The dynamical evolution of young clusters and galactic implications

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Star clusters are observed to form in a highly compact state and with low star-formation efficiencies. If the residual gas is expelled on a dynamical time the clusters disrupt thereby (i) feeding a hot kinematical stellar component into their host-galaxy’s field population, and (ii) if the gas-evacuation time-scale depends on cluster mass, then a power-law embedded-cluster mass function transforms within ten to a few dozen Myr to a mass function with a turnover near $10^5 M_\odot$, thereby possibly explaining this universal empirical feature.

1 Early cluster evolution

The star-formation efficiency (sfe), $\epsilon \equiv M_{\text{ecl}}/(M_{\text{ecl}} + M_{\text{gas}})$, where $M_{\text{ecl}}, M_{\text{gas}}$ are the mass in freshly formed stars and residual gas, respectively, is $0.2 \lesssim \epsilon \lesssim 0.4$ implying that the physics dominating the star-formation process on scales $< 10$ pc is stellar feedback. Within this volume, the pre-cluster cloud core contracts under self gravity thereby forming stars ever more vigorously, until feedback energy suffices to halt the process (feedback-termination), $[13]$. This occurs on one to a few crossing times ($\approx 10^6$ yr), and since each proto-star needs about $10^5$ yr to accumulate about 95 % of its mass $[15]$, the assumption may be made that the very young cluster is mostly virialised at feedback-termination. Its stellar velocity dispersion, $\sigma \approx \sqrt{G M_{\text{ecl}}/(\epsilon R)}$, may then reach $\sigma = 40$ pc/Myr if $M_{\text{ecl}} = 10^{5.5} M_\odot$ which is the case for $\epsilon R < 1$ pc. This is easily achieved since the radius of one-Myr old clusters is $R \approx 1$ pc with a weak, if any dependence on mass.

The above exercise demonstrates that the possibility may be given that a hot kinematical component could add to a galactic disk as a result of clustered

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star formation for reasonable physical parameters. But this depends on (i) $\epsilon$, (ii) $R$ (cluster concentration) and (iii) the ratio of the gas-expulsion time-scale to the dynamical time of the embedded cluster, $\tau_{\text{gas}}/t_{\text{cross}}$.

1.1 Empirical constraints

The first (i) of these is clearly fulfilled: $\epsilon < 40 \% \ [8]$. The second (ii) also appears to be fulfilled such that clusters with ages $\lesssim 1 \ \text{Myr}$ have $R \lesssim 1 \ \text{pc}$ independently of their mass. Some well-studied cases are tabulated and discussed in [5]. Finally, the ratio $\tau_{\text{gas}}/t_{\text{cross}}$ (iii) remains uncertain but critical.

The well-observed cases discussed in [5] do indicate that the removal of most of the residual gas does occur within a cluster-dynamical time, $\tau_{\text{gas}}/t_{\text{cross}} \lesssim 1$. Examples noted are the Orion Nebula Cluster (ONC) and R136 in the LMC both having significant super-virial velocity dispersions. Other examples are the Treasure-Chest cluster and the very young star-bursting clusters in the massively-interacting Antennae galaxy which appear to have HII regions expanding at velocities such that the cluster volume may be evacuated within a cluster dynamical time.

A simple calculation of the amount of energy deposited by an O star into its surrounding cluster-nebula also suggests it to be larger than the nebula binding energy [5]. Furthermore, [2] note that many young clusters have a radial-density profile signature expected if they are expanding rapidly.

Thus, the data suggest the ratio $\tau_{\text{gas}}/t_{\text{cross}}$ to be near one, but much more observational work needs to be done to constrain this number. Measuring the kinematics in very young clusters would be an extremely important undertaking, because the implications of $\tau_{\text{gas}}/t_{\text{cross}} \lesssim 1$ are dramatic.

To demonstrate these implications it is now assumed that a cluster is born in a very compact state ($R \approx 1 \ \text{pc}$), with a low sfe ($\epsilon < 0.4$) and $\tau_{\text{gas}}/t_{\text{cross}} \lesssim 1$. As noted in [5], “in the presence of O stars, explosive gas expulsion may drive early cluster evolution independently of cluster mass”.

2 Implications

Heating galactic-field populations

As one of the important implications, a cluster in the age range of $\approx 1-50 \ \text{Myr}$ will have an unphysical $M/L$ ratio because it is out of dynamical equilibrium rather than having an abnormal stellar IMF [2]. Another implication would be that a Pleiades-like open cluster would have been born in a very dense ONC-type configuration and that, as it evolves, a “moving-group-I” is established during the first few dozen Myr which comprises roughly 2/3rds of the initial stellar population and is expanding outwards with a velocity dispersion which is a function of the pre-gas-expulsion configuration [7]. These computations were in fact the first to demonstrate, using high-precision $N$-body modelling,
that the re-distribution of energy within the cluster during the embedded phase and the expansion phase leads to the formation of a substantial remnant cluster despite the inclusion of all physical effects that are disadvantageous for this to happen (explosive gas expulsion, Galactic tidal field and mass loss from stellar evolution). A “moving-group-II” establishes later as the “classical” moving group made-up of stars which slowly diffuse/evaporate out of the re-virialised cluster remnant with relative kinetic energy close to zero.

Thus, the moving-group-I would be populated by stars that carry the initial kinematical state of the birth configuration into the field of a galaxy. Each generation of star clusters would, according to this picture, produce overlapping moving-groups-I (and II), and the overall velocity dispersion of the new field population can be estimated by adding in quadrature all expanding populations. This involves an integral over the embedded-cluster mass function, $\xi_{\text{cl}}(M_{\text{cl}})$, which describes the distribution of the stellar mass content of clusters when they are born [4, 5]. Because the embedded cluster mass function is known to be a power-law this integral can be calculated for a first estimate. The result is that for reasonable upper cluster mass limits in the integral, $M_{\text{cl}} < \sim 10^5 M_\odot$, the observed age–velocity dispersion relation of Galactic field stars can be re-produced.

This theory can thus explain the much debated “energy deficit”: that the observed kinematical heating of field stars with age cannot, until now, be explained by the diffusion of orbits in the Galactic disk as a result of scattering on molecular clouds, spiral arms and the bar [3]. Because the age–velocity-dispersion relation for Galactic field stars increases with stellar age, this notion can also be used to map the star-formation history of the Milky-Way disk by resorting to the observed correlation between the star-formation rate in a galaxy and the maximum star-cluster mass born in the population of young clusters [14].

**Structuring the initial cluster mass function**

Another potentially important implication from this theory of the evolution of young clusters is that if the gas-expulsion time-scale and/or the sfe varies with initial (embedded) cluster mass, then an initially featureless power-law mass function of embedded clusters will rapidly evolve to one with peaks, dips and turnovers at “final” cluster masses that characterize changes in the broad physics involved, such as the gas-evacuation time-scale.

As an example, [6] assumed that the function $M_{\text{icl}} = f_{\text{st}} M_{\text{cl}}$ exists, where $M_{\text{cl}}$ is as above, $M_{\text{icl}}$ is the “classical initial cluster mass” and $f_{\text{st}} = f_{\text{st}}(M_{\text{cl}})$. The “classical initial cluster mass” is that mass which is inferred by classical $N$-body computations without gas expulsion (i.e. in effect assuming $\epsilon = 1$, which is however, unphysical). Thus, for example, for the Pleiades, $M_{\text{cl}} \approx 1000 M_\odot$ at the present time (age: about 100 Myr), and a classical initial model would place the initial cluster mass to be $M_{\text{icl}} \approx 1500 M_\odot$ by using standard $N$-body calculations to quantify the secular evaporation of stars.
from an initially bound and virialised “classical” cluster [10]. If, however, the sfe was 33 per cent and the gas-expulsion time-scale was comparable or shorter than the cluster dynamical time, then the Pleiades would have been born in a compact configuration resembling the ONC and with a mass of embedded stars of $M_{\text{ecl}} \approx 4000 M_\odot$ [7]. Thus, $f_{\text{st}}(4000 M_\odot) = 0.38$.

By postulating that there exist three basic types of embedded clusters, namely clusters without O stars (type I: $M_{\text{ecl}} \lesssim 10^{2.5} M_\odot$, e.g. Taurus-Auriga pre-main sequence stellar groups, ρ Oph), clusters with a few O stars (type II: $10^{2.5} \lesssim M_{\text{ecl}}/M_\odot \lesssim 10^{5.5}$, e.g. the ONC) and clusters with many O stars and with a velocity dispersion comparable to the sound velocity of ionized gas (type III: $M_{\text{ecl}} \gtrsim 10^{5.5} M_\odot$) it can be argued that $f_{\text{st}} \approx 0.5$ for type I, $f_{\text{st}} < 0.5$ for type II and $f_{\text{st}} \approx 0.5$ for type III. The reason for the high $f_{\text{st}}$ values for types I and III is that gas expulsion from these clusters may be longer than the cluster dynamical time because there is no sufficient ionizing radiation for type I clusters, or the potential well is too deep for the ionized gas to leave (type III clusters). Type II clusters undergo a disruptive evolution and witness a high “infant mortality rate” [8], therewith being the pre-cursors of OB associations and open Galactic clusters.

Under these conditions and an assumed functional form for $f_{\text{st}} = f_{\text{st}}(M_{\text{ecl}})$, the power-law embedded cluster mass function transforms into a cluster mass function with a turnover near $10^5 M_\odot$ and a sharp peak near $10^3 M_\odot$ [8]. This form is strongly reminiscent of the initial globular cluster mass function which is inferred by e.g. [11, 12, 9, 1] to be required for a match with the evolved cluster mass function that is seen to have a universal turnover near $10^5 M_\odot$.

This ansatz may thus bear the solution to the long-standing problem that the deduced initial cluster mass function needs to have this turnover, while the observed mass functions of young clusters are feature-less power-law distributions.

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