THE FUNDAMENTAL BUILDING BLOCKS OF GALAXIES

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ABSTRACT

Most stars form in compact, dense embedded clusters with memberships ranging from a dozen stars to many millions of stars. Embedded clusters containing more than a few hundred stars also contain O stars that disrupt the nebula abruptly. There are observational indications that the expulsion of gas from such clusters may occur within, or even quicker than, a stellar crossing-time scale. Because the star-formation efficiency is empirically deduced to be typically lower than 40 per cent, such clusters are left severely out of dynamical equilibrium with a super-virial velocity dispersion when they are exposed. As a consequence, they expand drastically. The velocity dispersion of expanding star-burst clusters may achieve values of a few tens km s^{-1}, which would have a significant impact on the stellar velocity distribution function and therefore the morphology of a galaxy. An application of these ideas to the vertical structure of the Milky Way (MW) disc suggests that such popping star clusters may constitute the missing heat source for understanding the age–velocity-dispersion relation. If the early MW disc experienced a vigorous epoch of star formation then perhaps even the thick disc may have formed from popping clusters. Thus we have an alternative hypothesis to understanding thick discs which does not rely on, or may act in addition to, sinking galaxy satellites or sinking cosmological sub-structures. The Gaia mission will test this hypothesis by allowing the kinematical fields around young clusters to be mapped to exquisite precision.

Key words: Methods: N-body simulations; Astrometry; Stars: formation; Galaxy: kinematics and dynamics; Galaxy: evolution; Open clusters and associations: general.

1. INTRODUCTION

Quoting from the review by Lada & Lada (2003), "observations of nearby cloud complexes indicate that embedded clusters account for a significant (70–90%) fraction of all stars formed in GMCs" (giant molecular clouds). This exciting discovery has deep implications for the stellar distribution function in galaxies, and it is verified at the other extreme of the star-formation scale, namely in violently interacting gas-rich galaxies. de Grijs et al. (2003) find that star cluster formation is a major mode of star generation in galaxy interactions, "with >35% of the active star formation in encounters occurring in star clusters". Indeed, the entire Milky Way (MW) population II stellar spheroid could have been build-up from a population of star clusters formed during the chaotic early merging epoch of the Milky Way (MW), with the present-day globular clusters forming the remaining high-mass end of the whole distribution (Kroupa & Boily 2002).

In order to assess the implications that the birth of stars in clusters may have on galactic structure and kinematics, we need to get a feeling for the physics of star cluster formation. This, however, leads us rather rapidly to the limits of our present means, because the formation of star clusters is intimately linked to stellar feedback during the first few 10^5 yr. This is evident empirically through the low star-formation efficiency in cluster-forming cloud clumps of less than 40 per cent (Lada & Lada 2003). The theoretical problem cannot be solved today because radiation transfer in a highly dynamic, turbulent hydrodynamical medium that contains complex chemical networks and magnetic fields is untractable. Today's theory of star-cluster formation is limited to purely hydrodynamic computations (e.g., Mac Low & Klessen 2004; Bonnell et al. 2003) that give an important insight into early fragmentation processes but cannot capture the essential physics that act to expose the cluster. We therefore need to resort to observations to constrain the important physical processes responsible for exposing an embedded cluster.

Table 1 provides a few well studied examples of very young stellar systems, some of which have not yet evacuated their remaining gas. Estimates of the crossing and relaxation times are also indicated[1], and it can be seen that $t_{\rm cr} >$ age for the embedded low-mass objects that do not contain massive stars, while the opposite is true for the rich clusters. The massive clusters are well mixed ($t_{\rm cr} <$ age) but not yet relaxed, so some information from their formation is still evident. Note that the evacuated clusters are likely expanding due to recent gas blow-out (Section 2.3) and so $R > R_{\rm ecl}$ probably.

[1] The nominal crossing time is given by: $t_{\rm cr} = 2\,R_{\rm ecl}/\sigma_{\rm ecl} \approx 4\ (100\,M_\odot/M_{\rm ecl})^{1/2}\ \ (R_{\rm ecl}/{\rm pc})^{3/2}$ Myr; the relaxation time is $t_{\rm rel} = 0.1\ N/{\rm ln}N\ t_{\rm cr}$. Here $R_{\rm ecl}$ is the characteristic radius and $\sigma_{\rm ecl}$ is the stellar 3D velocity dispersion; N, $M_{\rm ecl}$ are the number of stars and the stellar mass in the cluster.

Table 1. A few well-studied examples of very young clusters: Taurus–Auriga (T–A) constitutes perhaps the smallest unit of clustered star-formation and is heavily sub-clustered (Briceño et al. 1998). ρ Oph again is a low-mass cluster that contains no massive stars and which is also sub-clustered (Bontemps et al. 2001). The Orion Nebula Cluster (ONC) has already evacuated its gas and contains no sub-structure (Wilson et al. 1997; Hillenbrand & Hartmann 1998; Scally & Clarke 2002). R136 is the central cluster in the 30 Dor star-forming region in the Large Magellanic Cloud (Brandl et al. 1996; Bosch et al. 2001). It already appears to have blown out most of its gas, a large part of the cluster having been exposed. It contains no significant sub-clustering. The star-burst clusters in the interacting Antennae (Ant.) galaxies have typical radii $\approx$ 4 pc (Whitmore et al. 1999). $t_{\rm cr}$ and $t_{\rm rel}$ are estimated using $R_{\rm ecl} = R$ and an average stellar mass of 0.4 $M_\odot$.

cluster	age [Myr]	N	R [pc]	$t_{\rm rel}$ [Myr]	$t_{\rm cr}$ [Myr]
T–A (emb)	1	30	0.5	3.6	4.1
ρ Oph (emb)	1	100	0.4	3.5	1.6
ONC (evac)	1	5000	0.5	18	0.3
R136 (evac)	2	10^5	2	520	0.6
Ant. (evac)	< 10	10^6	4	3600	0.5

The important lesson from this table is that, while the radii of the objects are always similar, their masses vary by about 5 orders of magnitude. In order to make first steps towards understanding the implications star-cluster birth may have on galactic scales we therefore need to worry about the distribution of $M_{\rm ecl}$; $R_{\rm ecl}$ can be assumed constant for now.

2. THE BIRTH OF A CLUSTER AND ITS IMPLICATION

2.1. The Embedded Cluster

Assume a region of a molecular cloud becomes gravitationally unstable and contracts. Contraction appears to occur very rapidly, on a time-scale of 1–3 Myr for a wide range of cloud masses and sizes, (Hartmann et al. 2001). The free-fall collapse time, $t_{\rm ff} = t_{\rm cr}/2^{3/2}$, for a clump with a radius of 5 pc and a mass of 10^3 (10^5) $M_\odot$ is about 6 (0.6) Myr. As the cloud clump contracts it fragments because the increasing density leads to smaller Jeans masses, $M_{\rm J} \propto 1/\sqrt{\rho}$. Turbulent motions also lead to localised fragments (Mac Low & Klessen 2004). Within the fragments proto-stars form on a time-scale of 10^5 yr (Wuchterl & Tscharnuter 2003) and decouple from the hydro-dynamical flow thereby becoming ballistic. They consequently orbit within the contracting overall cloud clump. Age-dating of the young stars in the ONC, for example, suggests that the stars formed over a time-span of about 1 Myr (Hillenbrand 1997; Palla & Stahler 1999; O'dell 2001; Hartmann 2003), and so most of the stars have orbited the forming embedded cluster a few times before star formation was halted, probably due to the emergence of the O stars. Indeed, the short photo-evaporation time-scale of proplyds suggests that the central star θ1 C Ori with a mass of about 50 $M_\odot$ may only be a few 10^4 yr old (O'dell 2001). A similar picture emerges for the R136 cluster (Massey & Hunter 1998; Bosch et al. 2001).

Because most of the stars have orbited a few times until that critical time when the feedback energy from the massive stars ionises the gas throughout the cluster region (with a typical radius of a few pc) thereby mostly halting further star formation, the embedded cluster must be, at that instant, close to dynamical equilibrium. The stellar velocity dispersion is

$$\sigma_{\rm ecl} = \left(\frac{G\ (M_{\rm ecl}+M_{\rm g})}{R_{\rm ecl}}\right)^{\frac{1}{2}}, \qquad (1)$$

$$= \left(\frac{G\,M_{\rm ecl}}{\epsilon\,R_{\rm ecl}}\right)^{\frac{1}{2}}, \qquad (2)$$

where $\epsilon \equiv M_{\rm ecl}/(M_{\rm ecl}+M_{\rm g}) \approx$ 20–40 per cent is the measured star-formation efficiency (Lada & Lada 2003). Now note that for

$$\sigma_{\rm ecl} = 40\ {\rm km\ s}^{-1}, \qquad \frac{M_{\rm ecl}}{\epsilon\,R_{\rm ecl}} = 10^{5.5}\,M_\odot\ {\rm pc}^{-1}. \quad (3)$$

Since $R_{\rm ecl} \approx 3$ pc while $\epsilon \approx 1/3$ we find that an embedded cluster with the mass of a typical globular cluster has a velocity dispersion characteristic of the thick disc of the MW, and indeed of dwarf galaxies. *The notion thus emerges that the birth of massive clusters may have an important impact on the structure and internal kinematics of galaxies* (Kroupa 2002). But this can only be true (i) if such large velocity dispersions are actually observed in embedded clusters, and (ii) if the embedded velocity dispersion can be carried into the galactic field while the cluster emerges from its cloud core.

2.2. Dynamical State Just Before Gas Expulsion

Observations indicate that condition (i) may well be fulfilled:

ONC: age $\approx$ 1 Myr; $\sigma = 4.3$ km s^{-1} ± 0.5 km s^{-1}
(Jones & Walker 1988: proper-motion study, 900 stars)

R136: age $\approx$ 2 Myr; $\sigma = 55$ km s^{-1} ± 19 km s^{-1}
(Bosch et al. 2001: spectroscopic l.o.s. velocities, 48 O and B stars)

The velocity dispersion for R136 is the three-dimensional dispersion, based on the Bosch et al. (2001) line-of-sight value $\sigma_{\rm los} = 32 \pm 11$ km s^{-1}. The ONC (Wilson et al. 1997) and probably also R136 (Brandl et al. 1996) contain little gas and thus the measured 3D velocity dispersion is probably smaller than the pre-gas expulsion stellar velocity dispersion within the embedded clusters, $\sigma < \sigma_{\rm ecl}$, since the clusters are probably expanding unless the star-formation efficiency was 100 per cent ($\epsilon = 1$). Furthermore, for the ONC the velocity dispersion is only a lower limit because the proper motion analysis removes radial and tangential motions. In both clusters the observed stellar mass is too small to account for the measured velocity dispersion. The measured super-virial nature of the ONC has been a puzzle for some time (Jones & Walker 1988; Hillenbrand & Hartmann 1998). The astonishingly high velocity dispersion in R136 is attributed by Bosch et al. (2001) to be the result of the orbital motions of massive companions. The sample can be split into two mass bins each containing 24 stars. Quoting the line-of-sight dispersions and the average mass,

for $m > 23.5\,\mathrm{M}_\odot$, $\overline{m} = 49.6\,\mathrm{M}_\odot$, $\sigma_1 = 28$ km s^{-1},
for $m < 23.5\,\mathrm{M}_\odot$, $\overline{m} = 19.4\,\mathrm{M}_\odot$, $\sigma_2 = 37$ km s^{-1}.

If the large σ were due to orbital motions then the more massive sample ought to have a larger velocity dispersion since on average the binaries have more binding energy. Instead $\sigma_1 < \sigma_2$ which indicates that R136 is mass segregated with a kinematically decoupled core of massive stars. Mass segregation is indeed evident in star-counts of the cluster (Selman et al. 1999), and in a mass-segregated cluster the massive stars are expected to have a lower velocity dispersion. Therefore probably a substantial part of σ may be due to the motions of stars through the cluster.

Both clusters thus appear to be well out of equilibrium and therefore expanding. Observations of the velocities of stars of later spectral type in R136, and improved proper-motion studies of the ONC, are needed to further test this notion.

2.3. Gas Expulsion

Concerning condition (ii), $\sigma_{\rm ecl}$ will be conserved to some degree *if* the star-formation efficiency is small ($\epsilon \lesssim 40$ per cent) *and* gas expulsion occurs on a dynamical time or shorter ($\tau_{\rm g} \lesssim t_{\rm cr}$). This is not easy to verify empirically because we typically do not catch the cluster just at the time when it is expelling its gas, although the $\lesssim 0.2$ Myr old Treasure Chest cluster appears to be doing just that. Smith et al. (2004) find the Treasure Chest cluster to be very compact with a radius of less than 1 pc. The HII region is expanding with a velocity of approximately 12 km s^{-1} such that the cluster volume will be excavated within a few 0.1 Myr. Furthermore, the star-burst clusters in the Antennae have $t_{\rm cr} \approx 0.5$ Myr and Whitmore et al. (1999) and Zhang et al. (2001) find gas outflow velocities of 25–30 km s^{-1}. This corresponds to a gas evacuation time-scale of 0.2 Myr which is comparable to $t_{\rm cr}$. The star-burst clusters in the Antennae galaxies would thus appear to support explosive gas expulsion. Taking the evidence from the ONC and R136 into account, it appears that *in the presence of O stars explosive gas expulsion may drive early cluster evolution independently of cluster mass*.

Another handle on the evacuation time-scale can be obtained by considering the energy input from massive stars and comparing this to the binding energy, $E_{\rm bin}$, of the nebula. We have

$$|E_{\rm bin}| = \frac{G\,M_{\rm ecl+gas}^2}{R_{\rm ecl}} = 8.6\times10^{40}\,\left(\frac{M_{\rm ecl+gas}}{M_\odot}\right)^2\ \mathrm{erg},$$
$$t_{\rm cr} = 4.8\left(\frac{100\,M_\odot}{M_{\rm ecl+gas}}\right)^{\frac{1}{2}}\left(\frac{R_{\rm ecl}}{\rm pc}\right)^{\frac{3}{2}},$$

Table 2. Binding energy and crossing time of two characteristic embedded clusters.

$M_{\rm ecl+gas}$ $[M_\odot]$	$\vert E_{\rm bin}\vert$ [erg]	$t_{\rm cr}$ [Myr]
10^4	8.6×10^{48}	0.48
10^5	8.6×10^{50}	0.15

and some characteristic values are listed in Table 2 for $R_{\rm ecl} = 1$ pc.

Resorting to Maeder's (1990) stellar-evolution tracks to evaluate the mechanical (wind) and radiation energy output by massive stars we find that a star with mass

$m = 15\,\mathrm{M}_\odot$ injects 3×10^{50} erg per 0.1 Myr, and
$m = 85\,\mathrm{M}_\odot$ injects 3×10^{51} erg per 0.1 Myr.

The energy injected within a time shorter than the crossing time is thus larger than the binding energy of the nebula, and *this supports the conjecture that nebula disruption may typically occur within a dynamical time-scale*, i.e., very violently, explosively.

2.4. Evolution of the Exposed Cluster

As a result of explosive expulsion of about 70% of a cluster's mass the cluster stars are left orbiting with super-virial velocities and expand nearly freely outwards. The classical energy argument suggests that such clusters cannot survive (Hills 1980; Boily & Kroupa 2003). Basically, Pleiades- and Hyades-type open clusters ought not to exist, unless the stellar IMF with which they were formed had no O stars (Elmegreen 1983; Kroupa et al. 2001, hereinafter KAH). This was a very interesting proposition, but subsequent observations showed that clusters with $N \gtrsim 500$ also contain massive stars; evidence for a truncated IMF has never been found.

This problem of not being able to understand how open clusters form in view of (1) explosive gas expulsion and (2) $0.2 \lesssim \epsilon \lesssim 0.4$, has recently been solved by the advent of $N-$body work which treats the energy exchanges between stars due to gravitational encounters precisely. Such work has been made possible through theoretical research by Sverre Aarseth at Cambridge and Seppo Mikkola at Turku on finding numerical and arithmetical solutions to the non-linear gravitational dynamics problem (Aarseth 1999).[2] Using an amended version of the Aarseth integrator NBODY6 on a stand-alone PC, KAH calculated the evolution of an initially dense embedded cluster containing 10^4 stars and brown dwarfs, with a 100% fraction of binaries. The initial ONC model was taken to be the most likely configuration from a parameter survey of all possible dynamical states of the

[2] Recent work in this field has produced special-purpose gravity-pipe-line (GRAPE6) supercomputers that can achieve a peak performance of 1 TFLOP per sec (Makino et al. 2003), while the next generation GRAPE8 machines are expected to reach a peak performance of the order of peta-FLOPS.

ONC (Kroupa et al. 1999; Kroupa 2000). Following the seminal work by Lada et al. (1984), KAH modelled the gas component (initially 2/3rd of the total mass) as a time-evolving background potential. This approximation makes the calculations feasible on modern computers and is nicely consistent with the much more CPU intensive SPH modelling that also needs to treat radiative energy transfer in a highly simplified way (Geyer & Burkert 2001). The KAH models include stellar-evolution-induced mass loss and a solar-neighbourhood tidal field, and thus constitute the most realistic existing computations of all relevant physical processes acting during the emergence of a young cluster from its natal cloud.

The overall evolution of the embedded cluster with O stars is visualised in Figure 1 which shows the reaction of the mass shells to sudden gas removal. The Lagrange radii remain constant during the embedded phase, but during the final stage just before gas expulsion some mass segregation becomes apparent through a contraction of the core radius. Gas expulsion leads to expansion of the Lagrange radii, and by 1 Myr the theoretical velocity dispersion has dropped to the observed value in the ONC. The radial density profile also matches the observed ONC by this time. The 50% mass radius expands with a velocity of about 1.2 km s^{-1}. It crosses the tidal radius by about 1 Myr by which time about 50% of the embedded cluster mass becomes unbound. The inner ≈ 25 per cent Lagrange radius as well as the core radius contract after a few Myr to reach a new minimum by 10 Myr.

A young open cluster has thus formed. It retains approximately $f_{\rm st}$ =1/3rd of the population formed in the embedded cluster, and it fills its Roche lobe entirely. By 100 Myr it evolves to an object that resembles the Pleiades. Theoretical cluster evolution models by Portegies Zwart et al. (2001) furthermore show that the Pleiades will evolve to a Hyades-like cluster, and so we are left to marvel at the amazing coincidence that within less than one-third of a quadrant on the sky we can see the following evolutionary sequence with the naked eye:

ONC $\Longrightarrow$ **Pleiades** $\Longrightarrow$ **Hyades**
≈ 99 Myr ≈ 500 Myr

Much more work needs yet to be performed in order to better understand the role of two-body relaxation and binary-star energy exchanges during the critical gas-expulsion phase, and to quantify the function

$$f_{\rm st} = f_{\rm st}(M_{\rm ecl}, f_{\rm bin}, \epsilon, \tau_{\rm g}), \tag{4}$$

where $f_{\rm bin}$ is the primordial binary proportion, and to include the presence of the molecular cloud behind the ONC which is likely to affect the kinematical field. Nevertheless, these results have essentially solved the open-cluster-formation problem. *Bound clusters form readily despite a low star-formation efficiency and despite gas expulsion on a dynamical time-scale.*

2.5. Predictions

These results suggest that each cluster probably forms with about three times as many stars than are contained within the later re-virialised cluster. There are two moving groups (MGs) associated with each cluster,

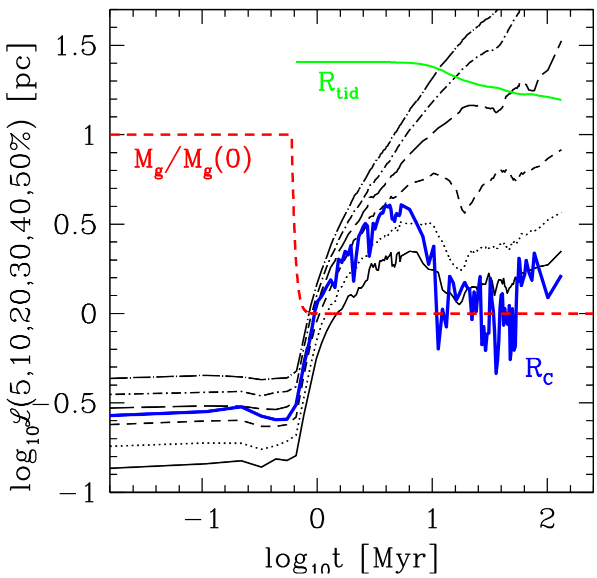

Figure 1. The evolution of Lagrange radii (from bottom to top: radii containing 5, 10, 20…50% of the stellar mass), of the gas mass ($M_{\rm g}$), of the core radius ($R_{\rm C}$), and of the tidal radius ($R_{\rm tid}$), of an ONC-type cluster. The initial embedded model has a central density of $10^{4.8}$ stars/pc^3 with $\sigma_{\rm ecl}$ =6.8 km s^{-1}, blows-out its gas after 0.6 Myr within a crossing time, and resembles the ONC by 1 Myr. After re-virialisation of about 1/3rd of the initial population the open cluster matches, by 100 Myr, the Pleiades (from KAH).

MG I: the 'new' MG stemming from explosive gas expulsion, and
MG II: the classical MG stemming from cluster evaporation,

such that the relative population of each is given roughly, at some time t after the formation time of the embedded cluster, by

$N_{\rm MGII} << N_{\rm MGI}$, for $t << \tau_{\rm ev}$,
$N_{\rm MGII} \approx (1/3) N_{\rm MGI}$, for $t \gtrsim \tau_{\rm ev}$,

where

$$\tau_{\rm ev}/[{\rm Myr}] \approx 10 (M/[M_\odot])^{0.75} \tag{5}$$

(Baumgardt & Makino 2003) is the evaporation or dissolution time of a secularly evolving open cluster of mass M on an approximately circular Galactic orbit close to the solar radius. The velocity dispersion of MGII is $\sigma \approx 0$ km s^{-1} because the stars leak out of the cluster with an energy close to zero (ignoring the rare runaway stars that are shot out as a result of three- or four-body encounters near the cluster core). The velocity dispersion of MGI is a function of the embedded configuration,

$$\sigma_{\rm MGI} = \mathcal{K}_{\rm th}(M_{\rm ecl}, \epsilon, \tau_{\rm g}) < \sigma_{\rm ecl}, \tag{6}$$

and this can be transformed to a correlation between the observed velocity dispersion and the observed cluster mass, $M_{\rm cl}$, at some time $t \ll \tau_{\rm ev}$,

$$\sigma_{\rm MGI} = \mathcal{K}_{\rm obs}(M_{\rm cl}), \tag{7}$$

which is expected to hold true for an ensemble of MGIs and for average values of $\epsilon, \tau_{\rm g}$. *We might thus be able to* *constrain important star-formation parameters related to feedback energy by studying Equation 6 theoretically and Equation 7 observationally*.

The theoretical research is time-consuming because the parameter space spanned by $M_{\rm ecl}, R_{\rm ecl}, \epsilon, \tau_{\rm g}, f_{\rm bin}$ needs to be sampled using precise N-body calculations. For $M_{\rm ecl} \gtrsim 10^4\,M_\odot$ ($\gtrsim 10^4$ stars) this work will need the afore mentioned special-purpose GRAPE6 supercomputers (Baumgardt & Makino 2003). The observational research will need space-based all-sky astrometry missions that capture a substantial fraction of local stars.

2.6. The Role of Gaia

According to the above theory, each young cluster should be surrounded by a radially expanding population of stars of similar age as the cluster population. The expansion field will not be exactly spherically symmetric because variations in the tidal field deflect the stellar orbits. Nevertheless, a relation of the form of Equation 7 should emerge upon measurement of the kinematical field surrounding young clusters.

The Gaia mission is ideally suited to uncover relation 7 locally in the MW and in the Large and Small Magellanic Clouds (respectively LMC, SMC). Locally the high precision of the proper motion measurements will allow highly detailed mappings of all existing MGI and MGII. In the distant LMC only the early-type stars can be measured around young clusters, but nevertheless $\mathcal{K}_{\rm obs}$ ought to become evident.

The tangential velocity to the line-of-sight is

$$V_{\rm T}[{\rm km\,s^{-1}}] = 4.74 \;\times\; \mu[{\rm as\,yr^{-1}}] \;\times\; d[{\rm pc}], \qquad (8)$$

where μ is the proper motion in arcsec per year, and d is the distance of the star. Neglecting pre-main sequence evolution for the sake of illustration, an A type star with $M_{\rm V} = 1.1$ at the distance of the LMC ($d = 50$ kpc) has an apparent magnitude $m_{\rm V} = 19.6$. From Table 8 in Perryman et al. (2001) the measurement accuracy for such a star corresponds to 28 km s^{-1}. This should uncover radial flows away from massive young clusters if young stellar samples can be combined in sub-regions around the clusters. A G-type star with $M_{\rm V} = 5$ at a distance of the ONC (450 pc) has $m_{\rm V} = 13.3$. For such a star Gaia will have a precision of 0.011 km s^{-1}, which will suffice to define the kinematical state of the entire ONC, although issues of crowding do arise.

3. CREATING A GALAXY

The ideas developed above can be explored further theoretically by considering their implications on galaxy morphology. In Section 2.1 it was already noted that the birth of massive clusters may impact the vertical structure of a disc galaxy such as our own MW. In order to study this in more detail it is necessary to build a field population from an ensemble of popping clusters.

3.1. Basics

The basic equation for the velocity distribution function of stars is obtained by adding all expanding populations from all clusters formed in one 'epoch'. Note that Weidner et al. (2004) find that the ECMF appears to be completely populated for star-forming epochs lasting typically about 10 Myr, independently of the star-formation rate (SFR). For this purpose we need only to consider the distribution of the clusters by mass formed in each epoch since the radii of very young clusters do not differ significantly (Section 1),

$$\mathcal{D}(v_z; M_{\rm ecl,max}, \beta) = \int_{M_{\rm ecl,min}}^{M_{\rm icl,max}} D(v_z; M_{\rm ecl})\, N(M_{\rm ecl})\, \xi_{\rm ecl}(M_{\rm ecl}, \beta)\, dM_{\rm ecl}, \quad (9)$$

where $\mathcal{D}\,dv_z$ is the resulting number of stars with z-components of their velocity vectors in the interval $v_z, v_z + dv_z$, $M_{\rm ecl,min} \approx 10\,M_\odot$, and $M_{\rm ecl,max}$ is the maximum embedded cluster mass in the cluster ensemble. The product $N\,\xi_{\rm ecl}\,dM_{\rm ecl}$ is the number of stars formed from clusters with masses in the range $M_{\rm ecl}, M_{\rm ecl} + dM_{\rm ecl}$. The expanding population of MGI stars emanating from a cluster of mass $M_{\rm ecl}$ has a velocity distribution function D, where $D(v_z; M_{\rm ecl})\,dv_z$ is the number fraction of cluster stars with velocities in the range $v_z, v_z + dv_z$. The physics of star formation is contained in $D(v_z; M_{\rm ecl})$, but for an assessment of the impact of clustered star formation on vertical Galactic disc structure it suffices to consider a Gaussian v_z distribution, i.e., a Maxwellian speed distribution in the vertical direction, with a dispersion given by Equation 2. The actual $D(v_z; M_{\rm ecl,max})$ would need to account for the MGII, i.e., the fraction of stars that re-virialise in the bound cluster, and which, upon secular evaporation from the cluster, contribute a population of stars with a small velocity dispersion to $\mathcal{D}$. Gravitational retardation would also need to be incorporated; the stars that expand from a cluster are decelerated by the mass within their distance from the cluster, such that $\sigma_{\rm MGI} < \sigma_{\rm ecl}$. These points are incorporated in the exploratory investigation of Kroupa (2002). Before proceeding further we need to specify the embedded cluster mass function.

3.2. The Mass Function of Embedded Clusters

As is apparent from Equation 9 the fundamental distribution function that governs $\mathcal{D}$ is the embedded cluster mass function (ECMF). Most empirical constraints suggest the ECMF to be a power-law,

$$\xi_{\rm ecl} \propto M_{\rm ecl}^{-\beta}, \qquad (10)$$

$dN_{\rm ecl} = \xi_{\rm ecl}\,dM_{\rm ecl}$ being the number of embedded clusters in the mass interval $M_{\rm ecl}, M_{\rm ecl} + dM_{\rm ecl}$.

Lada & Lada (2003) find, for the local embedded cluster sample with masses between about 20 and $10^3\,M_\odot$, that the ECMF can be described as a power-law with $\beta \approx 2$, with a possible flattening below roughly $50\,M_\odot$. The form of the ECMF below about a few dozen $M_\odot$ is very uncertain though because such stellar groups are difficult to find. They disperse within a time comparable to the gas removal time-scale (Adams & Myers 2001; Kroupa & Bouvier 2003).

The maximum mass of a cluster, $M_{\rm ecl,max}$, in a freshly hatched cluster ensemble correlates with the SFR of a galaxy (Weidner et al. 2004). In order to extend the ECMF to larger masses we therefore need to study galaxies that have a sufficiently high SFR. The Large and Small Magellanic Clouds are such systems, and Hunter et al. (2003) find $2 \lesssim \beta \lesssim 2.4$ for $10^3 \lesssim M_{\rm ecl}/M_\odot \lesssim 10^4$.

The Antennae galaxies are composed of two currently merging major disc galaxies, and the SFR in this system is sufficiently high to sample the cluster MF to $10^{7-8}\,M_\odot$. For a sample of <10 Myr old clusters in the Antennae galaxies, Zhang & Fall (1999) arrive at β =1.95±0.03 for clusters with masses in the interval $10^4 \lesssim M_{\rm ecl}/M_\odot \lesssim 10^6$ and ages 2.5< $t/[{\rm Myr}]$ <6.3. 'Clusters' more massive than about $10^{6-7}\,M_\odot$ are observed to be composed of star-cluster complexes (Kroupa 1998; Zhang, Fall & Whitmore 2001), thus setting an empirical maximum mass of about $10^{6-7}\,M_\odot$ for a true star cluster, i.e., an equal-age, equal-metallicity population (Weidner et al. 2004). Kroupa (1998) and Fellhauer & Kroupa (2002a,b) propose such cluster complexes to be the precursors to a number of recently found exotic objects: ultra-compact dwarf galaxies and low-density clusters.

For a variety of environments the ECMF thus appears to have

$$\beta \approx 2. \tag{11}$$

This is rather remarkable suggesting a possible universality of the ECMF.

Note that, apart from the Lada & Lada work, the above studies actually report the shape of the mass function of young clusters rather than embedded clusters. The studied cluster systems typically have ages younger than 10 Myr. Most clusters younger than 10 Myr would still contain the majority of their stars within a relatively compact region even if they are expanding as a result of gas blow out (Figure 1). Nevertheless, this is an issue worth keeping in mind; the ECMF underlying the young-cluster systems of Hunter et al. (2003) and Zhang & Fall (1999) may well have a somewhat different β. Kroupa & Boily (2002) stress that as a result of the low ϵ a distinction between the cluster mass function and the ECMF is necessary, because clusters lose significant stellar mass as a result of gas expulsion. Clearly, this is an important issue for future N-body work.

3.3. Thickening of Galactic Discs Through Clustered Star Formation

Given the ECMF and a prescribed $M_{\rm ecl,max}$, Equation 9 can be calculated. For $\beta = 1.5$ and different $M_{\rm ecl,max}$, the resulting $\mathcal{D}(v_z)$ is non-Gaussian, having a 'cold' peak with broad warm to hot wings (Figure 2). The width of the wings is determined by $M_{\rm ecl,max}$, while the strength of the cold peak is given by $M_{\rm ecl,min}$ and the cluster–cluster velocity dispersion.

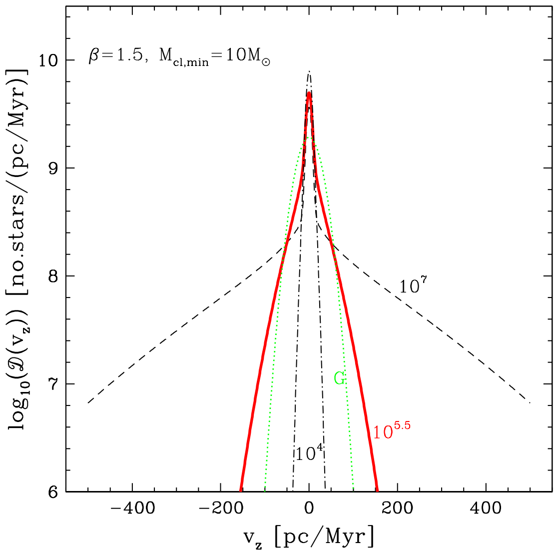

Figure 2. The resulting distribution function of vertical velocities for a population of stars formed in one epoch of star formation which produced a power-law ECMF with β =1.5. The distribution function is shown for different maximum cluster masses, $M_{\rm ecl,max}$ =10^4, $10^{5.5}$, $10^7\,M_\odot$. The curve labelled 'G' is a Gaussian distribution function with a velocity dispersion equal to the $M_{\rm ecl,max}$ =$10^{5.5}\,M_\odot$ case (26 km s^{-1}). The cluster–cluster velocity dispersion is 5 km s^{-1}. Note that 1 km s^{-1} ≈ 1 pc/Myr. From Kroupa (2002).

The distribution of the z-components of the velocity vectors of solar-neighbourhood M dwarfs indeed shows non-Gaussian features (Reid et al. 1995) that are, at least qualitatively, consistent with this scenario. Again, the Gaia mission will quantify the shape of the velocity distribution of field stars allowing tests of the present theory.

An immediate application of this theory can be seen in the hitherto unsolved problem that the observed velocity dispersion of solar-neighbourhood stars increases more steeply with age than is predicted from secular heating of the stellar orbits (Figure 3). According to the standard picture, stars are formed with a small velocity dispersion of about 10 km s^{-1}. The velocity dispersion increases with time because the stars scatter on giant molecular clouds and spiral density waves, and because the disc mass increases through accretion. Jenkins (1992) calculated this diffusion of stellar orbits with time (the solid curve in the upper panel of Figure 3). The observed vertical velocity dispersion data (Fuchs et al. 2001) are plotted in the top panel of Figure 3. The more recent work of Nordström et al. (2004) shows similar results. It can be seen from Figure 3 that the theory cannot account for the observed increase of σ_z. A 'heat source' appears to be missing.

Adding popping star clusters may resolve this problem of the missing heat source. The theoretical velocity dis-

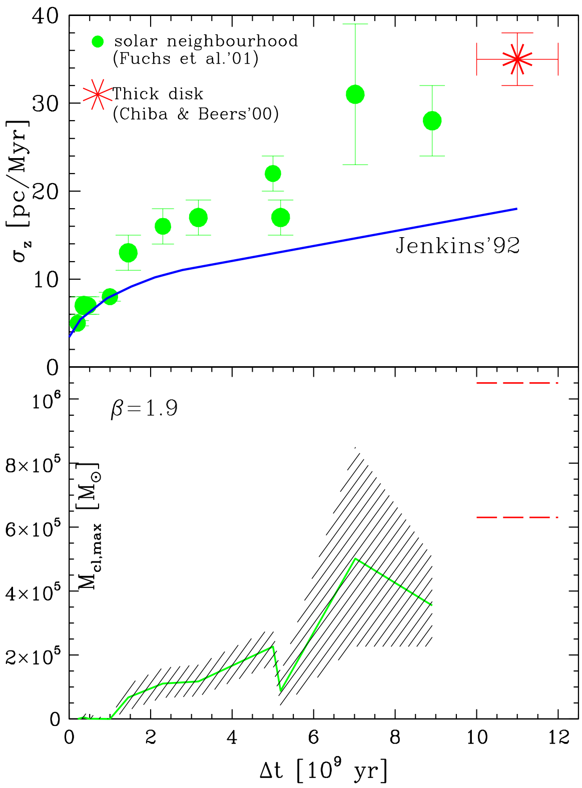

Figure 3. Upper panel: The age–velocity-dispersion data for velocity components perpendicular to the MW disc for solar neighbourhood stars as compiled by Fuchs et al. (2001) are shown as solid dots. Jenkins' (1992) theoretical relation is plotted as the solid curve. The thick-disc datum is indicated by the old star. Lower panel: The maximum cluster mass, $M_{\rm ecl,max}$, in the population of star clusters needed such that the difference in the top panel between observed data and theory vanishes is calculated and plotted as a function of time assuming β =1.9. The shaded region comprises the uncertainty range on $M_{\rm ecl,max}$ given by the observational uncertainties on σ_z (upper panel). The region between the old horizontal dashed lines indicates the $M_{\rm ecl,max}$ needed to account for the vertical thick-disc kinematics, the thick disc having been born between about 10 and 12 Gyr ago. From Kroupa (2002).

persion, σ_z, can be calculated readily from $\mathcal{D}(v_z)$ as a function of $M_{\rm ecl,max}$ for various β and an assumed small cluster–cluster velocity dispersion of 5 km s^{-1}. As a first ansatz we thus say that the clusters form in a very thin MW disc. Figure 3 indicates what sort of $M_{\rm ecl,max}(t)$ with $\beta = 1.9$ would be needed to explain the observed velocity dispersion assuming Jenkins' (1992) model applies. The result is that $M_{\rm ecl,max}$ takes reasonable values and that it decreases towards younger ages.

The interesting suggestion coming from this approach is that the MW disc may have been quietening down over time as its gas reservoir was depleted. It may have begun forming with a high SFR reaching to $M_{\rm ecl,max} \approx 10^6\,M_\odot$ thereby producing the thick disc about 10–12 Gyr ago. Such a high SFR in the early primarily gaseous MW disc may have been induced by a tidal perturbation from a nearby neighbour galaxy (Kroupa et al. 2004). Or it may be the result of an early disc instability (Noguchi 1999). A full solution to the ECMF needed to match the vertical thick-disc kinematics can be found in Kroupa (2002). The thin disc may then have begun its assembly from star-cluster populations with a maximum cluster mass decreasing to the present time. The decreasing $M_{\rm ecl,max}$ would come about from a decreasing SFR (Weidner et al. 2004) as the conversion of gas to stars proceeded.

The above constitutes a simple example of how clustered star-formation may affect the morphology of galaxies. The results are very encouraging, in that the constrained parameters $M_{\rm ecl,max}, \beta$ are reasonable. Combined with the observational evidence discussed in Section 2 the notion that star clusters are fundamental building blocks of galaxies is sharpened. Clearly, we need to calculate the velocity distribution function of expanding stellar populations, $\mathcal{D}(v_x, v_y, v_z)$, within a realistic and time-evolving Galactic potential in order to construct three-dimensional velocity ellipsoids at different locations in the MW disc and at some given epoch for a prescribed star-formation history. This needs treatment of the diffusion of orbits in the time-evolving potential. Furthermore, ancient thin-disc clusters with $M_{\rm ecl,max} \gtrsim 10^6\,M_\odot$ may be evident in the MW disc today as evolved cluster remnants (Equation 5).

4. CONCLUSIONS

The measured super-virial velocity dispersion of ONC and R136 stars suggests that both clusters may be out-of-dynamical equilibrium after blowing out their residual gas explosively. Explosive gas expulsion from massive young clusters is also supported by measurements of the outflow velocities of gas, and the Treasure Chest cluster may be caught in the act of doing so. Young clusters containing O stars therefore may expand rapidly after gas blow-out losing a large fraction of their stars. This expanding population forms a moving group (MGI) with a velocity dispersion, $\sigma_{\rm MGI}$, that is related to the pre-gas expulsion velocity dispersion of stars in the embedded clusters, and thus to the mass, $M_{\rm cl}$, of the re-virialised cluster that re-contracts as the nucleus of the expanding MGI. Gaia will measure this correlation $\sigma_{\rm MGI} = \mathcal{K}_{\rm obs}(M_{\rm cl})$, through which we will get an important handle on the basic physics acting during cluster formation.

Since most stars form in embedded clusters it follows that cluster birth may leave non-negligible imprints in the kinematical and structural properties of galaxies. An example has been presented by calculating the vertical velocity dispersion of a population of stars born in an ensemble of star clusters. Relating this dispersion to the missing heat source in the age–velocity-dispersion relation of solar neighbourhood stars allows us to estimate the evolution of the embedded-cluster mass function with time. The result of this exploratory work is that the MW may have been quietening down somewhat, that early epochs of the MW disc may have been characterised by more violent star formation within a thin disc producing clusters reaching to masses similar to those of present-day globular clusters. A thick disc may thus be a natural outcome of such events. The merging of cold-dark matter sub-halos may not be needed to explain the existence of a thick disc, but satellite mergers are of course not ruled out as having shaped the old MW disc (Abadi et al. 2003).

A more detailed theoretical study of these processes is needed to quantify the stellar velocity ellipsoid in dependence of various evolutionary models of the MW disc, and to construct statistical models of the MW for future comparison with Gaia data.

Because this notion that popping clusters may shape entire galaxies is so important, it will also be urgent to observe the velocity dispersion and the gas content in as many very young clusters as is possible. While Gaia will have the defining impact on these ideas, it will not be able to measure the kinematics of very young stars in dense clusters, so that ground-based proper-motion and line-of-sight velocity observations are definitely needed to quantify the dynamical state of as large a number of very young clusters as is possible.

The beauty of this entire approach lies in the realisation that small-scale baryonic processes may affect galaxy-scale structures through stellar dynamics. Star-formation scales may thus impact cosmological issues in a hitherto unappreciated manner.

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