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TWO SLOPES IN THE FREQUENCY DISTRIBUTION OF THE MASSES OF GALACTIC OPEN CLUSTERS?

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RESUMEN

Las masas de 130 cúmulos abiertos de la Vía Láctea se usaron para estimar la distribución en frecuencia de masas de cúmulos abiertos, $F(M_c)$. La conexión con la función inicial de masas, IMF de estrellas masivas y su relación con la función de luminosidad media relativa de 42 cúmulos abiertos muy jóvenes son discutidas. Se encontró que la pendiente de la distribución $F(M_c)$ muestra diferencias según se la evalúa en las regiones interior o exterior al círculo solar. Si esta evidencia estadística se suma a otros hechos observacionales, entonces podría indicarse que es el proceso de formación de cúmulos quien causa las variaciones observadas en la IMF de las mismas regiones. En particular, derivando el espectro de masas estelares de 42 cúmulos abiertos y combinando su pendiente con aquellas de la $F(M_c)$ se pueden reproducir resultados observacionales que indican variaciones galactocéntricas de la IMF de estrellas masivas.

ABSTRACT

Masses of 130 open clusters in the Milky Way were used to estimate the frequency distribution of the masses of open clusters, $F(M_c)$. The relation between the initial mass function, IMF, of massive stars and the relative mean luminosity function of 42 young open clusters are discussed. It was found that the slope of $F(M_c)$ is different when it is evaluated in the inner and outer part of the solar circle. If this statistical evidence is added to other observational features, then it would indicate that the process of cluster formation would cause the observed variation in the IMF. In particular, deriving the stellar mass spectra for 42 open clusters and combining its slope with that of $F(M_c)$, observational results may be obtained indicating galactocentric variations in IMF for massive stars.

Key words: CLUSTERS-OPEN – STARS-MASS

I. INTRODUCTION

According to Reddish (1978), the frequency distribution of the masses of open clusters, $F(M_c)$, and the initial mass function of isolated stars, IMF, can be intimately related. If the process by which an open cluster is created, is the same which originates an isolated star, as it is generally accepted, it appears reasonable that both, IMF and $F(M_c)$ show similar slopes within the observational errors. The acting mechanism in both processes would be gravitational contraction from an interstellar cloud. Since the earlier work of Burki (1977) it became clear that there are two different luminosity functions applicable to open clusters: one for open clusters placed outside the solar circle, and another one for open clusters located inside the solar circle.

After the derivation of the IMF by Lequeux (1979), which yielded about the same value as the one found by Salpeter (1955), the attention of researchers has been directed toward understanding the precise behavior of the IMF for massive stars. Some previous discussion has taken place around this topic. Garmany, Conti, and Chiosi (1982) computed the IMF for massive stars in the solar neighborhood and found two values for the slope of the IMF: (a) a very steep slope corresponding to stars placed outside the solar circle, and (b) a less steep slope corresponding to stars located within the solar circle. They computed the IMF using a sample of O type stars assumed to be complete up to within 3 kpc of the Sun. Similarly, Conti (1984) showed a decrease in the number of massive O type stars outside the solar circle. The reliability of these results was investigated later by Humphreys and McElroy (1984) using a more extensive sample of massive stars. These authors concluded that there are no differences between interior and exterior IMF. They argue that the star formation rate is perhaps different for both zones of the galactic plane in view of the lower number of massive stars found outside the solar circle. A recent work by Garmany (1984) using a more complete sample than the one of Garmany *et al.* (1982) confirms the existence of real differences in the slope of the IMF.

In this work we examine the question from a different point of view. The determination of masses of open clusters has not received major attention in recent years.

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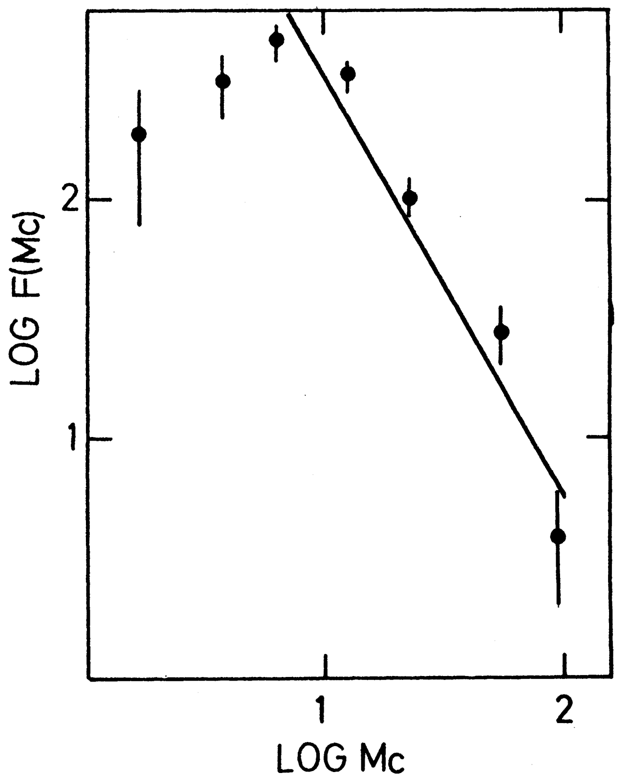

Fig. 1. log $F(M_C)$ versus log M_C for 130 open clusters. Solid line show the least squares solution. Error bars correspond to the square root of the number of clusters per mass interval.

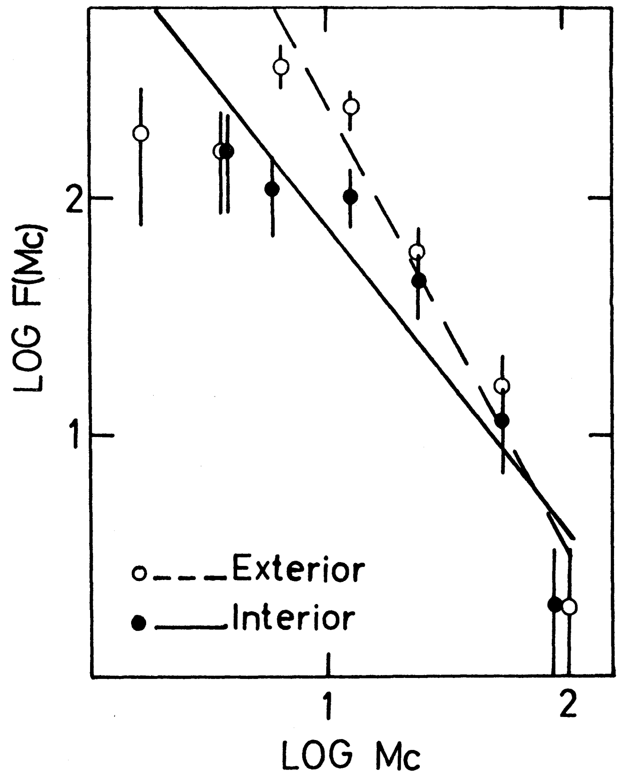

Fig. 2. Same meaning as in Figure 1. Solid and broken lines show the computed solutions for inner and outer regions.

However, such task would have a very important impact since it can greatly improve our knowledge of the scenario where the comparison of theory and observation of stellar evolution takes place. In this sense, some years ago, Bruch and Sanders (1983) transformed to absolute masses the relative masses given by Reddish for open clusters. However, Reddish's sample which contains only 72 open clusters, a rather small number of objects considering that nearly 1200 open clusters are listed in the solar neighborhood. We are now able to use masses from a sample of 130 open clusters, almost twice the number in Reddish's sample. Therefore we will use these clusters to investigate the $F(M_C)$ distribution.

TABLE 1

DATA USED FOR COMPUTING F(Mc) FROM 130 OPEN CLUSTERS

	General			Interior			Exterior		
Mass Interval	N	log Mc	log F(Mc)	N	log Mc	log F(Mc)	N	log Mc	log F(Mc)
1 – 2	3	0.22	2.28	0	...	...	3	0.22	2.28
2 – 4	10	0.57	2.50	5	0.58	2.20	5	0.56	2.20
4 – 8	30	0.80	2.68	7	0.77	2.05	23	0.81	2.56
8 – 16	43	1.10	2.54	13	1.10	2.01	30	1.10	2.38
16 – 32	26	1.36	2.01	11	1.38	1.64	15	1.38	1.77
32 – 64	14	1.74	1.44	6	1.74	1.07	8	1.73	1.20
64 –128	4	1.98	0.60	2	1.95	0.30	2	2.01	0.30

II. DATA AND ANALYSIS

To derive the $F(M_c)$ distribution, 130 masses listed in Lynga's (1981) catalogue were used. Although we do not find any estimate of the errors of the masses quoted in the catalogue, we assumed the whole sample to be a self-consistent set, as they were taken from a single source. Our main goal is to examine the behavior of the slope of the $F(M_c)$, in such a way that the internal consistency of the sample becomes more important than the exact value of the isolated mass of each open cluster. The method employed to compute $F(M_c)$ is the one developed by Reddish (1978). The counts were done in the way of reducing the mass of each open cluster to the mass of the open cluster NGC 2232 ($\log M_c = 2.0$). We have computed $F(M_c)$ as the number of clusters per unit mass interval, dN/dMc. Next, the clusters were divided into inner and outer clusters when their galactic longitudes lay in the range between 270° and 90° and between 90° and 270° respectively. In this way, although wrong inclusions may be produced due to distance effects, these should have little influence as most of the objects are within a radius of 3 kpc from the Sun. According to the criterion given above, 44 out of 130 open clusters are inside the solar circle. Table 1 lists the counts per mass interval for all the clusters and also for the inner and outer clusters. Figures 1 and 2 show the results of the counts for each case. From Table 1 it is easily noted that for both, the whole sample and the sample of outer clusters, there is a significant decrease in the cluster numbers below $\log M_c = 0.6$. Also, no cluster is found below $\log M_c = 0.5$ in the inner region. The small number of low mass clusters outside the solar circle can be attributed to incompleteness, as well as to the limited chance to survive the action of tidal forces in the galactic field. The lack of low mass clusters within the solar circle may be either the result of high visual absorption that hides poor clusters or some incompleteness effect. Inspecting Table 1, the number of very massive clusters is small. The same occurs in the sample of Reddish, who argued that the statistics for these points could be of low weight. But it is expected that the number of very massive clusters cannot be significantly increased (at least within 3 kpc of the Sun), and consequently these points must be taken into account to compute $F(M_c)$. To establish a confidence mass interval, we chose lower mass limits of $\log M_c = 0.6$ for outer clusters and of $\log M_c = 0.5$ for inner clusters. For each of the three sets of points in Table 1 we derive the following results, assuming a power law in adjusting the frequency distribution:

$$F(M_c) \propto M_c^{-1.74\,(0.09)} \text{, all clusters;}$$
$$F(M_c) \propto M_c^{-1.88\,(0.10)} \text{, outer clusters;} \quad (1)$$
$$F(M_c) \propto M_c^{-1.26\,(0.10)} \text{, inner clusters.}$$

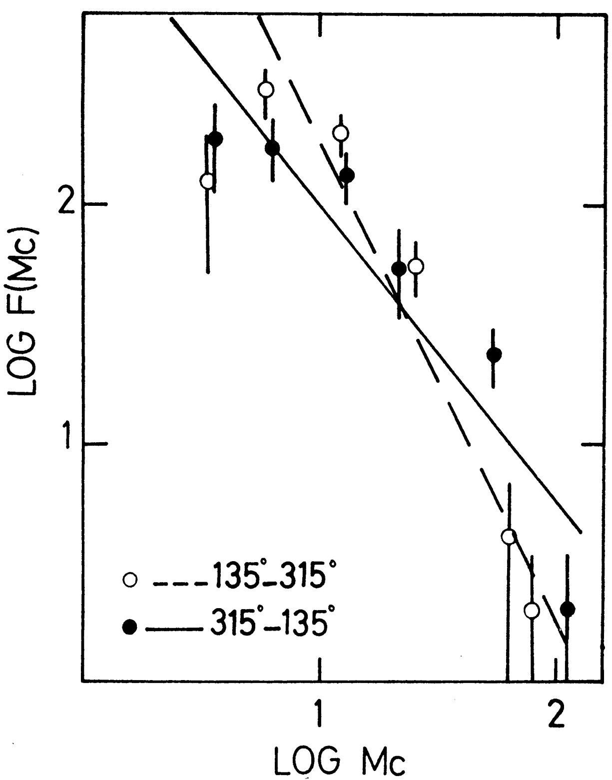

Fig. 3. Same meaning as in Figures 1 and 2 for the 315° – 135° and 135° – 315° regions respectively.

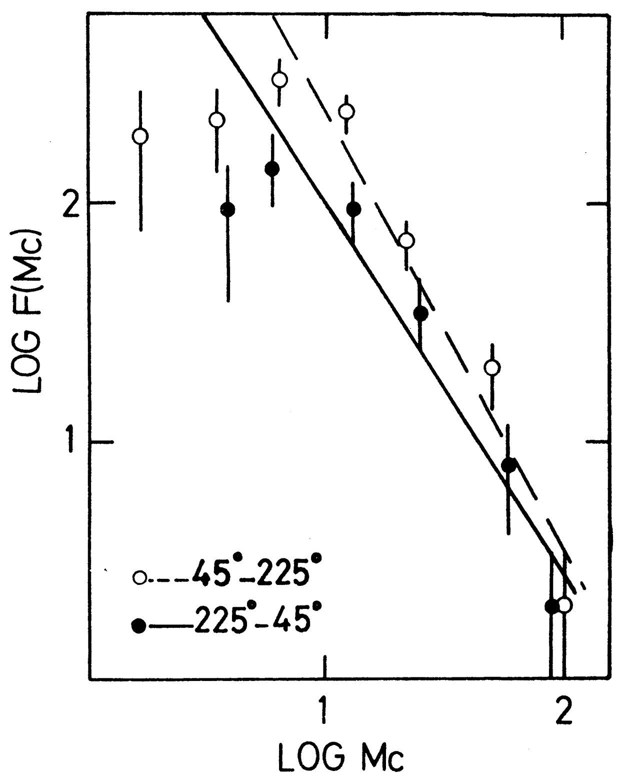

Fig. 4. Same meaning as in Figures 1 and 2 for the 225° – 45° and 45° – 225° regions respectively.

The coefficients of the power law were obtained through the least squares method, and the numbers in parentheses indicate the probable mean errors of the slopes. Error bars in Figures 1 and 2 are estimated from the square root of the number of clusters.

Different slopes for $F(M_c)$ are then evident for the inner and outer regions, being the slope for inner clusters flatter than that for outer clusters. On the other hand, there is observational evidence that a metallicity gradient exists in the Galaxy (Pagel and Edmunds 1981). Lynga (1982) listed 50 open clusters where metallicity had been measured. Their distribution on the galactic plane suggests that a diagonal metallicity gradient may be a better description than a radial gradient. He places the gradient along a line from 45° to 225° (galactic longitude). We think that it may be interesting to investigate the connection, if there is any, between the changes of the slope of $F(M_c)$ and this metallicity variation. The galactic enrichment is produced by massive stars and it appears reasonable that its variation must be followed by changes in the distribution of massive stars which, in turn, would follow the distribution of open clusters. We have computed $F(M_c)$ in the direction where Lynga suggested the existence of a diagonal gradient, but we have also evaluated it along a line perpendicular to 45° – 225° to examine the reliability of that result. The following regions were then considered: the first includes the zones limited by 135° – 315° and 315° – 135° (Figure 3); the second includes the zones limited by 45° – 225° and 225° – 45° (Figure 4); the results are presented in Tables 2 and 3 respectively. The least square solutions yield:

$$F(M_c) \propto M_c^{-2.02\,(0.10)} \quad , 135° - 315°;$$

$$F(M_c) \propto M_c^{-1.25\,(0.11)} \quad , 315° - 135°;$$

$$F(M_c) \propto M_c^{-1.84\,(0.10)} \quad , 45° - 225°;$$

$$F(M_c) \propto M_c^{-1.55\,(0.10)} \quad , 225° - 45°.$$

In the first region $F(M_c)$ shows two very different slopes whilst in the second region the difference in the slopes becomes smaller. The number of clusters involved in the first region is almost the same for the two subdivisions, but in the second region there are more clusters between 45° – 225° compared to 225° – 45° (see Tables 2,3). As a general rule there are more clusters placed outward of the solar circle in every zone we are discussing. By counting the number of clusters in each quadrant of the galactic plane, it is found that the second quadrant has 57 open clusters whilst the rest of the clusters are distributed in almost the same numbers in each of the other three quadrants. The large number of clusters in the second quadrant may be a consequence of more completeness, as this quadrant is available to observers of the northern hemisphere. Then, it would seem that Lynga's result is confirmed because the changes of the slope of $F(M_c)$ are more noteworthy between 135° – 315° and 315° – 135° than between 90° – 270° and 270° – 90°. On the other hand, between 45° – 225° and 225° – 45° the changes are substantially smaller.

As a whole, the sample of clusters used in this work may be affected by incompleteness. An estimation of the degree of incompleteness is very complex due to the irregular distribution of galactic open clusters. This could be more important for clusters of low masses placed inward of the solar circle because it becomes difficult to discover small clusters projected onto the dense stellar field of the southern Milky Way. Such incompleteness would diminish the slope of the interior $F(M_c)$, i.e., a progressive falling off in the number of interior open

TABLE 2

DATA USED FOR F(Mc) COMPUTED ALONG A DIAGONAL GRADIENT OF METALLICITY

	315° – 135°			135° – 315°		
Mass Interval	N	log Mc	log F(Mc)	N	log Mc	log F(Mc)
1 – 2	2	...	...	1	...	...
2 – 4	6	0.56	2.28	4	0.57	2.10
4 – 8	11	0.80	2.24	19	0.77	2.48
8 – 16	18	1.11	2.13	25	1.09	2.30
16 – 32	12	1.34	1.68	14	1.40	1.74
32 – 64	12	1.73	1.38	2	1.80	0.60
64 – 128	2	2.05	0.30	2	1.90	0.30

TABLE 3

DATA USED FOR F(Mc) ALONG A PERPENDICULAR LINE TO THAT OF TABLE 2

Mass Interval	225° – 45°			45° – 225°		
	N	log Mc	log F(Mc)	N	log Mc	log F(Mc)
1 – 2	0	...	...	3	0.22	2.28
2 – 4	3	0.59	1.98	7	0.55	2.35
4 – 8	9	0.78	2.15	21	0.81	2.52
8 – 16	12	1.12	1.98	31	1.09	2.39
16 – 32	9	1.40	1.55	17	1.35	1.83
32 – 64	4	1.79	0.90	10	1.71	1.30
64 –128	2	1.95	0.30	2	2.01	0.30

clusters when the masses become lower and lower, making thus flatter the slope of the interior $F(M_c)$. An important point to be discussed now is related to the influence of errors of the mass determinations on the $F(M_c)$ distribution. As it was pointed out, no indication about such errors is given in Lynga's catalogue, but we can make some acceptable assumptions about them for the estimation of their effect on $F(M_c)$. We considered 40% as a reasonable error in the masses. For calculation purposes we attributed an error of 50% in the mean mass for each interval where the counts are made. We adopted this error for all the mass intervals and checked the behavior of the slopes. We did not find variations greater than 15%, and in all cases the assumed error decreases the slopes of regression lines. A more serious error seems to be the one due to incompleteness of the data. Although incompleteness in the sample could explain the different slopes for interior and exterior regions, it is important to check this against other observational features.

III. LUMINOSITY FUNCTION, MASS SPECTRA AND $F(M_c)$

In what follows we will examine the behavior of the normalized relative mean luminosity function (RMLF), of 42 very young open clusters (age $< 23 \times 10^6$ years). The sources for spectroscopic and photometric data (*UBVRI*) in those clusters and also the procedure used to derive their intrinsic quantities are given in Vázquez and Feinstein (1988). All stellar data were carefully examined, i.e., membership and distance moduli were obtained using a similar procedure for each one of the clusters. Following a common method we computed the luminosity function for each cluster and then we obtained the RMLF for the clusters placed outside and inside the solar circle. Few red and yellow supergiant stars were included at the top of the respective parent main sequences. A comparison between both RMLF in Figure 5 indicates that there exists an important deficiency of luminous stars with M_v –7 to –3, for clusters placed outside the solar circle. RMLF reflect important changes in luminosity along the galactic plane, and in our opinion, any incompleteness will enhance this change (this result is opposite to the one encountered by Burki 1977). We think that this feature cannot be separated from the changes we encountered in $F(M_c)$.

Let us add some comments about the relation between IMF and $F(M_c)$. We will use, for comparison purposes, the IMF for massive stars determined by Garmany *et al.* (1982). They obtained:

$$\mathrm{IMF} \propto M^{-3.1} \quad \text{, for the outer region;}$$

$$\mathrm{IMF} \propto M^{-2.3} \quad \text{, for the inner region.}$$

The regions where the IMF of Garmany *et al.*. was computed is the same as the region where we determined the $F(M_c)$ distribution, namely: 90° – 270° and 270° – 90°. In comparing with expressions (1), the slopes of both distributions, IMF and $F(M_c)$, show a similar behavior in the sense that in the interior region they are flatter than outside the solar circle. The changes in the respective slopes are almost the same in both cases.

From Reddish (1978) it is known that the total mass which a stellar aggregate can have, follows a relationship where:

$$M_c \propto M_{max}{}^{\gamma - 1} \quad ,$$

being M_c the cluster mass and γ the slope of IMF. Moreover, the IMF for massive stars is determined by (Vanbeveren 1983):

$$\mathrm{IMF} \propto M^{-\gamma} \int_{M_c}^{\infty} F(M_c)\, dM_c \quad .$$

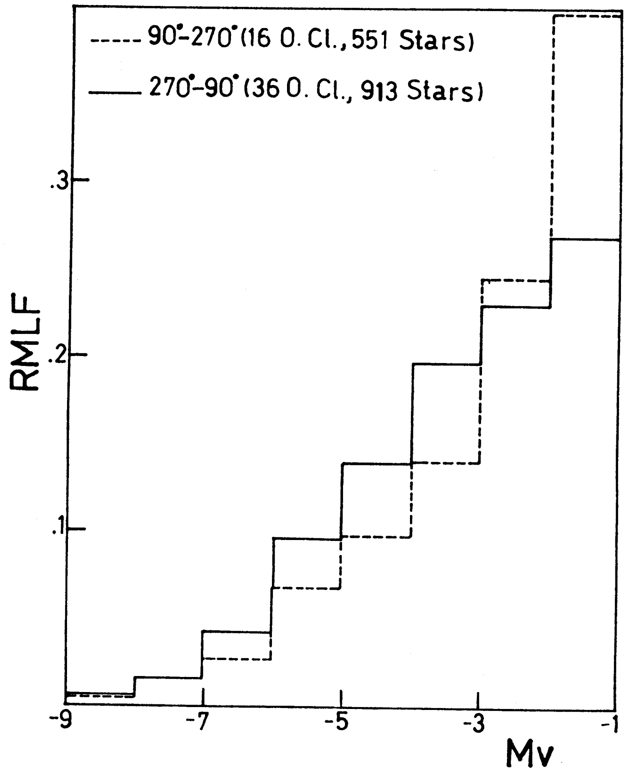

Fig. 5. The relative mean luminosity functions, RMLF, for 42 young open clusters. Dashed line is for the clusters in the region 90° – 270° and solid line is for the clusters in the region 270° – 90°. First region includes 16 open clusters (551 stars) and second region includes 26 open clusters (913 stars).

Here, M is the stellar mass and γ is the exponent for field stars used in the IMF (–2.35 from Salpeter; –3.1 to –2.3 from Garmany *et al.*). Then, $F(M_c)$ appears governing the IMF through the possible number of massive stars to be produced in an aggregate. From a statistical point of view, a star of mass M can be only originated in an open cluster if M is less than, or equal to the maximum stellar mass, M_{max}, that can be formed in the open cluster. This M_{max} depends on the total mass of the cluster:

$$M \leqslant M_{max} \propto M_c^{\,1/\gamma - 1} \quad .$$

From Vanbeveren (1983), the IMF for massive stars can be expressed as:

$$IMF \propto M^{\gamma_1 (1 - \gamma) - 1} \quad , \qquad (2)$$

where γ_1 is the slope of $F(M_c)$. If γ is a constant, different values of γ_1 will give different slopes of IMF. As the expression (2) indicates that IMF is governed by $F(M_c)$, it would be important to estimate the slope of IMF from open cluster stars. To do this the RMLF in Figure 5 were converted to stellar mass spectra using the M_v – $M/M_\odot$ relation given by Allen (1973). Table 4 lists the adopted mean mass per luminosity interval, the star counts and $\log\phi(M)$ for 90° – 270° and 270° – 90°. Figure 6 shows the solutions by the least squares method. The slope for each distribution is essentially the same: γ = 2.3 for outer clusters, and γ = 2.2 for inner clusters. This result is in excellent agreement with that derived by Sagar *et al.* (1986) for five young open clusters, γ = 2.4. If we substitute in the expression (2) the slopes from $F(M_c)$ and the mass spectra of the open clusters, we find that

$$IMF \propto M^{-3.3} \quad , \text{outer} \; ;$$

$$IMF \propto M^{-2.4} \quad , \text{inner} \quad .$$

TABLE 4

DATA FOR MASS SPECTRA IN 42 OPEN CLUSTERS

			90° – 270°		270° – 90°	
M_v Interval	log M	Δlog M	N	log ϕ(M)	N	log ϕ(M)
–9/ – 8	2.20	0.23	3	1.11	6	1.41
–8/ – 7	2.06	0.21	9	1.63	15	1.85
–7/ – 6	1.86	0.24	15	1.79	40	2.22
–6/ – 5	1.58	0.26	38	2.16	88	2.52
–5/ – 4	1.38	0.18	54	2.47	128	2.85
–4/ – 3	1.21	0.16	78	2.68	180	3.05
–3/ – 2	1.05	0.17	135	2.89	210	3.09
–2/ – 1	0.87	0.19	219	3.06	246	3.11

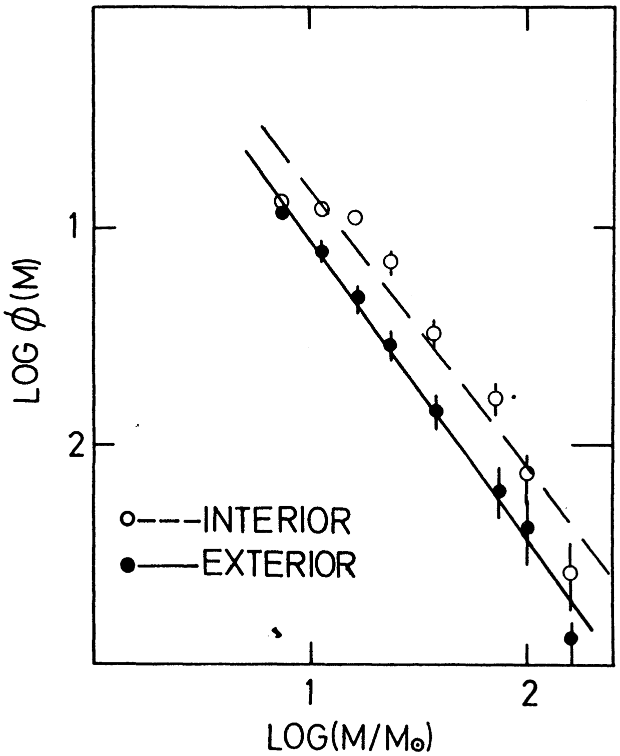

Fig. 6. Mass stellar spectra from inner and outer clusters in Figure 5. Solid and broken lines show the solutions from the least squares method.

There is a surprisingly good agreement between these values and those derived by Garmany *et al.* (1982). Our results suggest that $F(M_C)$ indeed governs the star production rate. Taking into account that most of the stars used by Garmany *et al.* for estimating IMF are field stars (see their Figure 2) one is inclined to assume that field stars are born in stellar aggregates. Reddish has estimated the slope of the $F(M_C)$ to be equal to −2.2. This is nearly Salpeter's (1955) value of the IMF, −2.35. The similarity between these two values may be taken as a support for the supposition of an identical process acting in both stellar and cluster formations. We did not encounter such similarity between mass spectra and the $F(M_C)$ slopes derived in this work. Indeed, if a least squares solution is used for adjusting Reddish's data the slope given by him can change from 2.2 to 1.9, which shows no similarity with Salpeter's value.

IV. CONCLUSIONS

$F(M_C)$ shows important galactocentric changes; and when compared with the IMF from Garmany *et al.*, it remains clear that both distributions vary in the same sense and quantity, but their moduli are very different.

If the changes of the slope of $F(M_C)$ we encountered in this work are true, then it is possible that what Conti (1984), Garmany *et al.* (1983), and Garmany (1984) have obtained is not a strong decrease in the number of outer massive stars obeying a particular evolutionary situation but that it is due to the changes in the $F(M_C)$ distribution. From a statistical point of view, $F(M_C)$ exhibits two slopes and incompleteness effects can adequately explain it. This result by itself may not be meaningful; it may have meaning when it is combined with other observational features. At first, $F(M_C)$ seems to be different in the 315° − 135° versus the 135° −315° zone where the number of clusters in each zone is almost the same and the effects of incompleteness due to the lack of low mass clusters is small. Indeed, after analyzing our data, we prefer the evidence that in every case, the change in the slope of $F(M_C)$ seems to confirm some radial gradient.

We can add, then, the following arguments: (1) the distribution of massive stars ($M > 40\ M_\odot$) on the galactic plane (Conti 1984) suggests that outside the solar circle there is a remarkable deficiency of these. (2) The IMF for massive stars shows two slopes suggesting thus a smaller production of massive stars outside the solar circle. (3) Using 42 very young open clusters we computed the luminosity functions for interior and exterior clusters. They show a flatter distribution of luminosity in the interior region. Outside the solar circle, the luminosity falls abruptly from $M_v = -3$ to −7. (4) Our analysis of the $F(M_C)$ distribution also indicates a decrease in the number of massive clusters outward of the solar circle. (5) The mass spectra for the open cluster stars suggest a universal slope ($\gamma = 2.3$) and when it is combined with the respective slopes of $F(M_C)$ we can reproduce very well the results of Garmany *et al.* Combining all these evidences one can argue that, primarily, the cluster formation process drives —in some way— the production of massive stars. This work only marks a statistical tendency which in our opinion should be investigated in detail with more and better known masses of open clusters. We are working on this matter by transforming to the Reddish system the masses of several galactic open clusters to examine this question with a more complete sample of galactic clusters.

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