THE UNUSUAL STELLAR MASS FUNCTION OF STARBURST CLUSTERS

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ABSTRACT

I present a model to explain the mass segregation and shallow mass functions observed in the central parts of starburst stellar clusters. The model assumes that the initial pre-stellar cores mass function resulting from the turbulent fragmentation of the proto-cluster cloud is significantly altered by the cores coalescence before they collapse to form stars. With appropriate, yet realistic parameters, this model based on the competition between cores coalescence and collapse reproduces the mass spectra of the well studied Arches cluster. Namely, the slopes at the intermediate and high mass ends, as well as the peculiar bump observed at 6 $M_\odot$. This coalescence-collapse process occurs on a short timescale of the order of the free fall time of the proto-cluster cloud (i.e., a few 10^4 years), suggesting that mass segregation in Arches and similar clusters is primordial. The best fitting model implies the total mass of the Arches cluster is 1.45×10^5 $M_\odot$, which is slightly higher than the often quoted, but completeness affected, observational value of a few 10^4 $M_\odot$. The model implies a star formation efficiency of ~ 30 percent which implies that the Arches cluster is likely to a gravitationally bound system

I. INTRODUCTION

Starbursts clusters such as the Arches cluster, the Quintuplet, NGC 3603, and R136 in the LMC's 30 Doradus star forming region, constitute probably a peculiar class of stellar clusters. They are characterized by high stellar surface densities (up to 10^5 $M_\odot$ pc^{-2} for the Arches cluster), radially integrated stellar mass functions which are shallower than the "universal' Salpeter power law function of $dN/dM \propto M^{-\alpha=-2.35}$ and display a significant amount of mass segregation (Figer et al. 1999, Yang et al. 2002, Stolte et al. 2002, Sung & Bessel 2004, Stolte et al. 2005, Harayama et al. 2007, Andersen et al. 2007). Over the past years, the development of high resolution near infrared instruments has enabled the measurements of the IMF of such clusters in different annuli from the center of the cluster. In the case of the Arches cluster, the IMF is observed to be nearly flat (i.e., $\alpha = -1$) between the center and the cluster core radius which is $R_{c0} \sim 0.2$ pc i.e., ($\alpha \sim 0$ Figer et al. 1999; Stolte et al. 2002) then α increases to $-[1.8 - 1.9]$ in the second annuli (between ~ 0.2 and 0.4 pc), before becoming a Salpeter like function in the outer regions.

As star counting in the inner annuli might still be affected by crowding, much attention has been given to the shallower than Salpeter IMF in the second annuli. This mass segregation has been interpreted as the result of dynamical processes (e.g., Kim et al. 2006).

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However, dynamical models do not address the question of whether the primordial stellar mass function of the cluster was shallow. Moreover, a few peculiarities of the observed Arches mass function such as the bump at ~ 6 $M_\odot$ are not explained by these models. Interestingly, peculiar features such as bumps and dips in the mass function are observed also in other clusters (NGC 3603, Harayama et al. 2007, and R 136 Andersen et al. 2007). In this work, we propose an alternative idea which is based on the efficient coalescence of pre-stellar cores (PSCs) in the proto-Arches cloud and their subsequent collapse into stars. The coalescence of cores can result in a shallower core mass function (CMF) than the initial Salpeter like CMF Salpeter. Under the assumption that individual cores collapse into individual stars, the stellar mass function will inherit this shallower than Salpeter mass function.

II. RESULTS

The coalescence model is discussed in detail in Dib et al (2007a,b). Here, its basic features are summarized. PSCs are embedded in an isothermal ($T = 10$ K) molecular (MC). The PSCs and MC have flat cores and follow r^{-2} and r^{-4} profiles in their outer parts. As time advances, the radius of a PSC will decrease under the effect of gravitational contraction, thus reducing the coalescence cross section. The PSC is assumed to contract on a timescale, $t_{cont,p}$, which is a number of times the PSC free fall time $t_{cont,p} = \nu\ t_{ff,p}$. At a given location r in the cloud, the time dependent coa-
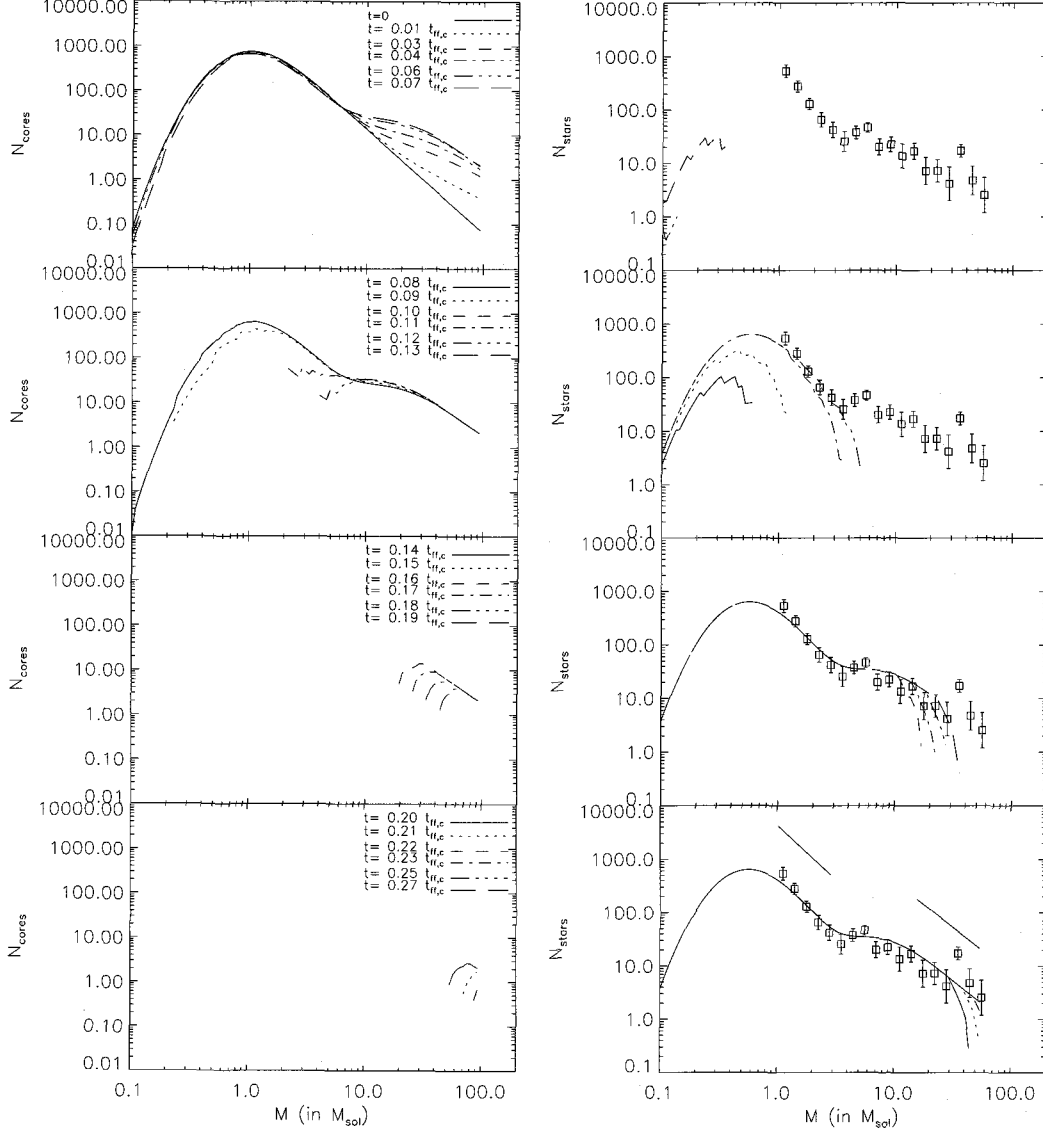
Fig. 1.— Time evolution of the pre-stellar cores mass function (left) and the stellar mass function (right) in the region of the proto-cluster cloud between 1 and 2 times the cloud's core radius $R_c = 0.2pc$. The stellar mass function is compared to that of the Arches stellar cluster mass function (Kim et al. 2006; open squares). Fits to the simulated IMF yield slopes of -2.04 ± 0.02 and -1.72 ± 0.01 in the mass range of [1-3] $M_\odot$ and ≥ 15 $M_\odot$, respectively, in very good agreement with the observations. The fits, over-plotted to the data, are shifted by 1 dex for the sake of clarity.

lescence cross section between a core of mass M_i and another of mass M_j and which accounts for the effect of gravitational focusing is given by:

$$\sigma(M_i, M_j, r, t) = \pi \left[R_{p,i}(r, M_i, t) + R_{p,j}(r, M_j, t)\right]^2$$
$$\times \left[1 + \frac{2G(M_i + M_j)}{2v^2(R_{p,i}(r, M_i, t) + R_{p,j}(r, M_j, t))}\right]. \quad (1)$$

As molecular clouds are unlikely to be virialized (e.g., Dib et al. 2007c), it is assumed that the cores relative velocity is not constant at a given position in the cloud and is rather better described by a Larson type relation $v(r) = v_0 r(pc)^\alpha$ (Larson 1981; $v_0 = 1.1$ km s^{-1}), with a lower limit being the local thermal sound speed, which is uniform across the isothermal

MC. As initial conditions for the PSCs mass distributions at different cloud radii, we adopt distributions that are the result of the gravo-turbulent fragmentation of the cloud, following the formulation given in Padoan & Nordlund (2002). The initial distribution of core resulting from the turbulent fragmentation of the proto-cluster in the second annuli (between 0.2 and 0.4 pc) cloud is show in Fig. 1 (full line, corresponding to $t = 0$). In order to follow the time evolution of the PSCs, one needs to solve the following integro-differential equation of $N(r, M, t)$

$$\frac{dN(r, M, t)}{dt} = 0.5 \times \eta(r) \times$$

$$\int_{M_{min}}^{\Delta M} N(r,m,t)N(r,M-m,t) \times$$

$$\sigma(m,M-m,r,t)v(r)dm$$

$$-\eta(r)N(r,M,t) \times$$

$$\int_{M_{min}}^{M_{max}} N(r,m,t)\sigma(m,M,r,t)v(r)dm, \quad (2)$$

where the first and second terms in the right hand side of Eq. 2 correspond to the rate of creation and destruction of a PSC of mass M, at location r, respectively. In Eq. 2, $\Delta M = M - M_{min}$, and $\eta(r)$ is a coefficient which represents the coalescence efficiency, with $\eta \leq 1$. In order to evaluate the transition from PSCs to stars, we compare, at each timestep, the local coalescence timescale to the local contraction timescale for PSCs of a given mass. The local coalescence timescale is $t_{coal}(r,M) = 1/w_{coal}(r,M)$ where w_{coal} is the coalescence rate which is given by:

$$w_{coal}(r,M) =$$

$$\frac{2^{1/2}v(r)}{V_{shell}(r)} \sum_{j=1}^{mbin} (R_i+R_j)^2 \left[1 + \frac{2G(M_i+M_j)}{2v^2(R_i+R_j)} \right], \quad (3)$$

where $mbin$ is the number of mass bins, and V_{shell} is the volume of the shell of width dr located at distance r from the MC's center. The contraction timescale is given by Eq. 1. Whenever the local contraction timescale is shorter than the local coalescence timescale, PSCs are collapsed into stars. When a PSC collapses to form a star, a fraction of its mass is re-injected into the proto-cluster cloud in the form of an outflow. This mass loss is accounted for in a purely phenomenological way by assuming that the mass of a star which is formed out of a PSC of mass M_p is given by $M_* = \psi M_p$, where $\psi \leq 1$. Matzner & McKee (2000) showed that ψ can vary between $0.25 - 0.7$ for stars in the mass range $0.5 - 2 M_\odot$. As there is no evidence so far, for or against, whether this result holds at higher masses, it is assumed here that a similar fraction of the mass of a PSC is lost in the outflow independent of its mass.

Fig. 1 displays the time evolution of the cumulative PSC populations in the region $[R_{c0} - 2 R_{c0}] = [0.2-0.4]$ pc, which corresponds to the second annulus of the Arches cluster for a model with $\eta = 0.5$, $\nu = 10$, mass of the cloud $M_c = 5 \times 10^5 M_\odot$, the radius and core radius of the cloud $R_c = 5$ and $R_{c0} = 0.2$ pc, respectively, an initial peak density of the PSCs $\rho_{p0} = 10^7$ cm^{-3}, $\alpha = 0.37$, $\psi = 0.58$, and the fraction of the total cloud mass present in the cores $\epsilon = 0.5$. In the initial stages, the most massive PSCs, that have a larger cross section, coalesce faster than the less massive ones, essentially by capturing the numerous intermediate mass PSCs and causing a rapid flattening of the spectrum at the high mass end. By $t \sim 0.07$ $t_{ff,c}$ ($t_{ff,c} = (3\pi/32G\bar{\rho}_c)^{1/2} \sim 3 \times 10^4$ yr is the MC free fall timescale), a first generation of the smallest PSCs collapses to form stars. As time advances, more massive stars are formed in the shell (massive cores collapse later because of their lower average density) and in parallel the PSCs population decreases. By $t \sim 0.1$ $t_{ff,c}$ the intermediate mass PSCs which constitutes the largest mass reservoir for coalescence collapses into stars. At this time, the turnover in the PSCs mass spectrum is located at $\sim 8 - 10 M_\odot$. Since the reservoir of intermediate mass objects is depleted, the remaining massive PSCs coalesce at a slower pace before they collapse. By $t \sim 0.25$ $t_{ff,c}$, all PSCs of different masses in the shell have collapsed and formed stars. Because of mass loss, the stellar IMF is shifted to lower masses (bump shifted to $\sim 6 M_\odot$). In summary, the resulting IMF is not very different from the PSCs mass spectrum after the initial and rapid stage of strong coalescence until $t \sim 0.01$ $t_{ff,c}$. In Fig. 1, over-plotted to the numerical result is the cumulative mass spectrum of the Arches cluster in the annulus of [0.2-0.4] pc (Kim et al. 2006). The coalescence-collapse model agrees better with the observations than models based on mass segregation by dynamical friction. In particular, the bump at $\sim 6 M_\odot$ is reproduced. Fits to the stellar spectrum yield slopes of $\alpha = -2.04 \pm 0.02$ and -1.72 ± 0.01 in the mass ranges of $[1-3] M_\odot$ and $\geq 15 M_\odot$, respectively, in very good agreement with observational values. With this set of parameters, the mass of the Arches clusters is found to be 1.45×10^5 which is slightly higher than the often quoted, completeness affect, observational value of a few $10^4 M_\odot$. This implies a star formation efficiency of (Mass of the cluster/Mass of the proto-cluster cloud)=$(1.45 \times 10^5 M_\odot/ 5 \times 10^5 M_\odot)$=0.29 which again implies that the Arches is likely to be a gravitationally bound cluster according to the results of Geyer & Burkert (2001).

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