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Initial Mass Functions of Massive Stars in OB Associations*

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ABSTRACT

We derived initial mass functions (IMF) of massive stars in three different regions of spiral arms within 2.5kpc from the sun. The derived IMF slope β of Local arm stars is found to be $-2.09 \sim -2.06$, very close to that of Bisiacchi et al. (1983). For Sagittarius-Carina arm stars β ranges from -1.77 to -1.72 which is close to that of overall stars given by Garmany et al. (1982). Possible causes inducing the regional difference in IMFs are discussed.

I. INTRODUCTION

The observation of young clusters in various part of our galaxy has opened a new possibility of studying the initial mass function (IMF) of stars in different regions in our galaxy. Larson (1982) showed some evidences for differences in IMFs between different regions. Their differences may reflect different modes of star formation (Larson 1981; Smith 1980), or different stages in the evolution of star formation complex (Herbig 1962).

For the massive galactic disk stars ($M \geq 20M_{\odot}$), Garmany et al. (1982) claim that there exists a gradient in IMF in the sense that there are more massive stars toward the center with respect to the anti-center of our galaxy. This gradient for the massive stars in stellar mass distribution can be explained as a consequence of the self regulation process in star formation by massive stars in OB associations and young open clusters (Franco and Shore 1984). It suggests, if intrinsic, a possible origin for at least part of the galactic chemical gradient (Garmany et al. 1982).

In deriving the IMF, one has to assume the distribution of stars is homogeneous to some limited distances. However, for massive stars the assumption is only successful to bring forth some averaged IMFs since the early type stars are known to be formed in spiral arms.

Further questions of the regional differences in IMF could be answered by investigating the IMF for massive stars which cluster in OB associations and young star clusters in

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spiral arms. For this purpose we attempt to derive IMFs of massive stars in three different regions of spiral arms within 2.5kpc from the sun.

II. DATA SELECTION

In this study we select luminous stars in associations and clusters from Humpherys (1978) catalog. This catalog contains supergiants, O stars plus B0-B1 main-sequence stars and giant stars of all spectral types in known associations and clusters. Most of stars listed in the catalog are considered to be a representative of supergiant population within 3 kpc from the sun which shows the characteristics of the spiral-arm population in the Milky way (Humphreys 1978).

Associations and clusters are divided into three different groups according to the associated spiral arms; Sagittarius-Carina(SC), Perseus(P) and Local(L) groups. In each group, we select the clusters and associations within mean distance of 2.5kpc from the sun. The reason for this limiting distance can be found in the completeness test of the data by Humphreys and McElroy (1984) and Garmany et al. (1982). Each group contains more than six associations, and includes clusters as well as associations, as listed in Table 1.

TABLE 1 Associations and Clusters Included in Each Spiral Arm Groups.

Spiral Arm Group	Associations and Clusters
L	Sct OB 2, Vul OB 1, Vul OB 4, Cyg OB 3, Cyg OB 1, Cyg OB 8, Cyg OB9, Cyg OB 2, Cyg OB 4, Cyg OB 7, Lac OB 1, Cep OB 2, Cep OB 3, Cep OB 4, Cas OB 14, Cam OB 1, Per OB 2, Aur OB 1, NGC 2129, Gem OB 1, Mon OB 1, Ori OB 1, Mon OB 2, CMa OB 1, Coll 121, NGC 2414, Pup OB 1, Vel OB 1, SCO OB 2
SC	Sgr OB 1, Sgr OB 7, Sgr OB 4, Ser OB 1, Sct OB 3, Ser OB 2, Car OB 1, Coll 228, Car OB 2, NGC 3766, Cru OB 1, Cen OB 1, Ara OB 1a, NGC 6204, Scu OB 1
P	Cep OB 5, Cas OB 5, Cas OB 7, Cas OB 1, NGC 457, Per OB 1, Cas OB 6

TABLE 2 The Number Distributions of Stars with Spectral Type for Each Spiral Arm Group.

Spiral Arm Group	O	B	A	F,G,K	M	Remarks
L	123(66) (39.2%)	156(83) (49.7%)	13 (9) (4.1%)	6 (4) (1.9%)	16(10) (5.1%)	
SC	93 (37.6%)	116 (47.0%)	15 (6.1%)	5 (2.0%)	18 (7.3%)	all stars inside the solar circle
P	34 (19.1%)	96 (53.9%)	18 (10.1%)	3 (1.7%)	27 (15.2%)	all stars outside the solar circle

* Numbers in the parenthesis are number of stars outside the solar circle.

The number distributions of stars with spectral type are presented for each spiral arm group in Table 2 and also they are shown in Figure 1. Here it is obvious that stars in spiral arms L and SC have almost the same distribution. However, P group shows a tendency of decreasing ratio of the blue to the red supergiants. This might be related to a gradient in the ratio of the blue to the red supergiants which is decreasing with distance from the center of our galaxy (Humphreys 1978) or related the lack of completeness of the selected data.

Figure 2 shows the local spiral structure from the distribution of massive stars in OB associations and clusters in the galactic plane. It can be noted from this figure and Table 2, that all stars in the P group are located outside the solar circle, $R=10$kpc from the galactic center, whereas the SC group consists of stars inside the solar circle.

Cumulative star counts in each spiral arm group which are shown as a function of distance from the sun in Figure 3 increase with distance at a uniform rate up to $r\simeq 2.5$ kpc, beyond which the increasing rate is rapidly decrease. Hence the completeness of massive star counts may be inferred from the uniform density within $r\simeq 2.5$kpc. However,

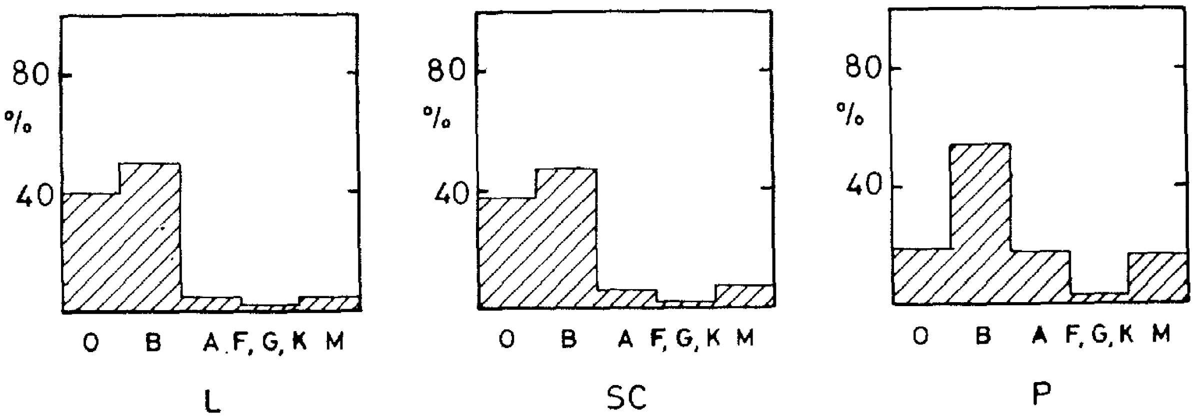

FIG. 1—The number distributions of massive stars with spectral type in each spiral arm group (L, SC, P).

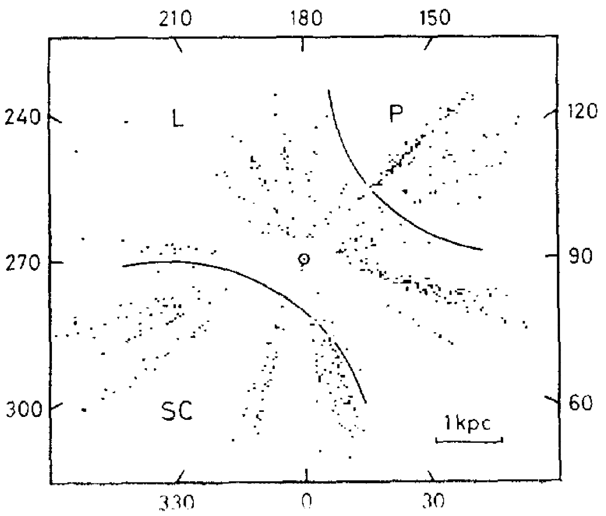

FIG. 2—The distribution of massive stars ($M\geq 20M_\odot$) in OB associations and clusters in the galactic plane. The letters L, SC and P represent Local, Sagittarius-Carina and Perseus arm, respectively. Coordinates and distances are taken from Humphreys (1978).

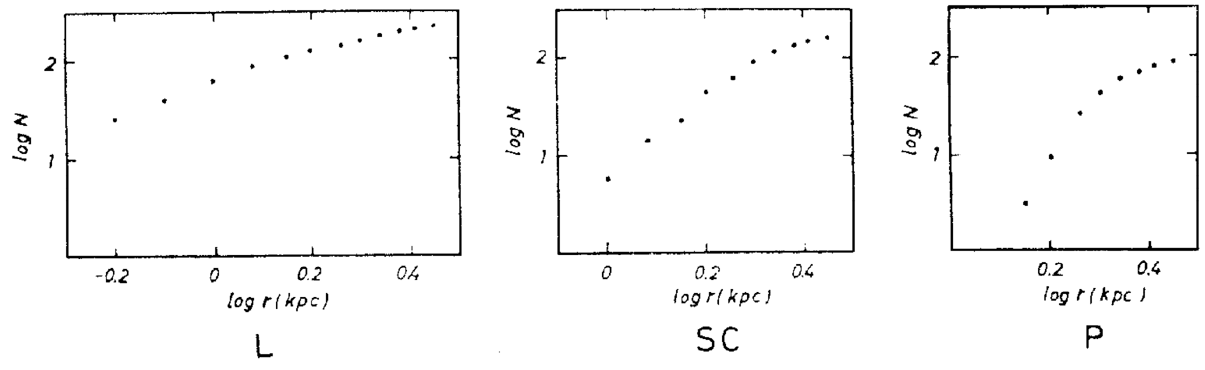

FIG. 3—Cumulative counts of stars in each spiral arm group as a function of distance from the sun.

it is very difficult to argue the completeness of massive stars ($M \geq 20M_\odot$) since there is seen the directional dependence in the distribution of massive stars in the galactic plane (see Fig. 2). Because of the local spiral structure and the corresponding interstellar absorption, the degree of the completeness of massive star counts will vary with galactic longitude. However, the effects of incompleteness are not so much serious than the less luminous, less massive stars in our galaxy (Humphreys and McElroy 1984).

In the derivation of IMFs, we excluded binaries, OC (carbon enhenced O type) and ON (nitrogen enhenced O type) stars in each spiral arm, since the IMF for the binaries may differ from that of single stars (Vanbeveren 1983), whereas OC and ON may be evolved stars (Baschek and Scholz 1974; Vanbeveren 1984).

III. DERIVATION OF IMF FOR SPIRAL-ARM GROUP

The IMF $\phi(M)$ can be defined as the number of stars per kpc^2 per year in mass interval ($\log M/M_\odot$) and ($\log M/M_\odot + d\log M/M_\odot$) (Lequeux 1979),

$$\phi(M) = d\dot{N}/d\log(M/M_\odot) \qquad (1)$$

where $\dot{N}$ is the number of stars per year per kpc^2. In a power law of mass, IMF can be expressed as

$$\phi(M) = \alpha M^\beta. \qquad (2)$$

For the derivation of the IMF an adequate set of evolutionary tracks in M_{bol} vs $\log(T_{eff})$ diagrams is required to deduce mass and life time of a star. To find the accurate position in the theoretical H-R diagram, the observed magnitude and spectral type should be converted to bolometric magnitude and effective temperature scale. In this study we used the data given by Humphreys and McElroy (1984) who adopted the bolometric correction and effective temperature scale from Flower (1977) and for the early O type stars from Kudritzki (1981) and Simon et al. (1983).

For the derivation of mass, we used two different sets of evolutionary tracks. The one

TABLE 3 Number of Stars per Mass Interval, Normalized Number, Adopted Stellar Life Time and Derived IMF for Massive Stars in Each Spiral Arm Group.

(Model A)

Mass Range ($M_\odot$)	τ (10^6yr)	L					SC					P				
		N	N_n	$\bar{M}$	$\log\bar{M}$	$\log\phi(\bar{M})$	N	N_n	$\bar{M}$	$\log\bar{M}$	$\log\phi(\bar{M})$	N	N_n	$\bar{M}$	$\log\bar{M}$	$\log\phi(\bar{M})$
15~30	9.2	135	11.80	22.3	1.35	−5.37	84	9.94	22.9	1.36	−5.45	69	14.39	22.2	1.35	−5.28
30~60	5.3	75	6.55	40.5	1.61	−5.39	64	7.57	43.1	1.63	−5.32	22	4.59	37.6	1.58	−5.54
60~85	3.5	11	0.96	68.6	1.84	−5.74	15	1.77	68.0	1.83	−5.47	2	0.42	70.0	1.85	−6.10
85~150	3.0	1	0.09	115	2.06	−6.93	1	0.12	85.0	1.93	−6.80	—	—	—	—	—

(Model B)

Mass Range ($M_\odot$)	τ (10^6yr)	L					SC					P				
		N	N_n	$\bar{M}$	$\log\bar{M}$	$\log\phi(\bar{M})$	N	N_n	$\bar{M}$	$\log\bar{M}$	$\log\phi(\bar{M})$	N	N_n	$\bar{M}$	$\log\bar{M}$	$\log\phi(\bar{M})$
20~30	6.2	50	10.43	25.0	1.40	−5.02	36	9.19	24.8	1.39	−5.07	13	10.51	25.8	1.41	−5.01
30~40	5.0	21	4.38	32.8	1.52	−5.15	17	4.34	34.8	1.54	−5.16	6	4.85	34.8	1.54	−5.11
40~60	4.6	16	3.34	47.9	1.68	−5.39	16	4.08	46.9	1.67	−5.30	3	2.43	46.9	1.67	−5.52
60~80	4.1	5	1.04	67.6	1.83	−5.69	6	1.53	69.3	1.84	−5.52	2	1.62	69.3	1.85	−5.50
80~100	3.3	1	0.21	90.0	1.95	−6.19	1	0.25	82.0	1.91	−6.10	—	—	—	—	—

is given by Maeder (1981, 1983) (hereafter Model A), in which the high mass tracks ($120M_{\odot}$, $85M_{\odot}$, $60M_{\odot}$, and $30M_{\odot}$) are calculated with high mass loss rate. The other one is made by Bressen et al. (1981) (hereafter Model B) which includes mass loss and convective overshooting in their calculations. Model A can be applied to calculate the mass of O stars and B0-B3 stars since this model has a somewhat wider main sequence (Meylan and Maeder 1982) in the effective temperature. Model B has been applied to derive the mass of O stars. By using these two different sets of evolutionary tracks, we determined the number of stars in each mass interval, the life time of stars and the mean mass of counted stars, which are summarized in Table 3. Here the adopted time τ represents the main sequence life time in Model A and the time required for O type stars to evolve to B0 type in Model B.

The counted number of stars N in each mass range are normalized by the following method given by Bisiacchi et al. (1983). That is, the number density $n=19.40/\mathrm{kpc}^2$ of O stars in the catalog of Cruz-Gonzales et al. (1974) is multiplied to the observed star number N in each mass range and then nN is divided by the total number of observed stars (ΣN) in each spiral arm group. The normalized density, $N_n=\frac{nN}{\Sigma N}\mathrm{kpc}^{-2}$, is listed in Table 3. After the normalization, one can compare results of IMF for the massive stars located in the small volume of spiral arms with the others such as IMF of the solar neighborhood.

Using the data listed in Table 1 we derived IMF which can be considered to be equal to the present-day mass function for massive stars. From equation (1), the IMF $\psi(M)$ can be rewritten as

$$\psi(\bar{M})=\frac{N_n/\tau}{\log M_{i+1}-\log M_i} \qquad (3)$$

where $\bar{M}$ is the mean mass of stars distributed in mass range $M_{i+1}\sim M_i$. The derived IMFs are plotted in Figure 4, where the open and closed circles represent the IMFs derived by using the evolutionary tracks given by Maeder (1981, 1983) and Bressen et al. (1981), respectively. The solid line represents the IMF derived by Miller and Scalo (1977). The dashed and dotted lines denote the IMFs given by Garmany et al. (1982) for the massive stars in the regions inside and outside the solar circle, respectively.

IV. DISCUSSION

Applying the different life time scales and evolutionary models, tho two sets of IMFs were derived for each spiral arm group as in Table 3. From this table two sets of parameters α and β in equation (2) for analytic expression of IMFs were determined for each spiral arm group and they are listed in Table 4. The difference between the two sets of parameters can be attributed to the use of different evolutionary models as follows: (i) Masses estimated by Model A are somewhat larger than those by Model B. (ii) Different

TABLE 4. Parameters for Analytic Expression of IMF in eq. (2)

this paper	L		SC		P		Overall (L+SC+P)	
	Model A	Model B	Model A	Model B	Model A	Model B	Model A	Model B
$\alpha(10^{-3})$	5.25	7.37	1.69	2.81	0.97	0.62	6.91	7.29
β	−2.09	−2.00	−1.77	−1.72	−1.66	−1.28	−2.17	−1.99

	Garmany et al. (1982)		Overall	Humphreys and McElroy (1984)	Miller and Scalo (1979)	Bisiacchi et al. (1983)
	Inside the Solar circle	Outside the Solar circle				
$\alpha(10^{-3})$	1.1	8.4	2.3	52		15
β	−1.3	−2.1	−1.6	−2.41	−2.3	−2.1

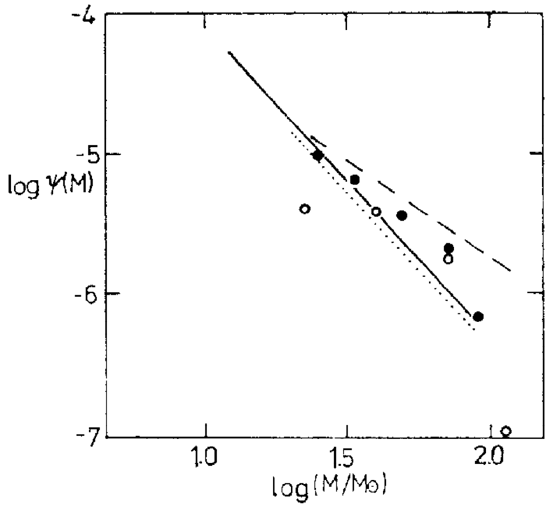

FIG. 4a—IMF of the massive stars in Local arm (*L*) defind in text. The open and closed circles represent the IMFs derived by using the evlutionry tracks given by Maeder (1981, 1983) and by Bressen et al. (1981), respectively. Solid line represents the IMF derived by Miller and Scalo (1979). Dashed and dotted lines denote the IMFs given by Garmany et al. (1982) for the massive stars in the regions inside and outside the solar circle, respectively.

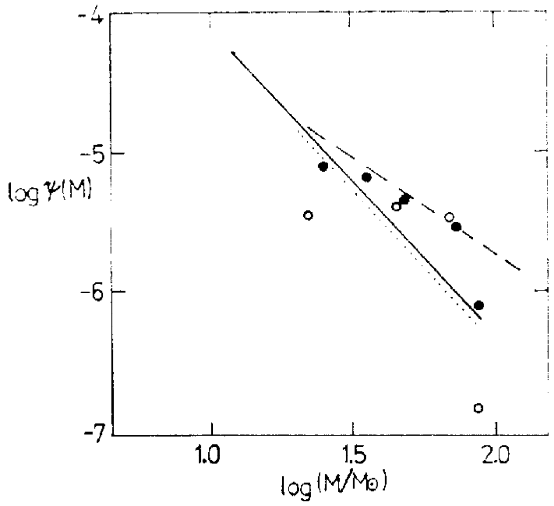

FIG. 4b—IMF of the massive stars in Sagittarius-Carina (SC) arm. The symbols are the same as in Fig. 4a.

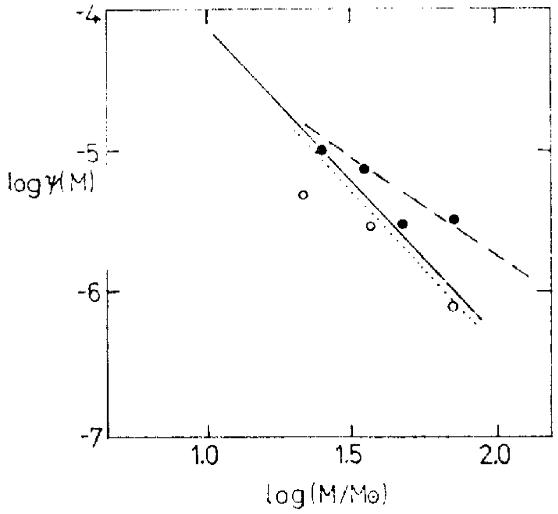

FIG. 4c—IMF of the massive stars in Perseus (P) arm. The symbols are the same as in Fig. 4a.

division of mass ranges in evolutionary tracks may affect the IMFs if the slope depends on the mass. (iii) The evolutionary tracks given by Model A were applied to the massive stars as late as B3 whereas the Model B was used for only O type stars. However in the case of (iii), it is not quite clear how far the main sequence of massive stars could be extended to the later type stars than the O type stars in H-R diagram (Meylan and Maeder, 1982) and therefore it is uncertain how much the later type stars could contribute to the IMFs of massive stars.

Another important factor which can affect IMFs of massive stars is the incompleteness of the sample due to undetected stras hidden in clouds. According to Garmany et al. (1982), some 20%～50% of O type stars should be hidden in dense cloud.

However, in our case the ratio of IMF slopes obtained from the two different evolutionary models is as large as 1. 30 which is comparable to 1. 14 of Garmany et al, (1982) and far less than the slope ratio 1. 93 for clusters given by Vanbeveren (1984).

In Figures 4a-4c, we may note that the IMF drops down sharply for less massive ($M \leq 20\ M_{\odot}$) stars. This tendency can be also found in the IMF derived by Humphreys and McElroy (1984). They interpreted this dropping-off in IMF as being attributed to the incompleteness of data of less massive stars. In the figures we can also note the dropping of IMF at the high mass end. This dropping-off seems to be due to the small number of the sample data.

It is interesting to point out that our IMF slope ($\beta=-2.09\sim-2.06$) of local arm stars is quite close to the slope ($\beta=-2.1$) of Bisiacchi et al. (1983) and also to the slope ($\beta=-2.1$) of outer solar circle stars given by Garmany et al. (1982), while the slope ($\beta=-1.77\sim-1.72$) of Sagittarius-Cariana arm is rather similar to that ($\beta=-1.6$) for the overall stars given by Garmany et al. (1982).

We also note that our IMF slope for the massive stars in local arm and Sagittarius-Carina arm differs not so much as the difference in IMF slopes between the outer ($\beta=-2.1$) and inner ($\beta=-1.3$) solar circle stars given by Garmany et al. (1982) and Garmany (1984). However the same tendency of increasing IMFs toward the galactic center can be seen.

The Perseus arm stars are located outside the solar circle. However, the slope ($\beta=-1.66\sim-1.28$) of their IMF is rather simillar to that of the inner solar circle stars given by Garmany et al. (1982). This is in contradiction to their arguments of IMF gradient with the galactocentric distance. However, at present we do not have any definitive answer for the apparent contradiction.

The IMF slope ($\beta=-2.17\sim-1.99$) of the overall stars is quite close to that of local arm which is located inside and outside the solar circle and has the largest number of stars among the spiral arm groups considerd in this study. The slope is also quite similar to the slope ($\beta=2.0$) obtained by Lequex (1979) and Bisiacchi (1983) who used the evolutionary tracks of Chiosi et al. (1978) which are practically the same as the ones calculated by Maeder (1981).

Although the IMFs for massive stars discussed so far highly depend on the adoped evolutionary tracks, the IMFs derived in the present study reveal some circumstantial evidence for their regional difference between Local arm stars ($\beta = -2.09 \sim -2.00$) and Sagitttarius-Carina arm stars ($-1.77 \sim -1.72$). However, a lot of work remains to be done in order to draw any conclusion for the existence of the regional differences in the IMF for all the spiral arm stars.

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