Ultra low-mass star and substellar formation in \( \sigma \) Orionis

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Abstract. The nearby young \( \sigma \) Orionis cluster (\( \sim 360 \) pc, \( \sim 3 \) Ma) is becoming one of the most important regions for the study of ultra low-mass star formation and its extension down to the mass regimes of the brown dwarfs and planetary-mass objects. Here, I introduce the \( \sigma \) Orionis cluster and present three studies that the JOVIAN group is developing: a pilot programme of near-infrared adaptive-optics imaging, intermediate-resolution optical spectroscopy of a large sample of stars of the cluster and a study of the mass function down to the planetary-mass domain. This paper is a summary of the content of four posters that I presented in the Ultra low-mass star formation and evolution Workshop, as single author or on behalf of different collaborations.

Key words: stars: low mass, brown dwarfs – stars: formation – Galaxy: open clusters and associations: individual (\( \sigma \) Orionis)

1. The \( \sigma \) Orionis cluster

Known for centuries, the star \( \sigma \) Orionis in the Ori OB1b Association (the Orion Belt), close to the Horsehead Nebula, gives the name to the open cluster that surrounds the star. It is, in reality, a quintuple system (at least) of OB-type stars that injects energy and turbulence into the interstellar medium. Garrison (1967) and Lyngå (1981) were the first authors to recognize the \( \sigma \) Orionis cluster. The existence of a population of low-mass stars has been known since the end of the nineties, when Wolk (1996) and Walter, Wolk & Sherry (1998) discovered an overdensity of X-ray sources in the region. Many studies have been performed there, from the search for strong H\( \alpha \) emitters (Haro & Moreno 1953; Wiramihardja et al. 1989) to the detection of objects below the deuterium burning mass limit (Zapatero Osorio et al. 2000), through the determination of the mass function in the substellar domain (Béjar et al. 2001), photometric variability of brown dwarfs and very-low-mass stars (Scholz & Eislöffel 2004), or the characterization in the mid-infrared of discs of Classical T Tauri stars (Oliveira, Jeffries & van Loon 2004).

The cluster has the most suitable properties for searching and characterizing its rich substellar population: it is young (\( 3^{+5}_{-1} \) Myr; Zapatero Osorio et al. 2002), nearby (\( 360^{+70}_{-60} \) pc; Brown et al. 1994) and has a low reddening (\( A_V < 1 \); Lee 1968). A complete review of the \( \sigma \) Orionis cluster is found in Caballero (2005).

Here I present preliminary results on three studies performed within the JOVIAN Collaboration aimed at shedding light on the substellar formation mechanisms. They are focused on the relationship between the stellar and substellar populations (Sections 2 and 3) and the investigation of the latter down to the planetary-mass domain (Section 4). Further details will be given in forthcoming papers.

2. Adaptive-optics imaging of stellar cluster members

Substellar objects, when companions to stars, are found at distances between \( \sim 50 \) and \( \sim 3 \) 600 AU of the primaries (e.g. Nakajima et al. 1995, Rebolo et al. 1998). While many multiple stellar systems and isolated substellar objects are found in the \( \sigma \) Orionis cluster, no brown dwarf or planetary-mass object has been detected yet at projected physical separations from stellar members at less than about 10 000 AU. Through a pilot programme of near-infrared adaptive-optics (AO) imaging of six stellar cluster members, we have investigated the corona between \( \sim 150 \) and \( \sim 7 \) 000 AU from the primaries.
2.2 Results

The observed stars cover a wide range of spectral types, from O9.5V to K7.0. Their names and spectral types are shown in Table 1. Apart from the AO images, we have used other near infrared, optical (VRI) and X-ray data to derive the real astrophysical nature of the detected visual companions. A total of 22 visual companions to the primary targets have been detected in this pencil-beam survey. Six sources show blue optical-near infrared colours for their magnitudes, and they do not match in any colour–magnitude diagram of the cluster. There is not enough information to derive the nature of other five sources (including a faint object ∼2 arcsec northeast of σ Orionis AB, labelled in Fig. 2). Eleven objects remain as cluster member candidates according to their magnitudes and colours.

- Three of them were previously known cluster members: σ Ori C, σ Ori D (surrounding σ Ori AB) and S Ori J053847.5–022711 (close to [W96] 4771–899).
- We have detected the near-infrared counterpart of the mid-infrared and radio source σ Ori IRS1, a dust cloud next to σ Ori AB discovered by van Loon & Oliveira (2003). We confirm the claim by Sanz Forcada et al. (2004) that it is also an X-ray emitter. The object is detected in Chandra archive images taken with the HRC-I instrument (see Fig. 2).
- One of the HD 37525 companions seem to be the pre-main sequence photometric candidate star P053902–0238, discovered by Wolk (1996).
- Two bright objects are the previously unknown secondaries of the HD 37525 and [W96] 4771–899 close binary systems, at angular separations of 0.45±0.04 and 0.40±0.08 arcsec, respectively.
- The four remaining objects are visual companions to σ Ori AB (1), HD 294271 (2) and HD 37686 (1) at sep-

| Name         | Sp. type     | Notes                  |
|--------------|--------------|------------------------|
| σ Ori AB     | O9.5V+B0.5V  | Multiple, 1 new comp.  |
| HD 294271    | B5V          | 2 new comp.            |
| HD 37525     | B5V          | Double, 1 PMS comp.    |
| HD 37686     | B9Vn         | Dust shell, 1 new comp.|
| HD 37333     | A1Vn         |                        |
| 4771–899     | K7.0         | Triple                 |

Fig. 1. An I vs. I − J colour–magnitude diagram showing most of the cluster members with spectroscopic features of youth (Li I in absorption, strong and asymmetric Hα emission, weak alkali lines, etc.). It covers 21 mag in I-band magnitude or four orders of magnitude in mass, with objects from 20 solar masses to 3 Jupiter masses. Member candidates have been gathered from the literature (e.g. Zapatero Osorio et al. 2002; Kenyon et al. 2005). Dashed horizontal lines denote the hydrogen (top) and deuterium (bottom) burning limits. NextGen and Cond isochrones for 3 Myr, roughly valid in the low-mass stellar and substellar domains, respectively, are also shown in solid lines (Baraffe et al. 1998, 2003). All new objects presented in this paper fall in the cluster sequence.

Fig. 2. NAOMI+INGRID J + H-band image of σ Ori AB and visual companions. Several objects are marked with a circle. North is up, east is to the left. Field of view is 41 × 41 arcsec. σ Orionis IRS1 is 3.3 arcsec to the north-northeast of σ Orionis AB.
3. A bridge between the stellar and the substellar populations

The \( \sigma \) Orionis cluster has become a unique laboratory for understanding the processes that originate brown dwarfs and isolated planetary-mass objects. In order to understand the formation process of substellar objects and the relationship between these and stars, it is necessary to determine first the substellar population of the cluster and its properties (spatial distribution, binary and disc frequency, etc.).

3.1. Photometric survey, target selection and wide-field multifibre spectroscopy

We performed shallow optical observations with the Wide Field Camera (0.333 arcsec pixel\(^{-1}\)) at the 2.5 m Isaac Newton Telescope in 2003 Jan. We observed in \( VRI \) bands more than 1 deg\(^2\) in four different points around the centre of the \( \sigma \) Orionis cluster. We subtracted the bias and divided by their respective flat-field images, and performed aperture and PSF photometry using common tasks within the \textsc{iraf} environment. We pre-selected several hundred sources from different colour–magnitude diagrams with photometric data in the \( VRI \) bands and magnitudes in the range 11 \( \leq I \leq 18 \). \( JHK_s \)-band follow-up photometry, using Two Mass All-Sky Survey data, allowed us to select the list of cluster star and massive brown-dwarf candidates to be observed spectroscopically.

In 2003 Nov, we used the Wide Field Fibre Optical Spectrograph instrument and the robot positioner AutoFib2 (WYFFOS+AF2) at the 4.2 m William Herschel Telescope to obtain about 200 intermediate-resolution (\( R \sim 8\,000 \); nominal resolution of 0.43 \( \text{Å} \) pixel\(^{-1}\)) spectra of sources in the direction of \( \sigma \) Orionis. We covered the wavelength range between 6 400 and 6 800 \( \text{Å} \). The \textsc{dohydra} task was used during the extraction, sky subtraction and wavelength calibration of the spectra.

3.2. Results

We compiled a list of 80 members of the \( \sigma \) Orionis cluster with WYFFOS+AF2 spectroscopy, based on the presence of \( \text{Li} \,\, \lambda\lambda 6707.8, 6717.0 \) in absorption and \( \text{H}\alpha \) in emission (mid- and late-type stars) or spectral type determination (early type).

Fig. 3. Example of ten spectra of cluster members taken with WYFFOS+AF2. The whole \( \lambda \) coverage is shown to the left, while the \( \text{H}\alpha/\text{[N II]} \) and the \( \text{Li} \,\, [\text{S II}] \) regions are shown in the centre and to the right, respectively. Spectral type increases from top (B2V, \( \sigma \) Orionis D) to bottom (intermediate M).

About one half out of the objects are spectroscopically studied here for the first time. Using available data on the members, we have investigated:

- the variation of the strength of the \( \text{Li} \,\, 1 \) with spectral type and with signal–to–noise ratio (from 0.05 \( \text{Å} \) in late F stars to 0.70 \( \text{Å} \) in intermediate M stars);
- the frequency of accretors according to the White & Basri (2003) criterion (46\(+10\,\%\) of K and M stars) and the presence of asymmetries in the profiles of the \( \text{H} \alpha \) line;
- the existence of forbidden lines in emission ([\text{N II}] \( \lambda \lambda 6548.0, 6583.5, [\text{S II}] \,\, \lambda \lambda 6716.4, 6730.8 \));
- the widening of photospheric lines (of up to 100 km s\(^{-1}\));
- the relationship between the \( L' \)– and \( K_s \)–band flux excesses and the spectroscopic features associated with accretion from protoplanetary discs;
- the average of the radial velocity of the cluster members (+30.2 km s\(^{-1}\)), the standard deviation with respect to the mean radial velocity corrected of systematic dispersion (\( \sim 2.4 \) km s\(^{-1}\)) and the existence of radial velocity outliers (probably due to unresolved close companions);
- and the frequency of X-ray emitters catalogued by \textsc{rosat} and \textsc{asca} space observatories as a function of spectral type (the bulk of the K stars are X-ray emitters).

The sample has also allowed us to create a complete database of stellar members of the \( \sigma \) Orionis cluster, necessary for studying the spatial distribution of the member stars and to find the typical distance between these and the substellar objects detected in deep surveys.

4. Mass function down to the planetary-mass domain

The main goal of the JOVIAN Collaboration is to characterize the mass function in the substellar domain and to search for objects that do not burn deuterium and have masses of less...
than 13 Jupiter masses ($M_{\text{Jup}}$), the boundary between brown dwarfs and planetary-mass objects. Our team has performed a new very deep photometric survey in the $IJ$ bands to the southeast of the centre of the $\sigma$ Orionis cluster, covering the whole brown-dwarf and part of the planetary-mass domains.

### 4.1. The $IJ$-band survey and the $HK$-band follow up

We have obtained photometric data using the Wide Field Camera at the 2.5 m Isaac Newton telescope in the $I$ band (2000 Dec) and with the ISAAC spectrograph and camera (0.148 arcsec pixel$^{-1}$) at the Very Large Telescope UT1 in $J$ band (2001 Dec). The overlapping area between the optical and the near infrared images was 790 arcmin$^2$ (there is an overlap of $\sim 80\%$ between this search and that presented in Sect. 3). Completeness and limiting magnitudes in each set of images were 23.4 and 24.0, and 20.6 and 21.8 mag, respectively. We have reduced the images, performed aperture and PSF photometry (using standard IRAF tasks) and searched the optical counterparts of the near-infrared sources. After the magnitude and astrometric calibrations, $I$- and $J$-band magnitudes and equatorial coordinates for about 10,000 sources were available. We selected new cluster member candidates in the $I$ vs. $I-J$ diagram in the same way as in Béjar et al. (2004).

In order to verify that the $IJ$-selected objects had near infrared colours typical of late M and L dwarfs, and to discriminate them from reddened stellar sources or high-redshift galaxies, we used the instruments OMEGA-2000 at the 3.5 m Calar Alto Teleskop and CHFT-IR at the 3.6 m Canada-France-Hawai`i Telescope to perform an $HK$-band follow up.

### 4.2. Results

A total of 39 cluster member candidates in the substellar mass domain have arisen from our deep survey and follow up. They have $I$- and $J$-band magnitudes in the ranges 16.5 to 22.8 and 14.5 to 19.5, respectively. Out of them, 30 objects had been detected in previously published surveys. We have spectroscopic data for 25 objects, most of them showing spectroscopic features common to very young low-mass objects.

We have derived a mass spectrum ($dN/dM \propto M^{-\alpha}$) after computing the mass for each substellar object using the mass-luminosity relation offered by theoretical models of the Lyon group and the relation between $BC_{J}$ bolometric correction and the $I-J$ colours of the field ultracool dwarfs with known parallax. The most probable masses for each object range between 74 and 6 $M_{\text{Jup}}$. Eight out of the 39 cluster member candidates have masses below the deuterium burning mass limit. The slope of the mass spectrum in this mass range is $\alpha \equiv -\gamma = +0.3 \pm 0.2$. The study of the stellar mass spectrum in this area will be presented in Caballero (2005).

### 5. Conclusions

We have gone deeper in the search for objects with masses close to the opacity limit for fragmentation in the nearby young $\sigma$ Orionis cluster and have performed different photometric, both optical and infrared, and spectroscopic studies with the aim of characterizing the cluster stellar and substellar populations and how they are connected.

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