VISTA Science Demonstration Proposal for a Galactic Mini-Survey in Orion

Team Members	Institute	EMAIL
M. Petr-Gotzens	ESO-Garching	mpetr@eso.org
J.M. Alcalá	INAF-OA Capodimonte	jmae@na.astro.it
C. Briceño	Centro de Investig. de Astr. (CIDA)	briceno@cida.ve
F. Comerón	ESO-Garching	fcomeron@eso.org
G. Hussain	ESO-Garching	ghussain@eso.org
M. McCaughrean	University of Exeter	mjm@astro.ex.ac.uk
T. Stanke	ESO-Garching	tstanke@eso.org
M.R. Zapatero Osorio	Inst. de Astrofísica de Canarias	mosorio@iac.es
H. Zinnecker	Astrophysikalisches Inst. Potsdam	hzinnecker@aip.de

Scientific Case:

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 all its stellar/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. Observational comparative studies across these populations of differing age are fundamental to elucidate e.g. the timescales for circumstellar (protoplanetary) disk evolution, the environmental effects or possible non-universality on the low-mass end of the Initial Mass Function (IMF), or the timescales for the dispersal of stellar ensembles. Wide-field imaging surveys in the infrared, e.g. with VISTA, are the best means to accomplish such large-scale studies in a homogenous way.

The Orion Star Forming Complex:

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 (see J. Bally in "Handbook of Star Forming Regions Vol. I", ASP 2008, ed. B. Reipurth). It is the closest GMC, at an average distance of ~400 pc, and actively forming stars within at least the last ~10 Myr, which is about the time-scale on which giant planets are thought to be formed. A wealth of stellar populations have been identified in Orion, among which are:

Very young ($\leq$ 1Myr) stellar clusters, sometimes still embedded in the molecular cloud material (e.g. NGC1976, 2024, 2023, 2068, 2071), intermediate-age clusters like the σ Ori cluster (~3 Myr), and older populations like the Ori OB1b (~5 Myr) and Ori OB1a (~10 Myr) association. Stars in the Ori OB1a association are widely dispersed over several degrees on the sky and are found "off" the main molecular clouds. This is also true for the Ori OB1b association, although it's less dispersed than OB1a (due to its youth). Recently, a kinematically distinct stellar group of almost 200 pre-main-sequence (PMS) stars has been identified around the B-star 25 Ori, which is located within the Ori OB1a association (Briceño et al. 2007). The age of the 25 Orionis aggregate was estimated as 10 Myr. Ten Myr seems also the approximate timescale for the dissipation of most of the gas in molecular clouds, as can be inferred from the absence of gas in regions like Ori OB1a; even by the 3-5 Myr ages of the σ Ori cluster and Ori OB1b, most of the gas of the parent clouds is gone. The advantageous location of Orion above the Galactic plane and almost in the direction of the Galactic anti-center implies that the contamination with foreground and background stars is low.

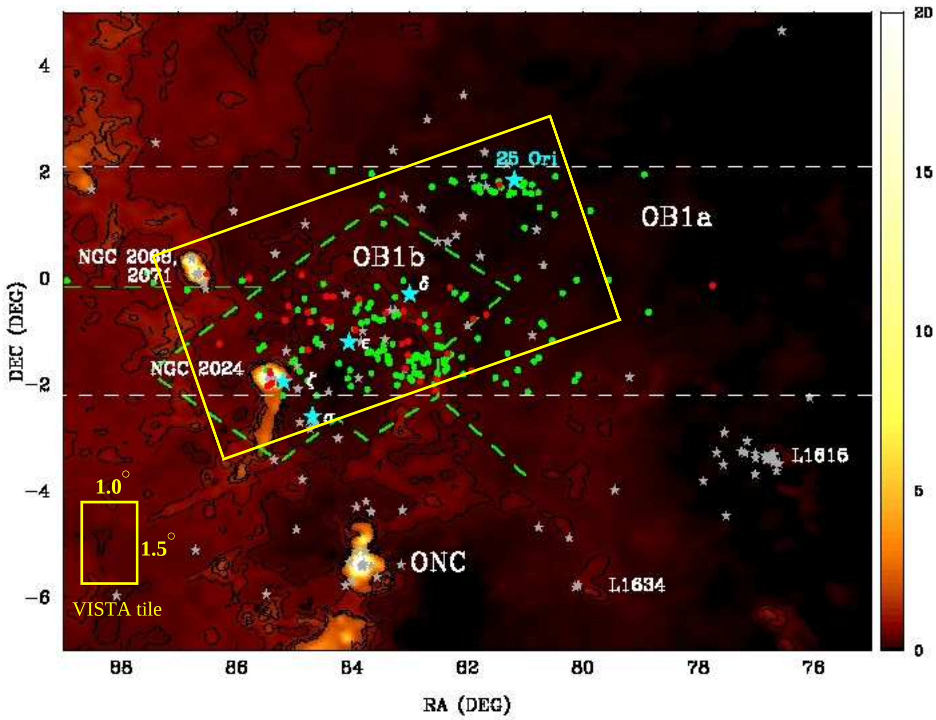

Figure 1: The yellow tilted square indicates the proposed VISTA survey area. The size is ∼30square degree and it will be mapped with 20 contiguous VISTA tiles. The figure has been adapted from Briceño (2008), with the underlying colour map showing the dust emission map of Schlegel et al. (1998), represented in false color calibrated to $E(B-V)$ reddening in magnitudes. The three Orion belt stars, and σ Ori and 25 Ori are plotted as large cyan starred symbols. Other symbols are pre-main-sequence stars: weak-line TTauri stars (green dots), classical TTauri stars (red dots) from Briceno et al. (2005, AJ, 129, 097). PMS stars identified by Alcalá et al. (2004) and in Herbig & Bell (1988) are shown as grey stars. The horizontal dashed lines indicate the limits of the Briceno et al. (2005) survey. The green dashed lines show the boundaries of Ori OB1a and OB1b association from Warren & Hesser (1977).

For the proposed VISTA survey, we chose to observe a ∼30 square degree field located in the northern part of the Orion star forming region, roughly centered at RA(05h 32m 00.4s), DEC(-00°17′57″) (see Figure 1). This field includes all the stellar populations described above, except for NGC1976. Thus, the survey will map various stages and environments of early stellar evolution, from protostars and embedded $\sim< 1$ Myr populations, across intermediate-age clusters and the $\sim$5 Myr old OB 1b region, to the $\sim$10 Myr old stars in the 25 Ori cluster and the general wide-spread population of the Ori OB1a association. It will truly provide clear immediate results for various issues in star/brown dwarf formation research and provide a large dataset with important legacy value. In detail, the following main science goals are addressed:

Search for young very-low mass (VLM) stars and brown dwarfs (BDs); the substellar IMF:

Despite the fact that Orion is probably the best studied nearby high-mass star forming region, the census of its very-low mass stars and brown dwarfs is far from being complete, especially for the older wide-spread populations of Ori OB1a and 1b. Only recently, Downes et al. (2008) presented a wide area optical-IR survey of the Orion OB1a/b association using the QUEST I CCD Mosaic Camera. Their I-band data go down to I$\sim$21.5, over $\sim$150 square degrees (DEC=-5 to +5 and RA= 5h to 6h) and were combined with 2MASS data. Several new very low-mass PMS stars and a few brown dwarfs were identified. However, 2MASS is too shallow and did not allow the identification of young Ori OB1 members less massive than $\sim 0.05 - 0.07 M_\odot$ (equivalent to 50-70M_{Jup}). It is the goal of the Orion VISTA survey to go significantly beyond that limit, and to detect objects down to 10-20M_{Jup} at an age of 10 Myr. According to the DUSTY evolutionary models of Chabrier et al. (2000) such objects at the distance of Orion have J$\approx$21.4-17.3 mag (Ks$\approx$18.7-16.5 mag) at 10 Myr, and J$\approx$19.4-17.2 mag (Ks$\approx$18.0-16.4 mag) at 5 Myr and A_V=0mag. Since from near-IR colours alone one cannot discriminate young VLM stars/BDs from the general (old) field population (in particular not in the extended off-cloud regions) it is planned to use all the VISTA ZYJHK_s filters. This way an optimal photometric selection of PMS candidate Orion members can be achieved. With inclusion of the Z and Y filters, the lowest mass objects should stand out in color-color diagrams involving those bands by appearing in a region inaccessible to other objects, regardless of their reddening. This is caused by the appearance of small dust particles in the atmospheres of objects cooler than 2,500 K, which cause a steep reddening of the colors involving wavelengths shorter than the J band with decreasing temperature, while keeping the spectral energy distribution at longer wavelengths nearly unchanged. The spectral energy distribution involving bluer filters like Y or Z thus provides a sensitive temperature indicator, easy to disentangle from the effects of extinction. Therefore, the lowest mass objects could be identified, and even roughly characterized, by doing SED fitting (Figure 2). Employing the full wavelength range of VISTA filters will also help to discriminate interloping old foreground late M-dwarfs or brown dwarfs. Still, spectroscopy will be needed for a final confirmation of all photometrically selected candidates. Also, at least for the brighter objects, proper motion selection can be a useful asset to separate foreground objects. Due to the fact that Orion is moving essentially radially away from us and proper motions are extremely small, establishing Orion membership is actually difficult.

The immediate question once having identified VLM PMS stars in the survey is about the shape of the substellar IMF. For example, is the mass function across the substellar limit (at $\sim 0.08 M_\odot$), in clusters like the 10 Myr old 25 Ori, like the mass

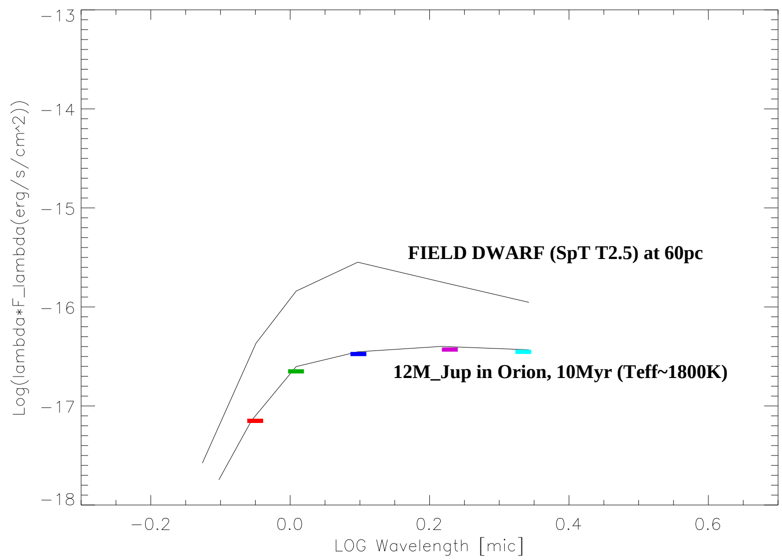

Figure 2: The observed SED of an old field T-dwarf (Chiu et al. 2008, MNRAS 385, L53) compared to the SED of a $12M_{Jup}$ mass object of age 10Myrs, at the distance of 400 pc, and seen through $A_V = 1$ mag (based on evolutionary models of Chabrier et al. 2000). The $12M_{Jup}$ object defines the sensitivity limits of our proposed VISTA survey. The VISTA $ZYJHK_s$ filters are overplotted as small coloured bars.

function in σ Ori or in the Orion Nebula Cluster? And, how does it compare to the widely spread "field" population in the Ori OB1a/1b association? Over the last years, different authors have studied the substellar IMF in regions like Chamaeleon, Taurus, the Orion Trapezium Cluster or in the σ Ori cluster down to planetary-mass objects ($\sim 1M_{Jup} - 12M_{Jup}$), with surprising results (Luhman 2004, ApJ 617, Briceño et al. 2002, ApJ, 580, McCaughrean et al. 2002, ESO Messenger 109, Slesnick et al. 2004, ApJ 610): the substellar IMF differs significantly, with the T-associations of Taurus and Chamaeleon apparently having a deficit of substellar objects compared to the Trapezium and σ Ori clusters. This difference may be related to an evironmentally dependent formation mechanism for brown dwarfs: in regions where strong UV-radition from massive OB stars evaporates the dust reservoir of low-mass accreting protostars *before* the object fully terminates its accretion, a low-mass brown dwarf emerges (Whitworth & Zinnecker 2004, A&A 427). Similarly, dynamical interactions in very young dense stellar clusters could eject the lowest mass members before their accretion process allows them to gain stellar masses. The total mass accreted during the early stages may also depend on the amount of turbulence in a molecular cloud core. Clearly, the formation mechanism of brown dwarfs (Whitworth et al. 2007, in Protostars and Planets V) is by no means secured yet and requires further observational support.

The proposed survey area also includes a few bright-rimmed clouds and cometary globules (No. 27, 35 and 40 by Ogura & Sugitani 1998) in which very low-mass star formation is not yet well investigated. An analysis of the presence of young sub-stellar objects will be very interesting and shall be compared to recent studies in the L1616/L1615 cometary cloud (just south of the proposed VISTA survey area) and in RCW 108, where some evidence of a lack of sub-stellar objects has been found (Gandolfi et al. 2008, Comerón & Schneider 2007).

Search for optically thick disks:

The proposed VISTA survey is also very well suited to investigate how Orion circumstellar disks evolved over a timescale of 1-10Myr, the range of ages of the populations present in the VISTA survey. In particular as all populations emerged from the same large-scale birth environment, any gross environmental effect can be excluded. Hernandez et al. (2007) showed that optically thick disks can still exist even at ages of $\sim$10 Myr. The detection of disks, however, will be difficult with only near-IR wavelengths especially for the oldest and latest spectral type objects. Spitzer/IRAC and MIPS observations provide helpful additional indications for disks, also because disks around substellar objects clearly stand out at these wavelengths. Several fields in the area of 25 Ori, σOri, and along the Orion belt stars are currently observed with Spitzer (PI: Briceño) which could be combined with the deep VISTA observations to allow identification of disk emission associated with low-mass objects in these regions. Understanding the evolution of accretion disks can provide strong constraints on theories of planet formation, and measuring the lowest mass at which young objects harbor circumstellar disks is crucial for determining whether planets can form around low-mass BDs (Lada et al. 2006, AJ 131, 1574). A way to approach these issues is through the study of the spectral energy distribution (SED). SEDs can be fitted using different recent models that assume reprocessing flared disks (Dullemond, et al. 2001, ApJ 560, 957) or simulate different combinations of accretion disk/envelope parameters (Robitaille, et al. 2006, ApJS 167, 256). The deep VISTA observations will provide constraints on the inner disk regions, allowing one to study relationships of fundamental parameters with disk parameters.

Protostars:

The youngest stellar objects are typically surrounded by large dusty disks 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 cloud A and B, have been identified by Spitzer imaging (Megeath et al. 2005, Allen et al. 2007) and been followed-up with mid-infrared spectroscopy ($\sim$ 70% of the sample). Accurate determination of the protostars' properties, e.g. from the analysis of multi-wavelength data, is required to establish a clear evolutionary picture of the gas-infall rate, angular momentum loss, or the envelope properties over the lifetime of a protostar. The proposed VISTA survey will cover parts of the Orion molecular cloud B and can significantly contribute to these goals. Especially, large extended scattered emission from protostellar envelopes could be detected in the deep VISTA images. A large wavelength range coverage of such structures is very useful for models of circumstellar envelopes as they provide a direct estimate of the envelope opening angles (outflow cones).

Complementary Data/Surveys:

There are several existing or planned observations at other wavelengths that will add valuable information, and can give support to the young (sub)stellar nature of pho-

tometrically selected candidates:
The Orion molecular cloud B, hence including the young stellar clusters NGC2024, 2023, 2068, 2071, have been imaged in the mid-IR by a Spitzer/IRAC survey (Megeath et al. 2005, Allen et al. 2007). There are also deep Spitzer/IRAC observations on the σ Ori cluster (Bouy et al. 2008, A&A in press). The CIDA VRI-imaging survey covers a large fraction of the wide spread off-cloud population (Briceño et al. 2005, AJ 129, Downes et al. 2008, AJ 136). Chandra has observed NGC 2024 (ACIS-I - which has a $17' \times 17'$ field of view) to a good depth. The σ Ori cluster was observed with Chandra/HRC-I, which has a $30' \times 30'$ field of view. ACIS-I observations of NGC 2068/2071 are scheduled for November of this year.
Clearly, spectroscopic follow-ups of the the most interesting targets coming from the VISTA mini-survey should be performed, using for example, X-Shooter, a forthcoming VLT instrument. X-Shooter will start operations almost in parallel to VISTA. Spectroscopic follow-up will allow: a) a characterisation of the VLM YSO populations and their circumstellar accretion disks from evolutionary/accretion disk models. b) the study of accretion and outflow phenomena in the VLM objects domain. c) to study the link between disk versus central object parameters.
Finally, we wish to note that, while the UKIDSS-GCS plans to observe a larger area of the Orion star-forming region, this VISTA survey will be more sensitive, available earlier, include optical-red filters (ZY) and should also provide a better spatial resolution.

Observing Strategy and Time Justification:
The Orion VISTA survey aims at mapping an area that encompasses different populations of different evolutionary stages to a substantial depth (Figure 1 and Table 1). Therefore, the strategy is to observe 20 contiguous VISTA tiles that shall be arranged in a 4-by-5 positions grid covering the $\sim 30\text{deg}^2$ field shown in Figure 1. Each tile has a size of approximately $1.0° \times 1.5°$ and defines a contiguous area made by six single VISTA exposures (pawprints). We plan to observe all 20 tiles at all filters, ZYJHKs. The targeted detection limits per filter (in Vega magnitudes) are given in Table 1, and are based on the survey goal to detect a $\sim 12\text{M}_{Jup}$ object with an age of 10Myr at the distance of 400 pc and A_V=1.0mag. Younger objects are even more luminous at NIR wavelengths and the survey is therefore sensitive to even lower mass objects for younger ages. In terms of T_{eff} we will be sensitive to young Orion members as cold as $\text{T}_{eff} \approx 1800\text{K}$, which corresponds to a spectral type of ∼L4. It is furthermore important to observe all five bands as close in time as possible, as young low-mass objects are known to be possibly variable on time scales of days. Hence, observing a tile in all filters within one and the same Observation Block (or with 2 OBs in immediate sequence) is necessary to obtain the correct SED sampling.
Using the VISTA ETC (at http://www.ast.cam.ac.uk/ psb/vista/etc/) we evaluated the exposure time per tile needed to reach the magnitude limits as listed in Table 1. The total execution time *per tile* (and therefore per OB) is the sum of the tile exposure times (sum of col. 2 of Table 1) plus the overheads as provided by the VISTA ETC, plus 4×30s for changing the filter, plus approximately 2 minutes for telescope preset and AO. The total sum gives 6918.0 sec, i.e. almost 2 hours. As we wish to observe 20 tiles the total amount of observing time required for the VISTA Orion

survey is 40 hours. Currently, about ten nights in January are scheduled for VISTA Science Verification, meaning that we can observe 4 hours per night (2 tiles). The remaining hours of the nights are spent on executing the VISTA SV extragalactic survey and on observing calibrations.

Table 1: Sensitivity limits (in Vega mag) of the Orion survey in each filter. The exposure times required to reach these limits have been obtained from the VISTA ETC, assuming seeing=0.8″, airmass=1.4, default sky magnitudes, and with the following (filter dependent) specific parameters: DIT=10-60s, NDIT=1-4, $N_{\rm jitter}$=3-4. The corresponding detection limits in terms of mass are given in the last two columns for 2 different object ages.

Filter	Exposure time per tile	Mag limit (Vega)	S/N	Mass detection limit at 5 Myr	Mass detection limit at 10 Myr
Z	2880.0	22.7	5	$8M_{Jup}$	$12M_{Jup}$
Y	960.0	21.0	8	$8M_{Jup}$	$12M_{Jup}$
J	540.0	20.2	8	$8M_{Jup}$	$12M_{Jup}$
H	540.0	19.2	8	$8M_{Jup}$	$12M_{Jup}$
K_s	720.0	18.4	8	$8M_{Jup}$	$12M_{Jup}$