Star cluster formation and some implications for GAIA

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Abstract
Stars form in spatially and temporarily correlated star formation events (CSFEs) and the dynamical processes within these “embedded clusters” leave imprints in the stellar populations in galactic fields. Such imprints are correlations in phase space (e.g. gravitationally bound star clusters, tidal streams), in the binary properties of stars and in the present-day stellar mass functions in the surviving clusters. The dynamical processes include expulsion of massive stars from cluster cores, disruption of CSFEs due to residual gas expulsion and energy-equipartition driven evaporation of stars from clusters leading to dark star clusters and cold kinematical streams with epicyclic overdensities. The properties of such phase-space structures in the Milky Way (MW) field depend on the effective gravitational potential of the MW. GAIA data will significantly constrain all of these aspects, and will in particular impact on gravitational dynamics via the properties of cold streams and on star-formation via the constraint on the gas expulsion process through the expanding unbound populations that must be associated with every CSFE.

1 Introduction

The data generated by the GAIA mission will provide historically unprecedented constraints on the formation and evolution of the MW and will also constrain gravitational theories in the ultra-weak field limit. In order to interpret the GAIA data we will require detailed knowledge on how the stellar phase-space distribution function, which defines the properties of the MW, comes about. This is a complex problem: To interpret the data we will need to compute models of how stars populate phase space. But in which dynamical theory? If we assume Newtonian dynamics the computations can be done today but are equivalent to assuming the concordance cosmological model to be the correct description of reality. The current astronomical constraints already suggest it to be excluded though [Peebles & Nusser 2010, Kroupa et al. 2010], and the so computed model MW would then not match the GAIA constraints unless some additional unknown physics is invoked. Alternatively, perhaps reality
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follows Modified Newtonian Dynamics (MOND, Milgrom 2009) or another alternative (e.g. Moffat & Toth 2009) in which case it may be possible to naturally obtain consistency of the data with the model. But, at present it is not possible to compute a dynamical model of the MW from scratch (i.e. the stars spreading into the field from their birth structures) with Milgrom’s dynamics. Until this becomes possible, we will not be able to correctly account for the evolution of the MW, since we will always end up with the trivial solution that the MW is described by Newton’s laws plus ad hoc dark unknowns, in order to match the GAIA data.

Irrespective of these issues, here an outline is provided of how the signatures of CSFEs are likely to be contained in astrometric and stellar-population survey data such as will become available with the GAIA mission.

2 Do all stars from in star clusters?

The phase space distribution of stars in the MW is not only defined by the effective potential of the MW but also by the dynamical origin of the stars. Here a fundamental QUESTION arises: Do all stars form in embedded star clusters (Bressert et al. 2010)? If this were the case then the stellar dynamical processes within the clusters need to be treated first in order to understand the properties of the phase-space distribution function of stars in the MW field. Each cluster of a given energy scale (given by its mass and radius) provides a unique contribution to the stellar population in the field. The concepts of kinematical population synthesis (Kroupa 2002), dynamical population synthesis (Kroupa 1995; Marks & Kroupa 2011) and of the integrated galactic initial mass function (IGIMF) of stars (Kroupa & Weidner 2003; Weidner et al. 2011b) arise from the concept of adding up the contributions of all clusters.

Rather than referring to embedded star clusters, the term Correlated Star Formation Event (CSFE) is applied here. A CSFE means a group (or “cluster”) of stars formed over a spatial scale of about one pc within about one Myr. Observations suggest that these are typical star-forming structures, ranging from the Taurus-Auriga sub-clusters of a dozen binaries in each, through dense-populous young clusters such as the Orion Nebula cluster (ONC), to massive star-bursting embedded clusters with masses \( > 10^6 \) M\(_\odot\). With the work of Larsen (2004) it has become clear that there is no special mode of globular cluster (GC) formation, but that there is as continuous distribution of star-forming events from the smallest to the most massive CSFEs. A CSFE does not have to be gravitationally bound in entirety.

Even if a CSFE were to be formally a gravitationally self bound structure (i.e. a classical star cluster), then a certain fraction of its stars will always be below a density threshold in its outer regions. An observer who applies a density threshold to define “clustered star formation”, implying that stars found in regions below this threshold would be termed stars formed in isolation, would thus always find isolated stars in star-forming molecular clouds. For example, an individual cluster represented by a Plummer model in virial equilibrium, i.e. being gravitationally bound, with a Plummer radius of 0.3 pc and with a mass of 20, 100, 1000 M\(_\odot\) has, respectively, 70, 30, 10 per cent of its stars outside a radius at which the projected surface density is 60 stars/pc\(^2\) (Pflamm-Altenburg, priv.comm.). The “efficiency” of clustered star formation thus appears to increase with CSFE mass. A whole population of 0.3 pc Plummer
CSFEs ranging from $10 \ M_\odot$ to $10^4 \ M_\odot$ has a fraction of 30 per cent “isolated” stars. Exponential density profiles (rather than Plummer profiles) or expanding stellar populations after the expulsion of residual gas from initially bound CSFEs would change these numbers such that the fraction may be larger or smaller depending on the characteristic length scale of the CSFEs, such that the observed fraction of star-formation in dense clusters (Bressert et al. 2010) may be arrived at. The fraction of stars which are apparently formed outside of dense clusters is enhanced due to low-mass embedded clusters dispersing on a few crossing time scales and stars being ejected from dense regions of their CSFEs (Weidner et al. 2011a). Despite the significant fraction of “isolated stars”, the stellar-dynamics of such CSFEs remains that of an embedded star cluster.

Thus the above question must be rephrased to the following form: Do all stars from in CSFEs? The answer is yes, because CSFEs are confined to the dense cores of molecular clouds which is where stars form. The least-massive CSFEs can be termed to be non-clustered star formation if these include groups of a few low-mass stars. With this answer, GAIA-relevant modelling can be performed on galaxy scales because the quantities of interest (e.g. velocity and space distributions, binary populations, stellar mass functions) are then given by time-dependent integrals over all CSFEs, once we know the mass and size distribution of the CSFEs.

This contribution touches upon the issue of how star formation in CSFEs affects various aspects of galactic astrophysics. A fundamental concept underlying the approach is that to make a galaxy one merely needs to add up all CSFEs over time (the cosmological lego, i.e. the concept that embedded star-clusters are the fundamental building blocks of galaxies (Kroupa 2005)).

### 3 Formation of CSFEs

It is by now well established observationally that a dense molecular cloud region of a typical scale of a few pc fragments into gas rich sub-clusters with individual diameters of less than a pc (Lada & Lada 2003). Numerical simulations of turbulent self-gravitating clouds also show this process (e.g. Klessen et al. 2004). This phase of star-cluster formation takes about 1 Myr by which time between about 10 and 30 per cent of the gas has formed stars with total mass $M_{\text{ecl}}$ distributed according to the stellar IMF with a most-massive-star—star-cluster mass relation as a function of the time $t$, (Bonnell et al. 2004; Peters et al. 2010, 2011b)

$$m_{\text{max}}(t) = 0.39 M_{\text{ecl}}(t)^{2/3},$$

in good agreement with the observed relation, $m_{\text{max}} = fn(M_{\text{ecl}})$, established after star formation has ended (Weidner et al. 2010).

Once the stellar feedback is sufficient to significantly impact the molecular cloud core the gas is blown out. An issue not fully answered yet is whether gas blow-out is explosive (i.e. faster than a cluster dynamical time) or whether it is adiabatic, and how this depends on cluster mass (see below).

Nevertheless, the theoretical problem of star formation can be divided into two computationally accessible phases. In the first phase, gravo-hydrodynamical simulations can be used to study the collapse and fragmentation of the cloud, while in the second phase purely stellar-
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dynamical \((N\text{-body})\) methods need to be used to treat the stellar-dynamical processes with high accuracy. The transition between the gas-dominated and the pure \(N\text{-body}\) dynamics dominated phases occurs at an age of about one Myr and can only be treated with simplifying assumptions, especially if substantial CSFEs with \(M_{\text{ecl}} > 10^3 M_\odot\) are to be studied. Here the sole computationally feasible approach is to model the time-varying gas potential as an additive analytical back ground potential \(\text{e.g.}\) Geyer & Burkert 2001 \citep{Kroupa2001} allowing major scans of parameter space \(\text{e.g.}\) Baumgardt & Kroupa 2007. Since the formation of each individual star takes about 0.1 Myr, most stars have been born by 1 Myr. For CSFEs with \(M_{\text{ecl}} > \text{few} 100 M_\odot\) they have had enough time to orbit through the CSFE once at least \(\text{Kroupa 2005}\) such that it can be assumed that such CSFEs are close to dynamical equilibrium when the gas is blown out.

4 Early stellar dynamical processes

An initially sub-structured stellar population within a CSFE can merge to an embedded cluster on a crossing time scale, or it can disperse into the field, depending on the velocity field of the cloud and the stellar feedback processes \(\text{McMillan et al. 2007}\) \citep{Clark2008, Fellhauer2009, Bonnell2011}. The individual sub-clusters are likely to be initially mass segregated because the most massive stars form in the densest regions \(\text{Maschberger et al. 2010}\). Even if the overall structure is not mass segregated, the mass segregation time scale is short and of the order of

\[
t_{\text{ms}} = \mathcal{O}\left(\frac{m_{av}}{m_{mass}} t_{\text{relax}}\right),
\]

where \(m_{av}, m_{mass}\) are the average stellar mass and the mass of the massive star, respectively, while \(t_{\text{relax}}\) is the two-body relaxation time. For example, for the ONC \(t_{\text{relax}} \approx 0.6\) Myr such that \(t_{\text{ms}} \approx 0.12 \text{ Myr} \ll \text{age of the ONC}\) \(\text{Kroupa 2008}\).

Once a few massive stars collect in the cluster core the core decays by ejecting the stars on a time scale

\[
t_{\text{decay}} = \mathcal{O}\left(N_m t_{\text{core,cross}}\right)
\]

where \(N_m\) is the number of massive stars in the core and \(t_{\text{core,cross}}\) is the core-crossing time. For the ONC the core has a radius of about 0.02 pc and the mass of the core is about 150 \(M_\odot\) such that \(t_{\text{core,cross}} \approx 10^4\) yr and \(t_{\text{decay}} \approx 10^5\) yr \(\ll \text{age of the ONC}\). Thus, dense clusters are efficient accelerators of massive stars such that a large fraction of them get dispersed into the galactic field as soon a core of massive stars forms \(\text{Pflamm-Altenburg & Kroupa 2006}\) \citep{Banerjee2011, Fujii2011, Gvaramadze2011}. Since most massive stars are born as multiple systems \(\text{Sana & Evans 2010}\) the dynamical encounters within the cores can be violent.

Indeed, initially mass segregated clusters in which all massive stars are massive binaries eject a large fraction of their massive stars within 3 Myr, as is demonstrated by the extensive young star-cluster \(N\text{-body}\) library of mass segregated and not mass segregated clusters with and without binaries \(\text{Oh et al., in prep.}\). The primary of an ejected massive binary ultimately explodes as a core-collapse supernova releasing the massive companion into a random direction. About 1-4 per cent of all ejected massive stars can therefore not be traced back to their cluster of origin \(\text{Pflamm-Altenburg & Kroupa 2010}\), while the observed fraction of
massive stars that appear to have formed in isolation is about 1 per cent only. Therefore there is no evidence for the formation of massive stars in isolation.

Concerning the binary population in clusters, it is well known from N-body work that binary stars can get disrupted but may also harden through stellar-dynamical encounters (Kroupa 1995; Portegies Zwart et al. 2001; Kaczmarek et al. 2011). It has been shown that a unified invariant birth binary population in which every star with mass \(< few M_\odot\) is in a binary naturally evolves into the observed binary population which has a smaller binary fraction (Marks et al. 2011). By summing all initial populations transformed by all CSFEs the observed period and mass-ratio distributions of the MW field are accounted for naturally through the stellar-dynamical disruptions of the birth population within the individual CSFEs (Marks & Kroupa 2011).

The expansion of the cluster associated with the dynamical activity of the core is not significant compared to the expansion induced due to the expulsion of residual gas.

5 The star formation history within a cluster

Some low-mass clusters show evidence for a significant age spread of their stars (Palla et al. 2007). This can be interpreted to have arisen through a slow formation time-scale of up to 10 Myr and would be in contradiction with cluster formation on a dynamical time-scale (Hartmann et al. 2001).

There are two processes which naturally lead to an age spread in star clusters such that CSFE formation can occur on a dynamical time but still contain older stars:

1. As the pre-cluster cloud core collapses on a dynamical time scale the potential deepens and young nearby stars from a surrounding older association can be captured to become cluster members. In this way 8 per cent of all ONC stars may be captured older stars (Pflamm-Altenburg & Kroupa 2007), while 30 per cent or more of stars in \(\omega\) Cen may be captured from the originally hosting dwarf galaxy (Fellhauer et al. 2006).

2. After its massive stars have died a young cluster can re-accrete gas if it enters a molecular cloud, because the cluster potential leads to a hydrodynamical instability (Pflamm-Altenburg & Kroupa 2009).

For massive clusters (about \(> 10^6 M_\odot\)) the gas cannot be removed readily due to the deep potential and shock thermalisation of stellar winds such that successive populations of stars may emerge (Tenorio-Tagle et al. 2003; Wünsch et al. 2008). How the observed peculiar chemical compositions in the massive GCs may be accounted for remains an active area of theoretical research (Romano et al. 2007; Decressin et al. 2009; de Mink et al. 2009; Decressin et al. 2010).

6 Expulsion of residual gas and initial cluster radii

Observations (Lada & Lada 2003) show that the star-formation efficiency

\[
e = \frac{M_{\text{ecl}}}{M_{\text{ecl}} + M_{\text{gas}}} \approx 0.3.
\]
In pure gravo-hydrodynamical simulations of star formation most of the gas can get accreted onto the proto stars (i.e. sink particles in the computations), and $\epsilon$ is determined by when the computation is halted. The first simulations of star formation in a turbulent magnetised cloud plus stellar feedback (Price & Bate 2009; Peters et al. 2011a,b), however, now demonstrate that $\epsilon$ is small on a global cloud scale, because the magnetic field stabilises the cloud on large scales (> 1 pc) while the feedback inhibits fragmentation on small scales. Since virtually all clusters older than about one Myr are free of gas, this can only mean that the residual gas amounting to about 70 per cent of the original cloud core mass is expelled from the cluster within less than one Myr.

A simple estimate of the cloud core binding energy, in comparison with the energy imparted by the feedback energy from massive stars, shows that within less than a crossing time an order of magnitude more energy is deposited in the cloud core. The parameters taken here are a cloud core of radius 1 pc and masses $10^4$ and $10^5 M_\odot$ leading to binding energies of $8.6 \times 10^{48}$ erg and $8.6 \times 10^{50}$ erg, respectively. The corresponding crossing times are 0.48 and 0.15 Myr. A single pre-supernova star of $15 M_\odot$ injects in total $3 \times 10^{50}$ erg while a single $85 M_\odot$ star injects $3 \times 10^{50}$ erg into the cloud, within 0.1 Myr (Maeder 1990). Thus, the disruption of the nebula is most probably rapid if not explosive, within less than a crossing time scale. Only in massive clusters with $M_{\text{ecl}} > 10^5 M_\odot$ is a more adiabatic evolution probably the case (Tenorio-Tagle et al. 2003; Baumgardt et al. 2008b), because neither individual core-collapse supernovae nor the feedback of all OB stars in the cluster contain sufficient energy to unbind the gas, parts of which shock-thermalises and may form further stars. The effective $\epsilon$ probably therefore increases with increasing $M_{\text{ecl}} > 10^5 M_\odot$.

There is ample observational evidence for explosive gas expulsion. The ONC is super-virial (Kroupa et al. 2001; Kroupa 2005), while star clusters appear to show a major expansion in the first 10s Myr of their life time (Bastian & Goodwin 2006; Goodwin & Bastian 2006; de Grijs & Parmentier 2007; Bastian et al. 2008; Brandner 2008, but see also Gieles et al. 2010). Very young embedded clusters, or CSFEs, appear to be very compact, with radii of less than a pc, as is inferred from direct observations (Kroupa 2005) and inverse dynamical population synthesis (Marks & Kroupa 2012, submitted). Inverse dynamical population synthesis is a potentially powerful tool to infer the initial conditions of star clusters by assuming the initial binary population to be invariant. The present-day binary population stores the dynamical history of the population and the deepest negative energy state of the cluster can be read off from the energy distribution of the present day binary population.

Such work leads to the result that there is a weak embedded-cluster-mass–radius relation for pre-gas-expulsion CSFEs (Marks & Kroupa 2012, submitted)

$$r_h = 0.14^{+0.08}_{-0.05} M_{\text{ecl}}^{0.12^{+0.05}_{-0.05}},$$  \hspace{1cm} (5)

where $M_{\text{ecl}}$ is the stellar mass and $r_h$ is the half-mass radius. It will have to be seen how this result, which is obtained by inferring the initial density given the present-day energy distribution of the binary population in each considered cluster, can be made conform to Pfalzner (2009)’s suggestion that there are two sequences of birth CSFEs following different density–radius scaling relations.

Concerning Eq. 3, a metallicity dependence also emerges in that metal-poor clusters appear to have had a systematically smaller $r_h$ at a given mass $M_{\text{ecl}}$ than metal richer clusters (Marks & Kroupa 2010). This may suggest that metal-poor gas can collapse to denser states...
while the more efficient coupling of photons to more metal-enriched gas increases the opacity and thus limits the depth of the collapse while also increasing fragmentation. This is the same physical reason for stellar winds being metal dependent and star-formation theory predicting a bottom heavy stellar IMF for metal rich star-forming conditions (e.g. Bastian et al. 2010). This finding would imply that metal rich CSFEs with $M_{\text{ecl}} > 10^4 M_\odot$ are less likely to form bound GCs in present-day galaxy–galaxy encounters, as has been surmised by Forbes et al. (1997), because by forming with larger $r_h$ they are more susceptible to damage from gas expulsion and tidal perturbations.

Taking gas-expulsion into account, it has been shown that one single pre-ONC CSFE evolves, via gas expulsion, through the ONC at an age of about 1 Myr, to the Pleiades at an age of about 100 Myr and then onto to the Hyades and Praesepe at ages of a few hundred Myr (Kroupa et al. 2001; Portegies Zwart et al. 2001). Even the binary and stellar populations, as well as the density and velocity profiles come out remarkably well in the models compared to the real clusters. It is remarkable that all these clusters at a mass scale of about 1000 $M_\odot$ are so similar. We will return to this further below (Sec. 8).

7 Thickening galactic disks, chain galaxies, stellar streams and dark star clusters

The origin of thick disks of galaxies remains unclear, and the reason why the MW thin disk thickened with age also remains unresolved. GAIA data will allow significant constraints to be placed on the acting heating mechanisms through a precise quantification of the phase-space distribution of the various stellar components. A popular hypothesis is that dark-matter sub-clumps and merging dark-matter dominated satellite galaxies thicken the disks. This scenario would be natural for the popular cold- or warm-dark-matter based cosmological models because they are synonymous with hierarchical galaxy formation and imply, by logical necessity, the harassment of thin galactic disks by myriads of dark matter sub clumps. It has proven to be difficult to account for the observed heating though, since the theoretically implied impact of the sub-structures would be far more damaging if not destructive to the thin disks. Sellwood (2010) discusses the various heating processes acting within galactic disks such as heating by bars, transient spiral patterns, molecular clouds, but the full heating has not been accounted for.

Young star clusters that expel their gas explosively loose a dominant fraction of their stellar population which expands, to first order, with the pre-gas-expulsion velocity dispersion. Thus, if the velocity dispersion in the embedded cluster is

$$\sigma \approx \left( \frac{G M_{\text{ecl}}}{\epsilon R} \right)^{\frac{1}{2}},$$

(6)

where $G$ is the gravitational constant, then $\sigma > 20 \text{ km/s}$ if $M_{\text{ecl}} > 10^5 M_\odot$ for $\epsilon R \approx 1 \text{ pc}$. These are realistic quantities since $r < 3 \text{ pc}$ and $\epsilon \approx 0.33$, suggesting that explosive gas expulsion may lead to thickened disks. Kroupa (2002) shows that the thickening history of the MW disk can be accounted for by clustered star formation if the star-formation rate (SFR) decreased over time therewith forming star cluster populations with maximal cluster masses that decrease with decreasing SFR (Weidner et al. 2004). That the thick disk of
the MW could have formed via “popping” CSFEs of mass $\approx 10^6 M_\odot$ has been shown with simulations by Assmann et al. (2011).

This model for the thickening of the MW disk is naturally consistent with the observed chain galaxies which show edge-on disk galaxies at high redshift undergoing star formation bursts in many knots within their disks (Elmegreen & Elmegreen 2006).

The relevance for GAIA is that each CSFE must be associated with a population of stars spreading apart along a thick tidal stream which resulted from the gas-expulsion event. A re-virialised star cluster may be the core of this expanding population, and if the CSFE did yield a bound star cluster then this cluster will be forming a thin kinematically cold tidal stream composed of stars that evaporate from the cluster due to two-body relaxation. These cold streams are of much interest because they may be used to probe how sub-structured the putative dark matter halo of the MW really is. It has already emerged, however, that the observed overdensities in known thin streams can be fully accounted for by epicyclic overdensities (Küpper et al. 2010). A star which is nudged out of its cluster through one of the Lagrange points orbits the MW on a slightly different orbit to that of the cluster and thus the angular separation between the star and the cluster oscillates as the star drifts away from its cluster. Since many stars perform essentially the same motions they accumulate in regions where stars turn around relative to the cluster.

This remarkable development, achieved through high-precision N-body computations that have become possible with Sverre Aarseth’s Nbody codes and the GPU-based computing platforms (Aarseth 2008), opens entirely new and extremely powerful tools for constraining the MW potential and gravitational dynamics in general, since the position and properties of the epicyclic overdensities are a measure of the cluster–MW combined effective potential. It is expected that the GAIA data will contain many thin streams, given that the entire MW field population of stars stems from dissolving CSFEs. It will become possible to measure how the streams diffuse apart with the age of their trace population.

Thus, around each star cluster, such as the Pleiades, the GAIA data ought to reveal two associated kinematical populations. The expanding population and the evaporated population. The total of the expanding population is likely to be about 2/3rds of the initial CSFE membership for the Pleiades (Kroupa et al. 2001), for example.

Furthermore, in each re-virialised post-gas-expulsion star cluster there is a competition of time scales: the remnants of massive stars (neutron stars and black holes) accumulate near the cluster center due to mass segregation. There they eject each other through three-body encounters on a core ejection time-scale. At the same time, low-mass stars evaporate from the cluster on a two-body relaxation time-scale, which is enhanced in stronger tidal fields. It turns out (Banerjee & Kroupa 2011) that the evaporation time scale is faster than the core-ejection time-scale in star clusters within about 5 kpc distance from the Galactic center. There, clusters with sufficient mass to contain many stellar remnants evolve to black-hole dominated objects with a few stars being bound, the dark star clusters. GAIA should find such super-virial (“dark”) clusters if they exist. Therewith the typical kick a remnant receives during the supernova explosion will be constrained to a small value as otherwise the cluster looses the remnants at explosion time. Once the existence of dark clusters has been observationally proven, it will be ascertained that star clusters must be the sources of gravitational wave emission (Banerjee et al. 2010).
Mining the GAIA data will therefore open entirely new doors into understanding the formation and disruption of CSFEs as well as into gravitational dynamics and the physics of stellar explosions.

8 The mass function of CSFEs, of globular clusters and the population II halo

Embedded star clusters have been found to have a power-law mass function (ECMF) with power-law index $\beta \approx 2$ (the Salpeter index would be 2.35; Lada & Lada 2003). If residual gas expulsion is relevant for early cluster evolution, then it follows that the relation between the final mass of the re-virialised young cluster is a fraction of the pre-gas expulsion stellar mass,

$$M_{\text{rev}} = f_{\text{st}} M_{\text{ecl}}, \quad (7)$$

where $f_{\text{st}} < 1$ is the fraction of stars remaining in the re-virialised cluster. Given that $f_{\text{st}}$ is likely to be a function of the depth of the potential well,

$$f_{\text{st}} = f_{\text{n}}(M_{\text{ecl}}), \quad (8)$$

and also of the number of massive stars in the CSFE (being $\propto M_{\text{ecl}}$ for an invariant IMF), it follows that $f_{\text{st}}$ may have a significant minimum around about $M_{\text{ecl}} = 10^4 M_\odot$. Here the potential well is still sufficiently shallow while O stars are already present in the population. It is at this mass scale that the expulsion of residual gas may be most damaging and $f_{\text{st}}$ may reach a minimum. Such ideas lead to the result that the post-gas expulsion MF of re-virialised young clusters have a structured MF which reflects the variation of $f_{\text{st}}$ with $M_{\text{ecl}}$.

Kroupa & Boily (2002) show that this ansatz naturally accounts for the turnover of the MF of clusters near $10^5 M_\odot$ as is observed for the ancient GCs. The gas expulsion process unbinds a large fraction of the embedded cluster population such that the MW halo population II spheroid emerges naturally – it is composed of the quickly dissolved low-mass star clusters that formed together with the present-day GCs plus the stars that were lost from the present day GCs due to residual gas expulsion. Such concepts have been incorporated into $N$-body modeling of cluster populations by Baumgardt et al. (2008b) and Parmentier et al. (2008).

The post-gas expulsion cluster MF may also have a pronounced peak near $10^3 M_\odot$ where the ONC, Pleiades, Hyades and Praesepe lie. This may explain why such open clusters may perhaps be overrepresented.

9 Top-heavy IMF in star bursting clusters

As discussed above, GAIA data will constrain the gas-expulsion process from CSFEs. Constraining the gas-expulsion process is of much importance also for the issue of globular cluster (GC) formation and the possible variation of the stellar IMF with physical cloud conditions. The data will thus touch upon a holy grail of star formation research, namely the finding of conclusive evidence of the long-expected variation of the IMF with star-forming cloud metallicity and cloud density.
The deep observations by De Marchi et al. (2007) of 20 GCs show that the present-day stellar MF (PDMF) becomes increasingly shallower over the stellar mass range 0.3 – 0.8 $M_\odot$ with decreasing cluster concentration. The same trend holds also with increasing metallicity. Both do not follow readily from theory (Marks & Kroupa 2010).

That low-concentration clusters are depleted of low mass stars was surprising because the expectation was the opposite, i.e. low-concentration clusters ought to retain their low-mass stars and high concentration (post core collapse) clusters ought to be more evolved dynamically having lost a larger fraction of their low-mass stars. Also, the theoretical expectation has been that low-metallicity clusters ought to have top-heavy IMFs, i.e. should have flatter PDMFs, contrary to the observations.

If clusters were to form mass segregated but with an invariant canonical stellar IMF for $< 1 M_\odot$ and filling their tidal radii then low-mass stars evaporate preferentially immediately and the observed trend between PDMF and concentration can be reproduced (Baumgardt et al. 2008a). This comes about because by being initially mass segregated, initially tidally-filling clusters loose the most weakly bound (and thus low-mass) stars preferentially. But this ansatz cannot reproduce the trend of the PDMF and of the concentration with metallicity. Also, it is not clear why star clusters should form mass segregated filling their tidal radii, given that the tidal radii of the young clusters are very large (e.g. about 120 pc for a $10^5 M_\odot$ cluster at a distance of 8 kpc from the MW).

The metallicity trend however gives a clue: If gas expulsion is more efficient for more metal-enriched gas then CSFEs forming out of such material would suffer more damage than low-metallicity CSFEs (compare to metallicity-dependent stellar winds). Indeed, it turns out that low-concentration clusters with flatter PDMFs result naturally if GCs were born mass segregated filling their tidal radii, given that the tidal radii of the young clusters are very large (e.g. about 120 pc for a $10^5 M_\odot$ cluster at a distance of 8 kpc from the MW).

The first ever $N$-body computation over the entire life-history of a low-mass globular cluster, Pal 14, verifies that a viable revirialised post-gas-expulsion solution to the low-concentration cluster Pal 14 suggests it may have had a stellar mass function depleted in low mass stars and a large half-mass radius of about 20 pc (Zonoozi et al. 2011).

The constraints arrived at for the 20 GCs with deep observations imply that in order to actually remove the residual gas a certain amount of feedback needs to be invoked. This feedback is only possible if the IMF was increasingly top heavy with increasing cluster+gas cloud core density and decreasing metallicity (Marks et al. 2012, submitted). This may perhaps be the first ever observationally derived evidence for a density and metallicity dependent IMF variation in consistency with star-formation theory. The onset of this suggested systematic IMF variation is at a pre-cluster cloud-core density $> 10^5 M_\odot/pc^3$ and a mass-scale of a CSFE on a pc scale of $> 10^5 M_\odot$.

10 Conclusions

An outline of some of the work done on the physical processes that shape young star clusters and which are relevant for GAIA by leaving imprints in the kinematical field of the MW has been given. An analysis of GAIA astrometric data across the MW is likely to unambiguously constrain the gas expulsion process from CSFEs, because it leaves characteristic signatures in
the MW disk. Once the gas expulsion process has been constrained, it will emerge whether galactic disks can be thickened by residual gas expulsion from compact CSFEs and whether the star-cluster MF undergoes the rapid transformation from a power-law embedded cluster MF to a structured MF for older re-virialised clusters. Also, it will then become evident whether the systematic IMF variation, deduced from the careful dynamical analysis of deep GC observations, is supported, since the analysis rests on the notion that residual gas expulsion is a major physical process governing the emergence of star clusters from their embedded phase. It need not be overemphasised that verification of a systematically variable IMF has profound cosmological implications.

The GAIA mission will thus provide fundamental constraints not only on gravitational dynamics and the potential of the MW, but will also constrain the star-formation process on a pc scale and how it affects the morphology of galaxies.

Acknowledgments

I would like to sincerely thank the organisers for a most memorable conference, and Michael Marks for proof reading this manuscript.

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