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OBSERVATIONAL EVIDENCE OF MULTIPLE STELLAR POPULATIONS IN STAR CLUSTERS

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ABSTRACT

An increasing number of observations have confirmed the presence of multiple stellar populations in Galactic globular clusters. Multiple populations evidence come from the complex chemical pattern of stars hosted in GCs and from the split or broadening of different evolutionary sequences in the color-magnitude diagrams. Multiple stellar populations have been identified in Galactic and Magellanic Cloud clusters, as well as in external galaxies. In this paper I will summarize the observational facts.

key words: Globular clusters: individual (NGC 5139); Stars

1. INTRODUCTION

The assembly of stellar populations in galaxies is one of the hottest open issues in astronomy. Globular clusters (GCs) are a major component of these old stellar populations. A clear understanding of the mechanisms that lead to the formation and evolution of GCs, as well as of the relations existing between GCs and field stars is a basic step forward in our understanding of how galaxies assembled their stars (see e.g. Bekki et al., 2008). In general, the properties of old stellar populations are important for the interpretation of the spectral energy distribution observed in far galaxies not resolved into star, and therefore of cosmological importance.

Since almost forty years, we know that large star-to-star abundance variations for several light elements are present in GCs (see Gratton et al., 2004 for a recent review). For long time, they have been regarded as intriguing anomalies, restricted to some cluster stars, but recent observational evidence is that the observed peculiar chemical composition is a universal phenomenon in GCs.

Even older is the so called "second parameter problem" (Sandage & Wildey, 1967), a simple way to indicate the complexity of the morphology of the horizontal branch in GCs. More recent, but not less intringuing is the discovery of the presence of multiple sequences in the color magnitude diagrams (CMD) of a still increasing number of GCs. We are starting to understand that all these "anomalies" may be part of the same, complex phenomena related to the globular cluster very same nature and origin.

In this paper, I will briefly outline the main observational facts which have put the multiple populations in GCs on solid basis, and stimulated a still ongoing vivid debate in the astronomical community.

2. PHOTOMETRIC EVIDENCE

2.1. Main Sequence Multiplicity

The presence of multiple, often distinct sequences in all evolutionary branches in the CMD of more than a dozen GCs can undoubtely be considered as a sort of smoking gun of the presence of multiple generations of stars in GCs. Surely, the first discovery of a triple main sequence (MS) in ω Cen (Bedin et al., 2004, but see Anderson 1997 PhD Thesis) represented a breakthrough

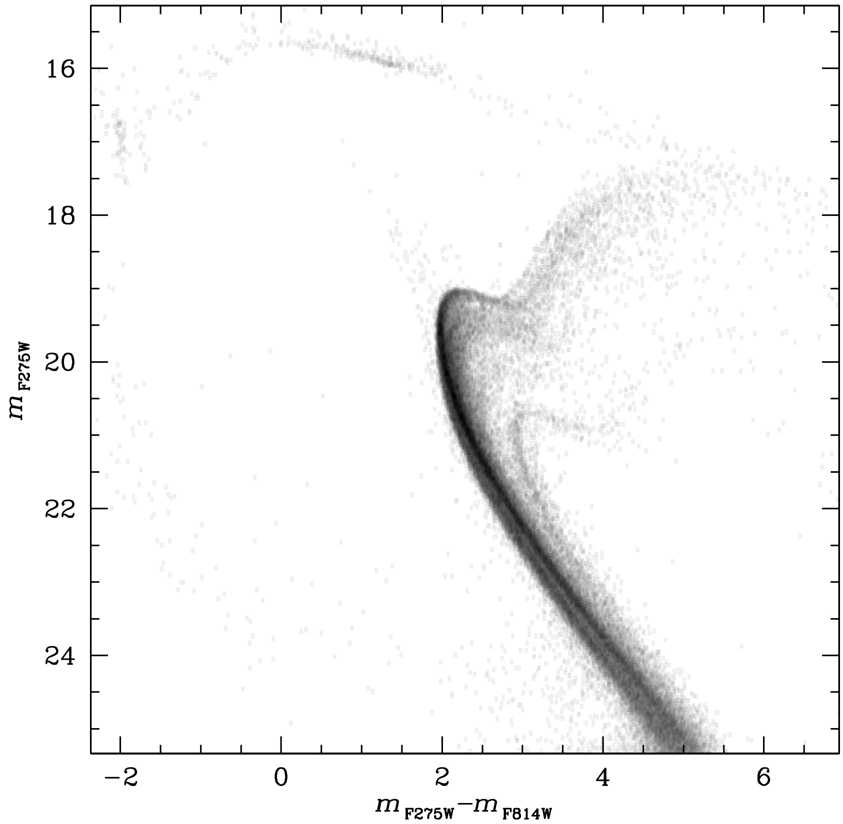

Fig 1.— CMD from recent WFC3/HST observations (Bellini et al., 2010). This Hess diagram (the darkness of each point is proportional to the number of stars present in CMD at that location) gives the most detailed picture of the complexity of the multiple populations in ω Centauri. Many new sequences (never seen before) can be distinguished in all evolutionary branches.

into the multiple population debate, though the presence of stars with different metal (including iron) content in this cluster was known since the 70s (Cannon & Stobie, 1973), and multiple red giant branches were discovered at the end of the 90s (Lee et al., 1999; Pancino et al., 2000).

After the evidence of the MS multiplicity, a totally unexpected discovery came from the spectroscopic analysis by Piotto et al. (2005), who revealed that the bluest MS (bMS) in ω Cen is more metal-rich than the redder one (rMS). At the present time, the only possible interpretation of the spectroscopic and photometric facts is that stars in the bMS must be greatly enhanced in helium.

The increase of our capability of obtaining high accuracy photometry with high spatial resolution and wide field imagers has increased our awareness of the complexity of the CMD of ω Cen, though not necessarily increasing our present understanding of its stellar population. On this respect, the spectacular CMD obtained from the WFC3 camera recently installed onboard HST (Figure 1, from Bellini et al., 2010) can be considered as the best example of the complexity of the phenomenon, and of the work needed to understand the nature and the origin of ω Cen stars. WFC3 surely represents a fundamental tool to accomplish this task.

No doubt, ω Centauri is the most-studied and the most-enigmatic among the Milky Way satellites. For long times, it has been considered a GC, but a number of peculiarities, like the mass, the chemical composition, the stellar content, and the kinematics suggest that it might be the remnant of a larger stellar system (Lee et al., 1999; Bekki & Freeman, 2003, and references therein). It might be instructive to compare the CMD of ω Cen (Figure 2, lower panel), with the CMD of M54 (Figure 2, upper panel). The two CMDs look rather similar. We know that M54 almost coincides with the nucleus of the disrupting Sagittarius dwarf galaxy. And the complexity of the CMD of M54 of Figure 2 is indeed due to the fact that we observe, in the same field, both M54 stars and background/foreground stars of the Sagittarius dwarf nucleus. M54 might have originated in the nucleus of its hosting galaxy, or ended there from elsewhere as a consequence of the dynamical friction (Bellazzini et al., 2008). The important fact here is that M54 and Sagittarius nucleus now are located in the same place, in mutual dynamical interaction. It is very tempting to think that, a few Gyrs ago, ω Cen could have been exactly what we now find in the nucleus of the Sagittarius. Recent chemical abundance measurements of the M54+Sagittarius nucleus stars (Carretta et al., 2010a, b) further confirmed the similarities in the stellar populations of the former and ω Cen, and their possible similar origin.

The spectacular case of ω Cen stimulated a number of investigations which showed that the multiple population scenario is not a peculiarity of a single object. Piotto et al. (2007) showed that also the CMD of NGC 2808 is splitted into three MSs. Because of the negligible dispersion in Fe peak elements (Carretta et al., 2006), Piotto et al. (2007) proposed the presence of three groups of stars in NGC 2808, with three different He contents, in order to explain the triple MS. These groups may be associated to the three groups with different oxygen content discovered by Carretta et al. (2006). Interestingly enough, three groups of stars, with different He contents (up to $Y \sim 0.4$) were already proposed by D'Antona & Caloi (2004) and D'Antona et al. (2005), who also identified an 'anomalous' spread in the MS of the cluster to reproduce the multiple, extended HB (EHB) in NGC 2808. The discovery of the triple MS is a further, indirect confirmation of the presence of three He groups in NGC 2808. NGC 2808 represents the best example of the possible link between the presence of He enhanced populations, best highlighted by the presence of multiple or spread MSs and the EHBs. Both ω Cen and M54 have very extended EHBs.

The search for and discovery of multiple MSs in GCs are of particular interest. Different abundance factors (CNO, Na, O, Mg, Al, He, ...) may be adduced to explain multiple populations, but MS splitting is a unique new source of evidence regarding the presence in the same GC of groups of stars with different He content. Helium abundance cannot be measured spectroscopically in cool GC stars, while in hot stars ($T_{\rm eff} > 11{,}500$ K) atmospheric abundances are not representative of the interior abundance, because of ionic diffusion. Huge effort (mainly with HST) is presently dedicated to the search for multiple MSs in Milky Way GCs that, because of the already known presence of multiple SGBs or RGBs (see also below) and/or anomalous EHBs are suspected to host He-enriched stars. On the other hand, Villanova et al. (2009) have demonstrated the feasibility of the measurement of He for the only GC stars where the obtained He abundance is indicative of the star He content, i.e. HB stars in the temperature range 8,000 K$< T_{\rm eff} <$ 11,000 K. No He enhanced stars have been found, for the moment, though the expected He enrichment in that temperature interval is expected to be low (but not null). The investigation continues.

MS spread, possibly split into two sequences has been found also in NGC 6752 (Milone et al., 2010). A small but significant MS spread has been identified also in 47 Tuc by Anderson et al. (2009). This is a noteworthy case: the result has been made possible by the huge amount of ACS/HST images (the field is a field used to calibrate the ACS camera), difficult to obtain, also in the future, for other GCs. Anderson et al. (2009) results pose the question on whether, at some level, all GCs show a spread MS, because of the intrinsic spread of abundances of iron and other chemical elements, which cannot be null. Interestingly enough, 47 Tuc has a red HB. Note, however, that this is a metal rich cluster, and a high He enhancement is needed to make its HB become bluer than the instability strip. Indeed, Di Criscienzo et al. (2010) have shown that the complex vertical structure (magnitude dispersion) of the HB of 47 Tuc and the spread in its sub-giant branch (identified by Anderson et al., 2009) can be interpret with a real, though very small spread in the He content of its stars (compatible with the MS spread).

2.2. *Sub Giant Branch Multiplicity*

Most of the clusters where a MS split have been identified show also a sub giant branch (SGB) split. There are many other clusters where the evidence of multiple stellar populations mainly comes from the SGB morphology. The best example is represented by NGC 1851 (Milone et al., 2008). The SGB split is visible all over the cluster, out to the envelope, without any radial trend in the star count ratio between the two SGBs (Milone et al., 2009a). This is in contrast with what

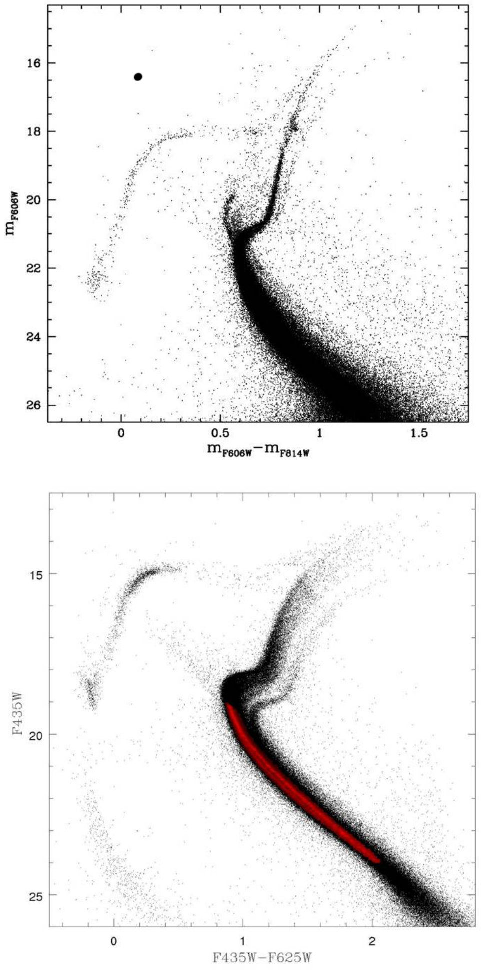

Fig 2.— The CMD of M54 (upper panel) resembles the CMD of ω Cen (lower panel) in many aspects. Do the two clusters have had a similar origin?

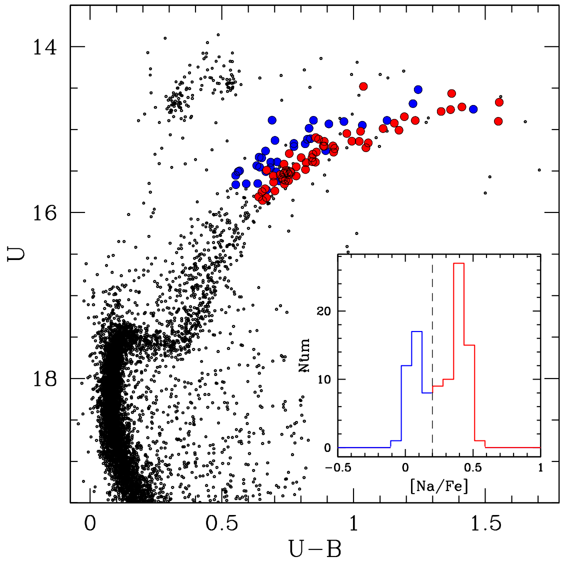

Fig 3.— The Na and O distribution in M4 are bimodal (see inset). The bimodal distribution in these chemical elemets reflects also in a bimodal distribution of stars along the RGB (from Marino et al., 2008).

found in ω Cen, where the blue, He enhanced MS is more concentrated than the redder one (Bellini et al., 2009). Would the magnitude difference between the two SGBs in NGC 1851 be due only to an age difference, the two star formation episodes should have been separated by at least 1 Gyr. However, as shown by Cassisi et al. (2008), and Ventura et al. (2009) the presence in NGC 1851 of two stellar populations, one with a normal α-enhanced chemical composition, and one characterized by a strong CNO-Na anticorrelation pattern could reproduce the observed CMD split. In this case, the age spread between the two populations could be much smaller, and the fainter SGB should have a CNO abundance 2 - 3 times larger than the bright one. In other terms, the SGB split would be mainly a consequence of the metallicity difference, and only negligibly affected by a (small) age dispersion. However, despite an earlier claim by Yong et al. (2009) of a spread in the CNO content of RGB stars in NGC 1851, Villanova et al. (2010), who identified two groups of stars with different s-process element content, probably related to the presence of the two SGBs, convincingly showed that the C+N+O content is constant, and the same, within a few hundredths of a dex for the two groups. The constancy in the CNO content in GCs, including clusters with confirmed multiple populations, poses serious questions on the origin of the two stellar populations. For example, He-enhanced stars have been explained in terms of second generation stars formed by material ejected by intermediate mass AGB stars (Ventura et al., 2001). But, this material, gone through H-burning process via CNO channel at high temperatures, should also be CNO enriched (Ventura et al., 2009). At variance with the present observational evidence. An interesting alternative to explain the two populations in NGC 1851 has been recently proposed by Carretta et al. (2010c), who find also a small, but significant difference in iron content between the two groups, and suggest that NGC 1851 may be the result of a merge of two clusters, with the two stellar populations having an age difference of ~ 1 Gyr.

There are many other clusters showing a double SGBs (see Piotto, 2009). Is the merger scenario viable to interpret these clusters, and, in general, how common is a merger scenario, possibly within a former dwarf spheroidal?

2.3. *Red Giant Branch Split*

Besides the spectacular case of ω Cen, many other clusters have broadened or split red giant branches (RGB), and this observational fact represents an additional, photometric evidence of the presence of multiple populations in GCs. RGB splits are usually better identified using ultraviolet filters, e.g. U-Johnson, u-Strömgren (see Figure 3).

Han et al. (2009) and Lee et al. (2009) have identified a large number of GCs with a significant RGB split by using Strömgren photometry and the Calcium filter, and proposed that the split of the RGB is due to a dichotomy in the Ca content. Spectroscopic investigations (Carretta et al., 2010d; Villanova et al., 2010) do not confirm the presence of Ca spread in many of the clusters observed by Lee et al. (2009). Though the origin of the RGB split in the CMDs of Lee et al. (2009) remains to be understood, Marino et al. (2008, 2009) have confirmed the relation between the RGB split in CMDs based on U-B colors and the presence of stars with different Na-O content (Figure 3), and argued that the color split may be due to the dichotomy in the strength of the CN and CH bands for the two stellar groups.

2.4. *Multiple Populations in Other GC Systems*

The multiple population phenomenon in star clusters is not confined to Galactic GCs only. The suspect that some cluster in the Large Magellanic Cloud (LMC) could host more than one generation of stars has been raised in the past (e.g., Vallenari et al., 1994). However, only when high precision photometry from ACS/HST images became available, Mackey & Broby Nielsen (2007) could clearly demonstrate the presence of two populations with an age difference of $\sim$300 Myr in the 2 Gyr old cluster NGC 1846, in the LMC. In this case, the presence of the two populations is inferred by the presence of two turn-offs in the CMD. Mackey et al. (2008) identified two additional LMC clusters with multiple populations. More recently, Milone et al. (2009b), from the analysis of the CMDs of 16 intermediate age LMC clusters using HST archive data, showed that the multiple population phenomenon might be rather common among LMC clusters: 11 (70%!) have CMDs which are not consistent with the presence of a single, simple stellar population. Also the Small Magellanic Cloud seems to host a cluster with a CMD not consistent with a single stellar population (Glatt et al., 2008).

An interesting case appeared in the literature is that of the massive star cluster Sandage-96 in the external galaxy NGC 2403, which seems to host two stellar populations, one with age of 10 - 16 Myr and one of 32 - 100 Myr (Vinkò et al., 2009). The search of multiple populations in massive, young star clusters can provide important information on the origin of the phenomenon.

3. SPECTROSCOPIC EVIDENCE

A significant dispersion in Li, C, N, O, Na, Al, Mg in GC stars is currently well assessed, thanks to several important milestones: (1) The presence of a Na-O anticorrelation is confirmed to be present in all clusters observed so far (Carretta et al., 2009). Carretta et al. (2009) proposed that the presence of a Na-O anticorrelation should be considered as the specific signature to distinguish GCs from other star clusters and stellar associations.

(2) Variations of other heavy elements (Mg, Al) is also generally present in GCs.

(3) The signature for other elements (Li, C, N) may be reproduced by assuming a mixture of primordial composition plus evolutionary changes due to two mixing episodes, occurring at the end of the main-sequence (the first dredge-up) and after the bump on RGB (Charbonnel et al., 1998).

(4) The variations are found also among MS stars of GCs (Gratton et al., 2001; see also Gratton et al., 2004). This implies that this composition has been imprinted in the gas by a previous generation of stars. In fact, low-mass MS stars are unable to activate the nucleosynthesis chains required to produce the observed inter-relations between the elements (in particular the Mg-Al anticorrelation).

(5) The variations are observed, with the same order of magnitude, among both MS and RGB stars (Cohen et al., 2002), that is, they are not washed out from surface during the first dredge-up, when the outer convective envelope deepens to include roughly half of the stellar mass.

(6) The amount of the variations among different clusters is related in a not trivial way to global cluster parameters, the most important one being the absolute magnitude (Carretta et al., 2007, 2010e).

Prantzos & Charbonnel (2006) showed that the observed anticorrelations can be reproduced by assuming a typical polluter composition, which is then diluted by different amounts of pristine material. Such a dilution would also help understanding the observed Li abundances, because significant amounts of this easily destroyed element appear to be present in most GC stars (D'Orazi et al., 2010 and references therein).

As discussed in the previous sections, in many cases there are clear correlations between multiple sequences in the CMD and the presence of groups of stars with different chemical composition.

4. SUMMARY AND CONCLUSIONS

Multiple populations may be ubiquitous: Na-O anticorrelations have been found in all clusters searched so far.

In general, the multiple population phenomenon differs from cluster to cluster, in the way it shows itself, in the ratio of the different populations within the same cluster, in the separation of the different sequences:

- There are clusters with discrete multiple main sequences, apparently implying extreme He enrichment, up to Y=0.40 (e.g., ω Centauri, NGC 2808). At the present time, multiple MSs represents our best evidence of the presence of He enriched stars in GCs.
- There are clusters with broadened or split MS (as NGC 6752 and 47 Tuc), again associated to He enhancement.
- There are complex objects like M54 (=ω Cen?), and somehow intermediate objects like M22 (= M54 and ω Cen?), which may be associated to star clusters embedded in the nuclei of disrupted (or disrupting) dwarf galaxies.
- There are clusters with double SGBs (e.g., NGC 1851, NGC 6388, NGC 5286, and many others). It remains to be understood whether the double (multiple) SGBs-turn off should be associated to stars with significant ($\sim$ 1 Gyr or larger) age difference, or to stars with different CNO content. At the moment, observational evidence points towards a constant CNO content for stars in GCs, including clusters with clear presence of multiple populations.
- There are clusters with double RGBs. The double RGB has been clearly associated to stars with different Na, O content, and possibly related to stars with different C and N content. A relation of double RGBs to stellar groups with different Ca content remains to be confirmed.
- A large fraction (2/3?) of LMC/SMC intermediate age clusters have double turn-offs/SGBs;

At the moment, we cannot say whether the different manifestations of the multimodality of cluster stellar populations reflect a single phenomenon. For example, it has been proposed (Bekki & Mackey, 2009) that the origin of the bimodal populations in LMC clusters could come from an encounter of a young cluster with a giant molecular cloud, where the formation of a second generation of stars is triggered by the encounter itself. Carretta et al. (2010c) proposed a merge of two clusters to explain the two populations in NGC 1851.

For many (generally massive) Galactic GCs, the multiple populations could be due to a second (or third) generation of stars which formed from material polluted by the ejecta from a variety of possible first generation stars (see Renzini, 2008 for a review). For sure, these GCs are clearly not simple, single-stellar-population objects. The emerging evidence is that the star-formation history can vary strongly from cluster to cluster, and that some GCs are able to produce very unusual objects, also with extreme (Y = 0.40) helium enhancement. No such He-rich MS stars have ever been found elsewhere. Reconstruction of this star-formation history requires a better understanding of the chemical enrichment mechanisms, but the site of hot H-burning requested to explain the He enhancement and the Na-O anticorrelation remains unclear. There are two requisites: (1) temperature should be high enough; and (2) the stars where the burning occurs should be able to give back the processed material to the intracluster matter at a velocity low enough that it can be kept within the GC itself (a few tens of km/s). Candidates include: (1) Massive ($M > 10$ $M_\odot$) rotating stars (Decressin et al., 2007); (2) the most massive among the intermediate mass stars undergoing hot bottom burning during their AGB phase (Ventura et al., 2001). These mechanisms act on different timescales (10^7 and 10^8 yr, respectively), and both solutions have their pros and cons (Renzini, 2008). The massive star scenario should avoid mixture of O-poor, Na-rich material with that rich in heavy elements from SNe, while it is not clear how the chemically processed material could be retained by the proto-cluster in spite of the fast winds and SN explosions always associated to massive stars. Producing the right pattern of abundances from massive AGB stars seems to require considerable fine tuning. The observed constancy of the CNO content may be an additional problem for this scenario. In addition, both scenarios require that either the IMF of GCs was very heavily weighted toward massive stars, or that some GCs should have lost a major fraction of their original population (Bekki & Norris, 2006; D'Ercole et al., 2010). Some massive GCs may even be the remnants of tidally disrupted dwarf galaxies, as suggested by the complexity in the chemistry and CMD morphology of ω Cen and M54, and possibly M22.

Capture of field stars by a cluster (Kroupa, 2007), encounter by a cluster and a massive molecular cloud (Bekki & Mackey, 2008), merging of a double cluster (Mackey et al., 2008), effects of Population III stars (Yi, 2009), multiple SNe explosions (Romano et al., 2010), and inhomogeneities in Big Bang nucleosynthesis (Moriya & Shigeyama, 2010) are proposed alternative scenarios.

Thanks to the new results on the multiple populations, we are now looking at globular cluster (and cluster in general) stellar populations with new eyes. De facto, a new era on globular cluster research is started: Many serious problems remain unsolved, and we still have a rather incoherent picture. The new HST camera WFC3 will play a major role in helping us to solve many open questions. But also multi-object spectroscopy, and high efficient spectrographs are mandatory to compose the puzzle. For the first time, we might have the key to solve a number of problems, like the abundance anomalies and possibly the second parameter problem (which have been there as a nightmare for decades), as well as the newly discovered multiple sequences in the CMD.

Finally, we should never forget that what we will learn on the origin and on the properties of multiple populations in star clusters has a deep impact on our understanding of the early phases of the star formation and chemical evolution of galaxies.

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