | 05 38 40.0 | −02 52 26 | SofI | $H$ | 21 (27) | 2006 Dec. 24 | 98 | 20.3 | 21.1 |
| 5-h | 05 38 39.7 | −02 57 09 | SofI | $H$ | 21 (27) | 2006 Dec. 27 | 75 | 20.1 | 20.5 |
| 6-h | 05 38 20.0 | −02 48 30 | SofI | $H$ | 21 (27) | 2006 Dec. 24 | 201 | 20.1 | 21.1 |
| 7-h | 05 40 05.1 | −02 30 40 | SofI | $H$ | 21 (27) | 2006 Dec. 27 | 132 | 20.3 | 21.1 |
| 8-h | 05 40 04.9 | −02 35 57 | SofI | $H$ | 21 (27) | 2006 Dec. 26 | 98 | 19.5 | 20.1 |
| 9-h | 05 40 03.6 | −02 42 10 | SofI | $H$ | 21 (27) | 2006 Dec. 25 | 56 | 19.9 | 20.7 |
| 10-h | 05 39 09.7 | −02 47 15 | SofI | $H$ | 21 (27) | 2006 Dec. 25 | 168 | 20.3 | 21.3 |
| 11-h | 05 39 27.7 | −02 47 15 | SofI | $H$ | 21 (27) | 2006 Dec. 25 | 95 | 20.1 | 21.1 |
| 12-h | 05 39 45.7 | −02 47 15 | SofI | $H$ | 21 (27) | 2006 Dec. 26 | 120 | 20.3 | 21.3 |
| 13-h | 05 40 03.1 | −02 47 04 | SofI | $H$ | 16 (33) | 2006 Dec. 26 | 140 | 20.3 | 21.1 |
| 14-h | 05 39 09.5 | −02 53 56 | LIRIS | $H$ | 16 (20) | 2006 Dec. 29 | 36 | 19.5 | 20.1 |
| 15-h | 05 39 45.4 | −02 53 57 | LIRIS | $H$ | 16 (20) | 2007 Dec. 14 | 45 | 20.3 | 20.9 |
| 16-h | 05 40 03.6 | −02 53 59 | LIRIS | $H$ | 16 (20) | 2007 Dec. 14 | 45 | 20.3 | 20.9 |

* Fields of view (and pixel scales) of the Omega2000, SofI, and LIRIS detectors are 15 × 15 arcmin² (0.45 arcsec pixel⁻¹), 4.9 × 4.9 arcmin² (0.288 arcsec pixel⁻¹), and 4.2 × 4.2 arcmin² (0.25 arcsec pixel⁻¹), respectively.

Table 3. Re-estimated depth of individual fields from Caballero et al. (2007) and Zapatero Osorio et al. (2008).

| ID | α (J2000) | δ (J2000) | Instr. | Filter | $m_{exp}$ | $m_{lim}$ |
|----|--------|--------|--------|--------|----------|---------|
| 1-h | 05 39 37.6 | −02 49 53 | Omega2000 | $H$ | 20.0 | 20.9 |
| 17-h | 05 38 38.7 | −02 49 01 | Omega2000 | $H$ | 19.1 | 19.6 |
| 17-k | 05 38 37.6 | −02 49 51 | Omega2000 | $K_s$ | 19.6 | 20.3 |
| 18-j | 05 38 12.4 | −02 35 18 | Omega2000 | $J$ | 21.1 | 21.9 |
| 18-h | 05 38 11.9 | −02 34 59 | Omega2000 | $H$ | 20.6 | 21.4 |
| 18-k | 05 38 13.3 | −02 35 37 | Omega2000 | $K_s$ | 20.0 | 21.0 |
| 19-h | 05 38 44.6 | −02 44 35 | CFHTIR | $H$ | 21.1 | 22.1 |
| 19-k | 05 38 44.6 | −02 44 35 | CFHTIR | $K_s$ | 20.9 | 21.9 |
| 20-h | 05 38 18.3 | −02 44 31 | CFHTIR | $K_s$ | 20.5 | 21.3 |
| 20-k | 05 38 18.3 | −02 44 31 | CFHTIR | $K_s$ | 20.5 | 21.3 |
| 21-h | 05 39 24.2 | −02 29 36 | CFHTIR | $H$ | 20.9 | 21.5 |
| 21-k | 05 39 25.6 | −02 29 37 | CFHTIR | $K_s$ | 20.5 | 21.3 |
| 22-h | 05 40 06.5 | −02 32 29 | CFHTIR | $H$ | 20.7 | 21.9 |
| 22-k | 05 40 06.6 | −02 32 29 | CFHTIR | $K_s$ | 20.5 | 21.5 |

* Re-reduced data from Zapatero Osorio et al. (2008); deep central areas (and total areas) in J, H, and $K_s$ are 215 (257), 208 (265), and 197 (278) arcmin². For the Omega2000 and CFHTIR data from Caballero et al. (2007), the deep central areas (and total areas) are 216 (236) and 6 (22) arcmin², respectively.

Other near-infrared data, already published in Caballero et al. (2007) and Zapatero Osorio et al. (2008), were used in the search. The Omega2000 data from the latter study were re-reduced to obtain untrimmed images. Completeness and limiting magnitudes of our new photometry (obtained as described above) are listed in Table 3, except for the $H$-band ~1100 arcmin² Omega2000 survey from 2003 (see Caballero et al. 2007), which is shallower. We note that the field 1-k is a combination of new data obtained on 2005 October 26 with published data obtained earlier the same year, on January 31 and February 1. The J- and HK-band data from Tables 2 and 3 correspond to overlapping areas of ~240 arcmin² and ~690 arcmin².
with the WFC + ISAAC survey, respectively (see Fig. 2 for the HK-band data).

Astrometry was obtained for all the near-infrared images similarly as for the optical images, with an accuracy of ~0.2–0.05 arcsec. A representation of the individual fields is provided in Fig. A.1 (top left and bottom panels).

We also used archival post-basic calibrated data (PBCD) from the Spitzer Space Telescope Infrared Array Camera (IRAC). For our new candidates (see Sect. 4), we have obtained the Spitzer photometry following the procedure described in Zapatero Osorio et al. (2007) and using the data published by Hernández et al. (2007) and Scholz & Jayawardhana (2008). A comparison of these two data sets is provided in Luhman et al. (2008, see e.g. Fig. 1 therein for a map of the IRAC surveys). We averaged our measurements in overlapping deep images and adopted their standard deviation as a representative error bar. We compared the [3.6]- and [4.5]-band measurements of Zapatero Osorio et al. (2007) with those of Luhman et al. (2008) for the six objects in common and found small average differences [3.6]ZO-L = 0.02 ± 0.12 mag and [4.5]ZO-L = 0.12 ± 0.07 mag, implying good agreement between the two sets of measurements.

3. The search for σ Orionis LT-type objects

Field dwarfs with spectral types T0–8 (effective temperature 1400–700 K) have typical colours of \( I - J > 4.5, J - H < 1.5 \), and \( J - K_s < 2 \) mag (Tinney et al. 2003; Zhang et al. 2009); the early types have redder \( J - H \) and \( J - K_s \) colours and higher effective temperatures than the later types. By extrapolating the \( \sigma \) Orionis cluster sequence using the field dwarf sequence, cluster members with a T spectral type appear to be at \( J \approx 20 \) mag (see Sect. 4 and Fig. 4). About the same apparent magnitude is found using the synthetic atmosphere J-band prediction of the 3-Myr COND model isochrone from Chabrier & Baraffe (2000). However, when predicted bolometric luminosities and effective temperatures are transformed into the observable using relations for field dwarfs (see also Sect. 4 and Fig. 4), a J-band value of \( \approx 21 \) mag is found.

T-type objects of this magnitude will still be detected within the completeness of the ISAAC data, whereas they will be relatively faint or undetected in the less deep HK-band images. For example, faint T-type objects with \( J = 21.5, I - J > 4.5, J - H < 1 \), and \( J - K_s < 1 \) mag will be undetected in all the optical images and only possibly detected in the near-infrared images of \((H\) or \(K_s\)-band) limiting magnitudes fainter than 20.5 mag (\( \sim 470 \) arcmin\(^2\)). Therefore, we opted for a search relying on the ISAAC J-band photometry, i.e., the deepest near-infrared photometry over the largest area, and with an automatic selection in terms of magnitudes and colours that is not too restrictive, to allow us to recover visually any potential cluster member candidate, including L-type objects.

First, we correlated the \( \alpha - \delta \) coordinates of the JHK\(_s\) band sources using the IDL srcoor procedure (IDL Astronomy User’s Library, Landsman 1993); for each J-band source, we searched for the nearest counterpart within 2 arcsec in the \( H \), \( K_s \), and \( I \) bands. The correlations with the WFC- and LRIS I-band catalogues were performed separately. We then selected \( 19.5 < J < 21.5 \) mag sources with no automatic J-band detection, or either \( I > 24 \) mag \( \approx I_{\text{lim}} \) (for unreliable or spurious detections) or \( I - J > 3.5 \) mag. As shown in Sect. 4, the \( I - J \) colour is essential for distinguishing LT-type objects from galaxies. The \( I - J > 3.5 \) mag sub-criterion intersects at \( J \approx 20.7 \) mag with a linear extrapolation of the selection criterion applied by Caballero et al. (2007, see therein Fig. 2) for their sources with \( I - I_{\text{lim}} \approx 23 \) mag. For continuity between the searches, we also selected sources redder than their \( I - J \) selection boundary and bluer than 3.5 mag. In the J versus \( I - J \) colour–magnitude diagram of Fig. 3, the shaded region represents the entire domain where we expected cluster member candidates, the dashed line represents the extrapolated selection boundary from Caballero et al. (2007), and the dotted line the \( I - J > 24 \) mag sub-criterion.

Finally, since the “3-J” Omega2000 J-band image (Table 2) overlaps with the northern ISAAC scans over \( \sim 210 \) arcmin\(^2\), we performed the selection process again for the sources with \( J_{\text{ISAAC}} - J_{\Omega2000} > 0.2 \) mag and those without ISAAC counterparts.

About 800 sources were chosen by our selection criteria from our JI-band catalogues. We checked each source visually in all of the optical and infrared images, using the SAOImage DS9 display programme (Joye & Mandel 2003) and commands in the X Public Access (XPA) messaging system\(^3\). The simultaneous visualisation in all available bandpasses and at all observing epochs allowed us to verify whether a source is real (or of low proper motion) and unresolved. Most sources were not detected automatically in the optical, because they are faint or very

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\(^2\) S Orion 54 was not included in the comparison because in Luhman et al. (2008) the object was probably misidentified with the brighter source [SE2004] 26, at about 5 arcsec.

\(^3\) http://hea-www.harvard.edu/saord/xpa/
close\textsuperscript{4} to brighter ones, and their clearly bluer $I - J$ colours imply that they should be stars or unresolved galaxies. Many are spurious detections of spikes or glares in the $J$-band. Others represent charge persistencies of bright sources in the ISAAC detector (following precisely and chronologically the offsets of individual pointings), resolved galaxies, sources cut at image borders, or very blended sources, which are too close to bright stars in the optical to be identified. The “$2J$” Omega\textit{2000} $J$-band sources with $J_{\text{ISAAC}} - J_{\text{Omega2000}} > 0.2$ mag were typically galaxies, resolved in the ISAAC images, whereas those without ISAAC counterparts were sources that could not be detected in the shallower survey region (see Sect. 2.2 and Fig. 2) and the gaps between the strips.

In a similar way, we searched for candidates in the additional areas of $\sim 15$ arcmin\textsuperscript{2} and $\sim 45$ arcmin\textsuperscript{2} represented by the shaded left and right regions in Fig. 2. These areas are common to the Omega\textit{2000} $JHK_s$-bands, WFC $I_s$, and LRIS $I$-band data. The $J$-band data of the left and right regions (fields 2-j and 18-j) are complete to 20.9 and 21.1 mag, respectively. They are therefore shallower by about 0.5 mag than the ISAAC data.

These searches allowed us to find four sources that are indeed undetectable by eye in the deepest $I$-band images (see Sect. 4), and a half-dozen of sources at $J > 20.7$ mag that are barely detected beyond the $I$-band limiting magnitudes. Most of the latter sources appear to be bluer than $I - J \sim 3.5$ mag. They have magnitude errors $\leq 0.1$ mag in the $JHK_s$-bands and red colours of $J - H = 1$ mag or $J - K_s = 2$ mag. Only one of them has a colour $I - J \geq 3.5$ mag. It was selected as a candidate (see Sect. 4), whereas the others were rejected because they are probable galaxies or faint field $M$- or early $L$-type dwarfs. Some sources could not be verified in the $I$-band images because of blending with extended stellar spikes and glares. We estimated that areas of $\sim 10$ and $\sim 5$ arcmin\textsuperscript{2} are lost in the main and additional areas, respectively. Thus, the total search area with $J$-band completeness $\geq 21.1$ mag (ISAAC and Omega\textit{2000} 18-j data) amounts to $\sim 790$ arcmin\textsuperscript{2}.

4. Results and discussion

Besides recovering the two faintest cluster member candidates\textsuperscript{5} S Ori J053932.4–025220 and S Ori J054011.6–025135 from Cabaliero et al. (2007) and the T-type S Ori 70, we detect three new $L$- and T-type candidates and two probable galaxies (see finding charts of Figs. B.1–B.4), among many other objects rejected because they do not meet our selection criteria. As shown in Fig. 3, the new candidates are about one magnitude fainter than S Ori 70. The photometric information that we compiled from the images of different depths are listed in Tables 4 and 5, where the $5\sigma$ flux upper limits correspond to the magnitude limits of the images.

In the $J$ versus $J - [3.6]$ and $J - [4.5]$ colour–magnitude diagrams of Figs. 4 and 5, we represent the candidates together with known $\sigma$ Orionis cluster members and candidates (Cabaliero et al. 2007; Zapatero Osorio et al. 2007, 2008). The solid line represents the spectrophotometric sequence of field mid-$M$- to late-T-type dwarfs, shifted to match the brightness of the late-M-type cluster members (Zapatero Osorio et al. 2008). For the field dwarfs, we use average absolute $I$-band magnitudes, $I - J$, and $J - K_s$ colours compiled by Cabaliero et al. (2008a), $J - H$ colours from Vrba et al. (2004)$^\dagger$, and mid-infrared magnitudes from Patten et al. (2006). In Fig. 4, the dashed line represents the 3 Myr COND model isochrone at the cluster distance, adapted by converting predicted effective temperature and luminosity into observables using relations for field dwarfs (procedure explained in Zapatero Osorio et al. 2008).

We also represent the candidates in $I$ versus $J$ – $H$ and $J - K_s$ colour–colour diagrams (Figs. 6 and 7) as well as in various diagrams with mid-infrared filters (Figs. 8–10), together with sources from the GOODS-MUSIC catalogue (Grazian et al. 2006) that we use as a control field to study the potential contamination by extragalactic sources in our survey. In all the figures, the open circles represent the new candidates (labelled) and the solid line represents part of the field LT-type dwarf sequence. The GOODS-MUSIC survey is centred on $(\alpha, \delta) = (3 32 30, -27 48 30)$, approximately, and covers an area of $143.2$ arcmin\textsuperscript{2} (except in the $H$-band, where the area is $78$ arcmin\textsuperscript{2}), i.e., less than a fifth of our search area. The limiting magnitudes are $i = 26.1, J = 23.6, H = 22.9, K_s = 21.9, [3.6] = 21.2, [4.5] = 20.1, [5.8] = 18.3$, and $[8.0] = 17.6$ mag, the late-M-type cluster members (Zapatero Osorio et al. 2008).

\textsuperscript{4} De-blended in the images subtracted by the PSF fitted sources (NOAO.DIGIPHOT, DAOPHOT, ALLSTAR) or subtracted by a smoothing obtained with a moving average box much smaller than the image size (NOAO.IMRED.CCDRED.NKSYCOR).

\textsuperscript{5} For the latter, we were able to measure $H = 18.8 \pm 0.2$ mag and $K_s = 18.5 \pm 0.1$ mag, implying early L colours $J - H = 0.8$ mag and $J - K_s = 1.1$ mag.

\textsuperscript{6} Note that the photometric values in Table 3 therein correspond to the spectral types M3V, M4V, M5V... instead of M3-4V, M4-5V, M5-6V... The $J - H$ colour is transformed back to the 2MASS photometric system using the same colour transformation of Carpenter (2001) as used in Vrba et al. (2004).

\textsuperscript{7} The $J - H$ colour is transformed back to the CIT- to the 2MASS photometric system using the same colour transformation of Carpenter (2001) as used in Vrba et al. (2004).
Table 4. Coordinates and photometry of the new L- and T-type cluster member candidates.

| Name       | \(\alpha\) (J2000) | \(\delta\) (J2000) | I (mag) | Z (mag) | J (mag) | H (mag) | \(K_s\) (mag) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) |
|------------|---------------------|---------------------|---------|---------|---------|---------|-------------|------------|------------|------------|
| S Ori 72   | 5 38 59.17          | -2 35 26.0          | >24.1   | >23.3   | 20.89 ± 0.06 | 19.57 ± 0.03 | 18.72 ± 0.05 | 17.60 ± 0.11 | 17.51 ± 0.29 | 17.28 ± 0.38 |
| S Ori 73   | 5 38 14.49          | -2 45 11.8          | >24.5   | 23.5 ± 0.5 | 20.91 ± 0.07 | 20.83 ± 0.12 | 20.91 ± 0.15 | 19.64 ± 0.35 | 18.77 ± 0.35 | >16.0      |
| S Ori 74   | 5 38 44.27          | -2 40 07.9          | 24.6 ± 0.4 | >23.3   | 21.1 ± 0.1  | >18.54\(^{b}\) | 19.38 ± 0.10 | ...         | ...         | >16.0      |

\(^{a}\) All have [8.0] > 15.1 mag. \(^{b}\) Lower magnitude limit computed for the UKIDSS GCS specific field. \(^{c}\) Blended with a spike from the star Mayrit 260182 (located at 11.8 arcsec).

Table 5. Coordinates and photometry of probable galaxy candidates.

| Name       | I (mag) | Z (mag) | J (mag) | H (mag) | \(K_s\) (mag) | [3.6] (mag) | [4.5] (mag) | [5.8] (mag) | [8.0] (mag) |
|------------|---------|---------|---------|---------|-------------|------------|------------|------------|------------|
| S Ori J053840.8–024022 | >24.3   | 21.12 ± 0.10 | 19.92 ± 0.07 | 18.94 ± 0.08 | 16.62 ± 0.18 | 16.29 ± 0.19 | >16.0      | >15.1      |
| S Ori J053811.0–023601 | >24.6   | >22.9   | 21.16 ± 0.40 | 20.66 ± 0.11 | 19.61 ± 0.09 | 17.16 ± 0.02 | 16.53 ± 0.04 | 15.56 ± 0.06 | 14.69 ± 0.12 |

\(^{a}\) S Ori J053811.0–023601 is at 28.0 arcsec from S Ori 70.

Fig. 5. \(J - [4.5]\) colour–magnitude diagram. Same as in Fig. 4.

Fig. 6. \(I - J\) versus \(J - H\) colour–magnitude diagram of stars (black crosses), AGN (red crosses), and galaxies (grey crosses) from the GOODS-MUSIC catalogue (Grazian et al. 2006), in the magnitude range 19.5 < \(J\) < 21.5 mag. The solid line represents the field L1–T7-type dwarf sequence, the filled circle represents S Ori 70, and the open circles represent the new candidates. S Ori J053840.8–024022 and S Ori J053811.0–023601 are labelled “glx 1” and “glx 2”, respectively.

when converted from the AB system to the Vega system\(^{a}\). In the magnitude range 19.5 < \(J\) < 21.5 mag, the catalogue contains 882 galaxies, 37 active galactic nuclei (AGN), and 83 stars, and in the smaller \(H\)-band area, 505 galaxies, 27 AGN, and 49 stars. Stars and AGN are distinguished from “normal” galaxies mostly by morphological and photometric criteria, or else by spectroscopic criteria. Stars are distinguished from AGN by spectroscopic criteria. In the infrared colour–magnitude diagrams of Figs. 9 and 10, the sequence of mid-L to early-T type field dwarfs overlaps with the domain of galaxies and AGN; only T type dwarfs tend to have different colours. The colour–magnitude diagrams of Fig. 8 also indicate that, from \(J = 19.5\) to 21.5 mag, the colour ranges of galaxies and AGN become broader and the number of galaxies increases (here by a factor of 1.4 in a 0.5-mag interval). However the optical-infrared diagrams of Figs. 6 and 7 show that mid-L to mid-T type dwarfs are clearly redder in \(I - J\) than the other sources. Thus, the \(I - J\) colour is essential to distinguishing these objects from galaxies and AGN, whereas the infrared colours only help us to guess the spectral type.

\(^{a}\) The \(I\) (or \(F775W\)) band photometry is from \(HST/ACS\) and similar to that from the Sloan Digital Sky Survey (SDSS). A transformation \(I_{\text{ Cousins}} = 0.3780 * (I_{\text{SDSS}} - 0.3974 (\sigma = 0.0063\text{ mag})\) has been obtained for stars (http://web.archive.org/web/2007101423413/http://www.sdss.org/dr6/algorithms/ sddsUBVRITransform.html); we assumed that this transformation is also valid for galaxies. The VLTI/ISAAC JHK\(s\)-band photometry was converted to the VEGA system using the transformations provided in the web page http://web.archive.org/web/20070814141937/http://www.eso.org/science/goods/releases/20050930/; it is found to be consistent within 0.05 mag with the 2MASS point-source photometry. For the Spitzer/IRAC [3.6][4.5][5.8][8.0]-band photometry, we used the transformations provided in the web page http://web.ipac.caltech.edu/staff/gillian/cal.html
4.1. New L- and T-type candidates

S Ori 72, with $J - H \approx 1.3$ mag and $J - K_s \approx 2.2$ mag, could be a late L-type object. It is clearly detected in the ISAAC J-band image from December 2001 and even better in Omega2000 $HK_s$-band images (observations 2-h and 2-k, Table 2), whereas it is slightly blended but detected in the $[3.6][4.5][5.8]$-band images (its visual neighbour is 2MASS J05385930-0235282, a field star located 3 arcsec south-east, with $J \approx 16.0$ mag and $I - J \approx 0.9$ mag). S Ori 72 is undetected in the WFC I-band image and the LRIS $IZ$-band images (1998iz3, Table 1). The $FWHMs$ in the $JHK_s$-band images are approximately equal to those of nearby faint point-like sources, of about 0.5, 1.2, and 0.8 arcsec, respectively. Among the new candidates presented in this paper, S Ori 72 is the only one that is detected in the GCS-U Orionis images, with $\sigma_{\text{UKIDSS}} = 18.60 \pm 0.28$ mag, in agreement with our measurement. In Fig. 11, we show its spectral energy distribution, together with average ones of field dwarfs of L7- and L8 spectral types (dotted lines). S Ori 72 is relatively brighter in the $HK_s$-bands. A preliminary measurement of S Ori 72’s proper motion using the ISAAC-Omega2000 images of 3.87 yr time baseline and the method described in Bihain et al. (2006) allows us to impose a $2\sigma$ upper limit of 30 mas/yr. Although the estimate should be improved before comparison with the $\mu \leq 5-10$ mas yr$^{-1}$ amplitude of $\sigma$ Orionis members (Caballerò 2007), it indicates that S Ori 72 is not a high-proper motion object and unlikely to be a nearby ($\leq 30$ pc) source. From the $J$ versus $J-[3.6]$ and $J-[4.5]$ colour–magnitude diagrams of Figs. 4 and 5, S Ori 72 could be an L/T transition cluster member candidate, but Figs. 6–10 imply that it could also be a galaxy or an AGN.

With $J - H \sim J - K_s \sim 0$ mag, S Ori 73 has near-infrared colours of a mid T-type object. It is clearly detected in the ISAAC J-band image, but appears very faint in the WFC Z-band image from November 2008, the CFHTIR $HK'$-band images from February 2004 (20-h and 20-k, Table 3), and the public Spitzer/IRAC $[3.6]$- and $[4.5]$-band images. It is undetected in the WFC I-band image, the LRIS $IZ$-band images (2000iz2, Table 1), and in the Omega2000 $HK_s$-band images (17-h and 17-k). Its $FWHMs$ in the $J$-band image is approximately equal to that of nearby faint point-like sources, of about 0.5 arcsec. In Fig. 11, we show its spectral energy distribution, together with average ones of field dwarfs of T4 and T6 spectral types. The position of S Ori 73 in the $J$ versus $J-[3.6]$ diagram of Fig. 4 agrees with both adapted field- and model sequences, securing this source as a good T-type- and cluster member candidate. The colour–colour diagrams of Figs. 6, 7, and 9 also indicate that there are neither stars, nor AGN, nor galaxies in GOODS-MUSIC as red in $I - J$ and blue in $J - H$ and $J - K_s$ as this object.

With $J - H = 3.5 \pm 0.4$ mag and $J - K_s = 1.7$ mag, S Ori 74 could be an L-type object. It is detected in the ISAAC J-band image and in the Omega2000 $K_s$-band image (18-k, Table 3). The object appears point-like in both images with a typical local $FWHM$ of 0.7 and 0.9 arcsec, respectively, whereas it appears faint and blended with a stellar spike in the $[3.6][4.5][5.8]$-band images, preventing us from determining its IRAC photometry. The candidate is barely detected in the LRIS J-band images (2000iz3 and 1998iz3, Table 1) and undetected in a stellar glare in the WFC I-band- and LRIS $I$-band images (1998iz3). In Fig. 11, we show its spectral energy distribution, together with average ones of field dwarfs of L2- and L8 spectral types. From Fig. 7, it could also be a galaxy or an AGN. However, S Ori 74 is located 11.8 arcsec north (~4250 AU; open square in Fig. 2) of the bright K7.5-type cluster star Mayrit 260182, 4.3 arcmin south of the cluster centre. The probability of chance alignment is only 5% for cluster members at this angular distance from the $\sigma$ Orionis centre (Caballerò 2009, Fig. 1). Mayrit 260182, Mayrit 270181, and Mayrit 277181 also form a possible triple system (Caballerò 2006). Caballerò et al. (2006) previously proposed that S Ori 68 + SE 70 is a planet-brown dwarf system candidate, of greater mass ratio and smaller separation. There are, however, known red galaxies at comparable angular separations to $\sigma$ Orionis cluster members. For example, the type I obscured quasi-stellar object UCM 0536-0239 is located about 14.9 arcsec south of the T Tauri star Mayrit 97212 (Caballerò et al. 2008b). Observational follow-up is necessary to confirm whether S Ori 74 is a cluster member and companion of Mayrit 260182.

4.2. Probable galaxy candidates

With $J - H = 1.2$ mag and $J - K_s = 2.2$ mag, S Ori J053840.8-024022 could be a late L-type object or a galaxy. It is detected with brighter magnitudes at longer wavelengths, from the Omega2000 $JHK_s$-band images (18-k, Table 3) to the $[3.6][4.5][5.8]$-band images, but is then undetected in the $[5.8][8.0]$-band images. It is undetected in the WFC and LRIS $I$-band images (2000iz3, Table 1). In Fig. 11, we show its spectral energy distribution, together with average ones of field dwarfs of L7- and L8 spectral types. In the ISAAC J-band image, it is found to be slightly extended and fainter than in the lower-resolution Omega2000 $J$-band image. The $FWHMs$ of the object in the Omega2000 $JHK_s$-band images are systematically larger by a factor $\approx 1.4$ than those of nearby faint point-like sources, suggesting that it is a galaxy. S Ori J053840.8-024022 could be an L/T transition object, but from the $J$ versus $J-[3.6]$ and $J-[4.5]$ diagrams (Figs. 4 and 5), it is redder than the expected sequence of the cluster. Galaxies from the GOODS-MUSIC catalogue with these red colours appear at magnitudes $J \approx 20.5$ mag (Fig. 8). Figure 9 illustrates its infrared excess in the $K_s$, $[3.6]$, and $[4.5]$-bands relative to the field dwarf sequence, and also suggests that this object is likely to be a galaxy.

Fig. 7. $I - J$ versus $J - K_s$ colour–colour diagram. Same as in Fig. 6.
Fig. 8. $J$ versus $J-[3.6]$ and $J-[4.5]$ colour–magnitude diagrams. Same as in Fig. 6. The blue solid line represents the field dwarf sequence shifted as in Fig. 4.

Fig. 9. Near- and mid-infrared colour–colour diagrams: $J-[3.6]$ and $J-[4.5]$ versus $J-H$ (top-and bottom left), $J-[3.6]$ and $J-[4.5]$ versus $J-K_s$ (top-and bottom right). Same as in Fig. 6.

Fig. 10. Mid-infrared diagrams: $[3.6]$ versus $[3.6]-[5.8]$ (left), $[3.6]-[5.8]$ versus $[4.5]-[8.0]$ (right). Same as in Fig. 6.
Osorio et al. 2007; Scholz & Jayawardhana 2008; Luhman der than most σ

It is detected with brighter magnitudes at longer wavelengths, from left to right IZJHK average ones of field dwarfs (dotted lines). [Image 314x84 to 416x85]

In Figs. 6, 7, and 9, its optical and near-infrared colours differ from those of AGN and galaxies, but in Fig. 10, its other colours are consistent with the AGN hypothesis (see also Fig. 1 in Stern et al. 2005, representing spectroscopically identified stars, AGN, and galaxies). Hence, although we cannot exclude completely this source being a peculiar cluster member with extreme infrared excesses, our data seem to indicate that it is more probably an AGN.

4.3. Cluster membership

Because our search area is larger than that of the GOODS-MUSIC catalogue, contamination by red galaxies and AGN is even more likely to explain some of our candidates. Caballero et al. (2008b) present low-resolution optical spectroscopy and spectral energy distributions between 0.55 and 24 μm of two sources fainter than the star-brown-dwarf cluster boundary, which were interpreted to be peculiar σ Orionis members with very red colours related to discs. They are instead two emission-line galaxies at moderate redshift, one with an AGN and the other ongoing star formation. In the present study, we assume that S Ori J053840.8–024022 and S Ori J053811.0–023601 are galaxy- or AGN contaminants and that the other objects are Galactic candidates awaiting confirmation by higher resolution imaging, proper motion, or spectroscopy.

In our search, we must also account for contamination by field dwarfs. Caballero et al. (2008a) provide predictions of the number of L5–T0, T0–T5, and T5–T8 field dwarf contaminants per square degree towards the σ Orionis region, in one-magnitude I-band intervals and from I = 21.0 to 29.0 mag. We convert the bright and faint boundaries of the range J = 19.7–21.1 mag (as a prolongation of the search range of Caballero et al. 2007) into the I-band magnitudes corresponding to the earliest and latest spectral types of each of the three contaminant groups. We then sum the predicted numbers of contaminants accounting for the I-band range and scale the sums to the search area that is complete to J ≥ 21.1 mag (~790 arcmin²). We obtain about three L5–T8-type field dwarfs, which all contribute the most to the light close to J = 21.1 mag. This predicted value remains mostly indicative, because the initial mass function and scale heights of late L- and T-type dwarfs are still uncertain. Interestingly, Caballero et al. (2008a) assume a rising mass function in the planetary mass regime and predict spatial densities of T0–8 dwarfs that are a factor of two higher than those derived from observations (Metchev et al. 2008; Lodieu et al. 2009a).

S Ori 73 and S Ori 70 are located9 at 11.9 and 8.7 arcmin from σ Ori AB, respectively. S Ori 72 and S Ori 74 are closer, at 3.6 and 4.1 arcmin, respectively. Interestingly, the location of these faintest, presumably least massive candidates contrasts with that of the eleven 13–6 M jov free-floating planetary-mass candidates from Caballero et al. (2007), further out at 26–13 arcmin in the survey area (see Fig. 2). Caballero (2008a) find an apparent deficit of low mass objects (M < 0.16 M⊙) towards the σ Orionis cluster centre. If the cluster membership census and the individual masses are confirmed, this configuration could be explained by several mechanisms, including e.g., a possible photo-erosion by the central OB stars (Hester et al. 1996; Whitworth & Zinnecker 2004) in the deep gravity well. Complementary studies of the dense cluster core (Bouy et al. 2009) and other cluster regions could thus help us to understand the formation of low-mass planetary-mass objects.

9 S Ori 73 is the only candidate found in one of the deeper multi-band search areas, summing up to ~470 arcmin², see Sect. 3.
or 440 pc (Sherry et al. 2008) instead of 360 pc (Brown et al. 1994). The effective temperature corresponding to that mass would be of ~1400 K. In Fig. 13, we display the mass spectrum (\(\Delta N/\Delta M\)) of the filled circles represent the contamination-corrected data points from Caballero et al. (2007) scaled to the search area of ~790 arcmin\(^2\). The last bin (shaded region) corresponds to the result from the present study for the magnitude range \(J = 19.7–21.1\) mag. Subtracting the three possible contaminants (see Sect. 4.3) from the four LT-type candidates and accounting for the Poissonian error, we estimate 0–2 cluster members with a mass of 0.006–0.004 \(M_\odot\).

Previous studies of the substellar population in the \(\sigma\) Orionis cluster find that the mass spectrum increases toward lower masses. Béjar et al. (2001) show that it can be represented by a potential law (\(\Delta N/\Delta M \propto M^{-\alpha}\)) with an \(\alpha\) index of 0.8 in the mass range 0.11–0.013 \(M_\odot\). González-García et al. (2006) and Caballero et al. (2007) extend this mass spectrum to 0.006 \(M_\odot\) and find a slightly lower index \(\alpha = 0.6\). For the substellar mass range of 0.073–0.006 \(M_\odot\), Caballero et al. (2007) obtain an even lower \(\alpha\) index of 0.4. An extrapolation of the mass spectrum with this index \(\alpha = 0.4–0.8\) predicts 3–7 objects in the mass range 0.006–0.004 \(M_\odot\). From our survey, the most likely number of cluster members in this mass interval is in the range 0–2. This could be an indication of a turnover in the substellar mass spectrum. However, given the low statistics and the possibility that the number of contaminants could be overestimated, such a change in the slope of the mass spectrum should be considered with caution. If real, the turnover could be related to an opacity mass limit, turbulence effects, or a different mass-luminosity relation (if less massive objects were fainter than predicted). Wider and deeper searches would be very valuable in constraining the mass spectrum more reliably at these and lower masses.

5. Conclusions

The mass function in open clusters can provide clues about the formation mechanism of free-floating planetary-mass objects. We therefore decided to explore the substellar mass function for \(M < 6 \, M_{\text{Jup}}\) in the ~3 Myr old \(\sigma\) Orionis open cluster. We extended to \(J = 19.5–21.5\) mag the ~780 arcmin\(^2\) INT/WFC-VLT/ISAAC \(J\)-band search of Caballero et al. (2007). \(J\)-band sources (ISAAC and CAHA 3.5 m with Omega2000) were cross-matched with \(I\)-band (WFC and Keck/LRIS) and \(HK\)-band sources (Omega2000, NTT/SofI, WHT/LIRIS, and CFHT/CFHTIR). We selected sources redder than a boundary at \(I – J > 3.1–3.5\) or without an \(I\)-band detection or fainter than \(I = 24\) mag. These sources were then checked visually in all available images, including \(Z\)-band images from LRIS and WFC, and archival mid-infrared images from Spitzer/IRAC.

We recover S Ori 70 and the two faintest cluster member candidates from Caballero et al. (2007), and we find five red \(I – J\) sources, with \(J < 21\) mag, located within 12 arcmin of the cluster centre. The near- and mid-infrared colours indicate that one of the sources, S Ori 73, is probably of T spectral type. If confirmed as a cluster member, it would be the least massive free-floating T type object detected in \(\sigma\) Orionis, with \(4.2 \, M_{\text{Jup}}\). The four other sources appear to be L/T transition objects, but two are likely to be galaxies because of their strong mid-infrared excesses, similar to those of galaxies at \(J \gtrsim 20.5\) mag. S Ori 72 and S Ori 73 are relatively close to the expected cluster sequence in the \(J\) versus \(J – [3.6]\) and \(J – [4.5]\) colour–magnitude diagrams. S Ori 74 is located 11.8 arcsec (~4250 AU) away from the solar-type cluster star Mayrit 260182. From the effective search area

**Fig. 12.** \(J\)-band luminosity function with the LT-type candidates at \(J > 19.7\) mag (dashed line) and the brighter cluster member candidates from Caballero et al. (2007) scaled to the search area (solid line).

**Fig. 13.** Mass spectrum with contamination-corrected data. The dotted segment represents the linear fit to the data points from Caballero et al. (2007) in the mass range 0.11–0.006 \(M_\odot\), which are previously scaled to the search area. The shaded region is our estimate of 0–2 cluster members in the mass range 0.006–0.004 \(M_\odot\). From left to right, the vertical dashed lines represent the hydrogen and deuterium burning mass limits, respectively.

**4.4. Mass spectrum**

We consider the luminosity and mass functions for the ISAAC- and additional areas, where the search is complete down to \(J \gtrsim 21.1\) mag (~790 arcmin\(^2\)).

In Fig. 12, we show the \(J\)-band luminosity function. The magnitude bins in the range \(J = 19.7–21.1\) mag correspond to the three new LT-type candidates and S Ori 70 (dashed line). The magnitude bins in the range \(J = 14.1–19.7\) mag correspond to the cluster member candidates from Caballero et al. (2007), i.e., in the ISAAC area; they are scaled by the area factor (790)/780 = 1.0128. The magnitude bins have equal widths of about 0.7 mag.

We estimate the masses of our new cluster member candidates by comparing with the theoretical bolometric luminosities from the Lyon group (e.g., Baraffe et al. 2003), using exactly the same method as in Caballero et al. (2007). If cluster members, S Ori 72–74 would each have an estimated theoretical mass of \(4.2 \, M_{\text{Jup}}\), accounting for age, distance, and photometric uncertainties. This rounded up result does not change significantly by using a cluster distance of 400 pc (Mayne & Naylor 2008).
Appendix A: Representation of individual fields in the IZJHK-bands

Fig. A.1. Individual fields used in the search: IJ-bands (top left), Z-band (top right), H-band (bottom left), and K-band (bottom right). Symbols are defined as in Fig. 2.

of ~790 arcmin² complete to $J = 21.1$ mag, we estimate there to be, after contaminant correction, between zero and two cluster members in the mass interval 6–4 $M_{\text{Jup}}$. The low number of candidates in this mass bin may be indicative of a turnover in the substellar mass function. Wider and deeper optical-to-infrared surveys are required to confirm whether this is the case, by constraining the mass function more tightly at lower masses.

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Appendix B: Finding charts

Fig. B.1. ISAAC $J$-band image of S Ori 72.

Fig. B.3. ISAAC $J$-band image of S Ori 74 and S Ori J053840.8–024022 (unlabelled circle).

Fig. B.2. ISAAC $J$-band image of S Ori 73.

Fig. B.4. Omega2000 $H$-band image of S Ori J053811.0–023601.

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