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# Very Low Mass Stellar Populations in Star-Forming Regions: Near-Infrared Luminosity Functions and Mass Functions

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**Abstract.** We briefly describe recent studies of the low-mass young stellar populations including substellar objects and of their luminosity functions and mass functions, especially at lower-ends, in different star-forming regions. The mass function is determined by the technique based on the near-infrared photometry for estimating stellar luminosities and then translating them into stellar masses. We compare the local environmental characteristics of regions in which high-mass stars form with those of regions producing only low-mass stars and intermediate stars. We find that there exist numerous very low-mass YSO candidates including young brown dwarfs and young isolated objects with planetary masses in common. Further, the luminosity functions and mass functions in the star-forming regions might not have a uniform shape below the hydrogen-burning limit.

## 1. Introduction

One of the most fundamental disciplines of astrophysical researches is the origin of star and stellar mass. In recent years, considerable progress has been made toward understanding of low-mass star formation and of the properties of low-mass young stellar populations. Various observations have revealed that there could be a significant population of young brown dwarfs in the nearby star-forming regions. However the substellar mass function (MF) in only part of the field, open cluster, and star-forming regions has very recently been demonstrated, and it is not yet clear whether they significantly contribute to the low-mass end of the luminosity function (LF), and therefore to the initial mass function (IMF). It is the issue under discussion whether the IMF continues to rise, is flat, or turns over. In addition, whether or not its form differs among regions where massive or low-mass stars formed is a question to be explored. In order to answer such questions, we have conducted near-infrared observations deep enough to take inventories of young stellar and substellar population. Such observations will provide a first step to test the universality of the IMFs. We have thus chosen a few of the nearest low-mass, intermediate-mass, and high-mass star-forming regions. Our surveys that have focused on unrevealed embedded populations in the star-forming regions are sensitive to YSOs completely down to the hydrogen-burning limit.

## 2. Observations and Results

Oasa, Tamura & Sugitani (1999a) and Oasa et al. (1999b) conducted deep near-infrared ($JHK$) imaging surveys of the Chamaeleon molecular cloud I North core and Heiles Cloud 2 in the Taurus molecular cloud. They are both low-mass star-forming regions located at a distance of $\sim$ 160 pc and $\sim$ 140 pc, respectively. These observations cover areas of 30 and 100 square arcminutes and have the 10 $\sigma$ limiting magnitude of $\gtrsim$ 16 mag in all three bands. Source classification is performed based on the near-infrared color-color diagram (presented Figure 2 of Oasa et al. 1999a). 31 and 8 % of all the detected sources in Chamaeleon and Taurus exhibit strong near-infrared excess emission and such objects are identified as YSO candidates. For both regions there are very low-luminosity YSO candidates such as those in other regions of the same cloud (Comeron et al. 1998; Itoh, Tamura & Nakajima 1999). Their luminosities and the recent evolutionary models for very low-mass objects suggest that they appear to be substellar objects. Moreover, some of them have masses comparable to those of giant planets, which are similar to those identified in Trapezium (Lucas & Roche 2000).

We have investigated the embedded cluster associated with NGC 1333 in the Perseus molecular cloud (Oasa 2001). NGC 1333 is one of the nearest (d $\sim$ 320 pc) and active intermediate-mass star-forming regions. The NGC 1333-S region was imaged in the $JHKs$ bands with the SIRIUS infrared camera mounted on the University of Hawaii 2.2 meter telescope at Mauna Kea in August 2000. SIRIUS enables simultaneous imaging in the $J, H$, and $Ks$ bands with a resolution of $0.''277$ per pixel on the UH telescope. Our observations cover an area of 25 square arcminutes including SVS 13. The 10 $\sigma$ limiting magnitudes exceed 18 mag in all three bands. Identification of YSOs follows the same procedure as that employed in other regions. The derived frequency of the YSO candidates among all the detected sources is 57 %. It is considerably higher than that of Chamaeleon and Taurus. Approximately half of our YSO candidates exhibit extremely low-luminosity, indicating substellar mass. Some of them are isolated objects with planetary masses.

We have carried out the extensive near-infrared imaging observations of S 106 in the Cygnus molecular cloud (Oasa 2001). S 106 is a massive star-forming region located at a distance of $\sim$ 600 pc and known as one of the richest young cluster such as Trapezium. The $JHK'$ band images of the S 106 region were taken at the SUBARU 8.2 meter telescope in May and June 1999 using the facility infrared camera of CISCO. The typical seeing size was measured to be around $0.''3$ FWHM and nearly $0.''2$ at best. Our observations cover an area of 25 square arcminutes including central OB star (IRS 4). The 10 $\sigma$ limiting magnitudes exceed 20 mag in all three bands, which is much deeper than another $JHK$ survey of star-forming regions. We identified $\sim$ 1700 sources in all three bands in spite of the small coverage. Approximately 600 YSO candidates ($\sim$ 35 %) with near-infrared excesses are revealed and a number of them appear young brown dwarf candidates. There is a concentration of more luminous YSO candidates around IRS 4 while fainter sources are distributed across over the S 106 region. Furthermore, there exist about 100 YSO candidates with planetary masses.

## 3. Estimates of Stellar Luminosities and Masses

Most of newly detected YSO candidates are of very low-luminosity, similar to young brown dwarfs in the star-forming regions. We have estimated apparent stellar luminosities from the measured $J$-band luminosity. The reddening-corrected $J$-band luminosity for each Class II candidate is derived from the extinction toward each object and the distance modulus. Here we have adopted a distance in general use in each region as shown above. Our approach to estimate mass as follows. Firstly, we assume the average age of the YSO candidates to be 1 Myr on the basis of the age distribution of typical T Tauri stars and very low-mass Class II objects, both of whose spectral type are already known. It is estimated on the H-R diagram with the evolutionary track of Baraffe et al. (1998). Secondly, we determine the relationship between reddening-corrected $J$-band luminosity and mass using the evolutionary models. Thirdly, each mass of the Class II candidate is deduced from reddening-corrected $J$-band luminosity and the $J$–mass relationship.

## 4. Luminosity Function and Mass Function

Our analysis of low- to high-mass star-forming regions has provided a quantitative census and properties of the embedded stellar population down to substellar objects embedded in the cloud. We compare the LFs and MFs of our embedded populations. Any systematic differences in the observations and analyses between various studies could readily cause an inaccurate estimation so that comparison for our sample which is performed in a uniform way can be meaningfully made.

### 4.1. Luminosity Function

It is advantageous to compare the LFs in direct rather than the MFs, since we do not rely upon the mass-luminosity relations derived from the evolutionary tracks with some uncertainty as described below. The bins of LFs are one magnitude wide, so that the effects of age difference can be somewhat reduced.

Comparison of our derived LFs with the luminosity predicted from theoretical models implies that all of these LFs are complete down to the substellar regime and contain a significant population of young brown dwarf candidates. LF in Taurus demonstrate a steep increase in the count down to the completeness limits, while those in Chamaeleon I and NGC 1333 exhibit a gentle count increase down to the substellar regime. On the other hand, a close inspection of the cloud and YSO properties of the S 106 cluster indicates that S 106 is not composed of just one population, but has several populations of YSOs (Oasa 2001). If we divide the S 106 region, extent to about 0.9 pc, into several subregions, LFs of the YSO candidates vary from region to region, but none of them appear to turn over down to the completeness limits. This implies that, even in the same cloud core, LFs do not tend to have uniform shape below the hydrogen-burning limit.

In summary, no convincing evidence for a universal LF is clearly exhibited. This difference in LFs suggests that these regions are forming stars with underlying different mass distributions.

### 4.2. Mass Function

In order to study the shape of the IMF, we compare the MFs in the star-forming regions. We characterize the stellar mass assuming the typical Class II age of $\sim$ 1 Myr, the younger age of $\sim$ 0.3 Myr and the maximum age of $\sim$ 10 Myr. To estimate MFs for our sample, we used combined mass-luminosity relationship of three evolutionary models (Burrows et al. 1997; Baraffe et al. 1998; D'Antona & Mazzitelli 1998). The mass-luminosity relations constructed from these models agree well within $\sim$ 0.1 - 0.2 magnitudes. However, we note that in the earlier stellar evolution, the relation between the dynamical collapse phase and the quasi-static accretion phase is significantly complicated and the resulting uncertainties are still larger in such younger stage.

Figure 1 shows the derived MFs of Chamaeleon, NGC 1333, and S 106. It indicates that there appears more abundant in substellar YSOs than low-mass YSOs in the all regions and the MFs slightly vary with assumed ages. For Taurus, our identified Class II candidates are only very faint sources and many have mass close to the giant planets. The poor statistics make it difficult to address the shape of MFs significantly. For Chamaeleon I, at a probable age of 1 Myr, the distribution shows somewhat flat. The two populations seen in the LFs have emerged in these MFs at any age. For NGC 1333, the MFs exhibit increasing shape regardless of ages. At a possible age of 0.3 Myr, the MF rises steadily and the slope is steeper than that of older age. For S106, the MFs exhibit steady increase toward completeness limits regardless of ages. At a probable age of 1 Myr, MF rises monotonously. If we divide the S 106 region into several subregions, as described above, the shape of MF in the central region including IRS 4 and that in the outer region are in disagreement at any age.

Consequently, we conclude the overall shape of MFs as follows:
(i) it is likely that a significant number of substellar YSOs form in common, (ii) all the MFs in these star-forming regions do not appear to decrease down to the substellar regime.

### 4.3. Star Formation Mode and Luminosity Functions

It is important to know the relation between the MFs and the physical conditions of the clouds. The different picture of star formation might result in the different MFs. Our observed regions of Taurus, Chamaeleon I, NGC 1333, and S 106 correspond to the isolated or clustered low-mass star-forming clouds, the clustered intermediate star-forming clouds, and high-mass star-forming clouds, respectively. The difference of LFs and MFs between these regions is possibly related to the properties of cloud itself. Furthermore, in the case of S 106, the properties of young stellar populations appear quite different from region to region despite the small extent of observed region. S 106 is a well known optically visible H II region associated with early-type O9.5V star, which is confirmed by radio continuum studies. Nevertheless subregion which is $\sim$ 0.2 pc apart from the central star appears to have physical properties similar to those in the low-mass and intermediate-mass star-forming regions. In the outer region of S 106, the YSOs fraction and their extinctions are considerably low compared to the neighbor clustering region and similar to the Taurus dark cloud. It appears that star formation in such region would be locally distributed although YSO surface density is relatively higher.

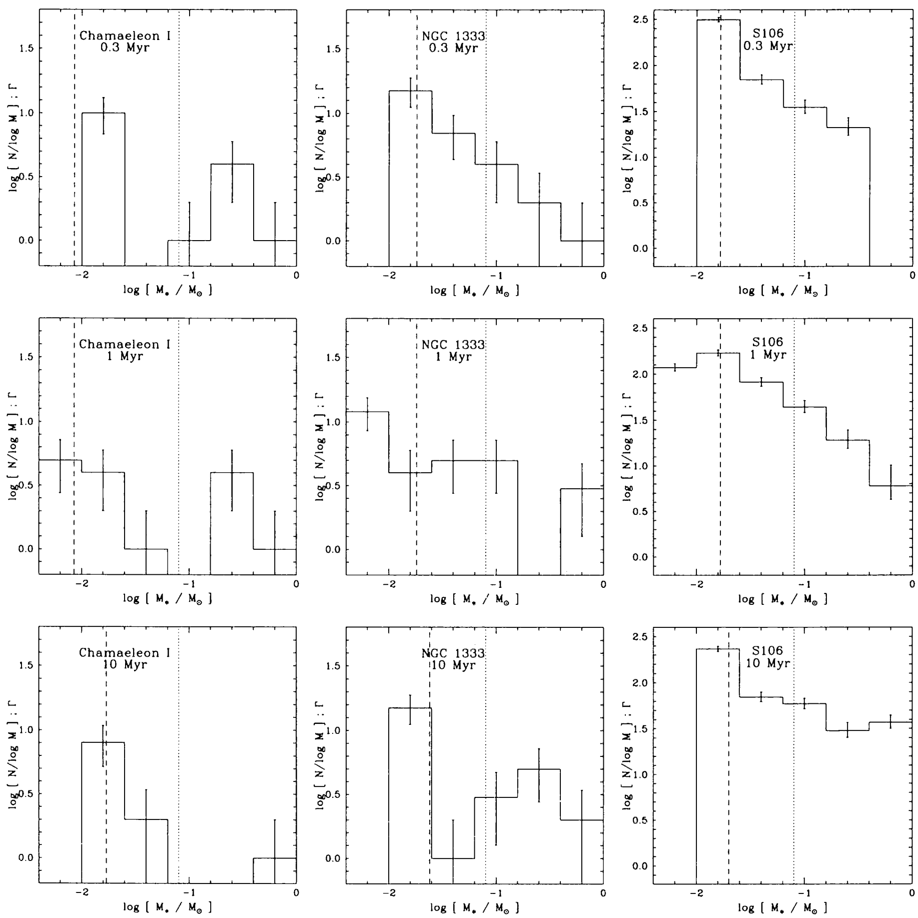


Figure 1. The MFs constructed from our identified Class II object candidates in Chamaeleon I (left), NGC 1333 (middle), and S 106 (right). Age assumption of 0.3 Myr, 1 Myr and 10 Myr are shown in the top, middle, and bottom panel, respectively. Masses are estimated using models of Baraffe et al. (1998) and of Burrows et al. (1997) for 1 and 10 Myr. For 0.3 Myr, DM 98 model, which calculates down to 0.017 $M_{\odot}$, is adopted. Thus there is no bin for 0.3 Myr and last two bins are uncertain. The vertical dash-dotted lines denote the star /brown dwarf boundary. The completeness limits are represented by dashed lines.

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Based upon the star-formation picture and difference in the local physical properties, we suspect that the initial conditions in the parent molecular cloud have a effect on the LFs and MFs. Moreover taking into account S 106, the local stellar density of YSOs are probably the primary driver in determining the LF and the resulting MF. In either case, these LFs and MFs do not present any hint of a turnover down to the substellar regime.

We conclude that the MFs at very low-mass side in these regions exhibit somewhat various shape, depending on the regions forming what kind of star and/or their number density, but MFs are in substantial agreement as regards no turnover toward substellar regime and the wealth of likely young brown dwarfs. If we can understand toward the influence of properties of parent cloud and of stellar clustering in the star formation process, we will be able to constrain the mechanisms of determining the MFs. Further observational works are required to asses variations in the very low-mass IMF.

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