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Young Stellar Objects in the Orion B Cloud

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Wide-field near-infrared imaging surveys offer an excellent opportunity to obtain spatially complete samples of young stars in nearby star-forming regions. By studying their spatial distribution and individual properties, the global star formation characteristics of a region can be established. Near-infrared wide-field imaging observations of a significantly large area in the Orion Molecular Cloud B, obtained with the VISTA telescope on Cerro Paranal are presented. On the basis of photometric selection criteria, we have identified 186 candidate young stellar objects that are associated with the stellar clusters NGC 2068 and NGC 2071, and with the stellar group around HH24-26. Overall, Orion B shows a lot of similarities in its star formation characteristics with other Galactic star-forming regions: a star formation efficiency of a few percent, a stellar mass distribution very similar to that of the Orion Trapezium cluster, and a high observed fraction of circumstellar discs.

VISTA wide-field observations of Orion B

The constellation of Orion is a beautiful night-sky object visible to both southern and northern hemisphere skywatchers, due to its location close to the celestial



equator. Orion is also the nearest region of active high- and low-mass star formation allowing us to study many aspects of the star formation process in great detail.

For the study presented here, we analysed the multi-band photometry of a ~ 1.6 square degree field in the northern part of the Orion Molecular Cloud B, which was observed as part of the Visible and Infrared Survey Telescope for Astronomy (VISTA) Science Verification (SV)

Figure 1. VISTA three-colour (ZJKs) mosaic image of the northern part of Orion B on a logarithmic display. The image covers ~ 1.6 square degree and contains more than 100 000 objects. Clearly visible in the north is the embedded stellar cluster NGC 2071, while the cluster in the centre is NGC 2068.

Orion mini-survey (Petr-Gotzens et al., 2011). The analysed field contains the prominent bright optical reflection nebulosities NGC 2068 and NGC 2071 which, observed at near-infrared wavelengths, beautifully reveal their full nature as young stellar clusters (Figure 1). The ages

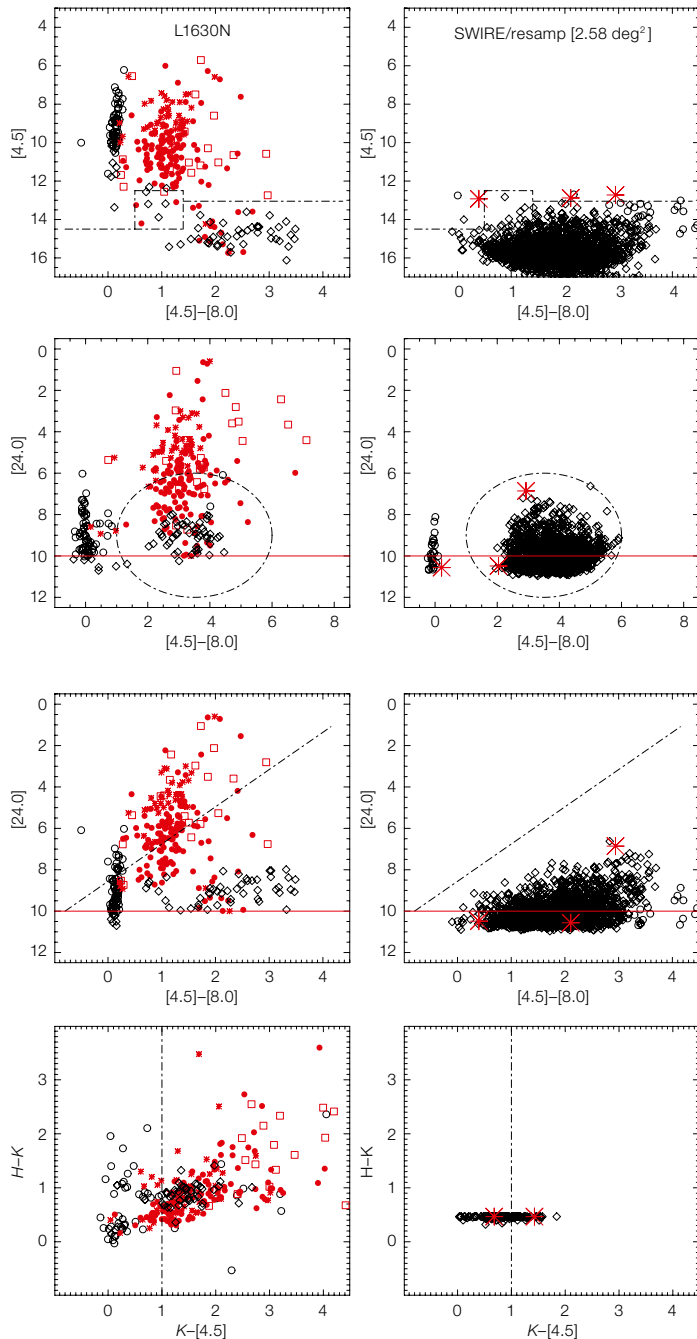


Figure 2. Upper four panels: VISTA/Spitzer colour–magnitude diagrams for objects in Orion B. The dot-dashed lines show fuzzy limits with exponential cutoffs that define the YSO candidate selection criterion in each diagram, excluding contamination from galaxies (diamonds) and field stars presenting normal photospheric colours (black circles). The continuous red lines show hard limits; fainter objects are excluded from the YSO category. Point-like and extended YSO candidates are indicated by red dots and open squares, respectively; YSO candidates with no VISTA morphological classification are indicated by asterisks.

Lower four panels: 2MASS/Spitzer colour–magnitude and colour–colour diagrams for the SWIRE galaxy catalogue. Three objects from the SWIRE catalogue (marked as asterisks) are classified as YSO candidates, according to our selection criteria.

of the clusters have been determined by Flaherty & Muzerolle (2008) to be 1–2 Myr, although star formation appears to be still ongoing, as suggested by the outflow sources that are clearly seen in the north of NGC 2071 and in a chain of young stellar objects to the southwest of NGC 2068. Our VISTA images were obtained through the ZYJHKs filters (0.9–2.2 μm) and achieved excellent sensitivity, e.g., a 5σ detection limit of Ks \sim 18.5 mag,

$J \sim 20.3$ mag and $Z \sim 22.5$ mag. All data reduction was performed by the Cambridge Astronomy Survey Unit (CASU) pipeline¹. We estimate that our survey should have detected, for a population as young as ~ 2 Myr at a distance of about 400 pc (i.e., the case of Orion B), essentially all objects from $\sim 1 M_{\odot}$ down to ~ 5 Jupiter masses (M_{Jup}) in a region showing less than 1 mag of visual interstellar extinction.

Selection of young stellar objects

The region of Orion B that we studied contains roughly 160 000 VISTA sources, among which less than 1% (!) are actually young objects belonging to Orion; the large majority of the sources are foreground and background stars. Efficient and reliable young stellar object (YSO) source selection is therefore a critical task. We employ a multicolour selection method that is based on the combination of JHKs near-infrared photometry with that in the mid-infrared, and has been proven to provide an optimal distinction between disc-bearing young stellar objects, reddened field stars and galaxies (Harvey et al., 2007). In detail, the location of an object in each of the colour–colour and colour–magnitude diagrams is compared with well-defined boundaries in these diagrams for the expected locations of young stellar objects (Figure 2). The selection is then decided on a combined probability for a source being a young stellar object, based on its location in colour–colour and colour–magnitude space.

This selection method has been applied very successfully to select YSO candidates in star-forming regions observed within the Spitzer c2d and Spitzer Gould Belt legacy surveys (e.g., Evans et al., 2009; Hatchell et al., 2012). In order to apply the same method, we matched our VISTA catalogue with the Spitzer combined Infrared Array Camera (IRAC) and Multi-Band Imaging Photometer (MIPS) catalogue by Megeath et al. (2012), resulting in ~ 58 500 sources with complete ZYJHKs, IRAC 3.6, 4.5, 5.8 and 8 μm and MIPS-24 μm photometry. Figure 2 shows the VISTA/Spitzer colour–colour and colour–magnitude diagrams used to select the YSO candidates in Orion B, which led to a total number of 188 such candidates that are indicated in Figure 2 with red symbols.

Even though we have used a well-tested, robust YSO selection method, remaining contamination from extragalactic sources, foreground main-sequence cool dwarfs, and background red giants is possible. Using the Galactic stellar population model by Robin et al. (2003), we find that the expected number of background giants in the direction of our observed

area, and within the magnitude limits of our survey, is very low (~ 3 stars). Red background giants generally appear much brighter than young Orion members in the same effective temperature range and are therefore easily distinguishable. Similarly, we find from the following experiment that the number of possible galaxy contaminants is very low: we take the SWIRE (Spitzer Wide-area Infrared Extragalactic) catalogue and select an area the same in size as our target area and then place this sample of extragalactic objects behind the Orion B Molecular Cloud. In practice this means applying extinction to the extragalactic objects according to our extinction map of Orion B. Then, we apply our YSO multicolour selection criteria to the reddened SWIRE catalogue objects and check how many targets would be classified as YSOs. Only three objects from the SWIRE catalogue were classified as YSOs (see also lower right panels of Figure 2). In fact, visual inspection of all 188 YSO candidates revealed two objects which appear extended in the VISTA images and could be clearly identified as galaxies. These were rejected from our sample of YSO candidates, i.e., it now numbers 186 objects. The full YSO candidate source list, including their photometry and further information, is described in Spezzi et al. (2015) and is available in electronic data format at the Centre de Données Stellaires (CDS²).

Almost all of the 186 YSO candidates are consistent with an infrared excess typical for young stars with a disc and/or protostellar envelope, i.e., these are sources of class II or earlier in the Lada classification scheme (see below). Moreover, their spatial distribution clearly follows the cloud extinction, i.e. there is a larger clustering of YSO sources at or close to the highest extinction regions of Orion B. Therefore, we conclude that any remaining contamination by foreground cool main-sequence stars (which we believe are the only remaining considerable “polluters” to our YSO sample) is most likely very low.

Properties of the YSOs: luminosity, mass and discs

Now that we have identified the candidate YSOs, we proceed to explore their detailed properties, such as their lumi-

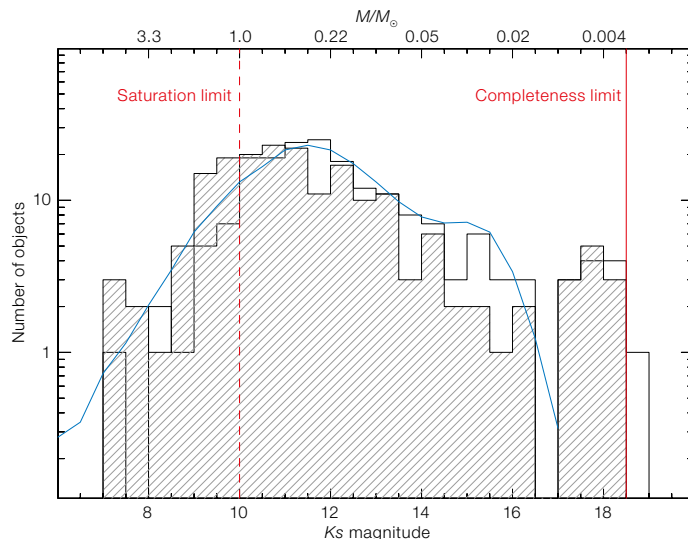


Figure 3. The K_s -band luminosity function (KLF) of the region targeted in Orion B before (empty histogram) and after (line-filled histogram) correction for interstellar extinction. The labels on the upper x-axis indicate the corresponding stellar mass according to the VISTA 2-Myr isochrone. The continuous and dashed vertical lines indicate the completeness and the saturation limit of the VISTA K_s -band photometry, respectively. The continuous curve is the KLF of the Trapezium Cluster, scaled to the peak of the Orion B KLF.

nosities, masses and presence of circumstellar discs. The estimate of the YSO masses is probably the most difficult and we derive it indirectly from the YSOs’ luminosity at K_s -band. Particularly interesting is the frequency mass distribution of the YSOs, i.e., the shape of the mass function, and, related to this, the number of substellar sources. Even though a number of surveys of different star formation regions have been carried out over the last decade, there is still an ongoing debate on the universality or non-universality of the substellar initial mass functions. It appears that, in the environment of a massive stellar cluster, more substellar objects are produced than in low stellar density star-forming environments, such as T-associations.

What is the situation for our studied region in Orion B, which includes the star clusters NGC 2068 and NGC 2071? We constructed the K_s -band luminosity function (KLF) as a proxy for the stellar/substellar mass function. We choose the KLF, rather than the J - or H -band luminosity functions, to minimise the effects of extinction, to maximise our sensitivity to intrinsically red, low luminosity members of this cluster and to make a comparison to the KLF of the nearby Orion Trapezium Cluster presented by Muench et al. (2002).

In Figure 3 we present the observed and de-reddened KLF of our target region in Orion B and overplot, for comparison purposes, the Orion Trapezium KLF. The

KLF of Orion B shows a broad peak at approximately $0.3\text{--}0.7 M_{\odot}$ before it steadily declines into the substellar mass regime. The fraction of substellar objects compared to the total number of YSOs is 28 %, which, after a correction for contamination with field stars, is more like $\sim 20\%$. This, as well as the overall shape of the mass function, is remarkably similar to the Orion Trapezium KLF, which has been reported to have a fraction of substellar objects of $\sim 22\%$ (Muench et al. 2002). We conclude that the star formation environment in Orion B is similarly productive in forming substellar objects as are more massive clusters.

Next, we investigated the circumstellar disc properties of the YSOs. Since YSOs are pre-main sequence objects by definition, the circumstellar discs are protoplanetary discs, i.e., the material surrounding the YSOs are the building blocks for planets. As a matter of fact, our selection criteria has been specifically sensitive to disc-bearing sources and biased against disc-less objects. Hence, it is no surprise that our observations indicate that 97 % of our YSO candidates possess a thick disc and/or a circumstellar envelope. This fraction, however, translates to at most $\sim 85\%$ disc fraction for the complete young stellar sample after accounting for a missed population of disc-less sources.

We further determine the specific nature of the discs from the slope of their spectral energy distributions measured

Region	No. of YSOs	Star formation efficiency (SFE) %	Area (pc ²)	Gas surface density $\Sigma_{\text{gas}} (M_{\odot} \text{pc}^{-2})$	SFR/Area $\Sigma_{\text{SFR}} (M_{\odot} \text{Myr}^{-1} \text{pc}^{-2})$
NGC 2071	52	3.8	2.17	180	6.0
NGC 2068	45	5.3	2.12	115	5.4
HH 24-26	14	3.3	0.77	161	4.6

Table 1. Properties of star formation in the substructures in Orion B. The star formation rate (SFR) is derived from the ratio of the YSO mass belonging to a substructure and its age.

over the 2.2 to 24 μm flux points. This so-called Lada classification scheme resulted in 13 % class I sources (envelope plus thick disc dominated YSO), 16 % flat-spectrum sources and 68 % class II sources (thick disc dominated sources). If star formation has been continuous over a period longer than the age of class II sources, the lifetime for each phase can be estimated by taking the ratio of number counts in each class with respect to class II counts and multiplying by the lifetime for class II. According to the statistics of the derived Lada classes in Orion B, we estimate a lifetime of 0.4 and 0.48 Myr for the class I and flat-spectrum phases, respectively. These values agree well with the average lifetimes derived for several star-forming regions observed in the Spitzer c2d legacy survey (Evans et al., 2009).

Spatial clustering and global star formation properties

Looking at the molecular cloud as a whole, the total number of YSOs and their spatial distribution allow us to characterise the efficiency of star formation of a cloud, as well as to establish any preferred star formation mode. The YSO candidates identified in Orion B are located close to the sites of highest extinction, which in turn are associated with the approximate centres of the young stellar clusters NGC 2068 and NGC 2071. We also find a clear concentration of class I and flat spectrum sources at the extinction peak associated with the HH 24-26 group of Herbig–Haro objects, confirming that this region is a place of currently very active star formation. A more detailed analysis of the clustering structures is based on the volume density of YSOs. We calculate that for all the sites of star formation (NGC 2068, NGC 2071, HH 24-26) the volume density

is $\sim 10 M_{\odot} \text{pc}^{-3}$. Following the criteria adopted in the Spitzer c2d legacy survey (Evans et al., 2009), this classifies NGC 2068 and NGC 2071, which each contain more than 35 YSOs, as clusters and HH 24-26 as a stellar group. More than half of all YSO candidates identified in our study belong to NGC 2068 or NGC 2071, hence the majority of star formation in this part of Orion B appears to occur in a clustered mode, which confirms the conclusions of the early study by Lada et al. (1991).

Another interesting aspect is to investigate the efficiency with which Orion B turns molecular gas into stars. Intuitively one might think that more massive molecular clouds are more active in forming stars, but some studies have shown that it is rather a question of how much of a cloud's mass lies above a gas surface density threshold of $\Sigma_{\text{gas}} \sim 129 M_{\odot} \text{pc}^{-2}$ (Lada et al., 2010; Heiderman et al., 2010).

We determined the overall molecular cloud mass and the gas surface density in our studied region of Orion B and in the respective substructures, i.e., in the clusters and group, using our extinction map and assuming a distance to Orion B of 400 pc. The extinction map was constructed from our multi-band near-infrared photometry utilising the near-infrared colour excess method (see details in Spezzi et al., 2015). The measured extinction is converted to a gas column density and gas mass surface density via the well-known relationship $N_{\text{H}}/A_{\text{V}} = 1.87 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1}$.

Furthermore, the star formation efficiency (SFE) for each of the clusters is derived from the gas mass associated with each and their mass in stars, i.e. $\text{SFE} = M_{\text{stars}} / (M_{\text{stars}} + M_{\text{cloud}})$. The results are presented in Table 1. These clearly suggest that NGC 2071 and HH 24-26 are active sites of star formation, while NGC 2068 appears to be in a more evolved state. The overall SFE is $\sim 4\%$ on average, which is generally consistent with the values measured for Orion A and B, and for

the majority of star-forming regions in the Galaxy (e.g., Federrath & Klessen, 2013).

Pre-main sequence isochrones in the VISTA photometric system

The CASU data reduction pipeline provides photometrically calibrated images and source catalogues in the VISTA filter system. However, the commonly used theoretical isochrones for low-mass stars and brown dwarfs by Baraffe et al. (1998) and Chabrier et al. (2000) are in the Cousins photometric system. Therefore, we transformed these isochrones into the specific VISTA photometric system and made them available to the community at the CDS website². Please refer to Spezzi et al. (2015) for details of the procedure adopted to perform the conversion of the evolutionary model isochrones. These VISTA isochrones should be a valuable tool for use in wide-field VISTA-based searches for very low-mass stars and brown dwarfs in other star-forming regions.

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Links

- ¹ CASU VISTA pipeline: <http://apm49.ast.cam.ac.uk/surveys-projects/vista/vdfs>
- ² Vizier at CDS: <http://vizier.cfa.harvard.edu/viz-bin/VizieR?-source=J/A+A/581/A140>