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THE FORMATION AND EARLY EVOLUTION OF BROWN DWARFS VIEWED THROUGH THE ORION DISPERSED POPULATIONS

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RESUMEN

Presentamos un resumen de los últimos resultados de un sondeo fotométrico y espectroscópico en curso, a gran escala, de estrellas de muy baja masa y enanas marrones con masas hasta $M \sim 0.02\ M_{\odot}$, en las poblaciones dispersas de región de formación estelar de Orion OB1. El sondeo se basa en la combinación de observaciones fotométricas multi-época en las bandas R e I, obtenidas con la cámara Quest-I del Observatorio Astronómico Nacional de Venezuela, con datos en el cercano infrarrojo de los sondeos VISTA y 2MASS, abarcando un área total de $\sim$200 gd^2. El sondeo fotométrico está siendo complementado con observaciones espectroscópicas de seguimiento realizadas con el instrumento Hectospec del telescopio MMT de 6.5 m, resultando hasta el momento en la confirmación espectroscópica de enanas marrones jóvenes con masas hasta $\sim$0.05 $M_{\odot}$ cubriendo 6 gd^2. Un resumen de los resultados basados en la muestra espectroscópicamente confirmada de miembros estelares y subestelares de Orion, así como en aquellos objetos que permanecen como candidatos se discuten con énfasis en la función inicial de masa, la dependencia de la distribución espacial como función de la masa, los excesos en el cercano infrarrojo y las fracciones de objetos con características tipo T-Tauri clásica o débil. Estos resultados se presentan y discuten en términos de las predicciones de los modelos de formación de enanas marrones en Downes, J. J., et al. (2011, en preparación).

ABSTRACT

We present an overview of the latest results of an ongoing large-scale, optical photometric and spectroscopic survey of very low mass stars and brown dwarfs down to $M \sim 0.02\ M_{\odot}$ in the dispersed, off-cloud populations of the Orion OB1 star forming region. The survey is based on the combination of multi-epoch optical photometry in R and I bands obtained with the Quest-I camera at the Venezuela National Astronomical Observatory, with near-IR data from the VISTA and 2MASS surveys, spanning a total area of $\sim$200 deg^2. The photometric survey is being complemented with follow up optical spectroscopy on the Hectospec instrument on the 6.5 m MMT, which so far has provided spectroscopic confirmation of young brown dwarfs down to $\sim$0.05 $M_{\odot}$ over 6 deg^2. An overview of the results on the sample of stellar and substellar objects spectroscopically confirmed as members of Orion and those that still remain as photometric candidates are presented, focus on the initial mass function, the mass dependence of the spatial distribution, the near infrared excesses and the fraction of objects with Classical or Weak T Tauri-like characteristics. These results will be extended and discussed in terms of the predictions from brown dwarf formation models in Downes, J. J., et al. (2011, in preparation).

Key Words: brown dwarfs — stars: formation — stars: low mass

1. INTRODUCTION

One of the main goals of contemporary astrophysics is understanding the processes of star and planet formation. Because brown dwarfs are objects with masses intermediate between those of stars and planets, understanding how they form can provide important constraints on the origin of stars and planetary bodies. The main problem in understanding the processes of the formation of brown dwarfs is that their masses can be two orders of magnitude lower than the Jeans mass in a typical star forming region. Several theoretical scenarios have been proposed in order to explain the processes that allow molecular clouds to reach the mass densities necessary to form brown dwarfs or the mechanisms for the interruption of mass accretion from the surroundings into a stellar core, resulting in an object with a mass lower than the substellar mass limit. The available models are generally classified in the five scenarios reviewed by Whitworth et al. (2007): (*i*) turbulent fragmentation of molecular clouds (e.g., Bate 2009), (*ii*) gravitational fragmentation (e.g.,

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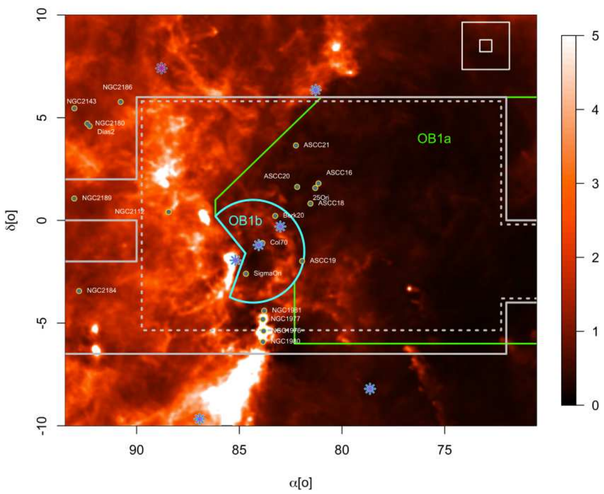

Fig. 1. Spatial distribution of the CVSO (solid gray line) and the deep optic photometric survey of Orion (dashed gray line). The colored scale indicates the A_V extinction from Schlegel maps (Schlegel et al. 1998) and the colored polygons the sub-regions OB1a and OB1b of the Orion complex. Clusters and bright stars are also indicated.

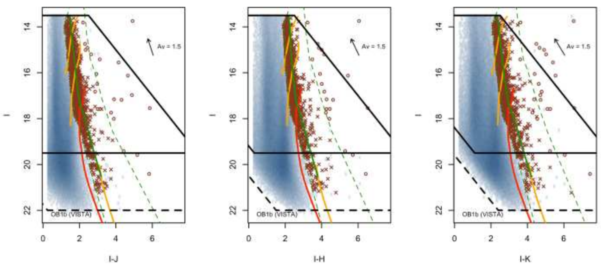

Fig. 2. Color-magnitude diagram used for the photometric candidate selection. Yellow lines indicates evolutionary tracks for 0.02 $M_{\odot}$ to 0.3 $M_{\odot}$. Red line indicates the evolutionary track for the substellar limit (0.072 $M_{\odot}$). The green dashed-line encloses the candidate sample. This area is centered on the isochrone corresponding to the age of the pre-main sequence stellar population obtained by Briceño et al. (2005) (green solid line). Isochrones and evolutionary tracks are from Baraffe et al. (1998). Crosses indicate the photometric candidates and circles photometric candidates with infrared excesses.

Bonnell & Bate 2006), (*iii*) premature gravitational ejection of stellar cores from their surrounding accreting material (e.g., Reipurth & Clarke 2001), (*iv*) fragmentation of massive circumstellar disks (e.g., Stamatellos & Whitworth 2009) and (*v*) photoerosion of stellar cores due to nearby massive stars (e.g., Whitworth & Zinnecker 2004). These models are not mutually exclusive (Whitworth et al. 2007) and their relevance needs to be observationally tested in terms of variables such as the initial mass function, spatial distribution, kinematics and the fraction of circumstellar disks. During the last years, several observational efforts have been carried out in order to compare observations with these models, resulting in evidence pointing for a common mechanism for brown dwarf and star formation (Whitworth et al. 2007) but with non-conclusive evidence about the relative relevance of the different theoretical escenarios proposed (Whitworth et al. 2007). In the continuation of such efforts, the observation of star forming regions under several environmental conditions and covering a range of ages is essential.

Here we summarize the latest results of an ongoing large-scale, optical photometric and spectroscopic survey of very low mass stars and brown dwarfs down to $M \sim 0.02\ M_{\odot}$ in the dispersed, off-cloud populations of the Orion OB1 star forming region. This sample includes regions such as Orion OB1a whose age around 10 Myr old is relevant in the study of the evolution of circumstellar disks. The observations and preliminary results presented here will be extended, explained and discussed in detail in Downes et al. (2011, in prep.).

2. THE CIDA DEEP SURVEY OF ORION

The CIDA Variability Survey of Orion (Briceño et al. 2005, CVSO) is a large scale multi-epoch optical photometric survey of the dispersed populations of Orion performed since 1998 with the Quest-I camera at the Jürgen Stock 1 m Schmidt telescope at the Venezuela National Astronomical Observatory (Baltay et al. 2002).

Based on these observations most of the pre-main sequence low-mass star population of the Orion OB1a and OB1b sub-regions has been detected and extensively studied by (e.g., Briceño et al. 2007a). In order to extend these studies down to the substellar domain we applied a co-adding technique over several epochs of the CVSO, resulting in a deep optical survey covering 200 sq. deg of the Orion star forming region with mean limiting magnitudes of $R = 21.0$ and $I = 21.5$ and completeness up to $R = 20.0$ and $I = 10.5$. The saturation occurs at $R = 13$ and $I = 13$.

With the combination of the R and I-bands optical photometry with near-IR data from the VISTA and 2MASS surveys, we select photometric candidates to stellar and sub-stellar members of Orion down to 0.02 $M_{\odot}$. Figure 1 shows the area covered by the survey and Figure 2 an example of the optical-near infrared color-magnitudes diagrams used for the candidate selection.

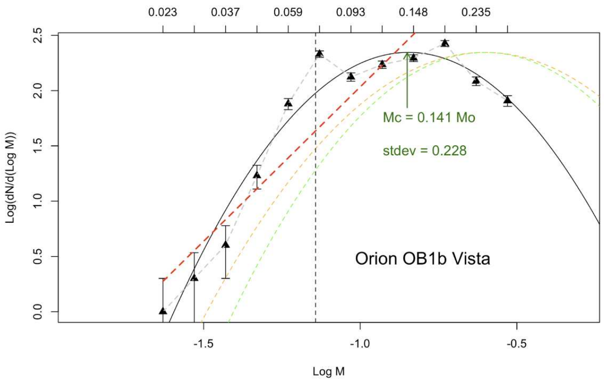

Fig. 3. Initial mass function computed from the photometric candidates found in Orion OB1b. Curves indicate the Pleiades MF from Lodieu et al. (2007), and the fit of the sample to a Kroupa MF and a log-normal MF.

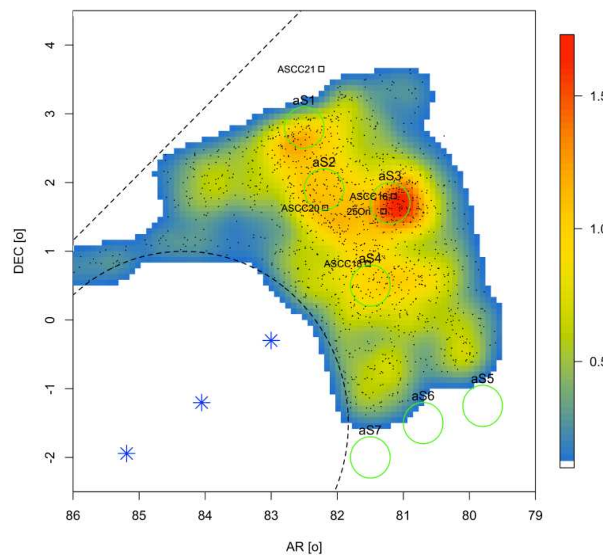

Fig. 4. Spatial distribution of photometric candidates in the OB1a subregion near the 25Ori cluster (Briceño et al. 2007b). These candidates came from the selection using photometry from our optic survey and J, H and K-band photometry from VISTA. The limiting magnitude and color from these sample allow the detection of brown dwarf candidates down to 0.02 $M_{\odot}$.

We identified $\sim 10^4$ photometric candidates to very low-mass stars and brown dwarfs from $\sim 9 \times 10^6$ point sources detected. Assuming the main distances to the Orion sub-region obtained by Briceño et al. (2005) and the models of Baraffe et al. (1998), the candidates cover the main mass interval within $0.3 < M/M_{\odot} < 0.02$, with main completeness down to ~ 0.04 $M_{\odot}$

3. PHOTOMETRIC CANDIDATES AND SPECTROSCOPICALLY CONFIRMED MEMBERS OF ORION

The photometric survey is being complemented with follow up low-resolution optical spectroscopy of photometric candidates on the Hectospec instrument on the 6.5 m MMT, which has provided spectroscopic confirmation of pre-main sequence very low mass stars and young brown dwarfs down to ~ 0.05 $M_{\odot}$ over 6 deg^2 (e.g., Briceño et al. 2005; Downes et al. 2008).

The confirmation of memberships to Orion was performed in terms of spectral features that are good youth indicators such as Hα line in emission, NaII in absorption and LiI in absorption (Downes et al. 2008). The substellar nature of the new members was defined in terms of the spectral types. Objects with spectral types M6 or later have been considered as brown dwarfs. The spectral classification was performed by fitting the equivalent width of several spectral features such as TiO and VO bands with a library of standards, following the scheme of Hernández et al. (2004).

4. RESULTS FROM THE PRELIMINARY ANALYSIS

The sample of stellar and substellar objects spectroscopically confirmed as members of Orion and those that still remain as photometric candidates were studied in terms of the initial mass function, their spatial distribution, the near infrared excesses and the fraction of objects with Classical or Weak T Tauri-like characteristics. These results are summarized as follows:

4.1. *The initial mass function*

From the sample of photometric candidates and computing the contamination of the sample by field stars following the procedure explained in Downes et al. (2011, in prep.) we obtain the initial mass function in several subregions of Orion. Figure 3 shows the resulting initial mass function for the Orion OB1b sub-region. We found no essential differences between the IMF for this dispersed populations and the IMF found in relatively old clusters such as the Pleiades (Lodieu et al. 2007).

4.2. *Spatial distribution*

Figure 4 shows the spatial distribution of brown dwarfs and very low mass star candidates nearby the 25Ori cluster in the Orion OB1a sub-region (Briceño

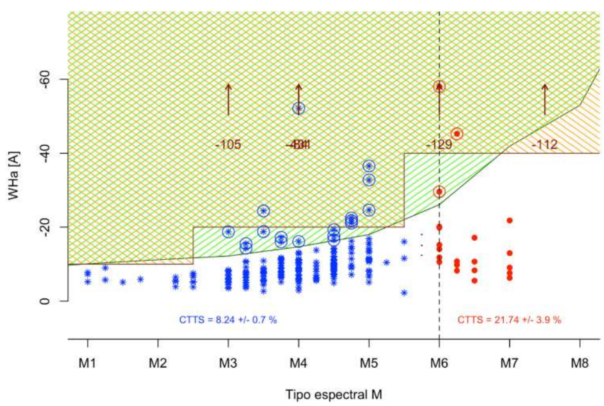

Fig. 5. Equivalent width of Hα line in emission as a function of spectral type. Objects placed above the limit defined by Baraffe et al. (1998) (solid lines) are CTTS.

et al. 2007b). The analysis of the spatial distribution of brown dwarfs and very low mass star shows non significant difference Downes et al. (2011, in prep.).

4.3. *Near infrared excesses, Classical and Weak T Tauri-like characteristics*

Using color-color magnitude diagram we compute the fraction of candidates showing infrared excesses at both sides of the sub-stellar limit. Additionally we measure the fraction of objects showing accretion signatures as we show in Figure 5. The fraction of VLMS with inner disks is ∼11% in OB1b and ∼3% in OB1a. The fraction of BDs with inner disks is ∼25% in OB1b and ∼9% in OB1a. The fraction of VLMS with accretion signatures is ∼8% in OB1b and ∼3% in OB1a. The fraction of BDs with accretion signatures is ∼20% in OB1b and ∼3% in OB1a.

5. CONCLUSIONS

We presented an overview of the last results of a deep photometric and spectroscopic survey for the very low mass and brown dwarf of the dispersed populations of Orion that will be discussed and compare with the predictions from brown dwarf formation models in Downes et al. (2011, in prep.). Summarizing, (*i*) from the spatial distribution of photometric candidates, we found that Orion OB1 extends from $\alpha \sim 79°$ to the east into the molecular clouds. Its western limit is defined by a mean overdensity composed by several small overdensities. We found there is not a global difference in the spatial distribution of BD and VLMS against the suggestions of the models of premature ejection of stellar embrios. (*ii*) The MF for Orion OB1a and OB1b can be described by a power law MF similar to the Pleiades (Lodieu et al. 2007). The later does not support the idea of a strong dependence of MF with the environmental conditions. Robust comparison with other MFs is still difficult due to observational biases. (*iii*) These inner disk fractions in brown dwarfs and its continuous behavior through the substellar limit do not support the ejection scenario. Consistent with observations of other star forming regions (e.g., Luhman et al. 2007). The results suggests that the fraction of inner disks decreases more quickly for BDs than for VLMS at ages between 3 and 7 Myr.

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