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STAR FORMATION EFFICIENCY IN CLOUDS OF VARIOUS MASSES

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ABSTRACT

The present study is aimed at finding out the effect of variation of the initial mass function (IMF) on star-formation efficiency (SFE) in clouds of various masses. Using the model of Elmegreen and Clemans, it is found that the star-formation efficiency depends on the IMF, and, if the slope of the IMF is steeper, rich clusters with relatively high SFEs will be formed. Steeper mass function also favors the formation of bound clusters. The results obtained in the present work also explain the concentration of the oldest clusters in the outer disk of the Galaxy and the increasing trend in the average total mass of clusters with age as suggested by Pandey *et al.*

Subject headings: clusters: open — luminosity function — stars: formation

I. INTRODUCTION

Recent studies indicate that the probability of formation of unbound clusters in our Galaxy is quite high because star formation is a destructive and inefficient process (Lada, Margulis, and Dearborn 1984). The majority of stars in our Galaxy are formed in giant molecular clouds, where the star formation efficiency (SFE), on average, is quite low (~5%). After the formation of massive stars, these provide energetic winds in their surroundings, which consequently disperse their parent molecular clouds. The resulting association becomes unbound and diffuse as a general field population (Margulis and Lada 1983; Wilking and Lada 1985).

However, the existence, within 1 kpc of the Sun, of about 115 bound open clusters, with typical life times of about 10^8 yr (Pandey and Mahra 1986) leads to an interesting problem for star-formation studies. Several studies have been carried out suggesting that the formation of a bound cluster system requires a SFE of nearly 50% where the cloud disruption is sudden and nearly 20% where cloud disruption takes place on a longer time scale. Therefore, whether a newly born cluster will be bound or unbound, depends on parameters such as SFE, gas removal time, and initial mass density (Margulis and Lada 1983).

Elmegreen and Clemens (1985), using a fixed initial mass function given by Miller and Scalo (1979), have theoretically concluded that SFEs are relatively higher in low-mass clouds than in high-mass clouds. However, the universality of the IMF of open clusters in the Milky Way does not seem to be a valid assumption. Stecklum (1985) has concluded that the IMF depends on the age of the cluster, and the steepness of the IMF of open clusters increases with increasing age. The work of Tarrab (1982) supports the conclusions of Stecklum (1985). Recently Pandey *et al.* (1989) have derived integrated parameters for Population I type clusters assuming an age-dependent IMF. A comparison of the theoretically obtained integrated parameters with the observational data of open clusters in the Milky Way shows a better agreement between the two than does previous work where a constant IMF was assumed.

The present study is aimed at finding out the effect of variation of the IMF on SFE in clouds of various masses.

II. ESTIMATION OF SFE

The SFE depends on the order in which stars of different masses form. The efficiency will be lower if the most massive and consequently most destructive stars form earlier. Herbig (1962) suggested that low-mass stars form first and high-mass stars form only near the end of cluster formation. This phenomenon could result from a stochastic process but the deficiency of low-mass stars in some clusters cannot be explained by a stochastic process and requires that the process of low-mass star formation ceases before high-mass star formation begins (Evans 1985). Therefore, it was assumed that stars form in a random manner and the formation of the most massive star terminates the star-formation process.

Larson (1982) has found that the mass of the most massive star, $M_{\rm star}$, associated with the cloud increases systematically with $M_{\rm cloud}$, the mass of the molecular cloud. This relationship can be represented by the equation

$$M_{\rm star} = 0.33 M_{\rm cloud}^{0.43} .$$

This relation has been used to obtain the mass of the most massive star which may form in a molecular cloud.

The first empirical derivation of the initial mass function was made by Salpeter (1955). The problem was reanalyzed by Scalo (1986), and it has been concluded that studies of composite IMFs for many clusters suggest slope of the IMF, $X = 1.7 \pm 0.2$ for $1.5 \lesssim M \lesssim 10\ M_\odot$, but there are indications of flattening at larger masses. Sagar *et al.* (1986) have concluded that the average value of X in the mass range 1.25 to 60 $M_\odot$, is about 1.5 ± 0.3. Rana (1987) has suggested a constant slope of 1.80 for the mass range $0.2 < \log M < 1.95$ and for mass range below $\log M = 0.2$ a quadratic power law may be fitted.

Thus, the present knowledge about the true IMFs of open clusters still remains a debatable question. But for the sake of simplicity, we have adopted a single power-law IMF. The true IMFs of open clusters may be more complex than this. However, any small variation of IMF from the assumed form may not have any significant effect on the results obtained in the present work. We have used the approach of Elmegreen and Clemans (1985) to determine the SFEs.

Stars are selected randomly according to the following relation

$$\log N = -X \log M + C ,$$

where N is the number of stars having mass M and X is the slope of the mass function. Following conditions were checked at each step (cf. Elmegreen and Clemens 1985).

$$M_* < M_{\rm cloud} \qquad (1)$$

$$L_* < 100 M_{\rm cloud} \qquad (2)$$

$$M_{{\rm cloud},\, i} < M_{\rm cloud}(1 - \epsilon_1) , \qquad (3)$$

where $M_* = \Sigma M_i$ is the total stellar mass formed up to that time, $L_* = \Sigma M_i$ is the total luminosity up to that time, $M_{{\rm clear},\, i} = 1.1(L_i/L_\odot)^{3/2} \quad (\alpha/0.05)^{3/2} M_{\rm cloud}^{-1} \quad (1 - \epsilon_i)^{-1/2}$ is maximum mass of gas that can be removed from the parent cloud by a stellar wind from the ith star, $M_{\rm cloud}$ is the mass of the cloud, and $\epsilon_i = \Sigma M_i / M_{\rm cloud}$ is the SFE at the time of formation of the ith star. We have used $\alpha = 0.05$. If any of the above-mentioned conditions is not satisfied, then star formation is assumed to stop.

III. RESULTS

A minimum of 200 simulations were run for each case of the clouds having masses 10^2 and 10^3 $M_\odot$, and 100 simulations were run for $M_{\rm cloud} = 10^4$ $M_\odot$. The normalized distribution of relative number of clouds, p, with efficiency between ϵ and $\epsilon + d\epsilon$ is plotted in Figure 1, which manifests that the SFE also depends on the IMF. It is also concluded that the SFE increases systematically with the slope of the mass function.

In Figure 2 we have plotted the probability of formation of bound clusters as a function of the slope of the IMF. This figure manifests that steeper mass functions favor the formation of bound clusters.

In Figure 3 we have plotted the number of stars in clusters having maximum probability of formation against the assumed range of SFE. From this figure it is concluded that the probability of formation of rich clusters is higher for higher values of the SFE.

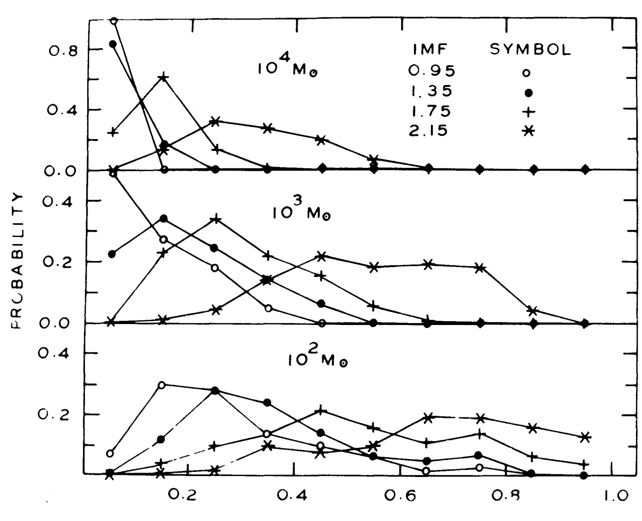

FIG. 1.—Probability that a cluster forms with an efficiency between ϵ and $\epsilon + d\epsilon$ in clouds of various masses as a function of efficiency.

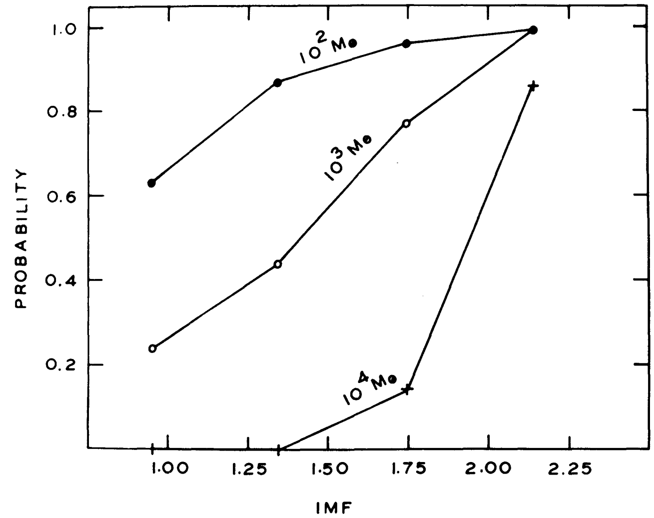

FIG. 2.—Probability, p, of formation of bound clusters as a function of the slope of the IMF. The critical value of the SFE for the formation of bound clusters has been assumed to be 20%.

IV. DISCUSSIONS

The oldest known open clusters are found to be strongly concentrated in the outer part of the Galactic disk (Lynga 1980, 1982; van den Bergh and McClure 1980). Van den Bergh and McClure suggest that the relatively high survival rate of clusters in the outer disk might be possibly due to the fact that such objects suffer relatively few disruptive encounters with giant molecular clouds, objects which are mainly located in the inner disk of the Galaxy. However, there are many large molecular clouds located in the outer disk of the Galaxy (see, for example, Mead and Kutner 1988). In fact, about a third of the molecular material in the Galaxy is located outside the solar circle. This suggests that van den Bergh and McClure's argument is probably wrong. Alternatively, Wielen (1971) suggests that the total life time of a cluster mainly depends on its initial mass.

The studies of Stecklum (1985) and Tarrab (1982) suggest that the slope of the mass function must have been steeper 10^8–10^9 yr ago than at the present time. Moreover, the slope of the mass function increases toward the outer disk of the Galaxy (Stecklum 1985). This means that the SFE should have been relatively higher 10^9 yr ago, especially in the outer disk of the Galaxy. Consequently, at that time rich massive clusters should have been formed in the outer disk of the Galaxy. Since rich clusters have comparatively longer life times (Pandey and Mahra 1986), the present work explains the strong concentration of oldest known open clusters in the outer disk of the Galaxy.

Due to the dynamical evolution of Galactic clusters, the total mass and the number of stars in open clusters will decrease with increasing age, since clusters continuously lose stars by escape processes. Consequently, one may expect that the average total mass of clusters decreases with age. Pandey *et al.* (1987) have found that the average total mass of clusters in the Galaxy decreases with age. However, there is an increasing trend after 10^8 yr. This may be due to the fact that 10^9 yr ago the slope of the IMF, as we have discussed earlier, was relatively steeper. This would produce rich, massive clusters at that time. Since rich, massive clusters have longer life times (Wielen

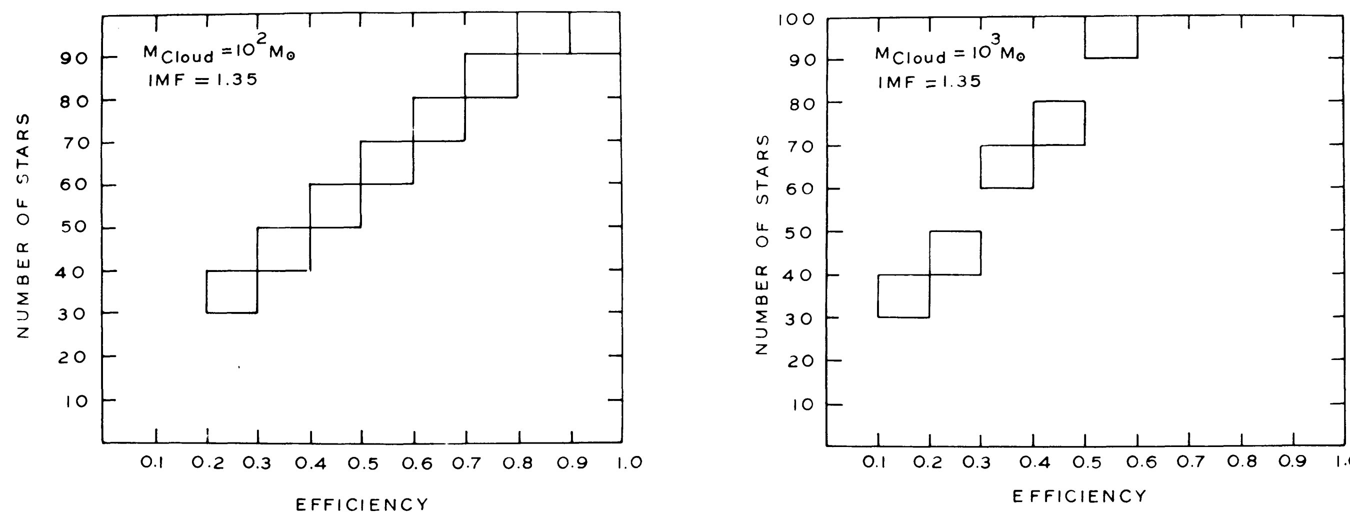

FIG. 3.—Number of cluster members in clusters having maximum probability of formation as a function of SFE in a cloud having mass $M_{\rm cloud} = 10^2\ M_\odot$ with a slope of mass function, $X = 1.35$. Each rectangle represents the SFE range and the dispersion in the number of cluster members, e.g., the first rectangle represents the maximum probability is that 30–40 cluster members will be formed for SFE range 0.2–0.3. (*b*) Same as (*a*) but for $M_{\rm cloud} = 10^3\ M_\odot$.

1971; Pandey and Mahra 1986), the oldest clusters may show a higher average total mass than medium-aged clusters.

V. SUMMARY

The model of Elmegreen and Clemens (1985) has been used to study the effect of varying the IMF on the formation of open clusters. It is found that the SFE depends on the IMF. If the slope of the IMF is steeper, rich clusters with relatively high SFEs will be formed.

The model explains the concentration of the oldest clusters in the outer disk of the Galaxy and the increasing trend in the average total mass of clusters with age as suggested by Pandey *et al.* (1987).

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