The Formation of Galaxies, the Formation of Old Globular Clusters and the Link with High-Redshift Objects

Denis Burgarella, denis.burgarella@astrsp-mrs.fr
Observatoire Astronomique Marseille-Provence, traverse du siphon, 13376 Marseille cedex 12, France

Markus Kissler-Patig, mkissler@eso.org
ESO, Karl-Schwarzschild-Str. 2, 85748 Garching bei Munchen, Germany

Veronique Buat, veronique.buat@astrsp-mrs.fr
Observatoire Astronomique Marseille-Provence, traverse du siphon, 13376 Marseille cedex 12, France

Abstract. In this paper, we are exploring the properties of old, metal-poor globular clusters in galaxies. We investigate whether their properties are related to the properties of their host galaxies, and whether we can constrain their formation. The main result is that the mean metallicities of old GC systems are found to lie in a narrow range -1.7 < [Fe/H] < -1.1 (80 % of the population). Moreover, no correlations are found between the mean metallicities and other galaxy properties which implies a GC formation independent of the host galaxies. Further, we try to identify the sites of old, metal-poor GC formation, with any currently known high redshift objects. We find that the metallicities of damped Lyα systems in the redshift range 1.6 < z < 4 are consistent with our GC metallicities, which suggests that these high-density neutral gas objects may be the progenitors of the old, metal-poor globular clusters.

1. Introduction

Statistics is always a key-point in scientific studies and it is no surprise that, as any scientist, the astronomer is looking for large, statistically significant samples to properly analyze the Universe and its content. Unfortunately, the intrinsic size of the Universe is turning this simple point into a difficult brain teaser due to the faintness of the above objects. Globular clusters are likely to contain some of the oldest known stellar populations of the Universe. As such, they potentially hold a cosmologically significant information on their formation and more generally on the conditions that prevailed more than 10 Gyrs ago.

In brief, we have started a study that is heading at selecting the oldest globular clusters (GCs) from the largest available sample of extragalactic GC systems. Previous studies often assumed the systems as an homogeneous population and used the mean properties (metallicity) of the GC systems as the
main parameter. Only in the most recent works GCs have been split up in sub-populations (Forbes et al. 1997; Côté et al. 1998). Going back to the very formation of the galaxies (and maybe before), asks to make sure that only the oldest (i.e. reliable fossils) GCs are picked up. Our choice is to select the metal-poor GCs. Indeed, if we can find old metal-rich globular clusters (Ortolani et al. 1995; Puzia et al. 1999), only in very limited cases could we have a late formation of metal-poor GCs. An important step has been to discover that galaxies other than our own contain metal-poor sub-populations that can be associated to a halo component (Puzia et al. 1999).

A more detailed report of this work will be published elsewhere (Burgarella, Kissler-Patig & Buat, 2000).

2. The compilation of Old Globular Cluster Populations

Our goal is to select the oldest GCs around galaxies and to compare their metallicities with the host galaxy properties, as well as to compare the systems with each other. The compilation includes galaxies of all types, however spiral galaxies are under-represented while bright elliptical galaxies dominate the sample. The detection of several peaks in the metallicity distribution function is always a problem and we use the mixture-modeling algorithm (KMM) developed by Ashman et al. (1994) to detect and quantify the bimodality and estimate the mean metallicity of the metal-poor GC populations around the sampled galaxies. This compilation of 38 GCs systems includes galaxies of all types and our sample includes galaxies over 10 magnitudes in absolute brightness (see Burgarella et al. 2000).

3. Mean metallicity against galaxy luminosity

Before a clear separation of metal-poor and metal-rich populations could be performed in other galaxies than in the Milky Way, the mean metallicities of the whole GC system was thought to correlate with the galaxy luminosity (van den Bergh 1975; Brodie & Huchra 1991). Actually, this apparent correlation was mainly due to the fact that the the brightest galaxies are ellipticals which have, on average, a higher GC mean metallicity than spirals and dwarfs (e.g. Ashman & Zepf 1998; Gebhardt & Kissler-Patig 1999).

The sample of GC systems presented in this paper is the largest database to-date, and about 3 times more numerous than Forbes et al.’s (1997) initial dataset. The mean [Fe/H] lies at [Fe/H]= −1.40 ± 0.06 with a dispersion of σ = 0.24 ± 0.05, that is slightly more metal-poor on average than, and exhibiting a scatter similar to the Forbes et al. sample. Fig. 1 shows the relative percentage of GC systems within each bin of the metallicity function. Indeed, the immediately apparent result is that the mean-metallicities of metal-poor GCs are not distributed at random: most of them are lying around [Fe/H]~ −1.4, with 64 % within -1.5 < [Fe/H] < -1.3 and 80 % within -1.7 < [Fe/H] < -1.1. We plot in Fig. 1 the metallicities of the GC systems as a function of the absolute magnitude $M_V$. The average metallicity of the metal-poor GCs is constant over a very large range in absolute magnitude of the host galaxy (−23 < $M_V$ < −16).
Figure 1. a) Distribution of mean metallicities for the GC system sample. Note the narrow peak at $[\text{Fe/H}] \approx -1.4$ with 80% of the population within $-1.7 < [\text{Fe/H}] < -1.1$. b) Mean metallicity of the old, metal-poor GC systems plotted against the absolute magnitude of the parent galaxy $M_V$ and the distance to the MW (right).

Figure 2. a) Mean metallicities and b) peak $V-I$ colors of the metal-poor populations plotted against the host galaxy environment density $\rho$. Black dots are new values.
4. Consequences on the formation scenarios of GCs, globular cluster systems, and galactic halos

Following Fall & Rees (1988), GC formation models “can be classified as primary, secondary or tertiary depending on whether GCs are assumed to form before, during or after the collapse of proto-galaxies.”. It seems, however, that the borderline between the three classes is not always very clear. To better identify the origins of GCs, we prefer to split the GCs on whether they are external to the galaxy, and not associated with the final host galaxy, or whether they formed internally, i.e. are associated in some form with the final host galaxy. This terminology is relatively unambiguous if we specify that pre-galactic fragments are not considered to be galaxies. And since we consider only old, metal-poor GCs assumed to have formed before or early in the galaxy formation process, we do not take into account mergers of already formed galaxies.

Now, if we concentrate our attention on the Milky Way GC system, it seems that halo GCs of the Milky Way host (at least) two populations that Zinn (1993) distinguished from their horizontal branch types. He called them ‘old’ and ‘younger’ halo GCs. There are hints for a similar differentiation in M33 (Ashman & Bird 1993). A probable internal halo old GC population which would have formed internally in the early galaxy lifetime by a dissipative collapse in a few Myr, and an external halo population which would have formed around other satellite galaxies and accreted afterwards. If such a complex GC formation history is valid for our own Galaxy and its nearest neighbors, it cannot be ruled out for other galaxies either.

We could retain that: i) the mean metallicity of halo GCs is independent of the host galaxy properties (M_V, type, environment (Fig. 2), metallicity) and ii) halo GC populations have very similar mean metallicities in all galaxies. These two points can be added to the dynamical information available for a number of metal-poor outer globular clusters that tends to show that these clusters are on tangentially biased orbits, as opposed to radially biased orbits expected if they had formed in a collapse (Eggen et al. 1962).

The bottom line from the above facts, is that the early cluster and star formation was remarkably homogeneous in the local universe (within several tens of Mpc). The first collapsing fragments were extremely similar in mass and abundances over large scales and collapse in very similar fashions independently of the potential well (dark halo) in which they were located. Presumably, the distinction between galaxy types only appeared after the first formation of stars and clusters in fragments.

5. Time and sites of formation of the metal-poor GCs

5.1. The measurement of metallicity at high redshift

In this section, we will look for measurements of metallicity at high redshift in order to compare with the average metallicity of our old GCs. Indeed, if the GC formation is the first stellar formation episode of what will become a new galaxy, the first-formed stars might have kept a memory of the genuine intergalactic medium as it was before the galaxy formation. Among the objects observed at high redshifts for which the metallicity can be estimated, two of them seem of
interest: Damped Lyα systems (DLAs), and Lyman Break Galaxies (LBGs). Both the typical column density in HI and the observed metallicities for DLAs and LBGs are plotted in Fig. 3, together with the same quantities for GCs (and the Lyman α forest for completeness). DLAs (Pettini et al. 1997) give a measurement for the metallicity as a function of redshift of high density neutral gas objects. Lyman Break Galaxies (Steidel et al. 1996) can, in addition, be used to estimate the star formation rate as a function of redshift. Assuming a metal ejection rate (Pettini et al. 1997), we can infer a chemical evolution of the Universe and compare it with other estimates, in particular with the mean metallicity of the metal-poor globular cluster systems.

However, [Fe/H] may not be a reliable estimate of the metallicity of DLAs, since some Fe may be locked up in dust and thus the measured [Fe/H] too low. Pettini et al. (1997) showed that [Zn/H] is a more reliable estimator because it essentially measures the metallicity independently of dust depletion. From a [Zn/H] analysis of 34 DLAs, Pettini et al. (1997) showed that $z > 1$ DLAs are generally metal-poor ($\log (\langle Z \rangle /Z_\odot) < -1.0$) with a possible trend for $z > 3$ DLAs towards a lower metallicity. However, the value at $z = 3$ is an upper limit and we would need better high redshift values. Although the dust depletion problem may make the direct use of DLA [Fe/H] questionable, we try here to use its variation with redshift in order to compare it with the information from GC systems. The compilation is given in Burgarella et al. (2000). The [Zn/H] and [Fe/H] variations as a function of the redshift are plotted in Fig. 3. We use the column-density weighted abundances: $\langle M/H \rangle_{DLA} = \log \langle (M/H)_{DLA} \rangle - \log (M/H)_{\odot}$ where $\langle (M/H)_{DLA} \rangle$ is the mean abundance in DLA systems.

The data presented in Fig. 3 can be used to constrain the GC system formation. In the first place, the analysis of the CMDs of old Galactic GCs suggests the age of halo GCs to be more than 10 Gyr which corresponds to a GC formation not later than $z \sim 1.6$ (H$_0 = 50$ km.s$^{-1}$.Mpc$^{-1}$ and $q_0 = 0.5$). On the other hand, the chemical evolution of DLAs and LBGs is below the lower limit for 80% of our metal-poor globular clusters at $z \approx 4$. The conclusion suggested by these data is that the GC formation occurred in average in the redshift range $1.6 < z < 4$ (i.e approximately in the range $10 < \text{age (Gyrs)} < 12$ with the assumed cosmology).

From the above discussion we retain that DLAs (and LBGs) have approximately the same range of metallicities and are observed in the redshift range expected for the formation of metal-poor GCs. Note, however, that DLAs contain neutral gas while LBGs are star-forming objects. As already suggested by Fynbo et al. (1999), we may wonder whether we are not observing the same objects at different location in space or in time. For instance, DLAs would be the source of dense gas out of which old GCs formed while LBGs would be star-forming regions e.g. spheroids as proposed by Giavalisco et al. (1996) and Steidel et al. (1996) but also surrounding fragments in the same potential well which are only directly visible at high redshift when the star formation turns on. Eventually these fragments would be accreted by the large galaxy to produce a MW-like object.

**Acknowledgments.** We would like to thank K. Gebhardt for his help in handling the data of the metal poor GCs and M. Pettini for helpful discussions.
Figure 3. a) This figure gives the rough location in metallicity against column density of neutral hydrogen for different components of the high redshift universe. We have added the results from our GC systems (80 % and 64 %) taking into account a low threshold N(HI) ≈ 20 for the star formation to occur (left side). b) Comparative variation of the metallicities with the redshift ($H_o = 50 \text{ km.s}^{-1}\text{Mpc}^{-1}$ and $q_o = 0.5$). Right hand panel: GC system metallicity distribution. Left hand panel: the limits at 80 % of the GC system mean-metallicity distribution are reported as dashed lines. The uppermost curves have been deduced from Steidel et al.’s (1999, Fig.9) star formation history (continuous line); the dashed line includes Barger et al. 1999 FIR data. [Zn/H] (continuous line crosses) and [Fe/H] (dashed crosses) values of DLAs are taken from Burgarella et al (2000). The age of the oldest Galactic GCs are reported as an horizontal right-bound arrow. Pettini et al. 1997 noted that assuming $q_o = 0.01$ would shift the [M/H] by a factor of 2.
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