Globular Cluster Systems, Extragalactic Star Clusters, Nuclear Star Clusters, Dwarf Galaxies

Star Clusters: From the Milky Way to the Early Universe
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Young, old, massive: Steps to understanding globular cluster formation

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Abstract. On observational grounds we now know a huge amount about the characteristics of massive star clusters in galaxies of all types, from the smallest dwarfs to the most massive giants and even into the Intracluster Medium. The old globular clusters (GCs) in particular exhibit a high degree of uniformity across all these environments in their physical properties including scale size, luminosity distribution, metallicity distribution, and age. As survivors of a long period of dynamical evolution, they are "unusual, but not special" among star clusters.

The past few years have seen major advances in theoretical modelling that are starting to reveal how these massive star clusters formed in the early stages of galaxy evolution. Several suites of models point to their emergence in GMCs (Giant Molecular Clouds), which provide the turbulent big reservoirs of gas within which star clusters can be built. At cluster masses $\sim 10^5 M_\odot$ and above, clusters form hierarchically through a nearly equal combination of direct gas accretion, and mergers with smaller clusters scattered throughout the GMC. GCs and YMCs (young massive clusters) in this high mass range should therefore be composite systems right from birth. To make such high-mass clusters, host GMCs of $\sim 10^7 M_\odot$ are needed, and these are most commonly found in galaxies at redshifts $z \gtrsim 2$.

Keywords. galaxies: star clusters, globular clusters: general, galaxies: formation

1. Introduction

Much research on the old, massive star clusters called globular clusters (GCs) is now directed to understanding their formation. This earliest epoch is now perhaps the least well understood part of their lives, certainly when compared with the longer story of their later dynamical evolution within the tidal field of their parent galaxy, which is gas-free and requires "only" N-body gravity to follow. We expect that GCs at their earliest stages should, in some way, resemble in their earliest stages the young massive clusters (YMCs) in the nearby universe that are associated with starburst galaxies, where large amounts of gas at high pressure and density have been collected.

This view, which might seem obvious now, is in itself a change in thinking from earlier times. Numerous early approaches suggested that GC formation might be special in some way, connected with the early universe; examples include Peebles & Dicke (1968); Fall & Rees (1985); Murray & Lin (1992); Moore *et al.* (2006); Chiou *et al.* (2019). However, those semi-cosmological ideas encounter fundamental and probably insurmountable obstacles: for example, there is no special mass scale for GCs (much current evidence indicates that their initial mass distribution has a power-law form, and the present-day GC luminosity function with its lognormal shape has been produced instead by dynamical evolution and preferential removal of lower-mass clusters). GCs in all galaxies are seen to be strongly associated with galaxy bulges and halos. And perhaps most tellingly, GCs (or star clusters generally) are not seen to form out of spherical, isolated, monolithic gas clouds (SIMCs): young star clusters, at any mass range, are embedded within Giant Molecular Clouds (GMCs) that provide large reservoirs of gas from which stars, and star clusters, can be built.

To ask how GCs formed can then be seen as a subset of the more general question: how do star clusters form? Fortunately, this is a field in which major progress is now being made, with a clear picture beginning to emerge. In this article, I will not attempt a comprehensive review of this very extensive literature, but will highlight a few of the recent results that represent key achievements.

2. A Look at Some Observational Evidence

YMCs that have the potential to evolve into GCs will need to be *massive* ($>10^5 M_\odot$ at birth) and *compact* (gravitationally bound and with $r_h \sim 1$ pc, so that they will not expand and dissipate during the first phases of early rapid mass loss). Metallicity cannot be a criterion, since we know already that GCs span a factor of at least 200 in heavy-element abundance with similar structures and mass distributions. Massive, compact star clusters are rare in the nearby universe, but Portegies-Zwart *et al.* (2010) identified some dozens of YMCs in and near the Local Group galaxies with ages <10 Myr. For ages more than about 10 Myr, however, very few such objects can be found, already indicating that GCs are survivors of a larger initial cluster population.

We would then like to see YMCs at their earliest possible stages to penetrate as directly as possible the environments that give rise to them. Here, much progress has been made in just the past few years. As one especially informative example, Turner *et al.* (2015, 2017) and Cohen *et al.* (2018) have investigated the most massive YMC in the starburst dwarf NGC 5253. This object has a stellar age of just 1 Myr, a total mass $2.5 \times 10^5 M_\odot$, and holds thousands of massive stars. Equally important, however, is that it is still accreting molecular gas, and that outgoing winds appear to be damped by radiative cooling effectively enough that they do not escape the protocluster environment. Here, we see young stars coexisting with their natal gas reservoir in roughly equal amounts, within a very small and dense region.

Similarities to this picture are also seen in the numerous YMCs within the central regions of NGC 253, a small nearby disk galaxy with highly active star formation. Leroy *et al.* (2018), using ALMA data, find that dense gas, dust, and a radio continuum are all present in the YMCs simultaneously with roughly equal amounts of stellar mass. Going still further back along the age scale, Finn *et al.* (2019) have used ALMA to investigate a large GMC (the "Firecracker" nebula) in the Antennae galaxies. This intriguing object, with a diameter roughly 40 pc and a stable, pressure-confined cloud mass of a few million $M_\odot$, appears to contain a *proto*-YMC; that is, we are seeing it just before star formation has fully started. An interesting side effect of their study is that HCN and HCO gas behave more or less oppositely with age: as a protocluster ages, HCO increases while HCN decreases, perhaps providing a useful tool for dating such objects. The new observational work in this area is a prelude to what will develop into far richer results in the near future.

Let us look now at the extreme opposite end of the age scale, at GC populations as they are today. In Figure 1, results from HST photometry are shown for the huge GC system around NGC 6166, the supergiant Brightest Cluster Galaxy in A2199 (Harris *et al.* 2016). Though these clusters exist in a very different galactic environment than the Milky Way, their range of luminosities, integrated colors (thus metallicitiies), and few-parsec scale sizes are all quite familiar. Because of sheer numbers, their color-magnitude distribution in this BCG extends to almost an order of magnitude higher (to $L \simeq 10^7 L_\odot$) than in the Milky Way; for example, ω Cen, which has a mass over $10^6 M_\odot$ and which we tend to think of as exceptional, would lie at F814W $\simeq 24.6$ in the left panel of Fig. 1, outranked

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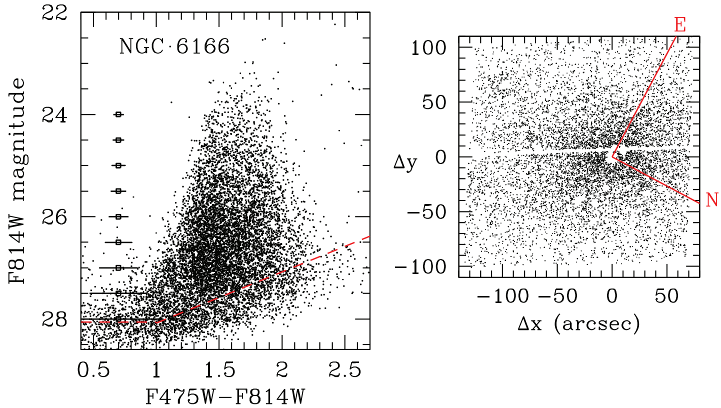

Figure 1. *Left panel:* Magnitude plotted versus color index for the globular clusters around NGC 6166, the BCG in Abell 2199. Each dot represents one cluster; in total, the galaxy is likely to contain more than 30,000 GCs (see Harris *et al.* (2016)). The spread in colors represents the metallicity range from [Fe/H] $\simeq -2$ on the blue side, up to roughly Solar abundance on the redder side. Classic bimodality, however, is not so obvious here; the distribution is broad and unimodal, as it is for most other BCGs (see text). *Right panel:* Spatial distribution of the GCs. The scale is 100 arcsec = 60 kpc. The GCs follow a rough power-law decline in surface density that fades smoothly into the Intracluster Medium of this rich Abell cluster.

by a hundred other clusters in NGC 6166 (or in other BCGs). In total, the distribution of GCs in Fig. 1 is seamlessly and smoothly populated over the entire measurable luminosity range, as it is in any other galaxy but the smallest dwarfs. A realistic model for the formation of GCs that is comprehensive enough to cover the full observed range will therefore need to be able to "build" star clusters from a lower limit of perhaps $\sim 10^3 M_\odot$ all the way up to $\sim 10^7 M_\odot$.

More recently, the existence of a remarkably simple correlation between the total mass in a GC system and the total mass (baryonic plus dark) of its host galaxy, of the form $M_{GCS} = const \cdot M_{gal}^{1.0}$, has been uncovered and developed; see, e.g., Blakeslee (1997); Spitler & Forbes (2009); Harris *et al.* (2017a). Its validity holds over 5 orders of magnitude in galaxy mass. Although a reasonably tight correlation between M_{GCS} and the galaxy's total *stellar* mass $M_\star$ also exists, it is quite nonlinear by comparison, the result of the detailed way the efficiency of galaxy-scale feedback during star formation depends strongly on galaxy mass (e.g. Harris *et al.* (2017a); Choksi *et al.* (2018)).

To put their observational characteristics in perspective, GCs as we see them in all galaxies form a smooth continuum of properties. Their luminosity function, with its lognormal shape, is to first order similar in all galaxies but when more precisely calibrated shows a gradual increase in the turnover luminosity and increase in dispersion with galaxy size, as discussed in Villegas *et al.* (2010); Harris *et al.* (2014). Measurements of scale sizes and King-model-type structures in a wide range of galaxies also show familiar ranges (e.g. Jordán *et al.* (2005); Harris (2009); Harris *et al.* (2010)). The color (metallicity) distributions extend from a minimum of [Fe/H] $\simeq -2.5$ to an upper limit near Solar abundance and possibly higher in the biggest giant galaxies. The metallicity distribution function (MDF) is concentrated toward metal-poor (blue) GCs in dwarf galaxies, changes to its more well known bimodal blue/red form in intermediate-luminosity systems such as the Milky Way and $L_\star$−type systems, and then into a broader, unimodal form in the biggest galaxies, as illustrated in Figure 2. This evidence by itself is a clear signal that the bigger galaxies are not simply built by piling together smaller ones.

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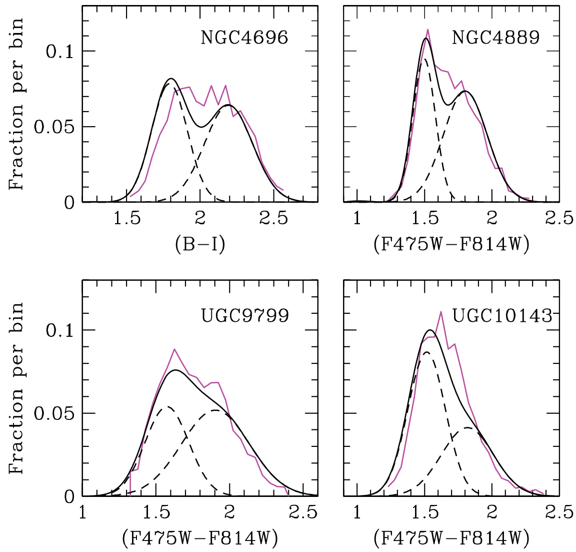

Figure 2. Color distribution functions for the GCs in four BCGs, from HST photometry (see Harris *et al.* (2017b)). In each case the distribution function is built from several thousand clusters. In each panel the black lines (dashed and solid) give the best bimodal-Gaussian fit to the number of clusters per color bin. The *magenta* lines give the *luminosity-weighted* distribution, which is preferred for showing how the mass in clusters is distributed by metallicity. The luminosity-weighted distributions are less obviously bimodal, and generally narrower than are the unweighted distributions.

3. Modelling the formation of GCs

Interpreting the origins of the GC system demographics described above in terms of galaxy formation modelling has received a huge boost in the past few years, an accomplishment worthy of celebration. Models and simulations that are capable of tracking GC formation build on earlier work, but are now reaching a new stage of maturity, as shown, for example, in Pfeffer *et al.* (2018); Hughes *et al.* (2019); Usher *et al.* (2018); Choksi *et al.* (2018); El-Badry *et al.* (2019); Reina-Campos *et al.* (2019); Kim *et al.* (2018). In particular, Pfeffer *et al.* (2018) isolate a key factor in the history of star cluster formation and GC formation with their finding that GMCs massive enough to form GC-mass clusters (that is, $M_{GMC} \gtrsim 10^7 M_{\odot}$) are most commonly found at redshift epochs $z > 2$ (see also Kim *et al.* (2018) and the discussion below).

Another key factor of these new models is the assumed correlation between *halo mass* and the *metallicity of the gas* contained in it. More massive halos systematically have higher-metallicity gas, and the details of the correlation must be tuned to reproduce the galaxies of today; see the discussions of Choksi *et al.* (2018); Pfeffer *et al.* (2018). This is one area where GC systematics can make clear contributions. The shape of the MDF (bimodal at lower galaxy masses, broad and unimodal at the highest masses) is one of the features that must be reproduced within these models by the mass distribution of the halos that merge hierarchically to build bigger galaxies. For example, in the biggest galaxies, which are built from a extended merger history comprising gas-rich halos at all masses, the final MDF takes on a broad unimodal shape. For dwarf galaxies, fewer mergers occur and involve only small, metal-poor halos. An interesting byproduct of these interpretations is that *very* massive, *very* metal-poor GCs should be quite rare: extremely low-metallicity gas belongs to the smallest halos, and these will not usually contain sufficiently large gas mass to build massive star clusters (Harris *et al.* (2006);

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Choksi & Gnedin (2019); Usher *et al.* (2018)). This factor helps explain the observed slow increase of GC metallicity with mass along the blue-GC sequence, as first seen by Harris *et al.* (2006); Mieske *et al.* (2006); Strader *et al.* (2006). Another, and related, byproduct of the same argument may explain why no GC more metal-poor than [Fe/H] $\simeq -2.5$ is known, whereas field stars of far lower metallicities have been found in the Milky Way: in ultra-low-metallicity halos, the small amounts of gas present can build only small star clusters, which do not survive to the present day (Kruijssen (2019)).

A physical explanation for the important linear correlation between M_{GCS} and M_{gal} is also beginning to emerge. An initial direct proportionality may exist in the smallest dwarfs ($M_{gal} < 10^{10} M_{\odot}$), in which case the same correlation would be replicated up to larger galaxies as hierarchical merging proceeds, as discussed in Kravtsov & Gnedin (2005); Harris *et al.* (2017a). However, even if the correlation starts out as more random, the action of merging and the central limit theorem will build in a linear relation such as we now see (Choksi *et al.* (2018); Forbes *et al.* (2018); El-Badry *et al.* (2019)). The net result is that the amount of mass going into GC formation is close to being directly proportional to the total amount of gas mass *initially* present in halos, which in turn should be proportional to halo mass, before the main action of feedback removes or heats up a large fraction of the gas that would otherwise have formed stars.

In short, GC formation in its broad terms can now be fit quantitatively, if roughly, into galaxy formation modelling simulations. We still need, however, to look at the events of GC formation in detail by understanding exactly how some fraction of the gas within a given GMC converts into star clusters. The underlying assumption in all such work is that *globular clusters are unusual, but not special.*† That is, GCs are unusual in the sense that they are at the high-mass end of the star cluster population, and the survivors of a long history of dynamical evolution. They are, however, not special in the sense that they do not belong to some entirely different formation process than other star clusters do. *GCs must have formed within GMCs of suitably high mass and physical conditions*, a view argued 25 years ago in broad-brush terms by Harris & Pudritz (1994).

To deduce the events of GC formation, there are two fundamentally opposite approaches:

(*a*) Take the existing properties of GCs today, and work backward to reverse-engineer their initial conditions. This is, to say the least, difficult. One must work backward through 10–12 Gyr of slow dynamical evolution within the galactic tidal field; then back through the earlier era of massive-star evolution, supernovae, and rapid mass loss; then back through the still earlier pre-SN era of star formation and accumulation of the original protocluster. Considerable information about these early stages has been erased over the long lifetime of a GC.

(*b*) Use the existing properties of the youngest massive star clusters forming at the present day to propose a model for the conditions of formation, and then evolve the model cluster forward in time to see how well it resembles present-day GCs. In this way, YMCs can be placed into their original context within GMCs, which are in turn embedded within galaxies of a range of sizes.

Just as for galaxy-scale simulations, GMCs can now be simulated at high enough resolution to identify the sites of star cluster formation and track their earliest evolution. Summaries of much of the recent literature here can be found in Li *et al.* (2019); Gavagnin *et al.* (2017). One recent suite of radiative-hydrodynamic realizations of GMCs done by Howard *et al.* (2017, 2018) with the FLASH2.5 code is pointed directly at how *massive* star clusters originate and grow within turbulent GMCs. In brief, this suite covers GMCs with initial power-law density profiles ($\rho \sim r^{-3/2}$ with a flat core), a Burgers turbulence

† This statement is due to Dean McLaughlin, but I have been unable to locate the original reference for it.

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spectrum imposed initially but not driven, and a wide range of initial virial parameters (internal kinetic to potential energy) ranging from very bound to very unbound. GMC masses of 10^4 to $10^7 M_\odot$ are simulated. Within any model GMC, a star cluster is defined to originate wherever the local gas density rises above a given threshold, is at a local potential minimum, has a converging gas flow, and is Jeans-unstable. The assumed density thresholds range from 10^4 cm^{-3} (the threshold at which star formation is seen to occur in local GMCs) up to 10^6 cm^{-3}. Within each cluster, gas is converted into stars at 20% efficiency per free-fall time through random sampling of a standard Chabrier IMF. Finally, feedback from the young clusters on the surrounding GMC includes ionizing radiation, radiative heating, and radiation pressure, but stellar winds are assumed to stay within the gas-rich protoclusters (see Cohen *et al.* (2018)). Sample calculations were run for metallicities of Solar and 0.1 Solar, the latter case intended to get closer to conditions in the early universe.

These simulations have a highest spatial resolution of $\simeq 0.6$ pc, so the internal structures and gas flows inside the young clusters are sub-grid (see, however, Li *et al.* (2019) for discussion of the relative gas and stellar distributions inside a young cluster). One important new element to these realizations is that the clusters – which form mostly along the filaments threading the GMC that were initially produced by the turbulent structure – are allowed to merge with one another if they pass within their own radii and are gravitationally bound. These simulations are terminated at lifetimes of roughly 5 Myr, which is when Type II SNe will start appearing. However, it appears to be the first few Myr that are the most important for cluster growth by the combination of direct gas infall and merging.†

Simulations like these yield several important new results that put our view of YMC formation into a new light:

• At *low* cluster mass ($\lesssim$ a few $10^4 M_\odot$), star cluster formation is simple: single-epoch, a short period of direct accretion of gas and then subsequent star formation.

• At higher masses, growth history become significantly more complex especially because of merging. For the highest-mass YMCs appearing in these simulations, the final YMC mass is gained about equally from direct gas accretion and from merging with many other, smaller clusters. In these more massive clusters, the main period of star formation is extended over the entire timespan of the simulations.

• The gas flows into a cluster are highly anisotropic and highly time-variable, but they slow down dramatically after 5 Myr because the gas reservoir in the neighborhood of the cluster has cleared out.

• The growth histories of the clusters have a stochastic nature, especially because of the random initial nature of the turbulence spectrum and the details of the gas flows. They have strongly contingent individual histories that are very unlike a simple, isolated monolithic collapse.

• At low metallicity, feedback on the surrounding gas is less important because of the much lower opacity, which makes it easier for clusters to grow to higher masses.

• Lastly, combining the results from the entire suite of simulations, the mass of the biggest central YMC found in each model GMC is nearly proportional to the host GMC mass itself, as seen in Figure 3. At low feedback (corresponding to low metallicity), $M_{max}(YMC) \sim M_{GMC}^{0.92\pm0.05}$. In absolute terms, the most massive YMC will incorporate almost 10 percent of the initial GMC mass. Typical local GMCs of $M \sim 10^4 M_\odot$ are capable of generating YMCs of a few hundred to a thousand $M_\odot$ at best. But to build

† Videos of selected model runs, along with much other supplementary material, can be found in Howard *et al.* (2018) at https://www.nature.com/articles/s41550-018-0506-0.

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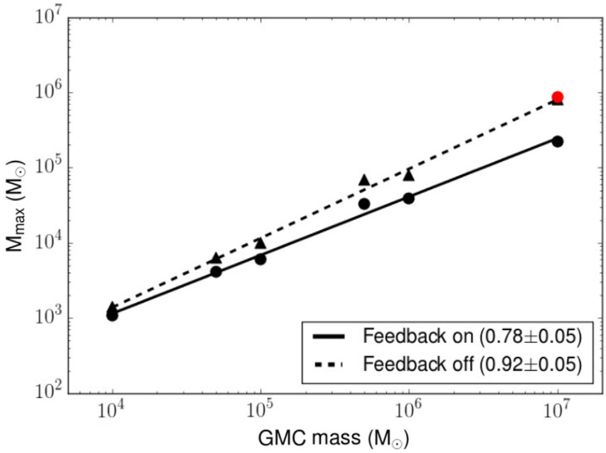

Figure 3. Mass of the most massive young star cluster formed within a GMC, plotted versus the initial mass of the GMC, as taken from the suite of simulations of Howard *et al.* (2018). GMC masses from 10^4 to $10^7 M_\odot$ are covered. The *solid line* shows models with Solar metallicity and full radiative feedback, while the *dashed line* shows the results with no feedback (pure hydrodynamic runs, equivalent to very low metallicity). The red symbol at $10^7 M_\odot$ GMC mass is for $Z = 0.1 Z_\odot$.

YMCs at the level of GCs (with initial masses near $10^6 M_\odot$), GMC masses of $10^7 M_\odot$ are needed. It is precisely during the redshift epochs $z \gtrsim 2$ when such massive GMCs are most common (see above).

Models like these represent a clear step forward in our physical understanding of how massive star clusters might have originated in the early universe. Other recent suite of simulations of GMCs over a similar mass range are presented by Li *et al.* (2019) and Grudić *et al.* (2018a,b), with many similar conclusions despite some differences in physical setup (initial density profile, metallicity, prescriptions for star formation, numerical code). Among the more robust results that appear to depend little on differences in the model setup are that star clusters grow hierarchically and are themselves substructured; that the most massive cluster is a dominant presence near the center of the GMC and can take up several percent of the GMC mass; and that the total lifetime of the GMC is approximately 1-2 free-fall times (a few Myr).

At their very most basic level, these recent modelling studies support one simple but extremely important conclusion: that globular clusters over their entire mass range can form in the early stages of galaxies in a *normal manner*, by growth within GMCs. Exotic and semi-cosmological scenarios are not needed. It remains to be seen in detail whether or not the intriguing multiple stellar populations with their distinct chemical abundance patterns (Bastian & Lardo (2018); Milone *et al.* (2018)) can emerge in a natural way within this formation picture, but the prospects for such results may be promising; see Howard *et al.* (2019) and also the presentations by Sills and Gieles at this conference.

Numerous questions need to be investigated. In Figure 4, I show a rough strategic view of where we stand on modelling of GC formation, and what might lie ahead. Admittedly this is sketched out from an observational astronomer's point of view, and therefore undoubtedly simplistic. Despite some big recent steps we are likely to be much less than halfway towards our goal. The existing RHD simulations of resolved GMCs with feedback need to be carried forward into higher-resolution modelling of the dense $\sim$1$-$pc-scale protoclusters that are predicted to be present scattered throughout the model GMC, so that we can trace out the gas flows inward and outward within them. Going beyond this,

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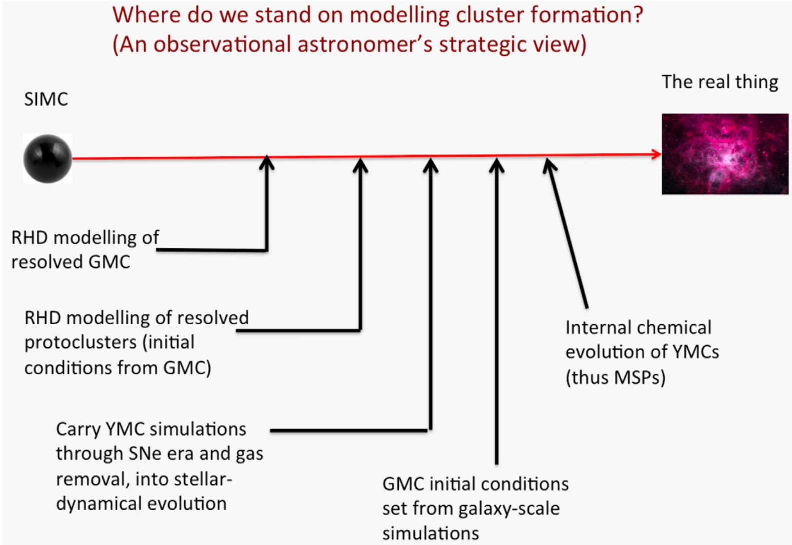

Figure 4. A strategic view of modelling GC formation. The red horizontal arrow at top stretches from early concepts of spherical isolated monolithic collapse of a gas cloud (SIMC) at left, to a fully realized GMC with its embedded star clusters at right. Various possible stages marking significant achievements in modelling are labelled.

we will need to track the YMC evolution onward through the supernova era and removal of the residual gas, bringing an end to their internal star formation history and bridging their history to the dynamical evolution era that dominates the rest of their lives. At some point soon as well, the details of stellar evolution of the massive stars within the YMC will need to be tracked right from the very beginning, with the hope (see above) that we can understand the unique challenge of the multiple stellar populations seen in most of today's GCs. Finally, stepping back outward to somewhat larger scales, the initial conditions for the simulated GMCs should be set from galaxy-scale simulations rather than treated in isolation. This is an ambitious agenda for modelling, but the computational and analytical tools for doing it are, for the first time, in our hands and improving steadily.

4. Summary

Recent observational results especially from HST and ALMA have begun to tell us in remarkably direct terms what the conditions of young massive star clusters are like, and where they form. Because of their high mass and compact structure, at least some of these should evolve into objects we would call globular clusters.

At the opposite end of the age scale, GC populations in all galaxies display a smooth continuum of physical properties in mass, metallicity, structure, and age. There is no obvious "break point" to be found in any of these global properties that would signal any changeover to different conditions of formation.

In the past few years, huge progress has been made on the theoretical modelling front that places GC formation solidly within the context of galaxy formation. Many of the broad demographic trends that have been found observationally for GC populations are now finding clear physical explanations within these models. The necessary intermediaries between the galaxy-scale potential well and the few-parsec scale of individual star clusters, are Giant Molecular Clouds. GMCs provide the high-mass concentrations of gas that can build star clusters. More quantitatively, GMC masses of $10^7 M_\odot$ and above

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appear to be necessary to build GC-sized star clusters; but GMCs in this mass range are exactly what will be present at early times (redshifts $z > 2$) in far larger numbers than we see around us today.

Finally, a new consensus is emerging that GCs, and YMCs, are *composite systems:* they are the results of hierarchical growth involving an almost equal combination of direct accretion of gas from their host GMCs, and merging with many of the smaller clusters scattered throughout the same GMC. In miniature, their rapid initial growth (taking only a few Myr) resembles the more familiar hierarchical merging that galaxies themselves experience. Advances in our understanding are now happening quickly, and the prospects on both theoretical and observational grounds are exciting.

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