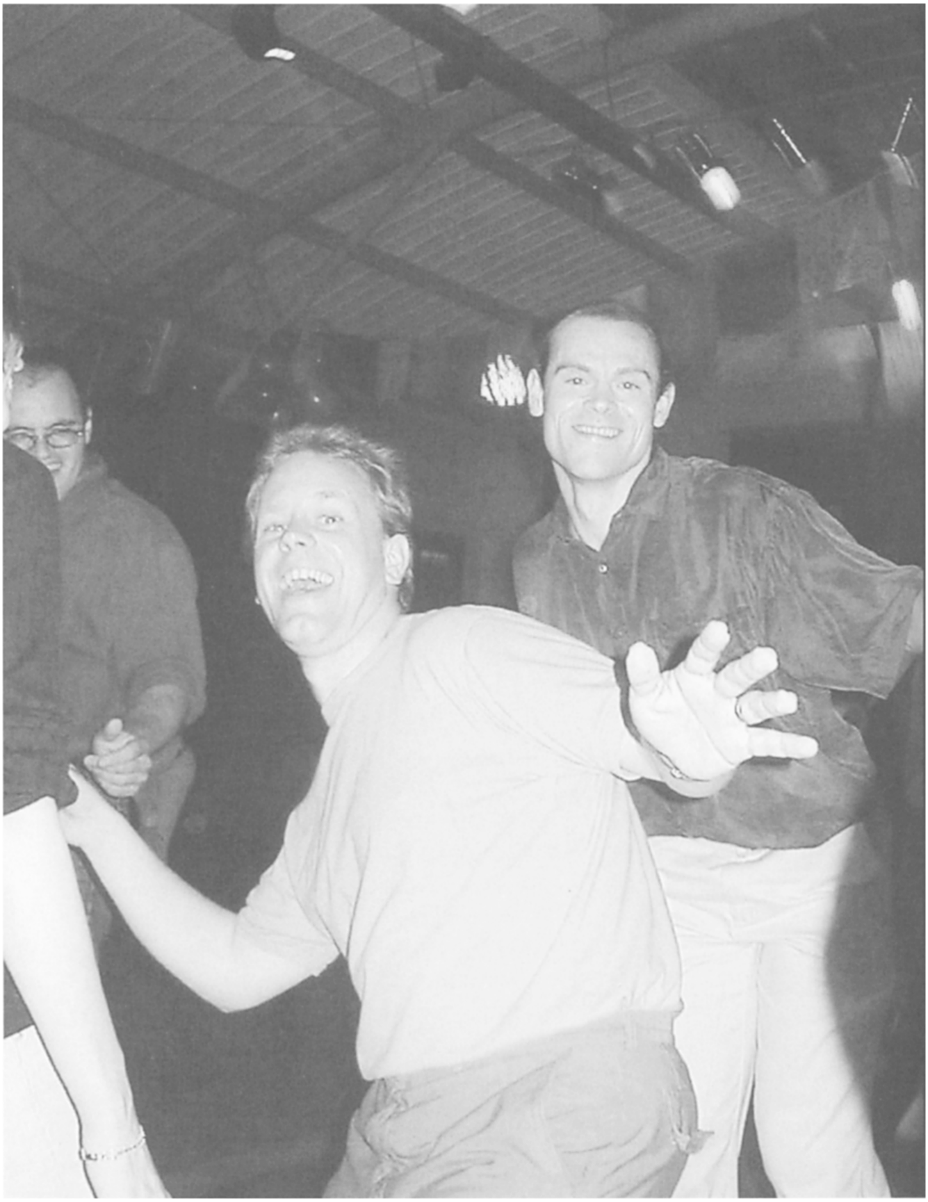
Part 2. Globular Cluster Systems of Distant Galaxies

Section A. Invited Reviews and Contributed Talks



The camera captures Markus Kissler-Patig's reaction to the first call for beer at the reception. Equally saddened are Paul Goudfrooij and Boris Dirsch.

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Metal-rich and Metal-poor Globular Clusters in Ellipticals: Did we Learn Anything? *or* Constraints on Galaxy Formation and Evolution from Globular Cluster Sub-populations

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Abstract. A brief review on globular cluster sub-populations in galaxies, and their constraints on galaxy formation and evolution is given. The metal-poor and metal-rich sub-populations are put in a historical context, and their properties, as known to date, are summarized. We review why the study of these sub-populations is extremely useful for the study of galaxy formation and evolution, but highlight a few caveats with the current interpretations. We re-visit the current globular cluster system formation scenarios and show how they boil down to a single scenario for the metal-poor clusters (namely the formation in "universal", small fragments at high z) and that a hierarchical formation seems favored for the metal-rich clusters.

1. History of blue and red populations

1.1. In the beginning...

Stellar sub-population in galaxies were introduced with the concept of population I and II in the Milky Way (Baade 1944). Galactic globular clusters were typically associated with the population II, although some were recognized as belonging to the disk/bulge (Becker 1950 and others). The idea of *globular cluster sub-populations* in the Galaxy was probably only brought to general acceptance with the work of Zinn (1985).

Ellipticals were not thought of as complex systems until the 80's and mostly viewed as hosting an old, metal-rich stellar population. The lack of resolution into single stars still prohibits us from clearly identifying stellar *sub-populations* in early-type galaxies. Only as spiral–spiral merger became an alternative to forming ellipticals, Ashman & Zepf (1992) came up with a simple model that *predicted* globular cluster sub-populations in ellipticals if these formed in major mergers. Shortly afterwards, Zepf & Ashman (1993) identified such sub-populations in the color distributions of globular clusters in giant ellipticals.

1.2. Are mergers the answer?

For several years, the idea of sub-populations associated with mergers raged within the community, still leading to hot debates today. The formation of new globular(?) clusters was observed in merging galaxies (Holtzman et al. 1992 for the first compelling evidence), further supporting the merger scenario. The debate shifted to whether these new clusters would actually evolve into *globular* clusters (which now appears to be the case, e.g Schweizer's contribution in this volume), and whether their general properties (spatial distributions, total number, specific frequency, ages and metallicities) are compatible with those of the metal-rich populations in ellipticals (which is still an open question). Note the caveat that we implicitly assume that what we learn from today's mergers applies to the mergers that potentially formed the giant ellipticals at much higher redshift, which might not be the case.

In the mid-90's, several groups started to propose alternatives to major mergers being the only explanation for multiple sub-populations (e.g. Kissler-Patig 2000 and references therein). But the alternative "scenarios" remain fairly vague in terms of predictions or details. Generally, all scenarios tend to mix to some degree globular cluster formation, globular clusters system assembly, and galaxy formation. Section 5 attempts to provide a critical summary.

2. Sub-population properties: room to improve

In order to understand the origin of the sub-populations (which is the first step required in order to use them to constrain galaxy formation and evolution), we need to understand their properties. Do the sub-populations differ in metallicity only (metallicity differences being the reason why we detected them in the first place)? Or do they resemble each other in many aspects? A brief summary of our current knowledge is given below.

2.1. Our biases

In the mid-90's several *giant* ellipticals were known to host sub-populations. Blue and red globular clusters were identified in the color distributions and sub-samples created based on the colors. A few aspects/selections of these studies are of interest and lead to biases that need to be understood as we try to understand the sub-population properties in more detail.

i) No "clean" sub-sample can be obtained from the color distributions alone; rather each sub-sample contains an unknown fraction of the other sub-population. That fraction is not trivial to quantify since it depends both on observational errors that smear each color peak, and on the necessary but too simple assumption that colors are driven by metallicity alone. *The fraction of contamination should be estimated and the impact on the uncertainty of the derived properties quantified.*

ii) The term *bi-modal* was introduced early on and is still widely used, driving our thoughts automatically to *two* sub-populations only. A third peak in the color distributions was mentioned in some galaxies, but in order to study the properties of individual sub-populations, only two groups were considered (true for all studies to date). The latter assumption seem acceptable as a first approximation since clear differences were noticed, but the question remains how long this perspective will limit our ability to understand systems that are almost certainly more complex. *We should keep in mind that not two but multiple sub-populations are most probably present, and should work towards a finer splitting of the sub-populations.*

iii) Our samples of galaxies are still very much biased in favor of central giant ellipticals, or at least very luminous giant ellipticals. The reason is of course that these galaxies host the most clusters and are therefore the easiest systems (with enough number statistics) to be studied. Unfortunately, these are the galaxies that we then tend to call "typical" despite the fact that they are the rarest and most extreme examples. A much more subtle bias is introduced in sub-population studies by an implicit selection of galaxies with well separated peaks in their globular cluster color distribution. For these cases the separation of the two sub-population is of course the easiest. However, assuming that the metal-poor population is rather constant in age and metallicity (see below) this selection does bias us against galaxies with less metal-rich clusters and intermediate age metal-rich sub-populations. *Future samples should include early-type galaxies of all types and luminosities, and in all types of environments (especially intermediate-luminosity field galaxies), irrespective of the properties of the globular cluster system.*

2.2. Differences and Similarities

In the following we briefly list common properties and differences between the metal-rich and metal-poor sub-populations, as studied to date. No long description is given and the list of references is restricted to a few studies that include further references (see also Ashman & Zepf 1998, Kissler-Patig 2000, Harris 2001 for further references).

The spatial distributions The first property that was studied separately for blue and red clusters is the radial surface density profile. Geisler, Kim & Lee (1996) first noticed, in NGC 4472, that the red clusters were more concentrated towards the center than the blue ones. The radial surface density profile of the red clusters is steeper than the one of the blue ones leading to a color gradient with radius for the whole system. This behavior was observed in the cluster systems of several giant elliptical galaxies.

Further, Kissler-Patig et al. (1997) first noticed, in NGC 1380, that red and blue clusters also differed in their 2-dimensional spatial distributions. The red cluster system appears more elliptical than the blue one. The blue clusters are not only more diffuse but also follow a rather spherical distribution, while the red clusters follow the ellipticity and position angle of the galaxy. Again, this behavior was confirmed in a few other galaxies.

This leads to an association of the blue clusters with the "halo" (although ill defined for early-type galaxies) and an association of the red clusters with the "bulge" or spheroid, which represents the majority of the stars in these galaxies (see also Sect. 4.).

The kinematics Kinematics for the red and blue sub-populations were investigated in three early-type galaxies only (M 87, NGC 4472, NGC 1399), all central giant ellipticals. It is thus unclear whether these can be regarded as typical. Nevertheless, it is clear that the kinematics (both the rotation and velocity dispersion) of the red and blue clusters differ in these galaxies. A consistent picture has not yet emerged (e.g. Kissler-Patig & Gebhardt 1998, Kissler-Patig et al. 1999, Zepf et al. 2000). Notice also that no clear predictions exist for the kinematics of the sub-populations as a function of assembly/formation scenario.

Ages and metallicities The difference in metallicity between red and blue sub-populations is clear from the color distributions (metallicity being the main contributor to color at old ages). However, it remains unclear how much red and blue populations differ in age. Relative age differences can be measured spectroscopically (e.g. Kissler-Patig et al. 1998, Cohen et al. 1998) or photometrically (e.g. Puzia et al. 1999). The bottom line is that red and blue clusters appear coeval to within the (large) measurement errors (2–4 Gyr), with some disputed claims of the red clusters being younger by a couple of Gyr. The absolute ages of the clusters in early-type galaxies appears similar to the one of the old clusters in the Milky Way and M 31, as judged by spectroscopic line indices.

The sizes Recently (Kundu & Whitmore 1998, Puzia et al. 1999, Larsen et al. 2000) size differences were discovered between red and blue clusters in early-type galaxies. The blue clusters appear systematically more extended in all galaxies, independently of radius. The currently favored explanation is that the size difference is a relic of the formation process: the blue clusters could have formed in a less dense environment than the red ones.

3. More than two sub-populations

The above differences in sub-population properties confirm that a splitting in color leads to two sub-groups with physical differences. A question that was seldom asked to date is: whether each sub-group really represents a single sub-population, or whether one or both sub-groups actually host multiple sub-populations.

The color (equivalent to [Fe/H]) histogram shows the distribution of a logarithmic metallicity value. In figure 1, we illustrate for three cases (with increasingly pronounced metal-rich population) how such a distribution would look in linear metallicity Z. The two clear peaks in [Fe/H] (translated linearly from $V - I$) disappear when plotted in Z. For this particular choice of zero point (solar=1), the blue peak gets "compressed" into an even clearer peak between 0 and 0.1–0.2 $Z_\odot$. The typical gap in color at [Fe/H]~ -0.7 dex can still be guessed at Z$\sim$0.2 . However, the red peak gets spread over several tenths in Z and is not recognizable as a single peak anymore. Simple simulations show that the spread of the metal-rich population is not artificially induced by the fixed errors in logarithmic space, but indeed due to a spread in metallicity that gets "played down" in [Fe/H].

While the blue clusters still appear to be a single physical group (see also the next sections), there is no compelling evidence that this is true for the red clusters too. Clearly, this prompts the question whether the metal-rich sub-group is, in many or most cases, just an amalgamation of multiple metal-rich sub-populations that do not necessarily share the same origin. Alternatively, for smaller red populations such as the one of the Milky Way, the spread could also be explained by an extremely fast enrichment of the material out of which the metal-rich clusters formed (contrary to the environment in which the metal-poor clusters formed). This would imply that the metal-rich clusters show a small spread in age too, and that they formed in a potential well deep enough to retain the enriched gas. It remains to be shown whether the latter scenario could also

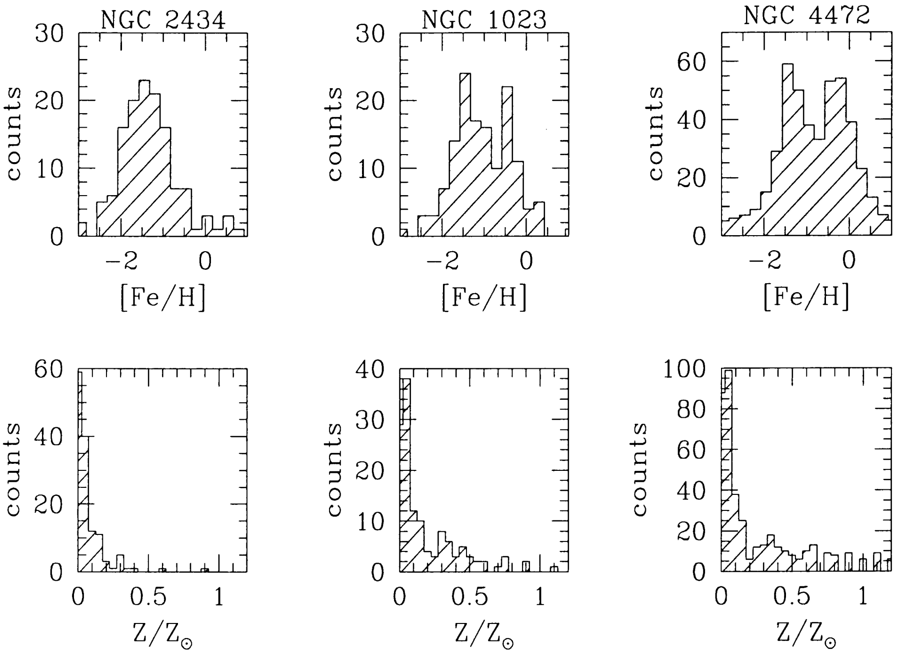

Figure 1. Comparing [Fe/H] and Z distributions of globular clusters in three early-type galaxies with a sequence of pronounced metal-rich sub-populations.

apply to the formation of several hundreds to thousands of globular clusters in giant ellipticals.

Thus, the interpretation of the metal-rich peak appears more complicated than originally assumed and the red population might well host multiple sub-populations. This would imply a complex star/cluster formation history, i.e. not a single collapse or single major merger event might be at the origin of the metal-rich clusters, but rather several such events. Given the above: Does the result of a KMM test (that imposes 2 Gaussians to the color distribution) make a physical sense? Or does it only mislead us to consider two and not more sub-populations in a system, and thus over-simplify the interpretation?

4. The globular cluster – star connection

The above problems lead us to consider the connection between globular clusters and stars. Can we identify the multiple stellar populations that should be associated with the multiple globular cluster sub-population?

4.1. The link between globular cluster and star formation

A shaky aspect of our current interpretation of globular cluster formation in terms of star-formation history of the galaxy is that we assume for simplicity that globular cluster formation traces star formation one-to-one. The fact that a strong correlation exists between star and cluster formation is supported by the fairly constant (within a factor of two) specific frequency in all galaxies, the correlation between star and cluster formation, etc... (e.g. Introduction in Puzia et al. 1999). However, a one-to-one correlation is certainly too simplistic. In fact, there is growing evidence that the blue globular clusters are associated with few stars, while the red clusters form together with the majority of stars.

The first piece of evidence comes from the fact that high specific frequencies are systematically observed in "halos" and in dwarf galaxies, both dominated by blue clusters.

The second hint comes from the fact that diffuse stellar population studies in early-type galaxies (Maraston & Thomas 2000, Lotz et al. 2000) imply only a small fraction (typically 10%) of old metal-poor stars as opposed to a majority of old metal-rich stars. In contrast, old metal-poor and metal-rich clusters are roughly present with a 50%/50% share in these galaxies, i.e. blue clusters have fewer stars associated with them than red clusters do.

The third indication comes from direct number counts of stars and globular clusters as a function of metallicity in the nearby elliptical NGC 5128 (see Harris, Harris & Poole 1999). A comparison of the metallicity distributions for stars and globular clusters shows the much higher ratio of stars to globular clusters at the metal-rich end.

4.2. The color of specific frequency

The conditions for formation of the metal-poor globular clusters do not seem favorable to the formation of a large fraction of stars, while the contrary seems true for the metal-rich population. A possible explanation could be that metal-poor clusters form in shallower potential wells and eject a lot of gas during their formation that cannot be processed further into stars. While the metal-rich clusters form in deeper potential wells retaining the gas and allowing an efficient star formation. This assumes that clusters collapse at the very beginning of a star formation burst.

The fact is that the specific frequency (Sn) of the blue sub-population is much higher than the one of the red sub-population. The specific frequency of a galaxy could thus be increased by forming (or accreting) a large quantity of metal-poor clusters+stars. On the other hand, when comparing the specific frequency of different galaxies, one should correct for the fraction of blue to red clusters present. Also the (in my opinion wrong) argument that specific frequency has anything to do with a major merger in the past history of the galaxy needs to be revised. From the above, a major merger, producing metal-rich clusters, could only decrease the specific frequency, and the specific frequency of a spiral–spiral merger could be equal to or lower than for one of the progenitor spirals alone. But such arguments imply that we know the Sn produced in mergers, which we do not.

In any case, the "color of the specific frequency" needs to be taken into account when using Sn to constrain any formation scenario, as well as the fact that "Sn" is constant when normalized to total baryons instead of just stellar light (McLaughlin 1999).

5. Formation models for dummies (by a dummy)

Ideally, we would like to use globular clusters to constrain the star formation history of their host galaxies. In practice, we need to know how/where globular clusters form in the first place, and what the assembly histories of the galaxies were. Information on all these points is contained in the globular cluster system properties. However, all the aspects are entangled and when we try to set up a "scenario" we often mix all these aspects in.

The currently discussed scenarios fall roughly into three categories: *i)* the formation of globular clusters and of the host galaxy in a major merger event; *ii)* the formation of all globular clusters within the host galaxy; *iii)* the formation of the globular clusters in fragments of different sizes that assemble later into a giant galaxy (e.g. Kissler-Patig 2000 for references to the different flavors of each scenario). Some more scenarios combine all or some of the above.

We quickly summarize what we know about blue and red populations and discuss these properties in the frame of the different scenarios.

5.1. The Truth about blue and red populations

Are the blue and/or red clusters closely connected with the final host galaxy? There are still too many Truths on blue and red populations. One recent topic to review critically is the correlations of sub-population color with host galaxy properties (Ashman & Bird 1993, Forbes et al. 1997, Burgarella et al. 2001, Forbes & Forte 2001, Larsen et al. 2001). Only a very weak correlation seems to exist between mean metallicity of the blue sub-population and mean metallicity/size of the final host galaxy. For the red sub-population a correlation appears more likely, although different dataset give different results. As an example we plot in Fig. 2 (for all studies reporting a clear or likely "bimodality" in the globular cluster color distribution) the red peak color versus galaxy metallicity (Mg_2 index). All values in the literature were used, values for a same galaxy from different studies were averaged. The clear correlation sometimes claimed for "cleaned" samples becomes less clear and more complicated to interpret unambiguously (see Kissler-Patig et al. 2001 for more details and further samples).

The essence Despite all the uncertainties, we can retain several properties for each sub-population.

For the **blue** sub-populations, the following facts are reasonably secure:

- The mean metallicity correlates only weakly if at all with the host galaxy metallicity, and if present it is much shallower than a one-to-one correspondence.
- Several properties (sizes, high Sn, ...) fit well with the idea of them having formed in shallow potential wells (small fragments).
- Their spatial distribution and kinematics favor them as being "halo" objects.

These clusters most probably formed in small "universal" fragments (falling back on the Searle & Zinn (1978) idea), some of them having formed with the dark matter potential of the galaxy (explaining a weak correlation of the metallicities) but some having formed in satellites and having been accreted later.

Concerning the **red** population, we know that:

- The red color peak correlates more or less well with the galaxy size and metal-

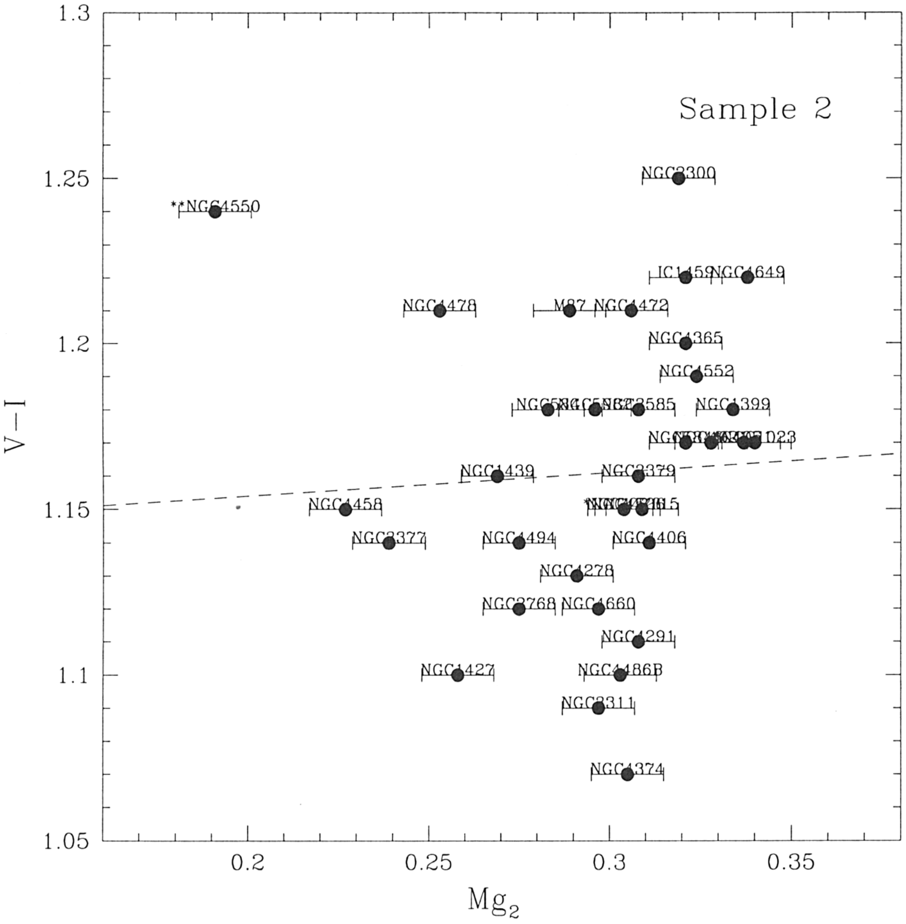

Figure 2. Correlation between red peak color of the globular clusters and Mg_2 index of the host galaxy, for a entire sample of clear and likely "bi-modal" systems, all values in the literature being used.

licity (although the correlation could still be driven by biases in our samples)

- The red sub-population is likely to consist of several metal-rich sub-populations, driven by the probably complex assembly history of the galaxy.
- These metal-rich clusters must have formed in denser environments (mergers?) and deeper potential wells (larger fragments) than the metal-poor ones, given their sizes and the many stars associated with them.
- The red globular clusters are as old (or almost) as the blue ones.

These properties are still compatible with all red clusters having formed in one collapse or one major merger event, but it appears more likely that several such "major" events contributed to build up the giant systems. The key to a discrimination will be the study of red sub-populations in order to identify or rule out sub-populations within the metal-rich clusters.

5.2. And the winner is ...

Is one model currently favored over another? The main problem is that no model makes a clear, unique prediction that would allow us to rule it out or confirm it, and as stated earlier, these models often mix a number of aspects.

Clearly, the current idea of the formation of metal-poor clusters is compatible with all three flavors of scenarios. Thus, at early stages (assuming that metal-poor material is related to an early epoch, which is probably true in most cases) all scenarios burn down to one: namely small "universal" fragments collapsing and assembling to "halos" with high Sn (e.g. see Burgarella et al. 2001 for a correspondence with the high-z universe). The main open question is: what fraction formed in clear association with the final host galaxy and what fraction formed independently and was accreted later?

Only for the metal-rich clusters, the scenarios might differ somewhat. We need to remember that most clusters (and spheroids) assembled as redshifts $z > 1$ (probably $z > 2$), at which stage the large collapse leading to the formation of the bulge might well have been induced by a gas-rich merger. The question thus is: did the red clusters form during the single collapse of the spheroid or did they form in multiple-collapses that assemble subsequently to form the final host galaxy? Probably both, but which mode dominated? **If** the red clusters really show distinct sub-populations, the latter, hierarchical mode, would be favored.

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Discussion

C. Grillmair: If all stars formed in clusters could differences between globular and stellar color (or [Fe/H]) distributions simply reflect different destruction rates? Old, metal-poor clusters have higher angular momentum and are more protected from bulge shocking etc, and contribute few field stars. Red clusters orbit in more violent environments, are destroyed more often and contribute lots of field stars. Comments? Do we need more spectroscopy of field stars?

M. Kissler-Patig: I like your idea, although I cannot comment on its likelihood. I guess that simulations of destruction rates would be "easy" if we could feed them with realistic initial conditions. Currently, not enough is known on red and blue cluster kinematics to make a secure guess. Another way of testing this hypothesis would be to compare in detail the abundances and abundance ratios in stars and clusters. This will be a by-product of T.H.Puzia's thesis, aiming at high S/N spectroscopy of clusters and stellar light in a sample of galaxies. So we might know more in a couple of years.

B. Elmegreen: Is enough known about the dispersed population of stars in clusters of galaxies (e.g. color) to identify them with one population or the other of globular clusters?

M. Kissler-Patig: I am afraid that our knowledge of the dispersed stellar population in clusters is still extremely sparse. So the answer is no. But as wide field cameras become available, the colors of the diffuse light is certainly an interesting way to follow-up this question.

S. Zepf: The width of the peaks in [Fe/H] might be dominated by observational uncertainties. In this case, when you take the linear errors in [Fe/H] to an exponential to get Z, you naturally produce a peak with a tail. So the inferred distribution in Z is hard to interpret. A critical point in this regard that you noted are the kinematic differences seen between the red and blue population.

M. Kissler-Patig: I agree that the photometric errors are still significantly contributing to the width of the peaks and produce part of the tail in the Z distribution. However, we conducted a few simulations that showed that observational errors cannot explain all the dispersion. Ideally, one wants to test this on a sample that is not dominated by errors anymore. Such samples could either be very high quality HST photometry, or infrared color distributions, were the metallicity sensitivity is largely increased with respect to the photometric errors. Such tests are currently being carried out by our group.

B. Whitmore: Zepf has already made most of the point I wanted to make, but let me add that this also shows why we tend to get a bi-modal distribution in most cases. The metallicity enhancement happens relatively rapidly, so any distribution in time with an initial peak at $\sim$ 15 Gyr will end up with a roughly bi-modal distribution in [Fe/H]. However, I again caution about amplified noise. If you start with 2 delta functions in age at say 15 and 10 Gyr, and then predict [Fe/H], it would be similar to the observations. I agree with the constancy of the blue peak and with a larger spread in the red peak, which we also discussed in AJ, 114, 1797 (1997).

M. Kissler-Patig: I think that your argument boils down to whether all globular clusters form faster than any enrichment process (in which case you would not automatically expect a spread in Z and a bimodal [Fe/H]) or whether the metal-rich clusters form over "longer" periods of time and can profit from the abundance enrichment of that star-burst. But note that this latter case would be indistinguishable observationaly from multiple metal-rich sub-population, unless these exhibit a large spread in age (more than several Gyr). An answer might come from the study of α-elements in metal-rich globular clusters, which probe the timescale of formation and will reveal whether in a star-burst the clusters formed before or after the bulk of stars (another aspect of T.H.Puzia's thesis).

D. Forbes: CDM models fail in many ways to reproduce the real universe. Any comment on how much we should trust them?

M. Kissler-Patig: Hierarchical clustering models might fail to reproduce some features of the real universe, but they get quite close in describing all essential aspects. Also, they are the best models we have so far. Of course, we can design formation scenarios for globular cluster system around hypothetic, sketchy models (nowhere described in details, not making any concrete predictions), but would that make more sense? I think the important point for the above discussion is that *i)* for the blue sub-population we do not need any galaxy formation model. We actually know enough on their properties and formation that we are in the ideal situation of being able to constrain any galaxy formation model, namely it should include at an early stage "universal", metal-poor fragments of 10^6 to 10^{10} solar masses. *ii)* concerning the red sub-population, we need to stay open minded, but from an observational side, large structures appear to be rare at redshifts $z > 1.5$, which roughly corresponds to their redshift of formation. Thus, red clusters have likely formed in larger structures than the metal-poor ones, but not in structures as large as their final host galaxies.