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THE SUBSTELLAR MASS FUNCTION IN σ ORIONIS

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ABSTRACT

We combine results from imaging searches for substellar objects in the σ Orionis cluster and follow-up photometric and spectroscopic observations to derive a census of the brown dwarf population in a region of 847 arcmin^2. We identify 64 very low mass cluster member candidates in this region. We have available three-color (I, Z, and J) photometry for all of them, spectra for 24 objects, and K photometry for 27% of our sample. These data provide a well-defined sequence in the I versus $I-J$ and I versus $I-K$ color-magnitude diagrams and indicate that the cluster exhibits little reddening despite its young age ($\sim$5 Myr). Using state-of-the-art evolutionary models, we derive a mass function from the low-mass stars (0.2 $M_\odot$) across the complete brown dwarf domain (0.075 to 0.013 $M_\odot$) and into the realm of free-floating planetary-mass objects ($\leq$0.013 $M_\odot$). We find that the mass spectrum $(dN/dm) \propto m^{-\alpha}$ increases toward lower masses, with an exponent $\alpha = 0.8 \pm 0.4$. Our results suggest that planetary-mass isolated objects could be as common as brown dwarfs; both kinds of objects together would be as numerous as stars in the cluster. If the distribution of stellar and substellar masses in σ Orionis is representative of the Galactic disk, older and much lower luminosity free-floating planetary-mass objects with masses down to about 0.005 $M_\odot$ should be abundant in the solar vicinity, with a density similar to M-type stars.

Subject headings: open clusters and associations: individual (σ Orionis) — stars: low-mass, brown dwarfs — stars: luminosity function, mass function — stars: pre–main-sequence

1. INTRODUCTION

Although there is no definitive theory to explain the formation processes of stars, the widely accepted scenario is that they form via fragmentation of rotating interstellar molecular clouds followed by gravitational collapse. However, given the typical conditions and properties of Galactic molecular clouds, this simple paradigm has difficulties (Bodenheimer 1998) explaining the genesis of numerous populations of substellar objects ($M < 0.075\ M_\odot$). Several arguments have also been proposed against the formation of objects below the substellar borderline (Silk 1995) or below the deuterium-burning mass limit (Shu, Adams, & Lizano 1987), which, according to Saumon et al. (1996) and Burrows et al. (1997), is located in the range 0.013–0.011 $M_\odot$ ($\sim$14–12 $M_{\rm Jup}$, where 1 $M_\odot$ = 1047 $M_{\rm Jup}$). The overall distribution of masses for individual objects resulting from star-forming processes can be described by the mass function (MF), defined as the number of objects per interval of mass on a logarithmic scale, $\xi(m) = dN/d\log m$, or, alternatively, by the mass spectrum, defined as $\phi(m) = dN/dm$. The MF was first studied for the stellar regime by Salpeter (1955), who found that a power-law relation of the type $\xi(m) \propto M^{-\gamma}$, with an index $\gamma = 1.35$, which corresponds to $dN/dm \propto m^{-\alpha}$ with $\alpha = 2.35$ for the mass spectrum, was adequate in the mass range 1–10 $M_\odot$. Subsequent studies of the field MF appear to demand lower values of α at smaller masses or even to suggest alternative functional forms (Miller & Scalo 1979). A recent study of the very low mass MF based on DENIS and 2MASS discoveries of nearby ultracool dwarfs suggests a value of α in the range 1 to 2 (Reid et al. 1999). A deep survey for methane dwarfs suggests, however, that $\alpha \leq 0.8$ for disk brown dwarfs (Herbst et al. 1999).

Early searches for brown dwarfs in stellar clusters and associations (see, e.g., Rieke & Rieke 1990; Stauffer, Hamilton, & Probst 1994; Jameson & Skillen 1989) and the subsequent confirmation of their existence (Rebolo, Zapatero Osorio, & Martín 1995; Basri, Marcy, & Graham 1996; Rebolo et al. 1996) prompted the questions, among others, of the nature of the behavior of the MF in the brown dwarf domain and of whether the fragmentation process can extend beyond the deuterium-burning mass limit. Several studies in very young clusters have provided partial answers to these questions (Bouvier et al. 1998; Luhman & Rieke 1999; Luhman et al. 1998, 2000; Barrado y Navascués et al. 2001a; Tamura et al. 1998; Lucas & Roche 2000; Hillenbrand & Carpenter 2000; Najita, Tiede, & Carr 2000; Martín et al. 2000; Moraux, Bouvier, & Stauffer 2001). In spite of considerable progress in recent years, the incompleteness of the photometric surveys at very low masses and the lack of a well-defined spectroscopic sequence have prevented a reliable description of the MF over the whole brown dwarf regime. Here we present a determination of the MF for the σ Orionis young stellar cluster that is reliable and complete down to the deuterium-

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burning mass limit and a first estimate of how this MF extends to smaller masses, i.e., to the planetary regime.

2. AGE, DISTANCE, AND EXTINCTION IN THE σ ORIONIS CLUSTER

The σ Orionis cluster belongs to the Orion OB 1b association, for which an age of 1.7–7 Myr and a distance modulus of 7.8–8.3 are estimated, based on studies of massive stars (Blaauw 1964, 1991; Warren & Hesser 1978; Brown, de Geus, & de Zeeuw 1994). The spectral type of the central star of the same name is O9.5 V. In order to account for the location of this star in the hydrogen-burning phase, its age must be younger than 5 Myr (on the basis of models with winds from Meynet et al. 1994). Recent investigations of the low-mass stellar and brown dwarf cluster populations have confirmed that σ Orionis indeed has a very young age, in the interval 1–5 Myr (Béjar, Zapatero Osorio, & Rebolo 1999, hereafter BZOR; Wolk & Walter 2000), which is consistent with the estimates found for the massive stars. The inferred MF in σ Orionis may be very close to the true initial mass function (IMF), because no significant dynamical evolution is expected for cluster members. In addition, the distance to the cluster is known through the determination provided by *Hipparcos* of the distance modulus $m-M = 7.7 \pm 0.7$ (value given for the central star). This measurement is in agreement with previous distance determinations of the OB 1b subgroup. The σ Orionis star is affected by a low extinction of $E(B-V) = 0.05$ (Lee 1968); thus, the associated cluster is expected to exhibit very little reddening. From the comparison of the colors of some of the σ Orionis objects with counterparts of the same spectral type in the Pleiades and the field, BZOR did not find any significant reddening. In addition, the location of a larger sample of objects in the $I-J$ versus $J-K$ color-color diagram shows that their infrared excess $E(I-J)$ is smaller than 0.3 mag (i.e., $A_V \leq 1$ mag, on the basis of the relationships given in Rieke & Lebofski 1985). All these properties of youth, proximity, and low extinction confirm this cluster as a very interesting site for investigating the IMF.

3. SURVEYS AND MEMBERSHIP SELECTION CRITERION

In order to construct the brown dwarf MF in the σ Orionis cluster we have combined optical (IZ) and near-infrared (J) surveys recently conducted around the central star (Zapatero Osorio et al. 2000; BZOR; Béjar 2000). New observations in the optical range were obtained with the Wide Field Camera instrument mounted on the primary focus of the 2.5 m Isaac Newton Telescope at the Roque de los Muchachos Observatory on 1998 November 12–13 (Béjar 2000). Images were bias-subtracted and flat-fielded within the IRAF[8] environment. Instrumental magnitudes were transformed into observed magnitudes by differential photometry of objects in common with images taken under photometric conditions with the IAC80 telescope (Teide Observatory), which were calibrated in the Cousins system by observing Landolt's (1992) standard stars at different air masses. Near-infrared photometry in the J band has been acquired with the 3.5 m telescope at the Calar Alto Observatory on 1998 October 27–31 (Zapatero Osorio et al. 2000). In addition, K-band photometry has been obtained on individual candidates with the 1.5 m Carlos Sánchez

[8] IRAF is distributed by National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

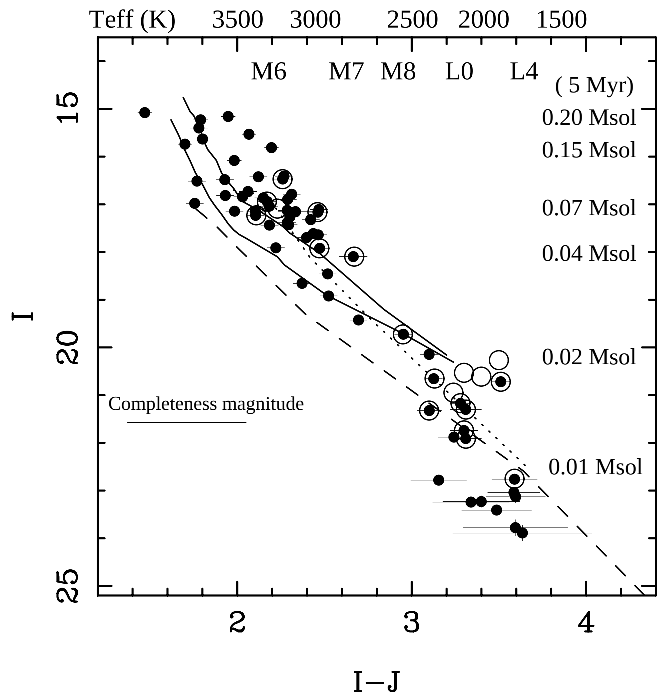

FIG. 1.—I vs. $I-J$ color-magnitude diagram for the σ Orionis cluster. Selected candidates are indicated with filled circles. The 5 Myr isochrones from the Lyon group (*solid line*, Nextgen models; *dashed line*, Dusty models) and from the Arizona group (*dotted line*) and the 10 Myr Nextgen isochrone (*solid line*, *bluer than the 5 Myr line*) are also shown for comparison. Open circles around filled circles denote candidates with available spectroscopy confirming their membership. Other open circles are for members with spectroscopy but located outside of the 847 arcmin^2 area and thus not included in the MF computation. Error bars are based on photometric uncertainties and are smaller than symbol size for the majority of the brightest objects. Completeness magnitude, spectral type, and estimated temperatures and masses for the age of 5 Myr are also shown.

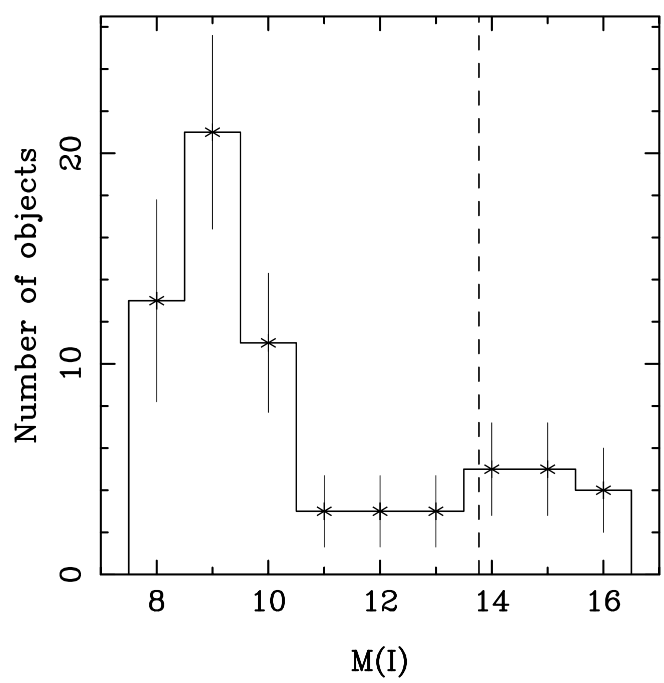

FIG. 2.—I-band luminosity function in the σ Orionis cluster. The dashed line indicates the completeness limit of our search. Error bars corresponding to Poissonian uncertainties are also shown.

TABLE 1

PHOTOMETRIC DATA OF THE SELECTED CANDIDATES

Name (IAU)	Previous ID	I	$R-I$	$I-J$	$I-K$	R.A. (J2000)	Decl. (J2000)
S Ori J053911.7−022741......	S Ori 1	15.08 ± 0.04	1.70 ± 0.07	1.47 ± 0.04	...	05 39 11.7	−02 27 41
S Ori J053920.8−023035......	S Ori 3	15.16 ± 0.04	2.15 ± 0.07	1.95 ± 0.04	...	05 39 20.8	−02 30 35
S Ori J053939.2−023227......	S Ori 4	15.23 ± 0.04	2.16 ± 0.07	1.79 ± 0.04	...	05 39 39.2	−02 32 27
S Ori J053920.1−023826......	S Ori 5	15.40 ± 0.05	1.86 ± 0.07	1.78 ± 0.05	...	05 39 20.1	−02 38 26
S Ori J053847.5−023038......	S Ori 6	15.53 ± 0.04	2.00 ± 0.07	2.07 ± 0.04	...	05 38 47.5	−02 30 38
S Ori J053908.1−023230......	S Ori 7	15.63 ± 0.04	2.07 ± 0.07	1.80 ± 0.04	...	05 39 08.1	−02 32 30
S Ori J053907.9−022848......	S Ori 8	15.74 ± 0.04	1.87 ± 0.07	1.70 ± 0.04	...	05 39 07.9	−02 28 48
S Ori J053817.1−022228......	S Ori 9	15.81 ± 0.04	2.06 ± 0.07	2.20 ± 0.04	...	05 38 17.1	−02 22 28
S Ori J053944.4−022445......	S Ori 10	16.08 ± 0.04	1.97 ± 0.07	1.98 ± 0.04	...	05 39 44.4	−02 24 45
S Ori J053944.3−023301......	S Ori 11	16.424 ± 0.008	1.94 ± 0.06	2.12 ± 0.05	...	05 39 44.3	−02 33 01
S Ori J053757.4−023845......	S Ori 12	16.471 ± 0.010	1.75 ± 0.05	2.26 ± 0.05	...	05 37 57.4	−02 38 45
S Ori J053813.1−022410......	S Ori 13	16.410 ± 0.018	1.93 ± 0.06	2.27 ± 0.05	...	05 38 13.1	−02 24 10
S Ori J053909.9−022814......	...	16.485 ± 0.012	...	1.93 ± 0.05	...	05 39 09.9	−02 28 14
S Ori J053746.6−024328......	...	16.514 ± 0.003	...	1.77 ± 0.05	...	05 37 46.6	−02 43 28
S Ori J053911.4−023333......	...	16.731 ± 0.011	...	2.06 ± 0.05	...	05 39 11.4	−02 33 33
S Ori J053848.0−022854......	S Ori 15	16.789 ± 0.014	1.81 ± 0.07	2.31 ± 0.05	3.31 ± 0.06	05 38 48.0	−02 28 54
S Ori J053849.2−022358......	...	16.813 ± 0.017	...	1.93 ± 0.05	...	05 38 49.2	−02 23 58
S Ori J053915.0−024048......	S Ori 16	16.843 ± 0.008	1.91 ± 0.06	2.03 ± 0.05	...	05 39 15.0	−02 40 48
S Ori J053721.0−022543......	S Ori 19	16.867 ± 0.008	2.06 ± 0.06	2.15 ± 0.05	...	05 37 21.0	−02 25 43
S Ori J053825.6−023122......	S Ori 18	16.896 ± 0.014	2.02 ± 0.07	2.29 ± 0.05	...	05 38 25.6	−02 31 22
S Ori J053904.4−023835......	S Ori 17	16.945 ± 0.009	1.88 ± 0.06	2.17 ± 0.05	...	05 39 04.4	−02 38 35
S Ori J053923.3−024657......	S Ori 28	16.979 ± 0.008	2.29 ± 0.08	1.76 ± 0.05	...	05 39 23.3	−02 46 57
S Ori J053829.0−024847......	...	17.040 ± 0.010	...	2.18 ± 0.05	3.09 ± 0.03	05 38 29.0	−02 48 47
S Ori J053835.2−022524......	S Ori 22	17.109 ± 0.008	2.11 ± 0.07	2.47 ± 0.05	...	05 38 35.2	−02 25 24
S Ori J053751.0−022610......	S Ori 23	17.128 ± 0.009	2.10 ± 0.06	2.29 ± 0.05	...	05 37 51.0	−02 26 10
S Ori J053755.6−022434......	S Ori 24	17.144 ± 0.009	2.01 ± 0.06	2.10 ± 0.05	...	05 37 55.6	−02 24 34
S Ori J053943.7−024729......	S Ori 32	17.144 ± 0.007	2.26 ± 0.07	1.98 ± 0.05	...	05 39 43.7	−02 47 29
S Ori J053934.2−023847......	S Ori 21	17.154 ± 0.007	1.91 ± 0.08	2.33 ± 0.10	...	05 39 34.2	−02 38 47
S Ori J053908.8−023958......	S Ori 25	17.163 ± 0.008	2.17 ± 0.10	2.46 ± 0.05	...	05 39 08.8	−02 39 58
S Ori J053829.5−022517......	S Ori 29	17.230 ± 0.008	1.98 ± 0.07	2.11 ± 0.05	...	05 38 29.5	−02 25 17
S Ori J053916.6−023827......	S Ori 26	17.264 ± 0.008	1.83 ± 0.08	2.30 ± 0.05	...	05 39 16.6	−02 38 27
S Ori J053907.4−022908......	S Ori 20	17.321 ± 0.009	1.68 ± 0.07	2.42 ± 0.05	...	05 39 07.4	−02 29 08
S Ori J053657.9−023522......	S Ori 33	17.385 ± 0.008	2.28 ± 0.06	2.29 ± 0.05	...	05 36 57.9	−02 35 22
S Ori J053820.9−024613......	S Ori 31	17.429 ± 0.008	2.03 ± 0.05	2.29 ± 0.05	...	05 38 20.9	−02 46 13
S Ori J053913.0−023751......	S Ori 30	17.438 ± 0.008	1.71 ± 0.08	2.19 ± 0.05	...	05 39 13.0	−02 37 51
S Ori J053755.5−023308......	S Ori 35	17.612 ± 0.008	2.25 ± 0.06	2.44 ± 0.05	...	05 37 55.5	−02 33 08
S Ori J053915.1−022152......	S Ori 38	17.640 ± 0.008	2.19 ± 0.09	2.46 ± 0.05	...	05 39 15.1	−02 21 52
S Ori J053821.3−023336......	...	17.697 ± 0.013	...	2.40 ± 0.05	...	05 38 21.3	−02 33 36
S Ori J053926.8−023656......	S Ori 36	17.911 ± 0.008	1.94 ± 0.14	2.22 ± 0.05	...	05 39 26.8	−02 36 56
S Ori J053832.4−022958......	S Ori 39	17.922 ± 0.008	2.24 ± 0.10	2.47 ± 0.05	3.18 ± 0.07	05 38 32.4	−02 29 58
S Ori J053736.4−024157......	S Ori 40	18.095 ± 0.009	2.18 ± 0.05	2.67 ± 0.08	...	05 37 36.4	−02 41 57
S Ori J053936.4−023626......	...	18.459 ± 0.017	...	2.52 ± 0.05	...	05 39 36.4	−02 36 26
S Ori J053926.8−022614......	...	18.657 ± 0.008	...	2.37 ± 0.05	...	05 39 26.8	−02 26 14
S Ori J053948.1−022914......	...	18.921 ± 0.009	...	2.52 ± 0.05	...	05 39 48.1	−02 29 14
S Ori J053912.8−022453......	...	19.425 ± 0.008	...	2.69 ± 0.05	4.09 ± 0.10	05 39 12.8	−02 24 53
S Ori J053825.6−024836......	S Ori 45	19.724 ± 0.009	2.75 ± 0.017	2.95 ± 0.05	4.07 ± 0.09	05 38 25.6	−02 48 36
S Ori J053946.5−022423......	...	20.144 ± 0.010	...	3.10 ± 0.05	4.21 ± 0.16	05 39 46.5	−02 24 23
S Ori J053910.8−023715......	S Ori 50	20.656 ± 0.015	...	3.13 ± 0.05	4.48 ± 0.05	05 39 10.8	−02 37 15
S Ori J053903.2−023020......	S Ori 51	20.72 ± 0.014	...	3.51 ± 0.05	4.58 ± 0.10	05 39 03.2	−02 30 20
S Ori J053825.1−024802......	S Ori 53	21.172 ± 0.023	...	3.28 ± 0.06	4.72 ± 0.09	05 38 25.1	−02 48 02
S Ori J053833.3−022100......	S Ori 54	21.30 ± 0.05	...	3.31 ± 0.09	4.35 ± 0.10	05 38 33.3	−02 21 00
S Ori J053725.9−023432......	S Ori 55	21.32 ± 0.03	...	3.10 ± 0.07	4.32 ± 0.10	05 37 25.9	−02 34 32
S Ori J053900.9−022142......	S Ori 56	21.74 ± 0.03	...	3.30 ± 0.08	4.65 ± 0.10	05 39 00.9	−02 21 42
S Ori J053947.0−022525......	S Ori 57	21.88 ± 0.03	...	3.24 ± 0.09	...	05 39 47.0	−02 25 25
S Ori J053903.6−022536......	S Ori 58	21.91 ± 0.03	...	3.31 ± 0.09	5.03 ± 0.20	05 39 03.6	−02 25 36
S Ori J053937.5−023042......	S Ori 60	22.76 ± 0.05	...	3.59 ± 0.13	5.07 ± 0.10	05 39 37.5	−02 30 42
S Ori J053852.6−022846......	S Ori 61	22.78 ± 0.05	...	3.16 ± 0.16	...	05 38 52.6	−02 30 46
S Ori J053942.1−023031......	S Ori 62	23.04 ± 0.07	...	3.59 ± 0.15	5.36 ± 0.15	05 39 42.1	−02 30 31
S Ori J053653.3−022414......	S Ori 64	23.13 ± 0.13	...	3.60 ± 0.17	4.51 ± 0.25	05 36 53.3	−02 24 14
S Ori J053724.7−023152......	S Ori 66	23.23 ± 0.12	...	3.40 ± 0.22	...	05 37 24.7	−02 31 52
S Ori J053826.1−022305......	S Ori 65	23.24 ± 0.12	...	3.34 ± 0.22	4.41 ± 0.30	05 38 26.1	−02 23 05
S Ori J053812.6−022138......	S Ori 67	23.41 ± 0.09	...	3.49 ± 0.20	...	05 38 12.6	−02 21 38
S Ori J053839.1−022805......	S Ori 68	23.78 ± 0.17	...	3.6 ± 0.3	...	05 38 39.1	−02 28 05
S Ori J053918.1−022855......	S Ori 69	23.89 ± 0.16	...	3.6 ± 0.4	...	05 39 18.1	−02 28 55

NOTES.—Units of right ascension (J2000) are hours, minutes, and seconds, and units of declination (J2000) are degrees, arcminutes, and arcseconds. Coordinates are accurate to $\pm 1''$. All the available R-band photometry and I-band data for candidates S Ori 1–S Ori 10 have been taken from BZOR. Photometric measurements for candidates S Ori 50–S Ori 69 have also been presented in Zapatero Osorio et al. 2000.

TABLE 2

SPECTROSCOPIC DATA OF σ ORIONIS MEMBERS

Name	I	$I-J$	$I-K$	Spectral Type (PC3)	Spectral Type
S Ori 12[a]	16.471 ± 0.010	2.26 ± 0.05	...	M4.5	M6
S Ori 17[a]	16.945 ± 0.009	2.17 ± 0.05	...	M4.6	M6
S Ori 29[a]	17.230 ± 0.008	2.11 ± 0.05	...	M4.8	M6
S Ori 25[a]	17.163 ± 0.008	2.46 ± 0.05	...	M5.1	M6.5
S Ori 39[a]	17.922 ± 0.008	2.47 ± 0.08	3.18 ± 0.07	M5.1	M6.5
S Ori 27	17.090 ± 0.04	2.23 ± 0.05	3.18 ± 0.05	M5.1	M7
S Ori 40[a]	18.095 ± 0.009	2.67 ± 0.06	...	M5.6	M7
S Ori 45[a]	19.724 ± 0.009	2.95 ± 0.05	4.07 ± 0.09	M8.0	M8.5
S Ori J053710.0−024302	20.266 ± 0.011	3.5 ± 0.3	4.9 ± 0.4	M8.2	M8.5
S Ori J053636.3−024626	20.614 ± 0.019	3.4 ± 0.11	...	M9.4	M9.5
S Ori 47	20.530 ± 0.05	3.30 ± 0.10	4.79 ± 0.15	L1.4	L1.5
S Ori 52	20.958 ± 0.016	3.24 ± 0.15	5.53 ± 0.15	L0.5	L0.5
S Ori 56[a]	21.740 ± 0.03	3.30 ± 0.08	4.65 ± 0.10	L0.5	L0.5
S Ori 60[a]	22.76 ± 0.05	3.59 ± 0.13	5.07 ± 0.10	...	L4

NOTE.—Spectral types have been derived using pseudocontinuous index PC3 [(823.0–827.0)/(754.0–758.0); Martín et al. 1999] and from comparison with standard M dwarfs.

[a] Candidates within the 847 arcmin^2 of present survey.

Telescope at Teide Observatory (1998 September 18, 2000 January 27, and 2000 February 20), the 2.2 m telescope at Calar Alto Observatory (2000 February 16–18), and the 3.8 m United Kingdom Infrared Telescope (UKIRT) at the Mauna Kea Observatory (2000 December 5–6). Raw frames were reduced following standard techniques in the infrared, which include sky-subtraction and flat-fielding. The photometric calibration in the UKIRT system was achieved with faint standard stars (Hunt et al. 1998) observed at different air masses on the same nights, except for the UKIRT data, which were calibrated later using objects in common with images taken under photometric conditions with the 1.23 m telescope at Calar Alto Observatory during 2000 January 22–23. The I-, Z-, and J-band data of these surveys overlap in a sky region of 847 arcmin^2 (the location of this region is shown in Fig. 1 of BZOR). Therefore, we restrict our MF analysis to the particular region of the cluster in which we have three-color photometry for all candidate members, with limiting $I_{\rm Cousins}$ and $J_{\rm UKIRT}$ magnitudes of 23.8 and 21.2 and completeness magnitudes of 21.5 and 19.5, respectively. We have adopted as the limiting magnitude of our survey the detection of 95% of the total number of pointlike sources on the frames and as completeness magnitude the value at which the number distribution of detections as a function of magnitude deviates from an exponential law.

Spectroscopic observations of a total of 14 candidates in σ Orionis have confirmed them as cluster members (see BZOR, Béjar 2000; Zapatero Osorio et al. 1999, 2000). We note that nine of them are located in the overlapping area of 847 arcmin^2. The 14 members give a well-defined spectroscopic sequence from M6 (the most luminous and bluest targets) down to L4 (the reddest ones, close to the limiting magnitude of the survey). Available I- and J-band observations for these objects allow us to define the location of the low-mass star and brown dwarf sequence of the cluster (Fig. 1), which we will adopt as a reference for the identification of cluster members. This location is suitably reproduced by the combination of the 5 Myr "dust-free and dusty" Lyon models (Baraffe et al. 1998; Chabrier et al. 2000), as shown in Figure 1. Below $I = 20$ we expect dust to condense in the atmosphere of cluster members cooler than M9, and so the dusty models seem to be more appropriate.

In the 847 arcmin^2 region under consideration we identify a total of 64 photometric candidates distributed along the theoretical and observational sequences with a dispersion around 0.5 mag. They seem to be very young objects and have colors redder than the 10 Myr isochrone given by the dust-free Lyon models (see Fig. 1). All the candidates have $I-Z$ colors and I magnitudes consistent with cluster membership. Follow-up K-band photometry for 17 of them also indicates their belonging to the I versus $I-K$ cluster sequence, which reinforces their very likely membership (BZOR; Béjar 2000; Zapatero Osorio et al. 2000). In addition, we have very recently obtained spectra for 15 of our faintest candidates; based on our preliminary analysis these objects fit the expected spectroscopic sequence and so are bona fide low-mass members with a very high probability (Barrado y Navascués et al. 2001c). The photometric and spectroscopic data of our candidates and of those members defining the cluster sequence are shown in Tables 1 and 2.

TABLE 3

SUBSTELLAR DENSITY IN THE SOLAR VICINITY

α	$\rho_{\rm BD}$ (systems pc^{-3})	$N_{\rm BD}$ $d < 10$ pc	$\rho_{\rm Pl}$ (systems pc^{-3})	$N_{\rm Pl}$ $d < 10$ pc	$N_{\rm tot}$ $d < 10$ pc
0.5	0.015	63	0.008	34	95
0.8	0.028	117	0.027	113	230
1.0	0.042	176	0.062	259	435
1.5	0.114	478	0.510	2136	2614

NOTE.—α indicates the exponent of the mass spectrum ($dN/dm \propto m^{-\alpha}$), and BD and Pl indicate brown dwarfs (0.075–0.013 $M_\odot$) and planetary-mass objects (0.013–0.001 $M_\odot$), respectively.

In the latter we have not included the candidates from Barrado y Navascués et al. (2001c). As explained in § 2, we do not find any evidence for reddening or infrared excesses, and so we have not applied any extinction correction to our data. From the successful spectroscopic results along the photometric sequences, we conclude that our selection criterion using optical and near-infrared photometry is very efficient in identifying true members of the cluster. A similar criterion for membership has proved successful in low-extinction clusters such as the Pleiades (Zapatero Osorio et al. 1997; Martín et al. 2000; Moraux et al. 2001) and IC 2391 (Barrado y Navascués et al. 2001b).

4. THE MASS SPECTRUM OF BROWN DWARFS AND ISOLATED PLANETARY MASS OBJECTS

The cluster luminosity function (LF) has been derived by counting the number of objects per magnitude interval in the I band, and it is shown in Figure 2. The first bin, $M_I = 7.5$–8.5, corresponds to stars so bright that they were saturated in some of the images of the surveys under consideration. Fortunately, the BZOR data allowed us to make an estimate of the counts for this massive bin, which was conveniently normalized to the present survey. We can see in Figure 2 that the LF is rising up to $M_I = 9$ mag and then falls and becomes flat from $M_I = 11.5$ mag. The LF remains flat down to the completeness limit of our surveys. We note that the bins where the luminosity function shows a peak correspond to a mass range (0.08–0.05 $M_\odot$) that includes both objects that have finished the deuterium-burning phase (the more massive ones) and those actually burning deuterium. Both types of objects will have similar luminosities, if the age of the cluster is in the range 3–6 Myr, and therefore will contribute to produce a peak in the LF.

In order to derive the IMF, we have first determined the masses for the σ Orionis members, following a procedure similar to that described in Zapatero Osorio et al. (2000), which means that we have adopted the mass-luminosity relationship given by the Lyon models (Baraffe et al. 1998; Chabrier et al. 2000). In favor of these models it can be argued that they have been successful in fitting the mass-luminosity relation in various optical and infrared passbands (Baraffe et al. 1998; Delfosse et al. 2000), as well as in predicting coeval ages for the members of several young multiple systems (White et al. 1999; Luhman 1999), and that they provide a good fit to the infrared photometric sequence in the Pleiades and σ Orionis clusters (Martín et al. 2000; Zapatero Osorio et al. 2000). In addition, the Lyon tracks provide magnitudes and colors in the filters of interest as a function of mass, while in order to transform the effective temperatures and luminosities of other models into observables we would have to use bolometric corrections.

The σ Orionis cluster substellar IMF is illustrated in Figure 3, where the mass spectrum is represented on a logarithmic scale. For the age of 5 Myr a single power-law fit facilitates a reasonable representation of the data points, with a slope of $\alpha = 0.8 \pm 0.4$ in the mass range from very low mass stars (0.2 $M_\odot$) through the whole brown dwarf domain to 0.013 $M_\odot$. The uncertainty of ± 0.4 in the α-index accounts for possible different ages of the cluster and the use of other evolutionary models. We have investigated the sensitivity of our mass spectrum to age by deriving α for ages from 3 Myr to 10 Myr. The values found were

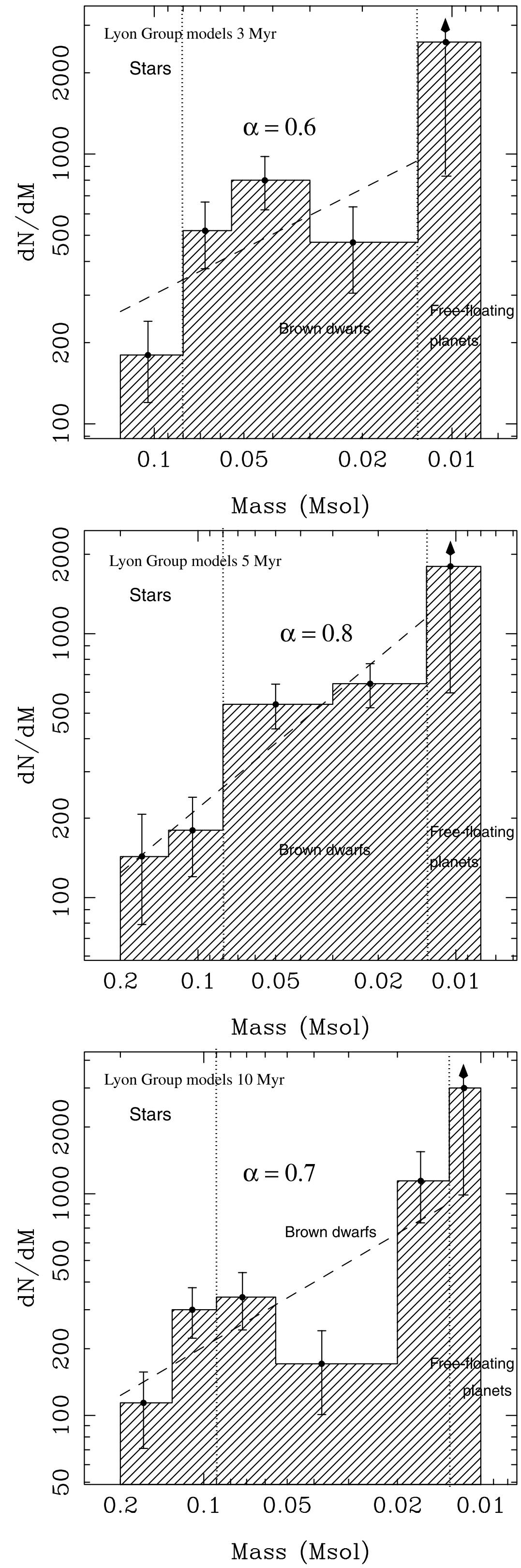

FIG. 3.—Mass function of the σ Orionis cluster for substellar masses adopting several plausible ages. The best power-law fitting ($dN/dM \propto M^{-\alpha}$; *dashed line*) down to the brown dwarf–planet boundary ($\sim 0.013\ M_\odot$) gives $\alpha = 0.8 \pm 0.4$ for the most probable age of 5 Myr. Error bars correspond to Poissonian uncertainties (from the finite number of objects), except for the planetary-mass interval, where the upper limit (*arrow*) denotes the incompleteness of the photometric and spectroscopic searches, and the lower error bar accounts for the possible contamination by nonmembers of the cluster, as discussed in Zapatero Osorio et al. (2000).

between 0.5 to 1.0. This interval also accounts for an uncertainty of 0.2 mag in the estimate of the cluster distance modulus. The dependence of the mass spectrum on theoretical models is even more uncertain. Our calculations considering Burrows et al. (1997) isochrones yield α-values up to 0.4 higher those from other models, depending on age. Our main result is that the very low mass stellar and substellar-mass spectrum of the σ Orionis cluster is generally rising toward lower masses. IMFs with slopes in the range 0.4–0.8 below the star–substellar mass borderline have been obtained recently for other young clusters (Luhman et al. 2000; Lucas & Roche 2000; Hillenbrand & Carpenter 2000; Najita et al. 2000; Martín et al. 2000; Moraux et al. 2001), showing that the formation of brown dwarfs is a quite common process in the Galactic disk.

A remarkable feature of Figure 3 is the evidence of an extension of the IMF into the domain of planetary masses (i.e., lower than the deuterium-burning mass). Despite the incompleteness of our survey and the possible contamination by several nonmembers of the cluster at these very low masses (see details in Zapatero Osorio et al. 2000), the planetary-mass interval is rather well populated. This indicates that free-floating planetary mass objects with masses 0.013–0.005 $M_\odot$ are abundant in σ Orionis. We find no evidence for a " bottom end " of the IMF in the mass interval covered by our analysis, i.e., there is no obvious deficit of objects near and beyond the deuterium-burning mass limit. Deeper surveys will be needed to determine the existence and location of a minimum-mass limit in the IMF.

5. CONCLUSIONS AND FUTURE PERSPECTIVES

Recent searches have found a significant population of brown dwarfs in the σ Orionis cluster. We have estimated the mass spectrum, $dN/dm \propto M^{-\alpha}$, from very low mass stars (0.2 $M_\odot$) to 0.013 $M_\odot$, and we have found that this is still rising across the whole brown dwarf regime, with $\alpha = 0.8 \pm 0.4$. Our results also suggest that the mass spectrum keeps rising down to 0.005 $M_\odot$. If the IMF in the σ Orionis cluster has $\alpha = 0.8$ down to 1 $M_{\rm Jup}$, isolated planetary-mass objects in the mass range 1–12 $M_{\rm Jup}$ would be as numerous as brown dwarfs, and brown dwarfs and free-floating planets together would be as numerous as stars (see below for further details). However, their contribution to the total mass in the cluster would be less than 10%.

The relatively large number of free-floating planetary-candidate members found in the σ Orionis cluster suggests that such low-mass objects form commonly in nature and that older and cooler isolated planets could be populating the Galactic disk and hence the solar neighborhood. Assuming that the IMF of σ Orionis is representative of the disk population and extrapolating it to a mass of 1 $M_{\rm Jup}$, we obtain the densities of free-floating substellar systems given in Table 3. They are anchored to a density of stellar systems in the solar neighborhood of 0.057 pc^{-3} (Reid et al. 1999). With this estimate for an index of $\alpha \sim 1$ in the mass spectrum, we would expect a total number of substellar objects around 435 within a radius of 10 pc, whereas there would be 239 stars. Isolated planets much older than objects in σ Orionis will be extremely faint and cool enough to show molecular features like the giant planets in the solar system. Therefore, even if they form a large population in the solar neighborhood, their detection is a challenge to present-day observational capabilities. According to theoretical predictions of radiated fluxes at different wavelengths (Burrows et al. 1997; Allard et al. 1997), these objects in the mass range 1–12 $M_{\rm Jup}$ at the solar age could have effective temperatures of 100–300 K and an absolute magnitude of $M_J = 20$–25 and $M_M = 15$–17. Current surveys such as 2MASS, DENIS, or Sloan are unable to detect them out to distances greater than 1 pc because they are too shallow. Deeper surveys, such as those reported by D'Antona, Oliva, & Zeppieri (1999) and Herbst et al. (1999) do not cover enough area. Free-floating planetary mass objects are extremely faint at optical and near-infrared wavelengths because of the absorption of methane and water, but they have a moderately transparent region around 5 μm. They could be identified with the *Space Infrared Telescope Facility* (*SIRTF*) out to distances of several parsecs from the Sun (Martín et al. 2001) or with wide, ultradeep, ground-based, near-infrared surveys, such as the one planned with Megacam on the Canada-France-Hawaii Telescope.

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