Star Clusters: From the Milky Way to the Early Universe
Proceedings IAU Symposium No. 351, 2019
A. Bragaglia, M. Davies, A. Sills & E. Vesperini, eds.

doi:10.1017/S1743921319007920

Super star clusters and their multiple stellar populations

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Abstract. We present a scenario for the formation of super star clusters (with masses larger than $10^5 M_\odot$) in which multiple generations of star formation will occur. We stress that the gas left over ($\sim$50%) from first generation (1G) star formation should be retained in such massive clusters (thanks to their deep potential wells, with escape speeds larger than 10 km/s) and be available for a second or even third generation of stars, with the basic HeCNONaMgAl chemical anomalies observed in globular clusters, the latter assumed to be the descendents of these super star clusters. One new feature of this model is the role of C^+ cooling of the dense warm trapped neutral or ionized gas which defines a characteristic temperature of $\sim$100 K, leading to a second generation (2G) of stars with a top-heavy IMF ($M > 5\ M_\odot$). The ashes of the 2G very massive stars (VMS, $M > 100\ M_\odot$) sampled in this IMF quickly pollute and dilute the left-over pristine gas with their slow winds (that cannot escape the cluster), while the majority of massive stars develop fast winds (that actually can escape from the cluster). Meanwhile, much of the remaining dense $T = 100$ K gas contracts gravitationally in the massive cluster and may reach densities of the order of $10^9\ cm^{-3}$, in which case the Jeans mass drops to about $0.2\ M_\odot$ and leads to a substantial low-mass pre-MS 3G population (most likely on a very short timescale). In this way, we may solve both the mass budget and the excess Helium problem in proto-globular clusters, while also explaining the Na-O and Mg-Al anti-correlations resulting from hot H-burning of very massive stars at 45MK and 75MK, respectively.

Keywords. star formation, star clusters, globular clusters, multiple stellar populations

1. Young star clusters and the powers of 10

Star clusters with young high-mass stars can be studied in increasing powers of 10, in terms of their mass and massive stellar content. Famous examples include the nearby Orion Nebula Cluster which has a mass the order of $10^3\ M_\odot$ and contains 1 O-star (theta-1 C Ori), the NGC 3603 Galactic cluster at 7 kpc which has a mass of the order of $10^4\ M_\odot$ and about 10 massive stars (O-stars and WR stars) in its center, and the most massive young cluster in the Local Group, R136, in the 30 Doradus HII region in the Large Magellanic Cloud at 55 kpc with a mass approaching $10^5\ M_\odot$ and more than 100 O-stars and WR-stars within its half-mass radius of a few parsec. For a comparison of these 3 dense iconic bound clusters, distance-scaled images have been displayed in a paper by Zinnecker (2004). Recent observational progress on these particular young clusters has been reported in major papers by Karl *et al.* (2018), Drew *et al.* (2019), and Schneider *et al.* (2018), respectively.

However, there are young star clusters in the Local Universe that are 1 or even 2 orders of magnitude (powers of 10) more massive than R136, e.g. the ones in colliding galaxies such as the Antennae, with masses in the range 10^6 to $10^7\ M_\odot$, and with an estimated number of 10^3 to 10^4 young luminous stars (see Mengel (2002)). These clusters beyond masses of the order of $10^5\ M_\odot$ are often called "super star clusters".

As we will show in this paper, these super star clusters are distinct and different from lower mass clusters in that they are able to gravitationally retain dense warm gas (HII regions) which will then be available for a second generation of star formation (likely with a top-heavy IMF). A second generation does not occur in lower mass clusters which quickly expel their residual gas by radiative and mechanical stellar feedback. This is essentially why globular clusters (the descendents of super star clusters) have multiple stellar populations, with chemically distinct characteristics between the first and second generation stars (see the key review by Bastian & Lardo (2018)).

2. The origin of dense super star clusters

We suggest the origin of dense massive clusters follows the scenario outlined in Zinnecker (2004) and Zinnecker & Yorke (2007)). In order to form a dense bound massive star cluster the initial conditions must be a very compact gas configuration (about 10^5 $M_\odot$ pc^{-3}) which in addition must be set up rather quickly to avoid early fragmentation (and hence the likely disruption of a less dense gas configuration by massive star feedback). The required rapid isothermal compression (factors 100–1000) with Mach numbers of 10 to 30 can come about by the action of fast shocks such as tidal shocks or those resulting from molecular or atomic cloud cloud collisions, and the shock-compressed layer can form filaments and dense cores (e.g. Inoue & Fukui (2013)) where both high-mass stars and low-mass stars can form. Subsequently the whole gaseous hierarchical sub-structure will undergo a quasi-2D global collapse, merging to a complex, turbulent proto-cluster cloud in near-virial equilibrium, with stars pulled in, too. For example, a 10^6 $M_\odot$ cloud will be gravitationally squeezed into a radius of a few pc with a velocity dispersion of 20–30 km/s and a gas number density of the order of 10^6 cm^{-3}. Many details have been neglected here, such as the possible role of magnetic fields and non-isothermal effects in the post-shock gas cooling, but this is the simple physical picture we have in mind to generate the dense initial conditions needed to give birth to a super star cluster.

3. First generation and second/third generation star formation in dense massive proto-clusters

We assume that the first generation of star formation will be triggered by the cloud-cloud collision, and that the resulting IMF will be normal, with a shape a la Kroupa or a la Chabrier. The R136 cluster is known to have a fairly normal IMF, with many low-mass stars (Andersen *et al.* (2009)). The first generation stars will settle into some quasi-spherical virial equilibrium configuration, and the left-over dense gas, heated by uv radiation and stirred up by the stellar motions, will also settle in the potential well of the cluster stars. Star formation stops as a consequence of stellar feedback (the residual gas is too hot and too turbulent). We assume a star formation efficiency of about 50% during the burst of star formation which formed the first generation (1G). This means half of the initial gas (retained in the cluster) is still available for a second generation (2G) of stars, after cooling. Note that for dense young super star clusters with masses of the order of 10^6 $M_\odot$ and radii of a few parsec, as considered here, the escape speed is 20–30 km/s, which is much higher than the velocity dispersion of ionized HII region gas (10km/s for a temperature of about 10^4K). Thus the dense HII gas (density 10^6 cm^{-3}) is gravitationally "trapped" and will remain in the cluster (cf. Bressert *et al.* (2012)). This is the key assumption to obtain a distinct 2G/3G stellar population.

If new stars were to form from this HII gas, it needs to cool, but how? In metal-poor gas of 1/100 to 1/10 solar abundance, from which globular clusters must form, the main coolant for warm neutral gas (after hydrogen recombination) is C^+ at 158 microns. This fine structure line should be optically thin, even at high gas densities. Its excitation temperature is 91K, which means the gas cooling would stall at about 100K and lower

https://doi.org/10.1017/S1743921319007920 Published online by Cambridge University Press

gas temperatures cannot be reached. At these temperatures and densities only high-mass stars can form (dependence of the Jeans mass on temperature and density), and we thus predict a top-heavy IMF ($M > 5\ M_\odot$) for the 2nd generation star formation. Indeed, the Jeans mass for 100 K and $10^6\ cm^{-3}$ gas is about 5 $M_\odot$. (This is similar to the prediction of a top-heavy IMF for Pop III stars when only molecular hydrogen cooling for the primordial gas to about 500 K is available). The maximum stellar mass is probably increasing with cluster mass and decreasing metallicity (up to several 100 $M_\odot$, see Vink (2018)). This very high-mass population can create the hot hydrogen burning products needed to explain the Na-O and Mg-Al anti-correlations, seen in globular clusters. The ashes of these stars, which are assumed to be fully mixed (chemically homogeneous) are transported by stellar winds which would pollute and dilute the cooling cluster gas from which a major third generation (3G) of low-mass stars ($M < 1\ M_\odot$) would form (see below how). These 3G low-mass stars can form during the MS lifetime of the the high-mass 2G stars, perhaps partly induced by the radiative and mechanical presssure of the high-mass stars. Also, low-mass stars can form, if either extra gas cooling comes in (e.g. by warm dust coupled to the dense gas) or if the gas density in the cluster goes up by further dissipation and contraction of the gas in the cluster potential (in this case the 3G low-mass stars would predominantly form nearer to the cluster center). For example, for a gas temperature of 100K and a pressure- or contraction-enhanced gas density of $10^9\ cm^{-3}$, the Jeans mass would drop to 0.2 $M_\odot$. All this could happen very quickly (easily within 10 Myr), before Type II supernovae explode and mess up the originally uniform Fe abundance (a constraint emphasized e.g. by Renzini *et al.* (2015)). It may well be that extended disks around low-mass pre-MS stars play a role to effectively sweep up and incorporate the polluted pristine gas, as suggested by Bastian *et al.* (2013). This alleviates the problem of gas accretion of the pre-MS stars by the Bondi-Hoyle mechanism which turns out to take too long ($\sim$100 Myr to accrete a gas mass of 0.1 $M_\odot$ for a relative speed of 10km/s and uniform gas density of $10^6\ cm^{-3}$).

Finally, how to account for the only moderate He enrichment observed between the two chemically distinct low-mass populations in globular clusters, i.e. how to avoid excess He pollution (Bastian et al. 2015) in our model. Here is our speculation: We assume stellar winds from the 2G ordinary massive stars are very fast and do carry their processed material (including He) out of the cluster. However, very massive stars (VMS) are inflated and rather cool as long as they grow in mass by strong accretion, see Hosokawa & Omukai (2009). Therefore they have initially slow winds while accreting, ejecting nuclear material which will not escape from the cluster. When accretion stops, the VMS stars turn hot and their winds turn fast. Thus, for a short time in their MS lives (<1 Myr), the VMS stars contribute most significantly to the self-enrichment of the pristine gas with hot H-burning products (ONa, MgAl at 45MK and 75MK, Prantzos et al. 2017), including small amounts of He (the cool winds are low in He). Gas with this modified chemical composition will then immediately be used in the formation of the 3G low-mass stars (Vink (2018)) and give rise to their distinct chemical anomalies. Our model is different from, but in some aspects reminiscent of, the supermassive star model of Gieles *et al.* (2018).

Surely these rough qualitative ideas are not the final approach to the subject, but we hope the discussion and comparison of our scenario with others will stimulate more and better ideas, and more quantitative simulations.

Acknowledgment

We thank Mark Gieles and Nate Bastian as well as John Bally and Shu-ichiro Inutsuka for most helpful discussions and comments. We are also thankful to the editors for their patience with the (late) manuscript and to the IAU for financial support.

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