PHYSICAL PROPERTIES OF SUBSTELLAR POPULATION IN THE YOUNG σ ORIONIS CLUSTER

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We review different searches for isolated brown dwarfs and planetary mass objects ($M < 13M_{\rm Jup}$) which we have conducted in the optical and infrared ranges, in the very young (age of 1–8 Myr), nearby ($d \sim 350$ pc) σ Orionis cluster. We describe the main characteristics of this substellar population: spectral properties, effective temperature, spatial distribution, and the presence of discs. We present an initial mass spectrum in the substellar domain.

INTRODUCTION

The separation between stellar and substellar objects is well defined. Substellar objects are those that are unable to sustain the stable hydrogen burning in their interiors. According to evolutionary models, for solar metallicity, this borderline is established in masses lower than $\sim 75\,M_{\rm Jup}$ [1]. They are two main kinds of substellar objects: brown dwarfs and planets, and their distinction is still a question to be discussed. Recently, several authors have proposed to establish the frontier between brown dwarfs and planets at the minimum mass which can sustain the deuterium fusion, so, for solar metallicity, planets are objects with masses below 12–13 $M_{\rm Jup}$ [13] and brown dwarfs are objects with masses in the range from 75 to 13 $M_{\rm Jup}$. In this paper we will follow this criterion.

The σ Orionis cluster is located around a multiple star of the same name, in the south–west part of the Orion belt. This multiple system, composed by an O9.5V, two B0.5V, and two A0 stars, belongs to the well known Orion OB1b association. From the first discoveries of numerous population of very low-mass stars and brown dwarfs [4, 14, 15], the σ Orionis cluster has become a paradigmatic place for the understanding of stellar and substellar forming processes, and we can find stars in the total range of masses from 25 $M_\odot$, brown dwarfs and objects down to a few Jupiter masses. It is one of the most interesting sites to investigate substellar objects because of its youth, proximity, and low extinction. The *Hipparcos* satellite has measured a distance of 350 pc to the central star [12]. The presence of Li in the atmosphere of pre-main sequence stars later than K7 restricts the age of σ Orionis to be younger than 8 Myr, with a most probable age of 2–4 Myr [17]. The cluster also seems to exhibit very little reddening [6, 11].

OPTICAL AND INFRARED SEARCHES FOR SUBSTELLAR MEMBERS IN THE CLUSTER

Our group has performed several studies in order to detect very low-mass stars and brown dwarfs in the cluster. First searches were performed in the RIZ bands, where these cool objects emit most of their light in the optical range. For these searches we used instruments like the CCD-camera on the IAC-80 telescope (Teide Observatory) and the Wide Field Camera (WFC) mosaic on the Isaac Newton Telescope (INT, Roque de los Muchachos Observatory). These surveys covered a total area of about 1 deg^2 reaching an I-band completeness magnitude of 22. From the colour–magnitude diagrams, we selected a sample of more than 200 very low-mass stars and brown dwarf candidates in the I magnitude interval 14–22. According to theoretical evolutionary models, they span the mass range from 0.3 down to 0.013 $M_\odot$, *i.e.*, cover the whole brown dwarf domain. Figure 1 shows a typical I, $R–I$ (top) and I, $I–Z$ (bottom) colour–magnitude diagram, where the selected candidates are indicated by solid circles. Completeness and limiting magnitudes are also shown. We have performed the follow-up infrared photometry of these candidates in order to discriminate between bona fide cluster members and reddened field objects. These studies confirm that the majority of our candidates ($>75\%$) follow the infrared photometric sequence predicted by the models and they seem to be very-low mass stars and brown dwarfs of the cluster.

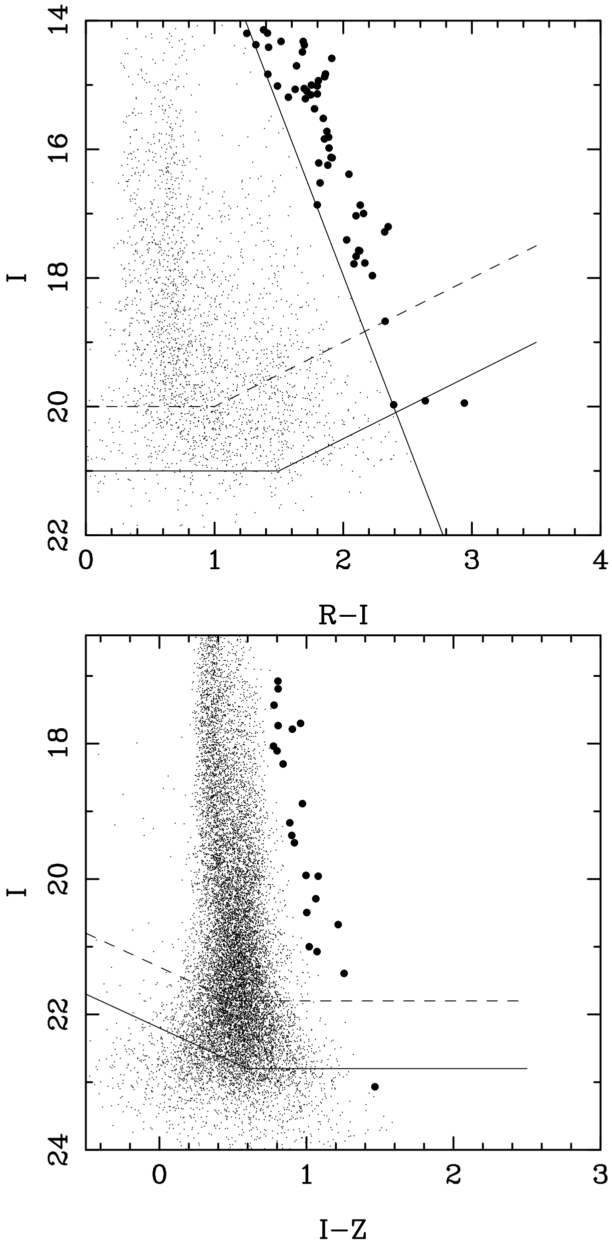

Figure 1. Optical colour–magnitude diagrams: I, R–I (top) and I, I–Z (bottom). Selected candidates are indicated by solid circles. Completeness and limiting magnitudes indicated by dashed and solid lines, respectively, are also shown

In order to detect fainter and less massive objects, we performed deeper surveys in the optical (I-band) and near-infrared (JH bands) regions. From the correlation of these data we have identified more than 15 candidates with J magnitudes fainter than 18, which, according to the models, are planetary mass objects, *i.e.*, $M < 0.013 M_{\odot}$. Figure 2 shows a J, I–J colour–magnitude diagram of the correlation of I-band data obtained with the WFC and J-band data obtained with the ISAAC instrument on the Very Large Telescope (VLT, Paranal Observatory). Bona fide candidates are indicated by solid circles. Open circles represent those candidates that follow the expected spectral sequence of the cluster. The 3 and 10 Myr isochrones from the Lyon group [1, 9] are also shown.

SPECTROSCOPIC CHARACTERIZATION OF SUBSTELLAR OBJECTS

We have obtained low-resolution ($\sim 20\,\text{Å}$) optical spectra in the range 635–920 nm for a sample of 30 brown dwarfs candidates, using spectrographs like ISIS on the William Herschel Telescope (WHT) and LRIS on

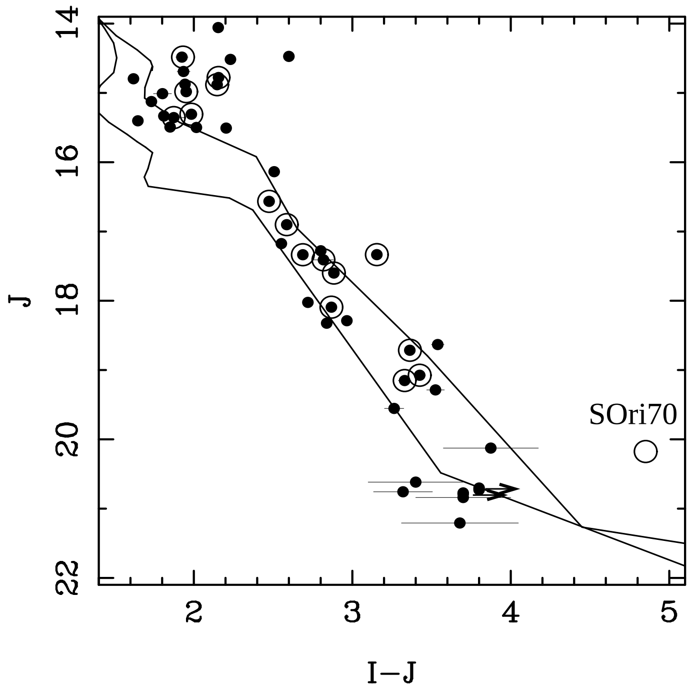

Figure 2. *J vs. I–J* colour–magnitude diagram. Selected candidates are indicated by solid circles. Open circles denotes the candidates with the spectroscopic confirmation. The 3 and 10 Myr isochrones from the Lyon group [1, 9] are also shown

the Keck I telescope. Their spectral types range from M6 to M8.5, showing the typical TiO and VO absorption bands. Their effective temperature ranges from 3000 to 2500 K. These objects also show spectral features suggestive of youth, like strong emission of the Hα and weak alkaline lines [4]. Several of the candidates ($\sim 5\%$) show near infrared excesses that could be associated with the presence of discs [3, 6]. For a few of them, we have obtained the higher resolution spectra, which also shows forbidden lines, thought to be associated with outflow events [8, 17]. Our studies of photometric variability of brown dwarfs in σ Orionis [7] also show that this process can be related with the presence of accretion discs in the similar way as Classical T Tauri stars.

We have also obtained low-resolution optical and infrared spectra for our planetary mass candidates, using LRIS and NIRSPEC spectrographs on the Keck telescope and FORS on the VLT [2, 10, 16]. They have spectral types from M9 to T6, and all except two follow the expected spectral sequence of the cluster. Their effective temperature ranges from 2400 to 1000 K. Our faintest candidate, S Ori 70 (T6) has an estimated mass of only 2–8 $M_{\rm Jup}$ [18]. Figure 3 shows the optical spectra of a typical M and L object of the cluster. Late M spectral types are characterized in the optical range by the presence of strong TiO and VO absorption bands. In L spectral types, these bands disappear and alkaline lines and hidrures become stronger. In the infrared range, the water bands become stronger from M to late L spectral types. T or "methane" objects are characterized by the presence of methane bands in their spectra. The effective temperature of late M dwarfs span from 3000 to 2200 K, L dwarfs are in the range 2200–1500 K, and T dwarfs are between 1500 and 800 K.

THE SPATIAL DISTRIBUTION AND SUBSTELLAR MASS FUNCTION

From the combination of our more extended surveys, we have obtained a census of the substellar population of the σ Orionis cluster. The projected spatial distribution of these objects decay very fast from the centre of the cluster, which is a clear indication of their association with the central multiple star. This distribution can be represented by an exponential law with a characteristic radius of ~ 1 pc.

Using evolutionary models, we have derived the masses of these objects and we have obtained the mass spectrum of the cluster from the low-mass stars ($0.2\,M_\odot$), covering the whole brown dwarf domain ($0.075\,M_\odot$ to $0.013\,M_\odot$). This is shown in Fig. 4. We find that the mass spectrum increases toward lower masses and can be represented by a power-law, $dN/dM \sim M^{-\alpha}$ with an exponent $\alpha = 0.8$. These results indicate that brown dwarfs can be very common, although their contribution to the total mass of the cluster is not significant [5].

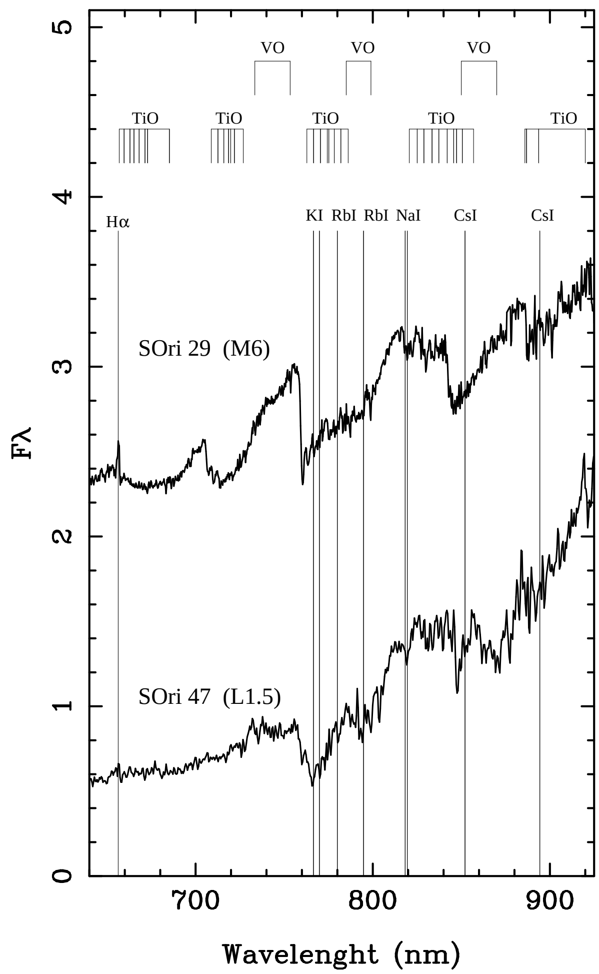

Figure 3. Optical spectra of an M and L object in the σ Orionis cluster. Main spectral features are indicated

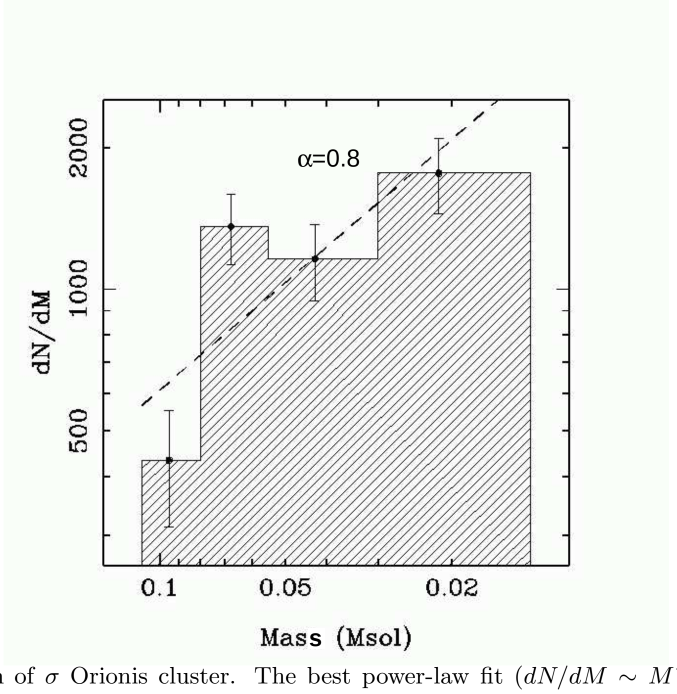

Figure 4. The mass spectrum of σ Orionis cluster. The best power-law fit ($dN/dM \sim M^{-0.8}$) in the brown dwarf domain is also indicated in dashed line. Error bars correspond to Poissonian uncertainties

CONCLUSIONS

We have performed optical and infrared searches to detect a substellar population in the σ Orionis cluster. We have found a numerous population of brown dwarfs and planetary mass objects down to 2–5 $M_{\rm Jup}$. The projected spatial distribution of brown dwarfs can be reproduced by an exponential law with a characteristic radius of $\sim$1 pc. The mass spectrum is an increasing function in the substellar domain ($dN/dM \sim M^{-0.8}$), but the contribution of substellar objects to the total mass of the cluster is less than 10%.

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