METALLICITY DISTRIBUTIONS IN EXTRAGALACTIC GLOBULAR CLUSTER SYSTEMS: CONSTRAINTS ON GLOBULAR CLUSTER AND GALAXY FORMATION

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1. Introduction

The merger model for elliptical galaxy formation has received increasing attention since it was first suggested by Toomre & Toomre (1972). Van den Bergh (1984) pointed out a problem with the idea that elliptical galaxies were formed by simply combining two, or more, spiral galaxies. He noted that the specific frequency (S_N, number of globular clusters per unit galaxy light) is systematically lower for spirals than for ellipticals. Schweizer (1987) suggested that globular clusters (GCs) might be expected to form in the merger process, thereby alleviating or possibly eliminating the S_N problem. Ashman & Zepf (1992) developed this idea into a merger model for GC formation with testable predictions.

We recently examined this model in the light of new HST and ground-based imaging data on the blue and red sub-populations of GCs in elliptical galaxies (Forbes, Brodie & Grillmair 1997). We concluded that the merger model for GC formation has serious problems, particularly in explaining the characteristics of GCs in giant elliptical galaxies with high S_N. A multi-phase collapse scenario was suggested as more consistent with the available evidence.

Below we describe two "case studies" which illustrate how optical spectroscopy with the new generation of 10m-class telescopes can help constrain both GC and galaxy formation models. Some of the issues that can be addressed with spectroscopic data include the following:

- Do GCs in other galaxies show the same abundance ratios as those in the Local Group?
- Are GCs in elliptical galaxies more metal rich than in spirals, as would seem to be indicated by their colors?
- What is the upper limit on [Fe/H]?
- Can abundances, abundance ratios, ages and kinematics identify GCs that formed during a merger?

Broad-band colors suffer from a well-known age-metallicity degeneracy and so have been of limited value in addressing these issues.

The first case study is an examination of the GCs in NGC 1399. The second is a spectroscopic study of the proto-globular cluster candidates in NGC 1275.

2. The NGC 1399 Globular Cluster System

NGC 1399 is the cD galaxy at the center of the Fornax cluster at a distance of 19.3 Mpc. Using the Keck telescope, we recently obtained 5 Åresolution spectra of 18 GCs in NGC 1399 (Kissler-Patig etal. 1998).

In general, we found no anomalies in the strengths of absorption line indices sensitive to metals (e.g. Mg, Fe), nor in the more age-sensitive Balmer-line indices (Figure 1). However, our sample contained two clusters for which: 1) Mg, Fe and Na were stronger than in any Milky Way or M31 GC. 2) There was tentative evidence for a Mg/Fe overabundance, similar to that seen in giant elliptical galaxies. Worthey et al. (1992) discussed possible explanations for this effect in galaxies, perhaps the most plausible of which was a variable (flatter) IMF. 3) Hβ and Hγ (effectively the only two Balmer lines in the spectral range) were abnormally strong. A similar effect was also seen

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in a few M31 GCs (Brodie & Huchra 1991), although at a lower metallicity. The Balmer lines are too strong to be reproduced by the spectral synthesis models (Worthey 1994, Fritze v. Alvensleben & Burkert 1995) at any age or metallicity. A component of blue horizontal branch stars might offer at least a partial explanation. Such stars are not represented in the models because they were not thought to be present in metal-rich clusters. However, Rich et al. (1997) recently discovered blue horizontal branches in two metal-rich GCs in the Milky Way, suggesting that a revision of the models may be in order.

Since the two "anomalous" NGC 1399 clusters are also very metal rich (see below), they must have formed from solar metallicity (i.e. enriched) gas, which may indicate that they are also younger than the rest. Judging by the photometric color distribution (these peculiar clusters are in the extreme red tail of the distribution), these clusters constitute less than 5% of the total GC population.

We calculated mean metallicity, [Fe/H], for all 18 clusters using the method described in Brodie & Huchra (1990). The Mg line-strengths were first corrected for a non-linear dependence of Mg index strength on metallicity for metallicities near and above solar, according to the models of Worthey (1994). With the exception of the two peculiar clusters, the range in metallicity seen in the NGC 1399 GCs is very similar to the range seen in the MW and M31: The metal-poor clusters have metallicities similar to those of the MW halo and the metal-rich clusters have metallicities similar to MW bulge/disk GCs. This suggests that the vast majority of NGC 1399 GCs formed from processes similar to those which formed the MW and M31 GC systems, and at roughly the same epoch (i.e. they are old).

V-I was found to correlate well with [Fe/H] and, although individual metallicities cannot be determined to better than 0.5 dex, a mean metallicity for a GC ensemble can be determined to about 0.3 dex from broad-band colors. However, the slope of the V-I vs. metallicity relation for the combination of Milky Way and NGC 1399 GCs was found to be twice as flat as the relation for Milky Way GCs alone. The consequence of this result is a much more homogeneous picture for extragalactic GC systems. Metallicity estimates for very red GCs are now roughly solar, rather than very super-solar as was previously thought, and metallicity differences between galaxies' GC systems are much less significant.

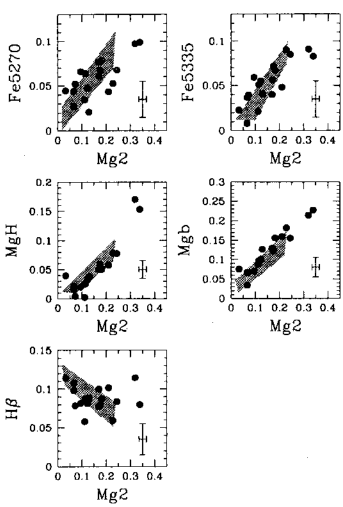

Figure 1. Mg2 versus various other indices, with the range spanned by Milky Way and M31 globular clusters shown as shaded region (taken from Brodie & Huchra 1990 and Burstein et al. 1984). Apart from two very metal-rich objects, all globular clusters are consistent with abundances found in the Milky Way and M31 globular clusters.

In summary, it appears that NGC 1399 and its GC system formed at early times. The same formation processes that were responsible for forming the MW GCs probably formed the vast majority of NGC 1399 GCs. Only a small percentage need have formed later from solar metallicity gas, e.g. in a merger.

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3. Proto–globular Cluster Candidates in NGC 1275

The discovery, with HST imaging, of proto–globular cluster candidates in NGC 1275 (Holtzman et al. 1992) was regarded by many as a major success of the merger model which predicted that newly–formed clusters should be observable in currently or recently merging systems. The NGC 1275 clusters constitute an important test of GC formation models. NGC 1275 is the peculiar cD galaxy at the center of the Perseus cluster. It shows evidence for a merger history and may indeed be undergoing a merger at present. It also has one of the largest know cooling flows. GC formation in cooling flows (Fabian et al. 1984) received some support from the photometric study of the NGC 1275 system by Richer et al. (1993).

Keck spectroscopy of 5 proto–globular clusters in NGC 1275 (Brodie et al. 1997) revealed that the candidates are not HII regions, are clearly dominated by early A–type stars, and are not similar to young or intermediate age Magellanic Cloud or MW open clusters.

The Balmer absorption lines were found to be too strong to be consistent with any of the standard IMF (Salpeter or Scalo), solar metallicity, Bruzual & Charlot stellar evolutionary models at any age (Figure 2). The preliminary Bruzual & Charlot (1997) models indicate that no appreciable increase in equivalent width can be achieved by changing the metallicity. However, a 2–3 $M_{\odot}$ IMF, adopted to simulate a flatter IMF, reproduces the observed equivalent widths and colors and indicates an age of $\sim$ 500 Myr for these objects.

The Fritze v. Alvensleben and Kurth (1997) models are able to reproduce the strong Balmer equivalent widths, with best agreement at 350 Myr. At this age the model colors are about 0.2 mag too blue to be consistent with the observed colors.

The proto–globular cluster candidates are extremely centrally concentrated. The entire sample (some 60 objects) is within 8 kpc of the nucleus and the brightest clusters are all within 2 kpc. We find a low velocity dispersion, $\sim$ 200 km/s, for our sample of 5 of the brighter candidates. This is lower than estimates of the stellar central velocity dispersion, $\sim$ 300 km/s (Lazareff et al. 1989).

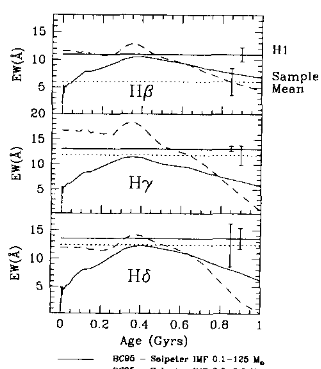

Figure 2. The time evolution of Balmer line equivalent widths for populations with different IMFs, produced by the Bruzual and Charlot models circulated in 1995. Also shown are the Balmer line equivalent widths measured for the brightest cluster, H1, (solid horizontal line) and the mean equivalent widths for the other clusters in the sample (dotted horizontal line). The value for Hβ is depressed, particularly in the lower signal–to–noise spectra, by under-subtracted Hβ emission in the galaxy background.

3.1. CONSTRAINTS ON CLUSTER ORIGINS

The spectroscopic information allows us to set some interesting constraints on the origin of these objects. We can clearly rule out formation in a continuous cooling flow. The spatial scale of the clusters is very much less than the cooling flow radius (by a factor of 60 for our spectroscopic sample and a factor of 20 for the entire candidate sample) and their age is very much greater than the cooling time ($\sim$ 10 Myr). Moreover, a star formation rate in excess of 400 $M_{\odot}$/yr is deduced from *the cooling flow (Allen & Fabian 1997) which implies a steep IMF to explain the absence of high* mass stars. We note that, if anything, the cluster's IMF may be biased *against* low mass stars.

It is equally clear that these clusters did not form in widespread shocks from merging galaxies. They are centrally concentrated and, if they formed far from the center and later fell in, a high rather than a low velocity dispersion would be expected.

It appears, then, that the clusters formed in a discrete event some 500 Myr ago. This may have been induced by a merger which provided the fuel for a short–lived gas inflow episode. It is not, however, clear to what extent processes such as these may have affected the global characteristics of GC systems. The resultant clusters are not distributed like old GCs in central cD galaxies which *are significantly more diffuse than the galaxy light. If they do indeed have an IMF which is biased* against low mass stars, they may fade very rapidly. A pure A–star population would fade away in only $\sim 10^9$ yr.

4. Summary

- The observational evidence fails to match merger model expectations in several respects and a multi–phase collapse scenario may be more consistent with the observed properties of extragalactic GC systems.
- The vast majority of GCs in NGC 1399 probably formed by the same processes and at the same epoch as those responsible for forming the MW GC system. Only a small subset (<5%) need have formed more recently (e.g. in a merger).
- The newly–defined V-I versus [Fe/H] relation suggests that metallicity differences between galaxies' GC systems are much less significant than previously thought and that there are no very super–solar GCs.
- The proto–globular cluster candidates in NGC 1275 probably formed in a merger–induced gas infall episode some 500 Myr ago. However, their properties are such that they may not represent formation processes that had a significant effect on the global properties of GC systems.

Acknowledgments

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