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The Substellar Population in σ Orionis

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Abstract. The σ Orionis cluster ($\sim$3 Myr, 350 pc) is an ideal site to investigate the early evolution of substellar (brown dwarf and planetary mass) objects. To date, the cluster photometric and spectroscopic sequence of free-floaters is known for a wide mass range from 1 $M_\odot$ down to roughly 3 $M_{\rm Jup}$. The substellar domain covers spectral types that go from mid-M classes to the recently defined "methane" T-types, i.e., surface temperatures between $\sim$3000 K and 800 K. We derive a rising initial substellar mass function in the mass interval of 150–5 $M_{\rm Jup}$ ($dN/dM \sim M^{-\alpha}$, with $\alpha = 0.9 \pm 0.4$). We also find evidence for a extension of this mass function toward lower masses down to 2–3 $M_{\rm Jup}$. This indicates that the population of isolated planetary mass objects with masses below the deuterium burning threshold is rather abundant in the cluster.

1. Introduction

Our present knowledge on the properties of substellar populations has experienced a substantial progress in recent years. Nearby star-forming regions have provided the largest contribution to the census of young brown dwarfs known today. The star cluster σ Orionis (Lyngå 1987; Walter et al. 1997) is particularly interesting because it reunites ideal conditions to study the early evolution of the least massive cluster members: youth ($\sim$3 Myr, Oliveira et al. 2002; Zapatero Osorio et al. 2002a), proximity (352 pc, Perryman et al. 1997), and richness. In addition, and besides its very young age, the σ Orionis cluster is unobscured

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by gas and dust (Brown et al. 1994), which assists the direct detection of the smallest and least luminous objects.

A considerable population of free-floating young brown dwarfs and planetary mass objects (with masses below the deuterium burning limit at around 13 $M_{\rm Jup}$, Saumon et al. 1996) is now identified in the σ Orionis cluster. Various photometric and spectroscopic searches, both at optical and near-infrared wavelengths, have led to the investigation and (partial) understanding of the individual and collective properties of these substellar objects. As shown in Béjar et al. (2001), the cluster brown dwarf mass function rises toward lower masses. Here, we present a possible extension of the σ Orionis substellar mass function into the planetary domain down to roughly 2–3 $M_{\rm Jup}$.

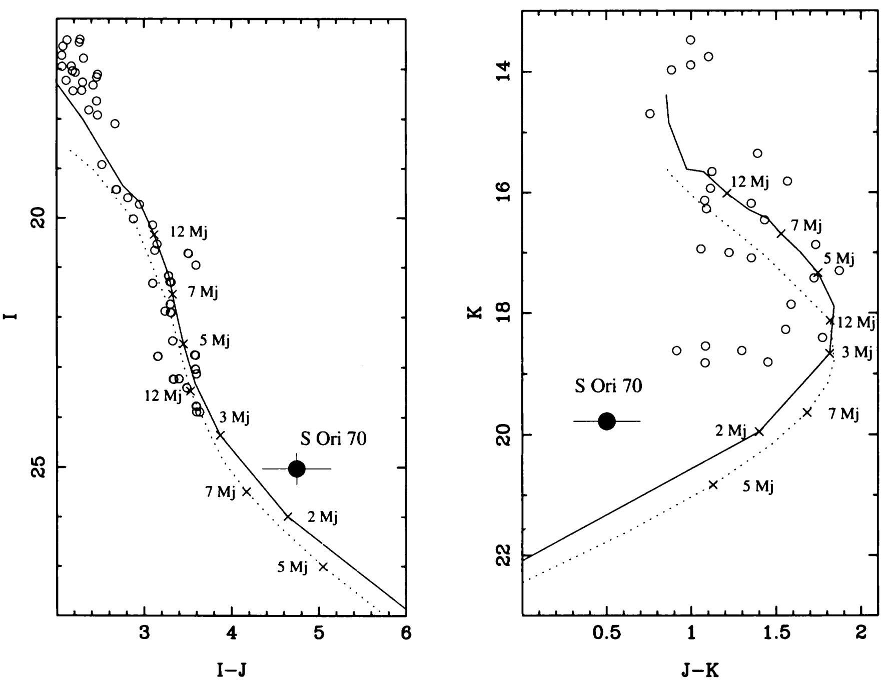

Figure 1. Substellar photometric sequence of the σ Orionis cluster. S Ori 70 extrapolates the optical and near-infrared sequence defined by more massive cluster members. Theoretical evolutionary models for 1 Myr (solid line) and 10 Myr (dotted line) are overplotted onto the data (Baraffe et al. 2002), and Jovian masses are also provided.

2. Photometric and spectral sequence of the cluster

Since Walter et al. (1997) reported on the discovery of a rich clustering of young, low mass, X-ray sources in the vicinity of the massive star σ Orionis, we have been conducting deep CCD-based surveys in this region with the goal of identifying its substellar population. Our earliest photometric exploration covered a central area of 847 arcmin^2 (Béjar et al. 1999; Zapatero Osorio et al. 2000) using optical (RIZ) and near-infrared (JK) filters. We found a large number of free-floating substellar candidate members with masses ranging from the star–brown dwarf borderline well down into the planetary regime. Follow-up optical and near-infrared spectroscopy (Martín et al. 2001a; Barrado y Navascués et al. 2001, 2002a; Béjar et al. 1999; Zapatero Osorio et al. 1999, 2000) confirms that a great majority ($\geq$70%) of the candidates are very likely members of the cluster. Figures 1 and 2 summarizes the present locus of the substellar photometric and spectroscopic sequence of σ Orionis. Note that the actual spectral sequence of cluster brown dwarfs and planetary mass objects goes from mid-M classes to mid-T types, i.e., effective temperatures in the range 3000–800 K (next Section).

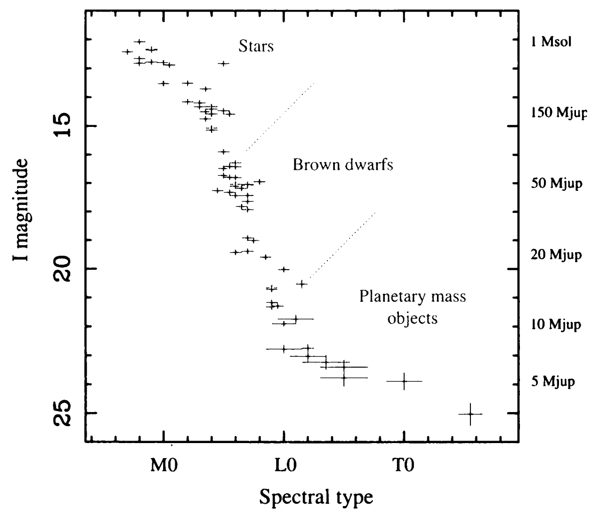

Figure 2. I magnitude against spectral type for σ Orionis members. All spectral classes have been derived from optical data, except for the two coolest objects (T-classes), for which we have used near-infrared spectra. Masses for an age of 3 Myr are also tabulated.

As in the field (see, e.g., Burgasser et al. 2002a), the colors and spectra of cool (later than spectral type M7), young substellar objects are characterized by the presence of condensates in the atmospheres. Near-infrared colors (Fig. 1, right panel) continue to redden to a limit at $J-K \sim 1.8$ mag and $I-K \sim 5$ mag (spectral types ranging from late-M to ~L3), and subsequently turn blueward at the faintest end of the cluster sequence (late-L and T classes, Martín et al. 2001a). This feature may be due to the gravitational settling of the dust grains at the bottom of the photosphere. The surface gravity of young ultra-cool ($\geq$L0) substellar objects of σ Orionis is, according to evolutionary models, one order of magnitude smaller than that of field spectral counterparts. This may influence the formation of condensates and their gravitational sedimentation, and indeed has effects in the output energy distributions (spectra and photometric colors): weaker atomic lines of alkalis, weaker molecular absorptions of CO and methane, and stronger absorptions of water vapor in the infrared (Allard et al. 2001).

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Because the optical and near-infrared spectra of late-L and T-class objects are governed by these features, gravity turns out to be a good indicator of youth.

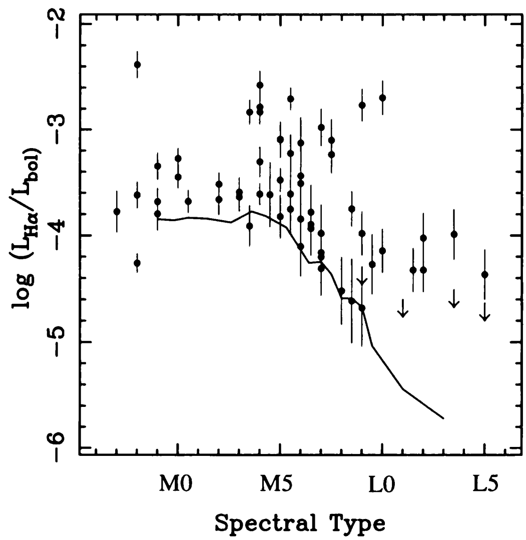

Figure 3. Ratio of Hα luminosity of the object to its bolometric luminosity as a function of spectral type. σ Orionis members are plotted with filled circles (arrows denote upper limits). For comparison, we have also indicated the averaged locus of field objects (solid line). At the age of the cluster, the star–brown dwarf borderline lies at spectral type M5, and the brown dwarf–planetary-mass frontier at around M9.

Many cool brown dwarfs and planetary mass objects of the σ Orionis cluster show Hα in emission (Béjar et al. 1999; Barrado y Navascués et al. 2001, 2002b; Zapatero Osorio et al. 2002b), as opposed to the majority of the field objects with similar spectral classes. Figure 3 illustrates the distribution of Hα luminosity over bolometric luminosity with spectral type for low mass stellar and substellar cluster members. Activity clearly decays in the substellar regime, which may indicate the presence of weaker magnetic fields. Among the cluster brown dwarfs, two of them stand out because of their very intense Hα emission: S Ori 55, M9, pseudo-equivalent width of ~400 Å (Zapatero Osorio et al. 2002b), and S Ori 71, L0, pseudo-equivalent width of ~705 Å (Barrado y Navascués et al. 2002b). The former object has a variable Hα emission, while the late one shows an asymmetric, broad line. The origin of such strong emissions is unknown. These objects might simply have undergone a chromospheric flare due to magnetic activity. Or they could be very close binaries undergoing some matter transfer. Another possibility is that the Hα emission has its origin in the object formation processes, i.e., accretion from disks surrounding the brown dwarfs. Oliveira et al. (2002), Jayawardhana et al. (these proceedings), and Zapatero Osorio et al. (2002a) argue that 6–30% of the σ Orionis low-mass stars could harbor disks based on infrared flux excesses and the presence of forbidden emission lines in optical spectra. Recently, both disk accretion and presence of thermal dust emission from a disk around young substellar objects have been reported by various groups (Muench et al. 2001; Muzerolle et al. 2000; Martín et al. 2001b; Apai et al. 2002), which may suggest that "circumstellar" disks are common among very young brown dwarfs.

3. A methane planetary mass object in the cluster

Very recently, we have explored an area of 55.4 arcmin^2 in the σ Orionis cluster using a near-infrared camera attached to the 4.2-m William Herschel Telescope. J- and H-band images (detection limit at 21 mag) were collected on November 2000, and were correlated with previous I- and Z-band data, which were taken with LRIS at the 10-m Keck II telescope on December 1998. Among various photometric candidates for possible membership in σ Orionis, one showed a rather blue $J-H$ color, in contrast to its very red $I-Z$ and $I-J$ colors. We have named it as S Ori 70 (Zapatero Osorio et al. 2002c). Table 1 provides its photometry and other important measurements. K_s-band data and HK low-resolution spectroscopy were collected with NIRC at the 10-m Keck I telescope in December 2001. Figures 1 and 4 (left panel) illustrate color-magnitude diagrams and the final smoothed HK-band spectrum of S Ori 70.

Table 1. Data of S Ori 70.

J	$J-H$	$J-K_s$	$I-J$	$T_{\rm eff}$ (K)	$\log g$ ($\mathrm{cm\,s^{-2}}$)	Mass ($M_{\rm Jup}$)
20.28±0.10	−0.14±0.15	0.50±0.20	4.75±0.40	700–1000	4.0±1.0	2–8

S Ori 70 presents broad strong absorption features that we safely identify as water vapor and methane bands. This object belongs to the recently defined "methane" spectral class T (Burgasser et al. 2002b; Geballe et al. 2002). Using water and methane molecular indices, we assign a spectral type of T5.5 $\pm$ 1.0 to S Ori 70. Its photometric colors also fall within the range of measurements for field T dwarfs. Based on the findings of the all-sky surveys 2MASS (Burgasser et al. 2002a) and SDSS (Geballe et al. 2002; Leggett et al. 2002), on the ESO public deep IJK images (D'Antona et al. 1999), and on the recent determination of the field mass function by Chabrier (2002), we estimate that 0.08–0.3 field, "old" T-class objects may be contaminating our survey.

We have compared our NIRC spectrum of S Ori 70 to a set of synthetic spectra provided by Allard et al. (2001) to determine the object's surface temperature and gravity. The models treat dust as if condensed in deep layers of the photosphere (Tsuji et al. 1999; Allard et al. 2001; Burrows et al. 2000). A least square minimization technique yields that the best fits are $T_{\rm eff} = 800\,^{+200}_{-100}$ K and $\log g = 4.0 \pm 1.0$ ($\mathrm{cm\,s^{-2}}$). For comparison, the same technique applied to the spectrum (Fig. 4) of the field T6V-class brown dwarf 2MASSI J0243137–245329 (Burgasser et al. 2002) gives $T_{\rm eff} = 950 \pm 50$ K and $\log g = 5.0 \pm 0.5$ ($\mathrm{cm\,s^{-2}}$), in perfect agreement with the values found for the well-known T6V field brown dwarf Gl 229B (Marley et al. 1996). The lower gravity of S Ori 70 and its pho-

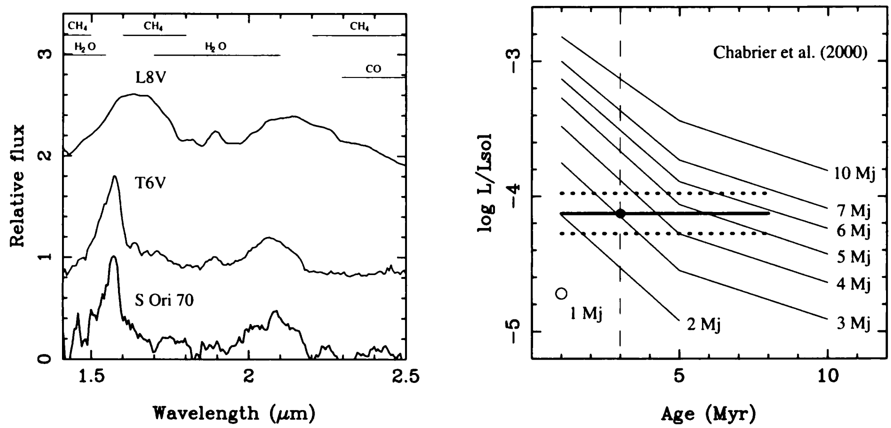

Figure 4. *Left panel:* NIRC spectrum of S Ori 70. Two field brown dwarfs (observed on the same night) with known spectral types are also included. *Right panel:* Mass estimation for S Ori 70 using the evolutionary models of Chabrier et al. (2000). The most likely cluster age is estimated at 3 Myr (vertical dashed line). The short-dashed lines indicate the error in luminosity.

tometry support this object's possible membership in the σ Orionis cluster. Its mass can be inferred by comparison with state-of-the-art evolutionary models, as shown in Fig. 4 (right panel). We estimate it to be at $3^{+5}_{-1}\,M_{\rm Jup}$ for the cluster age range of 2–8 Myr. Uncertainties also include differences between models (Burrows et al. 1997; Chabrier et al. 2000), and the errors in luminosity. In relative terms, if S Ori 70 is a member of the σ Orionis cluster, it is the least massive object so far identified in isolation beyond our solar system.

4. Substellar mass function

Optical and near-infrared photometry and spectroscopy have allowed us to assess the cluster membership of a quite significant number of substellar candidates. We have computed the brown dwarf and planetary mass initial mass function (IMF) of σ Orionis considering objects whose photometry and spectroscopy confirm them as very likely cluster members. One of the most relevant questions regarding the IMF is the minimum mass for the formation of very low mass objects in isolation, which would represent the bottom end of the IMF for free-floaters. So far, the best constraints are given by the σ Orionis cluster, since its substellar population is known to some detail and spans over a considerable mass range. Furthermore, σ Orionis is probably the youngest nearby cluster with very little internal reddening, which permits a relatively easy direct detection of the least massive cluster objects and the determination of their individual masses with no additional difficulties.

We have adopted a cluster age of 3 Myr (Zapatero Osorio et al. 2002a) and the mass-luminosity relationship of Baraffe et al. (2002) to obtain the σ Orionis IMF depicted in Fig. 5. A total of 66 confirmed cluster members lying within

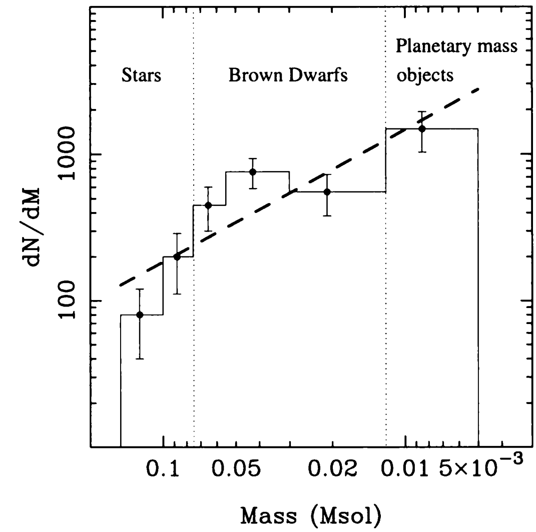

Figure 5. σ Orionis substellar mass function from very low mass stars down to about $5\,M_{\rm Jup}$ ($\sim 0.005\,M_\odot$). We have adopted a cluster age of 3 Myr, and the state-of-the-art mass-luminosity relationship of Baraffe et al. (2002). The power-law fit $dN/dM \sim M^{-\alpha}$, with $\alpha = 0.9 \pm 0.4$, is plotted as a dashed line. Error bars attend to Poisson statistics.

a central area of 847 $\rm arcmin^2$ account for this IMF (see Béjar et al. 2001). We remark that it is complete between $150\,M_{\rm Jup}$ and the deuterium burning mass limit, i.e., all over the entire brown dwarf domain. In addition, the planetary mass bin between $13\,M_{\rm Jup}$ and $5\,M_{\rm Jup}$ (which is already free from field contaminants, Barrado et al. 2001; Martín et al. 2001a) appears rather well populated. A reasonable representation of the cluster substellar IMF is facilitated by a single power-law with a slope of $\alpha = 0.9, \pm 0.4$ ($dN/dM \sim M^{-\alpha}$) in the mass range from very low mass stars ($150\,M_{\rm Jup}$) to planetary mass objects with $5\,M_{\rm Jup}$.

Despite the dubious reliability based on a single object, the finding of S Ori 70 ($3^{+5}_{-1}\,M_{\rm Jup}$) in a very small survey is consistent with a natural extension of the σ Orionis IMF toward very low masses that may still continue with a similar slope. Free-floating brown dwarfs and planetary mass objects are abundant in σ Orionis (they may outnumber stars in the cluster). From our investigations, we find very little evidence for a "bottom end" of the IMF in the mass interval covered by our analysis, i.e., no obvious deficit of objects beyond the deuterium burning mass limit. However, their formation process is not yet established, and presently, the investigation of their origin is one of the most exciting topics in modern Astrophysics.

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