

# Star cluster ecology: revisiting the origin of iron and age complex clusters

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## ABSTRACT

Typical globular clusters (GCs – young and old) host stellar populations with little or no star-to-star variations in heavy elements (e.g. Ca, Fe) nor in age. Nuclear star clusters (NSCs), on the other hand, host complex stellar populations that show multimodal distributions in Fe and often in age, presumably due to their unique location at the centre of a large galactic potential well. However, recently a new class of clusters have been discovered, exemplified by the clusters Terzan 5 and Liller 1, two high mass, high metallicity clusters in the inner Galactic regions. It has been suggested that these are not true GCs, but rather represent left over fragments of the formation of the Galactic Bulge. Here, we critically assess this scenario and find that the role of dynamical friction likely makes it untenable and that the method used to estimate the initial masses of the clumps was invalid. Instead, it appears more likely that these clusters represent a relatively rare phenomenon of existing GCs accreting gas and forming a second generation, as has been previously suggested.

**Key words:** globular clusters: general.

## 1 INTRODUCTION

Over the past 20-odd years, there has been a unification of stellar cluster types, which were previously thought to be unique and separate. Hence, while there appears to be a diverse ecology of clusters, advances in theory and simulations have emphasized their connectedness, representing different parts of a larger continuous parameter space. Examples include linking the young massive clusters (YMCs – Portegies Zwart, McMillan & Gieles 2010) with their lower mass counterparts, the Galactic open clusters (OCs), through a continuous mass distribution. Likewise, the Galactic OCs represent the young (and typically lower mass) end of a continuous age distribution that naturally extends into the classic globular cluster (GC) population (once cluster disruption is taken into account – Elmegreen & Efremov 1997). This can be seen most clearly in nearby galaxies, such as the large and small magellanic clouds, whose cluster populations suggest a continuum of formation throughout cosmic time, with cluster formation tracing the overall chemical build up of the galaxies over time (e.g. Horta et al. 2021).

Numerical simulations have also had recent success in linking YMCs/OC to GCs (e.g. Li et al. 2017; Choksi & Gnedin 2019; Pfeffer et al. 2019; Lahén et al. 2020), explaining both sets of objects with the same formation/evolution physics (Kruijssen 2015). Whether or not a massive cluster formed is not directly linked to cosmic age, rather it is the local conditions that determine the mass of clusters that form.

Beyond this framework, there is another class of cluster, the nuclear star clusters (NSCs – e.g. Neumayer, Seth & Böker 2020).

These clusters, typically residing (or have resided) at the centre of their host galaxy, are some of the most massive and dense clusters known. They also have complex formation histories, which appear to be linked to the properties of their host galaxies. For massive host galaxies, their NSCs appear to be formed primarily *in situ*, i.e. multiple epochs of star formation happen within the cluster. For lower mass galaxies, their NSCs are dominated by GC in-spiralling and mergers (Turner et al. 2012; Neumayer et al. 2020). There are a number of clusters in the MW (beyond the NSC at the centre of the Galaxy), which have been captured during the accretion event of a nucleated dwarf galaxy (Pfeffer et al. 2021).

Finally, there are two clusters which do not appear to fit in well with the taxonomy described above. The clusters in question are Terzan 5 and Liller 1, both of which host significant iron spreads ( $\sim 1$  dex)<sup>1</sup> and age spreads ( $\sim 5$ – $8$  Gyr) within their stellar populations (Ferraro et al. 2016, 2021). This could imply that they may be accreted NSCs. However, their current orbits are consistent with an *in situ* formation channel, i.e. they do not appear to be part of an accretion event. Additionally, their highest metallicity components ( $[Fe/H] \sim$  solar - Origlia et al. 2011) also suggest that they were not formed within a dwarf galaxy, as these galaxies typically do not reach these high metallicities until the current epoch (i.e. they should have been very low mass galaxies  $\sim 12$  Gyr ago when their first stellar populations formed – e.g. Kruijssen et al. 2019).

As a potential explanation for these two anomalous clusters, Ferraro et al. (2009, 2021) have suggested a new formation channel, namely that these two clusters are remnants of large, gravitationally

<sup>1</sup>Although in the case of Liller 1, further spectroscopic confirmation of the Fe-spreads is required.

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bound, long lived clumps, most of which eventually merged to form the bulge of the Milky Way. In this sense, these clusters would represent pristine fragments of the galactic bulge, which can be used to trace the formation and evolution of the bulge.

In the present work, we take a critical look at the ‘pristine fragments’ theory, as well as alternative theories which have been put forward in the literature. This paper is organized as follows: in Section 2, we outline the basic scenario of the ‘Pristine Fragments of the Galactic Bulge’ theory while in Section 3, we discuss problems with the suggested theory. In Section 4, we briefly discuss an alternative theory that has been put forward in the literature and in Section 5, we summarize our findings.

## 2 THEORY OF PRISTINE FRAGMENTS OF THE GALACTIC BULGE (PFGB)

Observations of high- $z$  spiral galaxies often show bright ultraviolet (UV) clumps within them (e.g. Cowie, Hu & Songaila 1995; van den Bergh et al. 1996; Giavalisco et al. 1996; Elmegreen, Elmegreen & Hirst 2004; Elmegreen & Elmegreen 2005; Guo et al. 2015; Shibuya et al. 2016), indicative of massive star-forming complexes. It is thought that many of these clumps will migrate to the centre of the host galaxy, due to dynamical friction, and deposit their stars there, effectively building the bulge of these proto-galaxies (e.g. Immeli et al. 2004; Dekel, Sari & Ceverino 2009). In fact, it has been suggested that many of the metal rich GCs may form in such clumps (e.g. Shapiro, Genzel & Förster Schreiber 2010).

Ferraro et al. (2009, 2021) have suggested that these clumps may be long lived ( $>5$ – $8$  Gyr), implying that they are gravitationally bound and separate structures within the host galaxies. The authors adopt a mass–metallicity relation from galaxy surveys, and use this to estimate that the initial masses of these clumps were  $\gtrsim 10^9 M_{\odot}$ . In this model, the massive clusters, Terzan 5 and Liller 1, are the remnants of these initial high mass clumps. Due to the high masses of the clumps, the authors suggest that they would be able to retain stellar ejecta and SNe and form new generations of stars which would largely mirror the formation and chemical enrichment history of the bulge.

In a sense, in this scenario, Terzan 5 and Liller 1 could be seen as the *in situ* NSCs of these clumps. However, the authors suggest that their formation mechanism is unique, hence they may not host light element abundance spreads within them (a.k.a., multiple populations). However, as the origin of multiple populations is still unknown (e.g. Bastian & Lardo 2018), it is unclear if the remnant clusters from such a clump would be expected to host such populations or not. In the case of Terzan 5, an initial study by Origlia et al. (2011) did not find evidence for multiple populations within the cluster using the Al–O anticorrelation as a diagnostic. However, Pancino et al. (2017) found that Al did not vary significantly in metal rich clusters, meaning that this is not the best element to use when looking for multiple populations in clusters like Terzan 5. On the other hand, Schiavon et al. (2017) and Nataf et al. (2019) found the normal CNO-based (anti)correlations typical of GCs within the older stellar population of Terzan 5, suggesting that it is a typical GC (within that population).

One potential caveat, however, is that recent results have shown, that younger clusters appear to host smaller light element abundance spreads (and below  $\sim 2$  Gyr no spreads have been detected), hence it is possible that only the older stellar population within the clusters would be expected to show (large) light-element abundance spreads (Martocchia et al. 2018). For Terzan 5, the younger population (at  $\sim 4.5$  Gyr) should be old enough to show signatures of light-element

abundance spreads, while for Liller 1, it is possible that the younger population is too young to show such signs.

## 3 PROBLEMS WITH THE PFGB THEORY

### 3.1 The estimate of the host clump mass

In order to estimate the initial mass of the clump, Ferraro et al. (2009, 2021) used the metallicity of the main stellar population in each cluster and apply the (redshift dependent) mass–metallicity relation of galaxies (Mannucci et al. 2009). Doing this, the authors arrive at an initial mass of  $\sim 3 \times 10^9 M_{\odot}$ .

However, the adopted mass–metallicity relation is for full galaxies, not individual regions within a galaxy, i.e. it only applies to self-enriching systems, not disc instabilities. The initial metallicity of the clump would not be set by its own mass, but rather simply from the metallicity of the gas clouds within the host galaxy from which it formed. The metallicity of this gas in turn was set by the chemical enrichment of the Milky Way up until that time. Hence, by adopting the metallicity of the main stellar population, what the authors are actually estimating is the mass of the Milky Way (assuming the clusters formed within the Galaxy) at the time of formation, not an individual clump within it.

Hence, based on the metallicity of the cluster/clump, it is not possible to estimate its initial mass based on the mass–metallicity relation of galaxies. In the same way, the metallicity of GCs is not linked to their mass, rather it is the metallicity of the gas within the host galaxy, at the time of their formation.

Without such high initial masses of the clumps, most aspects of the PFGB theory would not operate.

### 3.2 Chemical evolution

Ferraro et al. (2021) suggest that the PRGBs will be able to retain the stellar and SNe ejecta of their constituent stars (along with accretion from the surroundings) hence they will chemically evolve along an evolutionary track, in a similar way as dwarf galaxies. As discussed above, Ferraro et al. (2021) estimate a stellar mass of  $\sim 10^9 M_{\odot}$  for a typical clump. The authors argue that dwarf galaxies of similar stellar mass are able to chemically enrich themselves, hence the clumps would be expected to do the same.

However, galaxies with stellar masses of  $10^9 M_{\odot}$  will typically have large dark matter haloes around them, with a total mass of  $\sim 10^{11} M_{\odot}$  (e.g. Behroozi et al. 2019). It is this dark matter halo that allows the galaxy to retain SNe ejecta and chemically evolve accordingly. Bulge fragments, on the other hand, would not possess such a halo, hence we would not expect them to enrich significantly through SNe within their own populations. Hence, without a large dark matter halo surrounding the clump in order to retain stellar ejecta, the PFGB theory would not be able to explain the chemical evolution of the stellar populations within clusters like Terzan 5 and Liller 1.<sup>2</sup>

As an example, a number of young and intermediate age stellar clusters are known with masses between  $10^7$  and  $10^8 M_{\odot}$ . These include W3 in NGC 7252 (Maraston et al. 2004), C1 in NGC 34 (Schweizer & Seitzer 2007), and c113 in NGC 1316 (Bastian et al. 2006). None of these clusters show evidence of retaining gas/dust,

<sup>2</sup>This is in contrast with the NSCs, which were the central clusters of dwarf galaxies that did contain large dark matter haloes, allowing for such self-enrichment.

either through their light profiles (Longmore 2015), nor do they show evidence of extended star-formation histories (Cabrera-Ziri et al. 2014, 2016). Hence, objects with these stellar masses, which do not host large dark haloes, are unable to retain/accrete significant amounts of gas within them.<sup>3</sup>

### 3.3 Dynamical Friction

Whilst we have argued above that the estimate of the initial clump masses of  $\sim 10^9 M_\odot$  are invalid, here we adopt these values to see, if they were true, whether such clumps could survive long enough to be observable today.

A critical question is whether large, gravitationally bound fragments in the early life of the Galaxy could survive for long enough ( $\geq 8$  Gyr) to be able to retain/accrete gas and form new generations of stars. The key time-scale for this to be valid is the dynamical friction time-scale,  $\tau_{\text{dyn}}$ . If  $\tau_{\text{dyn}}$  is too short, the clump will spiral into the Galactic centre and dissolve. Hence,  $\tau_{\text{dyn}}$  must be longer than, or approximately equal to the age of the system if it is to survive to the present day.

In order to estimate  $\tau_{\text{dyn}}$  for the initial clumps we followed Lacey & Cole (1993; their appendix B), adopting an isothermal sphere as the Milky Way potential with a circular velocity  $V_c \approx 230 \text{ km s}^{-1}$ . For the fragments, we adopted masses of  $10^9 M_\odot$  (a lower limit to the estimates of Ferraro et al. 2021), a circular orbit and initial galactocentric radii between 3 and 11 kpc. Under these assumptions  $\tau_{\text{dyn}}$  is 0.15, 0.67, and 1.5 Gyr for initial radii of 3, 7, and 11 kpc, respectively. Hence, for a fragment of this mass, dynamical friction would act extremely rapidly, meaning that it would spiral into the centre of the Galaxy within a fraction of the time needed for it to survive. If the clump formed well outside 11 kpc, it could have survived to the present day, however it would not be expected that such clumps could form at such large galactocentric distances. Hence, the formation and long-term survival of such a clump can be ruled out at high significance.

Even for an initial mass of  $10^8 M_\odot$ ,  $\tau_{\text{dyn}}=0.9, 4.4, \text{ and } 10.2$  Gyr, for initial radii of 3, 7, and 11 kpc, respectively. If the clump needed to survive for  $>8$  Gyr, then it must have begun at extreme galactocentric radii ( $\gtrsim 10$  kpc), otherwise it would be expected spiral into the centre of the Galaxy too rapidly to account for the observed characteristics. Hence, even if the fragment was undergoing severe mass-loss (resulting in the loss of  $\sim 90$  per cent of its initial mass), it would still rapidly sink to the centre of the Milky Way.

Of course there is a sweet spot, where if the clumps underwent heavy mass loss they could avoid spiralling in to the centre of the Galaxy, i.e. that mass loss and dynamical friction happen in such a way to allow the clump remnants to survive, but to be brought into the inner regions of the Galaxy. However, we note that in the PFGB scenario, the clump must keep its large mass for an extended period of time (likely at least a few Gyr) in order to retain gas within it, to form a second generation of stars 5–8 Gyr later. This places further constraints on how quickly it could lose mass in order to avoid the destructive effects of dynamical friction.

On the other hand, by adopting an initial mass of  $2 \times 10^6 M_\odot$ , i.e. similar to the current masses of Terzan 5 and Liller 1, we find that

dynamical friction time-scale is longer than the Hubble time already for initial galactocentric radii of  $\sim 2$  kpc. Hence, if the clusters formed with approximately the current mass, we would expect them to be long lived objects.

### 3.4 High redshift observations

Beyond the arguments outlined above, there has been a number of studies that have investigated whether the UV-clumps observed at high-redshift are long lived objects or whether they are rapidly destroyed, either through dynamical friction or dissolution into the host galaxy (potentially driven by stellar feedback within the clumps). If the clumps were long lived, we would expect to see them not just in the UV (indicative of young ages) but also in the optical as they age. In fact, we may expect to see a number of these remnant clumps today in nearby galaxies.

One of the most systematic studies was performed by Shibuya et al. (2016), who used *HST* imaging to investigate the evolution of clumpy galaxies from  $z = 0-10$ . They find that the redshift evolution of the fraction of clumpy galaxies in the rest-frame UV broadly traces the cosmic star formation rate density. This is consistent with the scenario where the clumps form via disc instabilities in star-forming galaxies.

At  $z = 1-3$ , the fraction of galaxies that have clumps in the rest-frame UV is 50–60 per cent (with a lower fraction in ‘quiescent’ galaxies with lower SFRs). However, only  $\approx 10$  per cent of galaxies have clumps in rest-frame optical over the same redshifts, indicating that the clumps are not long lived. The fraction of galaxies with optical clumps could instead be explained by galaxy mergers (see their fig. 5; see also Zanella et al. 2019).

Shibuya et al. (2016) also investigated the  $m_{\text{UV}} - m_{\text{opt}}$  colour (an indication of age) of clumps as a function of galactocentric radius. Only very massive galaxies ( $> 10^{11} M_\odot$ ) show a correlation between clump colour and radius, such that clumps are redder at smaller distances. They found no strong correlation in galaxies with stellar masses  $10^9-10^{11} M_\odot$ , indicating that the clumps may be rapidly destroyed before significant clump migration. This is in agreement with the lifetimes estimated for high redshift clumps, which are probably not more than  $\sim 500$  Myr on average due to a combination of feedback, dynamical friction, and tidal disruption (e.g. Genzel et al. 2011; Zanella et al. 2019).

We conclude that the UV clumps are likely not long-lived objects and would not be able to survive the  $\sim 5-8$  Gyrs needed in order to form the observed second generation of stars within them, i.e. as seen in Terzan 5 and Liller 1.

## 4 ALTERNATIVE

As an alternative explanation for clusters such as Terzan 5 and Liller 1, McKenzie & Bekki (2018) have suggested that massive clusters in the inner galaxy may have orbits which rarely align (within some tolerance) in position and velocity with giant molecular clouds (GMCs). Once such a chance super-position happens, the massive cluster may be able to accrete large amounts of gas/dust rapidly from the GMC. If this accretion is rapid and dense enough, it can overcome the stellar feedback from the original stellar population, and may be able to form a second (or more) generation of stars. This is largely analogous to the *in situ* formation within NSCs observed today.

Running a series of simulations, McKenzie & Bekki (2018) found that such an alignment may happen once or twice per Hubble time, with the likelihood a strong function of cluster mass (with more massive clusters having a higher chance of gas accretion). Hence,

<sup>3</sup>While many models have been put forward that invoke multiple generations of star formation within typical GCs to explain the origin of multiple populations, observations of young massive clusters, as well as the properties of full populations of ancient GCs do not support such scenarios (see the recent review in Bastian & Lardo 2018).

this is an effect that would be expected to happen predominantly for massive clusters orbiting within the inner few kpc of the Galaxy, where the gas density is highest. Additionally, the probability would be highest for GCs with disc-like orbits (as the GMCs are expected to be largely confined to the disc) as found for both Terzan 5 and Liller 1 (Massari et al. 2015; Baumgardt et al. 2019).<sup>4</sup>

Typically, other than NSCs (Neumayer et al. 2020), clusters (OCs, YMCs, or GCs) are not able to accrete significant amounts of gas from their surroundings. This is due to a combination of ram pressure and stellar feedback (winds, SNe, and photionization), which act to expel the ejecta from stars within the cluster and stop accretion from the surroundings (e.g. Chantereau et al. 2020). Additionally, most GCs have orbits away from the disc, both spatially and kinematically. However, as seen in NSCs, if a large amount of gas can be dumped on to the cluster in a short time, this can overwhelm the stellar feedback, allowing the gas to avoid being photoionized and overcome the outflowing stellar feedback. Due to the relative velocities of the NSC and the gas cloud, ram pressure stripping would also not act in the McKenzie & Bekki (2018) scenario. In such a case, the gas may cool (if it is optically thick) and form a new generation of stars. Depending on how much gas is dumped on to the original cluster, the second generation of stars could make up anywhere between a small and large fraction of the final cluster stellar mass. One caveat to this scenario is that such a close passage to a GMC may actually disrupt the cluster before a large amount of gas could be transferred on to it. However, it would be the most massive GCs that would have the highest chance of surviving such an event (e.g. Gieles et al. 2006; Elmegreen & Hunter 2010).

This scenario would suggest that the older populations present within Terzan 5 and Liller 1 would be the remnants of classic GCs (likely of high mass) and the younger populations would be formed from gas accreted by the ancient cluster due to the GMC interaction. We note that there is expected to have been a population of GMCs in the disc of the Milky Way, continuously for the past 7 Gyr or more (given the relatively constant star-formation rate of the Galaxy over that period, e.g. Snaith et al. 2015). The GMCs are not expected to have bulge-like kinematics/orbits, rather they would be part of a disc. The interaction and subsequent accretion from a GMC on to an existing GC would then only happen when the GCs orbit passed through the disc and happened to have a very low relative velocity. In fact, both Terzan 5 and Liller 1 have orbits confined to the plane of the Galactic disc (typically only reaching  $\sim 200$  pc above the disc plane, Massari et al. 2015; Baumgardt et al. 2019), which may increase the likelihood of such a chance encounter for these GCs. The larger the vertical scale height, or the further the radial apocentre/pericentre of the GC orbit, would lead to a reduction of the probability of a GC/GMC interaction that could lead to the accretion of gas by the GC, due to the centrally peaked and thin disc of GMCs in the Milky Way (e.g. Kennicutt & Evans 2012). This may explain why the other very massive ( $M > 10^6 M_{\odot}$ ) bulge GCs NGC 6388 and NGC 6441 do not similarly show multiple iron peaks. Both GCs have orbits which are inclined to the Galactic disc by  $\sim 30$  degrees (Baumgardt et al. 2019), reaching  $\approx 1$  kpc above the disc plane, which would significantly lower their probabilities of GC/GMC interactions.

In passing, we note that star formation is likely to have been happening within this gas-rich (GMC-rich) disc throughout the history of the Galaxy, however these stars have not been perturbed

on to orbits significantly out of the disc due to the Milky Way's relatively quiescent merger history over the past  $>7$  Gyr (e.g. Wyse 2001; Hammer et al. 2007; Stewart et al. 2008; Kruijssen et al. 2020).

A prediction of such a scenario is that it should be relatively rare, i.e. even for massive clusters within the inner Galaxy, we would only expect a handful of such clusters to have undergone such a process. Additionally, as these would be rare events, we would expect to see largely discrete star-formation events. If the star-formation histories of Terzan 5 and Liller 1 were to be found to be extended, or continuous over many Gyr, this would strongly disfavour the McKenzie & Bekki (2018) scenario. One caveat to this point, however, is that while in most clusters the capture rate of field stars by a GC is low (e.g. Mieske & Baumgardt 2007), for high mass clusters, in the inner regions of the Galaxy, this can begin to become significant, due to the much higher field star densities. Hence, for clusters such as Terzan 5 and Liller 1, we may expect a background population of stars, over a range of metallicities (and possibly ages), to be present within the clusters, although these populations should be sub-dominant. This could explain the purported third, minor, low metallicity population (e.g. Massari et al. 2014). Also see Khoperskov et al. (2018) for a discussion of the transfer of stars between GCs on disc orbits.

## 5 CONCLUSIONS

We have critically assessed theories for the origin of the iron/age complex stellar clusters, Terzan 5 and Liller 1, in order to better understand their origin. Ferraro et al. (2009, 2021) have suggested that such clusters are the remnants of fragments of the Galactic bulge, hence they would represent a unique window into the formation of the bulge. Critically, for this theory to be valid, the initial fragment must have a mass far in excess of the current cluster mass, and it must have been able to survive for at least a Hubble time. We showed that the method used to estimate the initial clump masses was invalid, as the adopted mass-metallicity relation of galaxies would not correspond to a specific sub-region (clump) with the galaxy, but rather to the full galaxy. In this way, the estimate mass of the clumps would correspond to the stellar mass of the Milky Way at the time of formation, not the mass of an individual clump.

The critical time-scale is that of dynamical friction, which is the time-scale that any such clump would spiral into the Galactic centre. For the estimated initial mass of the fragments ( $\sim 10^9 M_{\odot}$ ; Ferraro et al. 2021), we estimate dynamical friction time-scales of  $< 1.5$  Gyr for initial galactocentric radii of 11 kpc or less. This is far shorter than the estimated duration of star formation (hence survival) of the fragments, even when assuming severe mass loss during its evolution. This effectively rules out this class of theory as the origin of these anomalous clusters.

Instead, we favour the theory of McKenzie & Bekki (2018), where, under certain, relatively rare conditions, a GC is able to accrete a significant amount of gas/dust from its surroundings (essentially when the cluster and GMC orbits coincide in time, velocity and space) and form a second generation of stars. Since the gas accreted would be from the Galaxy, it would have undergone the same chemical enrichment processes and follow the same track as the rest of the inner Galaxy. Hence, we would expect the first and second generations of stars within clusters such as Terzan 5 and Liller 1 to follow the same age/metallicity relation. In this scenario, the ancient populations of these clusters would be the remnants of classical GCs and the younger populations would be the second generation stars formed in these rare events. This scenario predicts that the process should be most likely for high mass clusters with disc-like orbits in the inner regions of the Galaxy, consistent with what is seen in Terzan 5 and

<sup>4</sup>While Massari, Koppelman & Helmi (2019) classify Terzan 5 as a bulge GC, this is due to it being located in the inner 3.5 kpc of the Galaxy, irrespective of its orbit.

Liller I. Additionally, the scenario predicts that the large old, metal poor population should show the canonical light element abundance patterns seen in all massive ancient clusters, while the large young population may or may not show such anomalous chemistry.

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## DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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