The Formation Histories of Metal-Rich and Metal-Poor Globular Clusters

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Abstract

This review presents the results of ongoing studies of the formation histories of metal-poor and metal-rich globular clusters and their host galaxies. I first discuss the strong observational evidence that the globular cluster systems of most elliptical galaxies have bimodal metallicity distributions. I then focus on new results for metal-poor and metal-rich globular cluster systems. Metal-poor globular clusters are often associated with early structure formation, and I review new constraints on their formation epoch based on the “bias” of the number of metal-poor clusters with host galaxy mass. For metal-rich globular clusters, I discuss new results from ongoing optical to near-infrared photometric studies which both confirm an intermediate-age population in NGC 4365 and generally reveal a variety of formation histories for now quiescent ellipticals.

1 Introduction

As noted by several speakers at this meeting, many of us begin our talks and proposals giving reasons why we study globular clusters (GCs) to learn about the formation of their host galaxies. However, even if standard, listing these reasons is important because the characteristics that make globular clusters useful for studying the formation of their host galaxies are often revisited when comparing the results of the many different programs aimed at constraining galaxy formation and evolution. In this spirit, the following are some of the key reasons globular clusters are valuable tools for understanding the formation history of their host galaxies.

1) Because the age and metallicity can be determined for each globular cluster individually, the distribution of ages and metallicities within a galaxy population can be constrained.

2) Globular clusters are the best example we have of a simple stellar population, so determining the age and metallicity of individual GCs is much
simpler than studies of integrated light in which the stars of many different metallicities and ages are seen as one luminosity weighted average.

3) Globular clusters are observed to form in all major star formation events in galaxies, making them tracers of the major formation episodes of their host galaxies.

4) Some globular clusters are among the oldest known objects, so they may provide constraints on early structure formation.

5) As dense concentrations of $\sim 10^6$ stars, globular clusters can be observed in galaxies across the local universe. This enables the formation history of a representative sample of galaxies to be studied, including those of normal elliptical galaxies which are not present at very nearby distances.

In this review, I will focus on two new results regarding the formation history of globular cluster systems (GCSs) and their host galaxies. One of these new results is a constraint on the formation epoch of metal-poor globular clusters from the determination of their cosmological “bias” with host galaxy mass (see also Rhode, Zepf, & Santos 2005, and Katherine Rhode’s talk at this meeting). The second set of results are constraints on the formation history of elliptical galaxies from the age distributions of their globular cluster systems. I specifically review new work on the optical to near-infrared colors of globular cluster systems, which includes deep NICMOS data confirming previously identified intermediate age populations in the giant elliptical galaxy NGC 4365, and new PANIC data showing an effectively completely old population in another giant elliptical, NGC 4472. I then discuss the overall status of work on ages, and look to future samples and comparisons with elliptical galaxy formation histories estimated in other ways.

2 A Note about Metallicity and Color Distributions

The primary results discussed below involve using metal-poor globular clusters to probe early structure formation and metal-rich ones to probe the formation epochs of their host galaxies. While clearly some globular clusters have higher or lower metallicities than others, it is still natural to consider the basis for dividing globular cluster systems into metal-poor and metal-rich populations.

The obvious observational starting point is that most globular cluster systems of elliptical galaxies are observed to have bimodal color distributions. This was first noted many years ago now (Zepf & Ashman 1993) and much subsequent work has made it clear that the globular cluster systems of most, although not all, elliptical galaxies have bimodal color distributions (e.g. Kundu & Whitmore 2001, Larsen et al. 2001). It was also realized early on that for most elliptical galaxies GCSs, the optical color primarily traces metallicity. This is because metallicity is the primary driver for optical colors at ages greater than a few Gyr, and elliptical galaxies generally do not have huge amounts of recent star formation. It turns out the minority of ellipticals which have unimodal GCS color distribution may be an interesting exception.
to this rule as several of these have been found to have younger GC populations (see Section 4), but for typical bimodal systems, the GC color primarily traces metallicity.

Given that GC color primarily traces metallicity in typical bimodal systems, the next question is what is the detailed relationship between these two, and specifically whether the bimodal color distribution observed for most elliptical galaxy GCSs reflects a truly bimodal metallicity distribution. One common way to determine the relationship between color and metallicity is to fit the observed relation for the Milky Way GCS. Data for Galactic globular clusters is fundamental for this question, because only for these GCSs are there true abundances from high resolution spectra for individual stars, as well as detailed color-magnitude diagrams for age and metallicity determination. This approach to the relationship between color and metallicity is then limited by the Galactic globular cluster sample. Its primary limitation for this purpose is the absence of high metallicity clusters. Additional concerns are that some of the few with higher metallicities also have large and uncertain redenings, that the Galactic GCs do not extend to young ages, and simply the modest total number of Galactic GCs.

Another common approach is to use stellar populations models. However, these are not a panacea, because they are tested on Galactic data, and therefore have many of the same concerns at old ages and high metallicities as empirical fits of the Galactic GCS color-metallicity relation. Another possibility is using absorption-line indices for extragalactic systems to investigate the behavior of colors at higher metallicities. However, these indices are only related to actual abundances through stellar populations models or through Galactic GCs, and are therefore also strongly dependent on uncertainties in the models and any gaps in the Galactic sample on which these are tested.

There is a large body of work on determining color-metallicity relations using the above approaches and applying these to extragalactic globular cluster systems. These cover many color indices, including B—I and C—I for which there are extensive datasets, and V—I for which there is significant HST archival data. The conclusion of these many studies is that while the exact shape of the metallicity distribution varies somewhat depending on the color-metallicity relation, the general bimodal nature of the metallicity distribution remains. It is very difficult to create a strong dip right in middle of the color distribution without a bimodal-like metallicity distribution. A variety of kinematical studies also find differences between the metal-poor and metal-rich globular cluster systems (e.g. Zepf et al. 2000, Côté et al. 2003), providing independent evidence for the presence of these two subpopulations, similar to the way in which kinematics provides further evidence for two populations of GCs in the Milky Way. One contrary claim has recently been put forward and was presented at this meeting by Yoon et al. (see these proceedings). They use a stellar populations model with a specific treatment of the horizontal branch, and show their model gives a very sharp feature in the color-metallicity relation at the precise place to mimic a
metallicity bimodality. They also claim that this sharp feature is consistent with the preliminary \( g-z \) Galactic GC data in Peng et al. (2006), although no comparison is made to other well-established Galactic GC colors with a similar wavelength baseline.

A powerful argument that the observed color bimodality is due to a truly bimodal metallicity distribution is that the Galactic GCS is known without question to be bimodal in metallicity. While one might say we happen to live in a galaxy with a complicated history, it would seem quite strange for us to have ended up in a complicated galaxy, while other galaxies have the virtue of uncomplicated pasts. This “Copernican” argument for metallicity bimodality is strongly supported by a number of other observational results.

One observation that provides a clear indication of a bimodal metallicity distribution is bimodality in the \( I-H \) color distribution for the M87 GC system (Kundu et al. 2006). The near-infrared \( I-H \) color is dependent almost completely on metallicity, and it is very hard to image how a horizontal branch effect as proposed by Yoon et al. can account for bimodality at these near-infrared wavelengths. This evidence for bimodality in metallicity is supported by a wide variety of other data. Perhaps the simplest is the analysis of many different colors vs metallicities for Galactic GCs, including the \( B-I \) and \( C-T1 \) shown in talks at this meeting, both of which have broad wavelength ranges, does not show the very sharp and precisely located jump in color vs. metallicity required to produce the observed bimodal color distribution from a unimodal metallicity distribution. As noted in Smits et al. (2006), even linear fits of these Galactic GC color-metallicity relations do not have much more scatter than the observational uncertainties. Cohen et al. (2003) also noted in their fits of color to Galactic GC metallicities and absorption-line indices for extragalactic systems that a second-order fit is only slightly better than a linear fit, and their Figs. 13 and 15 do not provide evidence for sharp jumps in the color-metallicity relation. In this context is it worth noting that most absorption line studies of extragalactic GCSs are not fair samples of the cluster metallicity distribution, as many intentionally select their GC targets to have colors in the middle of the distribution in an attempt to decrease contamination of the sample by non-clusters. Therefore, while the comparison of colors and absorption-line indices for individual objects is valuable (e.g. Cohen et al. 2003), the distribution of absorption-line indices in extragalactic samples is not generally useful because of the preferential selection of GCs with intermediate colors.

Thus, there is both direct evidence for bimodal metallicity distributions as described above and the simple argument that it seems unlikely we are privileged to live in one of the few galaxies that has GC system with a unimodal metallicity distribution. These strongly indicate that the bimodal color distributions observed for GC systems arise from bimodal metallicity distributions. Therefore, for the remainder of this review, we will consider the metal-poor and metal-rich GC populations separately.
3 The Formation Epoch of Metal-Poor Globular Clusters from Their Bias with Galaxy Mass

It is natural to associate metal-poor globular clusters with early epochs of structure formation when the overall enrichment in galaxies was not high. Moreover, for many Galactic globular clusters, age determinations also indicate an early epoch of formation, although the uncertainties in GC ages even for Galactic clusters are large when converted to redshift in the early universe. Therefore, an independent method to assess the formation epoch of metal-poor globular clusters would be very interesting.

One idea for constraining the general formation epoch of the metal-poor globular cluster population is to take advantage of the feature of hierarchical structure formation models that more massive objects have a greater fraction of their mass collapsed at higher redshift, and that this “bias” increases fairly steeply at very high $z$. This has recently been pursued by Rhode, Zepf, & Santos (2005), based in part on the discussion in Santos (2003), and is also discussed in this meeting in Katherine Rhode’s talk. Specifically, we used new wide-field multi-color imaging for both ellipticals and spirals in a range of environments to determine the total number of metal-poor globular clusters around these galaxies. We then determined the galaxy-mass normalized number of metal-poor globular clusters for each galaxy (their $T_{\text{blue}}$ value, and plotted this versus galaxy mass. If the metal-poor globular clusters formed at moderate redshift when most of the mass has collapsed for typical galaxies, there would be little or no bias and all galaxies would have similar $T_{\text{blue}}$ values regardless of galaxy mass. With an extremely high redshift of formation for the metal-poor globular clusters, the mass-normalized number of metal-poor GCs would show a steep rise to higher galaxy masses, as only the most massive galaxies had even a small fraction of their mass collapse at very early epochs.

Our results are that the mass-normalized number of metal-poor GCs ($T_{\text{blue}}$) increases with increasing galaxy mass (Rhode et al. 2005). However, the increase is not particularly steep, suggesting extremely high redshifts for the typical formation epoch of metal-poor globular clusters are unlikely (see Katherine Rhode’s talk for relevant plots). Moreover, most systematics tend to steepen the relation, hinting that the current result may be an upper limit to the cosmological “bias” of the metal-poor GC population and its formation redshift. Further work in this area will include more detailed modeling of the theoretical expectations (see Moore et al. 2006 for such effort), use of the radial profile of the GCSs as a constraint, and of course needed increases in the size of the galaxy sample with data that provides sufficient areal coverage and depth to obtain a reliable determination of the total number of metal-poor GCs.
4 The Formation Epoch(s) of Elliptical Galaxies from the Ages of Their Metal-Rich Globular Clusters

Determining the formation history of massive early-type galaxies is one of the primary challenges of current extragalactic astronomy. These elliptical and S0 galaxies make up a significant fraction of the stellar mass in the local universe, but there is not yet a consensus on when they formed. Because the age of individual globular clusters can be determined, and globular cluster formation is observed to be a ubiquitous feature of starbursts, determining the age distribution of their globular clusters is a valuable way to constrain the formation history of elliptical galaxies.

There are several different observational approaches for determining the age and metallicity of extragalactic GCs. Although I have been involved in some way with nearly all of them, in this review I will focus on the optical to near-infrared color approach, as it is both very promising and not the subject of other talks at this meeting. The optical to near-infrared color technique is very promising because it relies on straightforward stellar physics to determine the age and metallicity, and because it is a photometric technique and therefore observationally efficient. The technique solves the age-metallicity degeneracy for unresolved simple stellar populations because the infrared color (e.g. $I-H$) is primarily sensitive to metallicity, while the optical color (e.g. $g-I$) has a greater sensitivity to age. Thus in plots of optical to near-infrared colors age and metallicity are separated (see Fig. 1). This separation is about 0.3 mag between intermediate ($\sim 3$ Gyr) and old ($\sim 15$) Gyr. A comparable example from another area is that 0.3 mag is similar to the difference in SN Ia brightnesses in an accelerating universe compared to an open one.

One of the first results to come from the application of the optical to near-infrared technique was the discovery of a substantial population of intermediate age globular clusters in the elliptical galaxy NGC 4365 (Puzia et al. 2002, hereafter P02). This result was originally thought to be surprising, in part because spectroscopy of the integrated light of NGC 4365 was originally thought to indicate an old age and thus presented a puzzle. However, recent calculations using alpha-enhanced isochrones necessary for NGC 4365 and its large observed $[\text{Mg/Fe}]$ give younger ages (Brodie et al. 2005, hereafter B05). Extant spectroscopic studies of the globular clusters themselves are inconclusive as one finds intermediate ages and the other does not, even for objects in common between the two studies (B05).

Therefore, to pin down the ages and metallicities of the GCs around NGC 4365, we obtained new, very deep NICMOS near-infrared photometry in three fields, and combine this with new ACS data. As shown in Figure 1, these independent and much higher signal-to-noise data confirm the previous result that NGC 4365 has a substantial population of GCs with optical to near-infrared colors that can only be accounted for by intermediate ages of $2 - 7$ Gyr (Kundu et al. 2005). We also show in this paper that the result is independent of which stellar population models are used, although the exact
Fig. 1. The g–I vs. I–H plots of globular clusters in NGC 4365 and NGC 1399 from NICMOS and ACS data from Kundu et al. (2005). These show a substantial population of GCs with optical to near-IR colors indicative of intermediate age in NGC 4365, in agreement with earlier work (P02), while NGC 1399 has few such GCs. Only GCs with uncertainties less than 0.1 mag in each axis are shown. The lines trace age (1, 3, 5, 8, 11, and 15 Gyr from the left) and metallicity ([Fe/H] = −1.7, −0.7, −0.4, 0.0, and 0.4 dex from the bottom) contours from BC03 models. The size of the points are inversely proportional to the I–H uncertainty as shown at the bottom right. The g–I uncertainties are comparable to the I–H values in NGC 4365 and are much smaller than the I–H uncertainties in NGC 1399.

The age of the intermediate age population does vary with model. In addition, Kundu et al. (2005) used archival data for NGC 1399 to show that its GCS is predominantly old with a small younger component, in agreement with previous spectroscopic work.

A comparison of optical to near-infrared photometry and the absorption-line spectroscopy for different galaxy GCSs reveals generally good agreement (see Kundu et al. 2005). Another example shown in Figure 2 is new PANIC data we have obtained for NGC 4472, which shows an almost exclusively old GC system (Hempel et al. 2006). This is in agreement with extant spectroscopic studies (Cohen et al. 2003, Beasley et al. 2000). The key advantages of the optical to near-infrared approach are that as a photometric technique it is more efficient to obtain age and metallicity estimates of a given uncertainty in the same amount of observing time, and that it relies on straightforward stellar astrophysics. The advantages of absorption-line indices are that they enable estimates of abundance ratios, which are interesting probes of timescales of formation (e.g. Pierce et al. 2006).

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The $V-K$, $V-I$ plots for globular clusters around NGC 4472, indicating that the GCS of NGC 4472 appears to be nearly completely old. In this plot, the model ages decrease left to right, going from 15 Gyr on the upper left to 3 Gyr on the lower right, and metallicity increases from $[\text{Fe/H}] = -2.2$ in the lower left part to 0.5 on the upper right part of the plot. All of these are BC03 models, and the data are from our ongoing work (Hempel et al. 2006).

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