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Star Formation in Clusters: The YMC - GC Link

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Abstract I discuss our recent work on Globular Clusters (GCs) in dwarf galaxies, where the high ratio of GCs vs. field stars provides an interesting constraint on GC formation scenarios. I also briefly review the evidence (or lack thereof) for multiple populations in young star clusters based on their color-magnitude diagrams.

1 Introduction

The relation between various types of star clusters was a matter of debate for much of the 20th century. The modern distinction between “open” and “globular” clusters may be traced back to Harlow Shapley (Shapley 1916) who suggested in 1916 that, due to the differences in spatial distribution and “other characteristics just coming to light”, “we are led to believe that there is a fundamental difference between the two main classes – the condensed globular objects and the open clusters”.

However, by the 1950s it was already becoming increasingly clear that some objects did not belong unambiguously to one class or the other. This can be appreciated for example by reading the summary of the discussion at the 1959 symposium on “The differences among globular clusters”, printed in the 1959 Astronomical Journal (vol. 64: p. 447). Some of the proto-typical examples of objects that resemble globular clusters in some respects (masses, structure), but appear more similar to open clusters in other ways (e.g. relatively young ages), are objects like NGC 1856 and NGC 1866 in the Large Magellanic Cloud, both of which were in fact listed by Shapley as globular clusters in his 1930 monograph (Shapley 1930), but are now known to have ages of only \( \approx 10^8 \) years. Such “Young Massive Clusters” (YMCs) have been found in a wide variety of extragalactic environments, ranging from dwarf galaxies (such as NGC 1569 and NGC 1705), to on-going and recent major mergers (e.g. NGC 4038/4039, “the Antennae” and NGC 3256) and starbursts like M82 (see e.g. the compilation in Larsen 2006).

For a while it was a puzzle that no such objects appeared to exist in the Milky Way, but our location within the Galactic disc makes it difficult to find these relatively rare objects, and it is now clear that young clusters with masses extending up to at least \( 10^5 M_\odot \), such as Westerlund 1, are indeed still forming in the Galaxy.

By the late 1990s, YMCs had been found in sufficiently large numbers that the consensus was starting to move towards a picture where they were viewed as the plausible young analogues of the ancient globular clusters observed around the Milky Way and other large galaxies. It was suggested (Elmegreen & Efremov 1997) that all star clusters form by a universal mechanism, with an initial power-law mass distribution of the form \( dN/dM \propto M^{-2} \) possibly arising from the fractal structure of the interstellar medium. While the low-mass end of the mass function of old GC populations differs from this shape by being nearly flat \( dN/dM \approx \)}
const), this may be due to the dynamical evolution and disruption of low-mass clusters over a Hubble time. However, this type of power-law mass functions seem to be obeyed by young cluster populations quite generally, although there is now strong evidence that a steepening or exponential cut-off may set in at some upper limit which may vary from \( \sim 2 \times 10^5 \, M_\odot \) in quiescent spiral discs to greater than \( 10^6 M_\odot \) in starburst environments (Larsen 2009).

2 Star clusters as simple stellar populations - or not

In spite of the attractiveness of a universal cluster formation process, questions about the degree of similarity between young star clusters in the local Universe and GC formation in the early Universe remain. Most young clusters appear to be good approximations to “simple stellar populations” with very small internal age spreads, generally less than \( 10^6 \) years (Elmegreen 2000; Kudryavtseva et al. 2012). This is as expected if they formed quickly, roughly on a free-fall time scale, from a single gas cloud. Globular clusters, however, may not be quite so simple. While this is most spectacularly demonstrated by the complex Color-Magnitude Diagrams (CMDs) with multiple parallel main sequences and sub-giant branches revealed by Hubble Space Telescope (HST) imaging, it has been known for several decades that many light elements exhibit significant star-to-star abundance variations within GCs (Kraft 1979). Some elements are found in relative proportions that are not observed in halo field stars, or at least only in a small fraction (2%-3%) that may have escaped from GCs (Martell et al. 2011). Perhaps the best-known of these anomalies is the Na-O anticorrelation, whereby Na is enhanced in some stars and O depleted, relative to the composition observed in field stars. Other relations include anti-correlated Mg-Al, C-N and O-N abundances, as well as a N-Na correlation (Yong et al. 2008). These relations all suggest that the material out of which the anomalous stars formed had been processed by H burning at high temperatures, \( 20 \times 10^6 \, K - 60 \times 10^6 \, K \). Since many of the anomalies have been detected even in unevolved stars which do not reach these temperatures, they must have been present already at the time of formation of the stars.

The number of plausible polluter candidates is relatively limited. Since heavier elements (such as Ca and Fe) do not generally vary within a given cluster, supernovae can be ruled out. Alternatives include massive Asymptotic Giant Branch (AGB) stars (D’Ercole et al. 2010), fast rotating massive main sequence stars (“spin stars”, Decressin et al. 2007) or massive interacting binaries (de Mink et al. 2009). However, a major challenge faced by many of the proposed scenarios is to explain the large fractions of stars with anomalous abundances that are generally observed. Typically, at least half of the stars in a GC have non-standard chemical composition (Carretta et al. 2009), in stark contrast to the few percent of the initial mass of a stellar population that is released in the form of enriched ejecta. This is referred to as the “mass budget problem”, and a commonly proposed solution is that a very large fraction of the original unpolluted (“first-generation”) stars have been lost from the cluster. In this picture, the present-day GCs are the surviving remnants of objects that were initially far more massive, by perhaps an order of magnitude or more. An alternative possibility is that pollution took place already during the formation of the clusters. For example, merging binary stars may in principle provide sufficient polluted material that may be captured by low-mass stars which are still surrounded by accretion discs (Bastian, these proceedings).
3 Constraints on GC formation scenarios from dwarf galaxies

It turns out that observations of GCs in dwarf galaxies can play an interesting role in constraining the above scenarios. The key point here is that dwarf galaxies often have very rich GC populations (Georgiev et al. 2010). A well-known example is the Fornax dwarf spheroidal galaxy which has 5 GCs, a very large number for its low luminosity ($M_V \approx -13.2$). This gives it a GC specific frequency of $S_N = 26$ (where $S_N$ is the number of GCs normalised to a host galaxy $M_V = -15$). For comparison, spiral galaxies typically have $S_N \approx 1$ and giant ellipticals have $S_N \approx 3-5$. The high $S_N$ in Fornax becomes even more striking when one considers the metallicity distributions of the stars and the GCs. The field star metallicity distribution peaks at $[\text{Fe/H}] \approx -1$ with only a small number of stars below $[\text{Fe/H}] = -2$ (Battaglia et al. 2006; Kirby et al. 2011). In contrast, four of the five GCs in Fornax have $[\text{Fe/H}] < -2$ (Larsen, Strader & Brodie 2012). Together with the already high global $S_N$, this implies that about 1/4–1/5 of all metal-poor stars in Fornax currently belong to GCs (Larsen, Strader & Brodie 2012). Even if all the stars in this metallicity range initially formed as members of these GCs, this ratio suggests that no more than 75%-80% of the stars could have been lost. The obvious caveat, of course, is that some stars may have been lost from the Fornax dSph, but detailed N-body simulations seem to indicate that this is not the case (Peñarrubia et al. 2009).

Is the Fornax dSph a special case? As already noted, many dwarf galaxies have high $S_N$ values, in some cases exceeding that of Fornax, but there are few studies of the detailed metallicity distributions of the GCs and stars. An interesting case is the IKN dwarf spheroidal in the Ursa Major group. Like Fornax, the IKN dSph has five known GCs, but with an absolute magnitude of $M_V \approx -11.5$ the galaxy is nearly two magnitudes fainter than Fornax, yielding an extremely high $S_N \approx 125$ (Georgiev et al. 2010). The metallicity distribution of field stars in IKN appears quite similar to that in Fornax (Lianou, Grebel & Koch 2010). We have recently obtained a spectrum of the brightest of the five GCs, IKN-5, from which we found a low metallicity of $[\text{Fe/H}] \approx -2.1$ (Larsen et al., in prep.). While the metallicities of the other four GCs remain unknown, the GC IKN-5 alone has an estimated mass similar to that of all the metal-poor field stars in IKN. It seems that Fornax is not a unique, or even a particularly extreme, case of a very high GC$field star ratio at low metallicities.

Clearly, a crucial piece of information is whether the GCs in these dwarf galaxies actually display the same abundance anomalies as their Milky Way counterparts. High-dispersion spectroscopy is available for 9 individual RGB stars in three of the Fornax GCs, and hints at anomalous composition in one star (Letarte et al. 2006). Integrated-light spectra also hint at low [Mg/Fe] ratios, possibly an indication that the Mg-Al anticorrelation is present in the clusters (Larsen, Brodie & Strader 2012). However, these measurements must be considered tentative, and a more detailed study is clearly desirable. To this end, we are obtaining HST photometry of the four metal-poor Fornax GCs aiming to quantify internal abundance variations. Specifically, the NH band at $\sim 3370$ Å makes the F343N filter very sensitive to N abundance variations. Fig. 1 shows the F555W vs. F343N-F555W colour-magnitude diagrams for Fornax 2 and the Galactic globular cluster M15, the latter of which is known to have a large spread in N abundance. Also shown are model colours for “normal” and N-enhanced composition. In both Fornax 2 and M15, the colours of the RGB stars show a large spread, consistent with the spread expected for [N/Fe] variations of about 2 dex, as observed in M15 (Cohen, Briley & Stetson 2005). The observed colour spread is significantly larger than the observational errors in both clusters and shows little correlation with magnitude, implying a
real N abundance spread. At the time of writing, a preliminary analysis of data for Fornax 3 suggests that the situation there is similar.

We may thus conclude that the Fornax GCs appear to be similar to their Milky Way counterparts in displaying large internal light-element abundance variations.

4 Multiple populations in young clusters?

Finally, let us return to the question of similarities and differences between young star clusters and GCs. Did GCs, after all, form in a special way, or do we have some hope of observing the processes responsible for the observed anomalies in the local Universe?

Open star clusters do not generally exhibit internal abundance variations (Pancino et al. 2010), but this may simply be due to their relatively low masses. Indeed, it may be argued that if a significant fraction of the Galactic halo formed in now-disrupted low-mass clusters, then these clusters must also have had a composition similar to that observed in the halo stars today. Globular clusters must have had initial masses above \( \approx 10^5 \, M_\odot \) in order to survive to the present day, and young star clusters with masses above this threshold are relatively rare, as discussed in the introduction. Nevertheless, a number of such clusters are sufficiently nearby that they can be resolved into individual stars and studied in some detail.

The intermediate-age star clusters in the Large Magellanic Cloud (LMC) represent somewhat of a puzzle in this regard. Several studies have shown that a number of LMC clusters with ages around 1–2 Gyr have very broad “fan”-shaped main sequence turn-off regions and complex red clump morphologies (Mackey et al. 2008; Milone et al. 2009; Goudfrooij et al. 2011). These features can be reproduced if the clusters have large internal age spreads, in some cases up to 300–400 Myr. This appears consistent with the expectations in the AGB enrichment scenario. However, similarly large age spreads have been ruled out in younger LMC clusters of comparable masses; an upper limit of 35 Myr for any age spread has been found for the clusters NGC 1856 and NGC 1866 (Bastian & Silva-Villa 2013). It has been
suggested that the broad main sequence turn-offs seen in the intermediate-age clusters may be due to effects of stellar rotation, although it remains unclear whether this works in detail (Bastian & de Mink 2009; Girardi, Eggenberger & Miglio 2011).

Further away, the colour-magnitude diagrams of a number of YMCs with ages in the range 5–50 Myr in galaxies at distances of 2–4 Mpc were found to be poorly matched by single isochrones (Larsen et al. 2011), with a range of 1–2 mag in the $M_V$ magnitudes of the red supergiants, as well as a number of stars filling the Hertzsprung gap between the main sequence turn-off and the post main-sequence stars. In some cases, the fit could be improved by assuming an age spread, particularly for a cluster in the galaxy NGC 1313 where a model CMD with a range of ages between 20 and 50 Myr gave a rather good fit to the data. However, it was also found that merging binary stars might produce an effect on the CMDs similar to that of an age spread.

In conclusion, the current body of evidence regarding young and intermediate-age clusters is somewhat confusing. It is quite clear that the CMDs are not always well approximated by single isochrones, but it is less clear whether age spreads are the only explanation. Little is currently known about the detailed chemical composition of these clusters, although hints at the Na-O anti-correlation and nitrogen abundance variations have been found in a few intermediate-age LMC clusters (Martell et al. 2013). Hence, the relation to old GCs remain unclear.

5 Summary

The complex stellar populations within globular clusters are challenging to explain in any formation scenario. However, the high GC specific frequencies in dwarf galaxies appear to favour scenarios that can accommodate the observed GC properties without requiring very large amounts of initial mass loss. Whether or not star clusters form by a universal process, or the observed anomalies imply that GCs formed by some special process, remains an open question. To settle this question, it is essential that globular clusters are compared against young clusters of similar mass, an observationally challenging requirement since such objects are relatively uncommon and thus tend to be far away.

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References

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