Science Results from the VISTA Survey of the Orion Star-forming Region

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As part of the VISTA Science Verification programme, a large set of images in Orion was obtained at five near-infrared wavelength bands, from 0.9 to 2.2 μm. The resulting multi-band catalogue contains approximately three million sources, allowing investigation of various issues concerning star and brown dwarf formation, such as a) the difference in the shape of the substellar mass function in a cluster *vs.* non-clustered environment, b) the influence of massive OB stars on the process of brown dwarf formation, c) the size and morphology of dust envelopes around protostars, and d) the comparative role of mass and environment on the evolution of circumstellar discs. The data from the VISTA Orion Survey, including catalogues, are available to the community. In this article we present an overview of selected science results that have emerged so far from this survey.

In order to fully understand the star formation history of a star-forming region, it is of the highest importance to obtain a complete census of its entire stellar and substellar populations since the earliest epoch of star formation. For the large majority of stars in our Galaxy the complex process of star formation takes place in giant molecular clouds (GMCs), from which typically several generations of stars are formed sequentially. Comparative observational studies across these populations of differing age are fundamental to elucidate issues such as the timescales for circumstellar (protoplanetary) disc evolution, environmental effects leading to possible non-universality of the low-mass end of the initial (sub-) stellar mass function (IMF) and the timescales for the dispersal of stellar ensembles. Wide-field imaging surveys in the infrared are the best means to accomplish such large-scale studies systematically and consistently homogeneously.

The Orion star-forming region is an ideal target for studying almost all aspects related to the physics of star formation, early stellar evolution or the interplay between OB associations and the ISM (c.f., Bally, 2008). It is the closest GMC, at an average distance of 400 parsecs (pc), and has been actively forming stars within at least the last ~ 10 Myr, which is also the approximate timescale on which giant planets are thought to be formed. A particularly interesting region for the purpose of a wide-field survey, investigating stellar and substellar properties in different evolutionary stages and environments, is the region around the Orion Belt stars.

The Belt is a prominent part of the constellation of Orion and is marked by three luminous OB stars, namely ζ Ori (Alnitak), ε Ori (Alnilam) and δ Ori (Mintaka), from east to west. To the east of ζ Ori there are very young populous stellar clusters, like NGC 2024, which is still partly embedded in the Orion molecular cloud (OMC) B and which has an age of one million years or less. Nearly one degree southwest of ζ Ori there is the well-known intermediate-age cluster σ Ori (age ~ 3 Myr), while members of the slightly older Ori OB 1b association (~ 5 Myr) populate a wide area around the Belt stars over a few degrees on the sky and are found ''off'' the main molecular clouds (Briceño, 2008). Only recently, yet another group of kinematically distinct young stars has been identified northwest of δ Ori, which is the group of ~ 10-Myr-old stars around the B-type star 25 Ori (Briceño et al., 2007).

Using VISTA, the world's largest near-infrared survey facility (Emerson et al., 2006), which provides a field of view of ~ 1 by 1.5 degrees, we have carried out a deep multiwavelength survey of a large region around the Orion Belt stars. This survey has delivered a new census of very low-mass stars and brown dwarfs and detected new brown dwarf candidates down to ~ 3–4 Jupiter masses at an age of 3 Myr. The advantageous location of Orion below the Galactic Plane and almost in the direction of the Galactic anti-centre implies that the contamination by foreground and background stars is low.

Survey strategy, observations and data reduction

The survey consists of *Z*, *Y*, *J*, *H*, *Ks* images obtained during 14 nights between 16 October and 2 November 2009. The survey area is a mosaic of 20 VISTA fields covering a total of 30 square degrees around the Orion Belt stars; the surveyed area is shown in Figure 1a. Whenever possible the observations in all filters were carried out sequentially for one field, before observing the next field. The one VISTA field that included the young stellar group 25 Ori was imaged up to 23 times at *J*- and *H*-bands with the aim of detecting the photometric variability among the very low-mass stars and brown dwarf members of the 25 Ori group. More details on the observing strategy, the exposure times per filter and particular observing patterns were described in Arnaboldi et al. (2010). Figure 1b shows as an example of the data, a colour-

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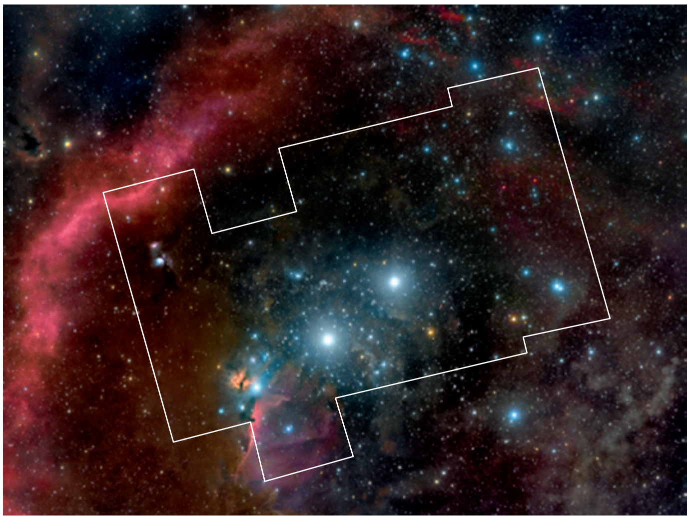

Figure 1a. The boundary of the VISTA Orion Survey is indicated in white, overplotted on an optical image. The size of the image is 10.5 by 8.4 degrees and the orientation is north up, east left.

Figure 1b. VISTA colour image of the young stellar cluster NGC 2071 located in the Orion molecular cloud B (in the northeast of the surveyed area in Figure 1a). The size of the image is ~ 16 × 16 arcminutes and shows a three colour composite (*Z* – blue, *J* – green, *Ks* – red). Orientation as Figure 1a.

composite image of the young cluster NGC 2071.

The amount of data collected for the VISTA Orion Survey was 559 Gigabytes, not including calibration data, clearly making data handling and reduction a challenge. The data reduction was performed by a dedicated pipeline, developed within the VISTA Data Flow System (VDFS), and run by the Cambridge Astronomy Survey Unit (CASU). The pipeline delivers science-ready stacked images and mosaics, as well as photometrically and astrometrically calibrated source catalogues. A total of 3.2 million sources was detected in the VISTA Orion Survey.

The photometric calibration was deduced from 2MASS photometry. The photometric errors are usually below 5% and the overall 5σ limiting magnitudes of the survey are Z ~ 22.5 mag, Y ~ 21.2 mag, J ~ 20.4 mag, H ~ 19.4 mag, Ks ~ 18.6 mag; different parts of the survey can have slightly better or poorer limits due to varying observing conditions. Additional data taken at *Z*- and *J*-bands for the field centred on the cluster σ Ori significantly improved the sensitivity, and achieved 5σ limits of Z ~ 22.9 mag and J ~ 21.4 mag. To further estimate the completeness, artificial stars of different magnitudes were added to the images and the statistics of the re-detected stars were used to estimate the completeness limits as a function of magnitude. In this way we find that the survey should have detected, for a population as young as 1 Myr, essentially all objects down to around six Jupiter masses in a region showing less than 1 mag of visual interstellar extinction.

Selected science results

Young very low-mass stars and brown dwarfs close to ε Ori

The photometric identification of the lowest mass objects has greatly benefitted from the broad wavelength coverage of the survey. With inclusion of the *Z* and *Y* filters, the lowest-mass objects stand out in colour–magnitude diagrams involving those bands, appearing in a region inaccessible to other objects regardless of their reddening. This feature is caused by the appearance of small dust particles in the atmospheres of objects cooler than 2500 K, which causes a steep reddening of the colours involving wavelengths shorter than the *J*-band with decreasing temperature, while the spectral energy distribution at longer wavelengths remains nearly unchanged.

The photometric analysis of a ~ 1 square degree region close to the B0 supergiant ε Ori, in a Z–J versus Z colour–magnitude diagram revealed a high number of potentially young substellar objects (Figure 2, shown as blue squares). These candidate brown dwarfs populate a sequence that clearly separates from the older main sequence objects of the surrounding general field. In the same figure the position of the spectroscopically-confirmed T Tauri stars, the higher mass counterparts to the brown dwarfs, are plotted (green diamonds in Figure 2), showing convincingly that the candidate brown dwarf sequence is an extension of the higher mass pre-main sequence stars. Note that the gap in between T Tauri stars and brown dwarfs is artificial and due to the selection criteria on one side and the spectroscopic sensitivity limit on the other side. A similar sequence of pre-main sequence objects in the ε Ori cluster has previously been reported by some authors from an analysis of optical colour–magnitude diagrams (Caballero & Solano, 2008; Scholz & Eislöffel, 2005).

Employing the full wavelength range of the survey, it can be further tested whether the spectral energy distribution of the candidate brown dwarfs is indeed consistent with brown dwarf atmosphere models. One example is shown in Figure 3, where the 0.9 to 2.2 μm fluxes of one of the brown dwarf candidates from Figure 2 is compared to the theo-

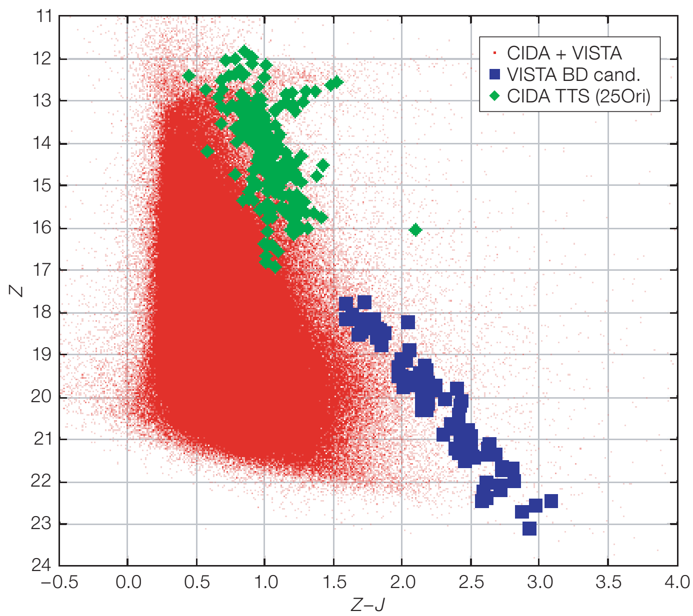

Figure 2. Colour–magnitude diagram of brown dwarf candidates (blue) close to ε Ori. The red dots show field objects, mostly fore- and background dwarfs and giants, in the Orion Belt region, detected in the VISTA Orion Survey and having optical counterparts in the CIDA catalogue (Briceño et al., 2005; 2011). Spectroscopically confirmed T Tauri star (TTS) members of the 10-Myr-old group around 25 Ori are plotted as green points; the brown dwarf (BD) candidates may have a similar age.

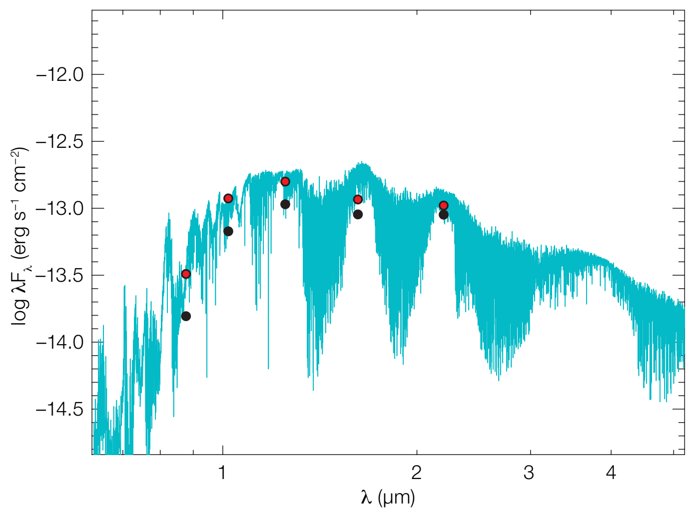

Figure 3. Spectral energy distribution of a candidate brown dwarf in the ε Ori cluster. Black dots are the observed fluxes, while the red dots are the fluxes dereddened with A_V = 1.5 mag. The spectral energy distribution model of a source with T_{eff} = 2500 K, L = 7.9 × 10^{-4} $L_{\odot}$, at a distance of 420 pc is shown in cyan (model from Allard et al., 2001).

retical flux distribution of a source with T_{eff} = 2500 K, L = 7.9 × 10^{-4} $L_{\odot}$ — the overall agreement is quite good, supporting the brown dwarf nature of the candidate. A further step would be the assignment of masses to all the candidate brown dwarfs in order to extract the substellar IMF. This, however, is difficult from the colour–magnitude diagram alone, because the isochrones are very tightly bunched together in the low-mass regime and the age of the brown dwarf candidates are thus not well constrained. Hence assigning masses is very uncertain although future spectroscopy may help constrain them by probing surface gravity sensitive features.

The σ Ori cluster

The σ Ori cluster is one of the most studied clusters in Orion. It is essentially free of gas and dust, making the study of its stellar and substellar content little affected by interstellar extinction. Due to its youth (~ 3 Myr) substellar objects of σ Ori are relatively easy to detect, because they are brightest when they are young. The VISTA Orion Survey detected the well known T-dwarfs S Ori 70 and S Ori 73 (Peña Ramírez et al., 2011) and has been further explored to identify the lowest mass brown dwarfs, the L- and T-dwarfs, in a circular area of radius 30 arcmin around the bright, multiple star σ Ori. Photometric candidates were selected from the *Z*–*J* versus *J* colour–magnitude diagram (Figure 4). Out of 106 selected brown dwarf candidates, 37 are candidate free-floating planetary mass objects (6–13 Jupiter masses). Of the latter, 23 are new VISTA discoveries and have near-infrared colors compatible with spectral types L and T. All the new detections are fainter than J ~ 18.5 mag, which indicates they are on the planetary mass boundary or below, assuming they are members of the 3-Myr-old σ Ori cluster.

Scattered light images of protostellar envelopes

The youngest stellar objects are typically surrounded by large dusty discs and infalling envelopes and are located at or close to the cores of the molecular cloud. They represent the earliest phase of stellar evolution. About 350 such protostars (class 0 to class I sources), distributed all over the Orion molecular clouds A and B, have been identified by Spitzer imaging (Megeath et al., 2005; Allen et al., 2007). For several of the protostars located in parts of the Orion molecular cloud B which were covered by the VISTA Orion Survey, large extended scattered emission from protostellar envelopes was detected in the images.

One of the best examples is the edge-on disc and associated bipolar envelope of the source HOPS333 shown in Figure 5. The diameter of the envelope, as seen in the deep VISTA images, is roughly 2500 astronomical units (AU). The central protostellar source was detected with Spitzer in all IRAC bands, i.e. from 3.6 to 8.0 μm, as well as with MIPS at 24 μm. The 24 μm flux of HOPS333 is 20 mJy, but it has not been detected in deep submillimetre continuum maps, suggesting that HOPS333 is a slightly more evolved protostellar object.

A serendipitous re-discovery: Berkeley 20

Northeast of δ Ori we detected a local stellar density enhancement, which turned out to be the Galactic old open cluster Berkeley 20. Most recently, Berkeley 20 has been studied at optical wavelengths by Andreuzzi et al. (2011) who determined an age of ~ 5 Gyr and a distance of 8.7 kpc. In Figure 6 we plot the VISTA colour–magnitude diagram of Berkeley 20 for stars within one cluster

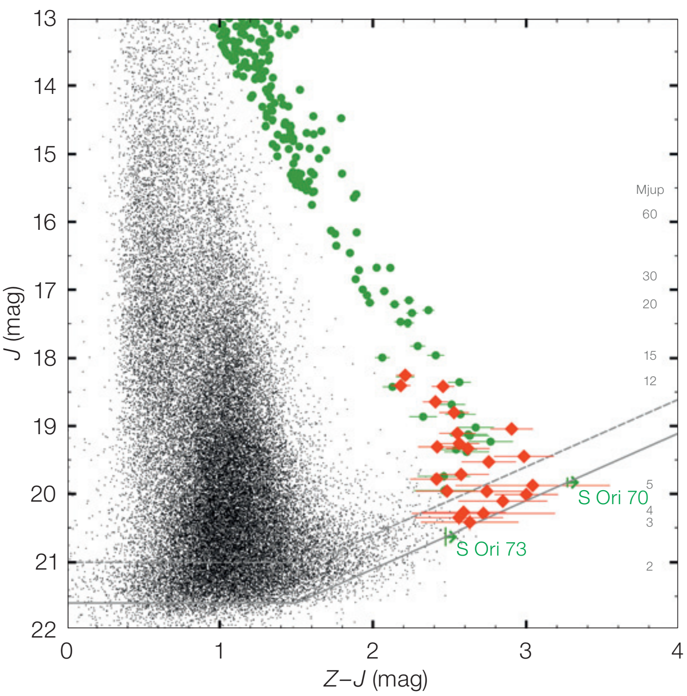

Figure 4. Colour–magnitude diagram of a 0.78 square degree field centred on σ Ori (Peña Ramírez et al. 2012, in prep.). Green dots are previously known very low-mass stars and red diamonds indicate new brown dwarf detections from the VISTA Orion Survey. The grey solid and dashed lines are the 4σ and 10σ detection limits. Object masses are labelled on the right of the diagram based on (sub-) stellar evolutionary models from the Lyon group (Chabrier et al., 2000; Baraffe et al., 2003).

radius (1.8 arcminutes) of the cluster centre; the cluster radius has been determined based on the *Ks*-band radial stellar density distribution. The 5 Gyr isochrones from the stellar evolutionary models of Girardi et al. (2002) are overplotted. Both isochrones, for metallicity *[M/H]* = −0.6 as well as for *[M/H]* = −0.3, fit the stellar

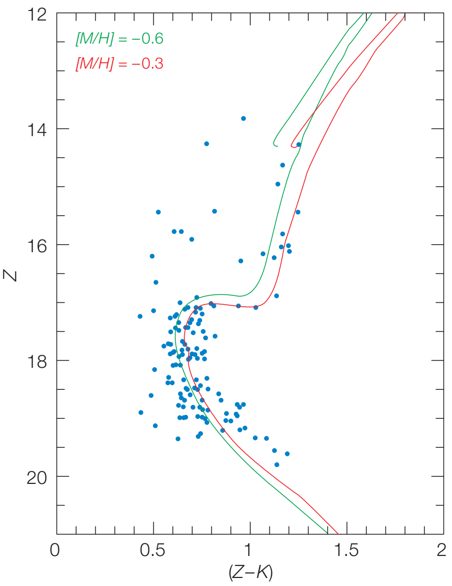

Figure 6. Colour–magnitude diagram of the Galactic old open cluster Berkeley 20, which was serendipitously re-discovered in the VISTA Orion Survey. Both isochrones represent a 5-Gyr population (Girardi et al., 2002), but at different metallicity, as indicated.

sequence quite well. Spectroscopic observations of two cluster members confirm a metallicity of *[M/H]* = −0.45 (Sestito et al., 2008). From isochrone fitting we derive a distance of 8.4 kpc for Berkeley 20 with an interstellar extinction of 0.32 mag, in agreement with previously published values.

Outlook and data access

Further analysis of the full census of candidate very low-mass stars and brown dwarfs over the whole survey area is underway. Detailed investigations of the stellar and substellar content of the youngest stellar clusters imaged in the survey, e.g., NGC 2071, NGC 2068 and NGC 2024, will discuss their substellar IMFs out to large cluster radii. Spectroscopic follow-up of circumstellar discs surrounding cluster stars and brown dwarfs will allow the physical properties of these objects to be characterised in great detail. Complementary data from Spitzer and/or Chandra and XMM will help to distinguish young Orion sources from field stars. About one third of the sources, i.e. roughly one million objects, in the full area catalogue, have been classified as extended, suggesting that these are most likely background galaxies. All of these await scientific exploitation.

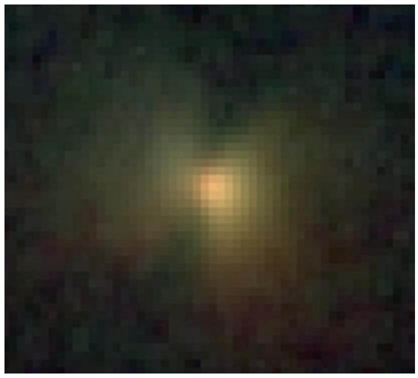

Figure 5. Three colour composite image (*Z*, *J*, *Ks*) centred on the protostar HOPS333. Clearly visible is a dark central obscuration, indicating an edge-on disc, and a large bipolar envelope structure showing up in scattered near-infrared light. The full size of this image is ~ 18 arcseconds, which corresponds to almost 8000 AU at the distance of the Orion B molecular cloud.

Access to the data products, including images and source catalogues, will be available via the ESO Archive Query Interfaces for Phase 3 ingested data products at: http://archive.eso.org/wdb/wdb/adp/phase3_vircam/form

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