A NEW LOOK AT GLOBULAR CLUSTER COLORS IN NGC 3311 AND THE CASE FOR EXCLUSIVELY METAL-RICH GLOBULAR CLUSTER SYSTEMS

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ABSTRACT

NGC 3311, the central cD galaxy in the Hydra Cluster, was previously thought to host the most metal-rich globular cluster system known. Ground-based Washington photometry had indicated the almost complete absence of the population of globular clusters near [Fe/H] ~ -1 dex; these globular clusters are normally dominant in the metallicity distribution functions of giant elliptical galaxies. Lacking the normal metal-poor globular cluster population, NGC 3311 was an outstanding exception among galaxies and was not easily understood under any of the current globular cluster formation scenarios. Our Hubble Space Telescope Wide Field Planetary Camera 2 data yield normal globular cluster colors and hence metallicities for this galaxy. We find a bimodal color distribution with peaks at (V-I)$_0$ = 0.91 ± 0.03 and 1.09 ± 0.03, corresponding to [Fe/H] ~ -1.5 and -0.75 dex (somewhat dependent on the choice of the conversion relation between color and metallicity). We review the evidence for exclusively metal-rich globular cluster systems in other galaxies and briefly discuss the implications for our understanding of globular cluster and galaxy formation.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: star clusters

1. INTRODUCTION

Globular cluster systems are thought to be good tracers of the star formation history of their host galaxies (see recent reviews by Ashman & Zepf 1998, Harris 2000, and Kissler-Patig 2000). A variety of theories exist to explain the presence of distinct globular cluster subpopulations in many galaxies. For example, the bimodal color distributions seen in many bright early-type galaxies can result from spiral-spiral mergers (Ashman & Zepf 1992), in situ multiphase galaxy/globular cluster formation (Forbes, Brodie, & Grillmair 1997; Kissler-Patig, Forbes, & Minniti 1998b), and/or accretion/stripping mechanisms (Côté, Marzke, & West 1998; Hilker, Infante, & Richtler 1999). Implicit in these theories is the presence of an old, metal-poor (halo?) globular cluster population that should exist in essentially all galaxies.

As a class, cD galaxies have “abnormally” high specific frequencies (i.e., the number of globular clusters per unit galaxy light; Harris & van den Bergh 1981), and generally these galaxies have similar (large) numbers of blue and red globular clusters or a preponderance of blue clusters (e.g., Forbes et al. 1997). Their high specific frequencies may have resulted from the augmentation of the low-metallicity component by galaxy accretion or globular cluster stripping. Alternatively, star formation may have been truncated at an early stage; i.e., these galaxies do not have too many globular clusters but rather too few stars (Blakeslee, Tonry, & Metzger 1997; Harris, Harris, & McLaughlin 1998; McLaughlin 1999).

The globular cluster system of NGC 3311 is of particular interest for understanding galaxy and globular cluster formation because it is the next nearest cluster central cD galaxy after M87 in Virgo and NGC 1399 in Fornax and its specific frequency is one of the highest known (Harris, Smith, & Myra 1983; McLaughlin et al. 1995).

In this context, the result of Secker et al. (1995) was surprising. Using Washington (C-T)$_0$, photometry from the Cerro Tololo Inter-American Observatory (CTIO) 4 m telescope, these authors found that NGC 3311, the central cD galaxy in the Hydra Cluster, had an unusually red globular cluster system with a median metallicity of [Fe/H] = -0.31 dex. A third of the clusters were estimated to exceed solar abundance, and the population of clusters near [Fe/H] ~ -1 dex that is normally dominant in the metallicity distribution functions (MDFs) of giant elliptical galaxies (see above reviews) was found to be almost totally absent in NGC 3311. The MDF was found to be bimodal at the 97.6% confidence level in a KMM analysis (Ashman, Bird, & Zepf 1994), with peaks at [Fe/H] = -0.5 and 0.15. These results meant that NGC 3311 was host to the most metal-rich globular cluster system known and required extensive preenrichment of the entire halo before essentially any of the stars or clusters formed. This posed serious problems for all three of the main contending scenarios for the formation of globular cluster systems.

Here we examine the color distribution of the NGC 3311 globular cluster system using new data from the Hubble Space Telescope (HST) Wide Field Planetary Camera 2 (WFPC2) and show that this distribution is in fact quite normal and that the system is not especially rich in metal. A paper examining other properties of the NGC 3311 globular cluster system is in preparation and will include comparisons with a number of other galaxies from our HST database.

2. DATA AND REDUCTION

Our data consist of Cycle 6 WFPC2 observations. The integration times were 3700 and 3800 s in the F555W and F814W filters, respectively, split into four exposures for each filter. The raw exposures were processed by the standard STScI pipeline,
and subsequent reduction and analysis were performed using IRAF. The individual exposures were aligned using the IMSHIFT task and were then combined using IMCOMBINE. Cosmic-ray events were eliminated by setting the REJECT parameter in IMCOMBINE to CRREJECT.

A first set of background-subtracted images was generated by smoothing the original images with a 15 × 15 box median filter and subtracting the smoothed images from the original images. Objects were detected on the background-subtracted images using the task DAOFIND in the DAOPHOT package within IRAF (Stetson 1987) and were then removed from the original images using the ISHAPE algorithm (Larsen 1999). The object-subtracted images were then median-filtered once again and subtracted from the original images, providing our final set of background-subtracted images for further analysis.

A new object-detection process was performed on the combined background-subtracted images in both F555W and F814W. The two object lists were then matched, and aperture photometry was obtained using the PHOT task in DAOPHOT, using an r = 2 pixels aperture. At the distance of NGC 3311 (with a distance modulus of ~33, assuming a pure Hubble flow, \( V_0 \approx 3400 \text{ km s}^{-1} \) [NASA/IPAC Extragalactic Database], and \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \)), one WF camera pixel corresponds to a linear scale of ~19 pc, so globular clusters are unresolved on our HST images. The use of a small aperture to minimize random errors is thus unlikely to introduce any systematic errors due to the extendedness of the objects. We considered only the objects in the WF chips. Since our WFPC2 chips were centered on the nucleus of NGC 3311, we thus avoid the central region of the galaxy out to a radius of ~3.5 kpc. The PC frames contain ~20% of the total number of objects in the four WFPC2 chips. Since we have so many clusters from the WF chips, including the PC objects does not significantly improve the statistics or alter the location of the \( V-I \) peaks. However, PC objects do require different aperture corrections, and they are excluded to avoid any possible resulting systematic errors. Figure 1 shows NGC 3311, the nearby galaxy NGC 3309, and the location of the WF camera chips for this pointing.

The photometry was calibrated to standard \( V \) and \( I \) magnitudes following Holtzman et al. (1995). We calculated the aperture corrections between our \( r = 2 \) and the standard Holtzman et al. \( r = 5 \) pixel apertures by measuring objects brighter than \( V = 25 \) in both apertures. We found a small difference in the F555W and F814W aperture corrections of \( \Delta(V-I)_{2-5} = 0.026 \text{ mag} \). Although the differences between the aperture corrections in the two filters are in good agreement with those found by other authors (Puzia et al. 1999; Whitmore et al. 1997), the aperture corrections themselves are about 0.1 mag larger than the values obtained by Whitmore et al. This is most likely due to the resampling of the point-spread function (PSF) that is done by IMSHIFT when aligning the images. As a check, we also carried out photometry on a combined subset of two images in each filter in which no shifts were required; in this case, we found aperture corrections in very good agreement with those of Whitmore et al. However, we are not going to refer to absolute magnitudes in this Letter but only to colors, and we will use the photometry based on four combined images because of the better noise characteristics and superior cosmic-ray rejection.

We checked our results by performing an ALLSTAR PSF-fitting reduction of the data. There is an insignificant effect on the location of the \( V-I \) peaks (at the level of 0.01 mag, which is well within our estimated uncertainties), and no subsequent conclusions are affected by choosing aperture rather than PSF photometry.

3. REVISED COLORS AND METALLICITIES FOR GLOBULAR CLUSTERS IN NGC 3311

3.1. Colors

The top panel of Figure 2 is the reddening-corrected color-magnitude diagram of all objects in the WF camera chips. An

1 IRAF is distributed by the National Optical Astronomical Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.
extinction correction of $E_{V-I} = 0.13$ (from $E_{B-V} = 0.079$ and $A_v = 0.24$; Schlegel, Finkbeiner, & Davis 1998) has been applied. Note that Seeker et al. (1995) used $E_{B-V} = 0.045$ from Burstein & Heiles (1984), corresponding to $E_{V-I} = 0.072$; i.e., there is a systematic difference of 0.05 mag in $E_{V-I}$ between our colors and the corresponding colors quoted by Seeker et al. Although it is in the right sense, this difference is not nearly sufficient to account for the disagreement.

Global cluster candidates were selected from within the range $0.6 < V-I < 1.4$. There are 1971 candidates with $V < 26$ and 882 with $V < 25$. Using a KMM test, we find peaks at $V-I = 0.91$ and 1.09 for the magnitude interval $22 < V < 25$ (corresponding roughly to $-11 < M_r < -8$); the distribution is bimodal at the 94.4% confidence level. We find peaks at $V-I = 0.87$ and 1.09 for the interval $22 < V < 26$, with bimodality indicated at a confidence level greater than 99.9%. Changing the magnitudes thus yields consistent values for the $V-I$ peaks, and we estimate that the peak colors are accurate to about 0.03 mag. About half of the clusters belong to the blue population and half to the red. The bottom panel of Figure 2 shows a color histogram for the globular clusters down to a magnitude limit of $V = 25$. The two best-fitting Gaussians from the KMM analysis as well as their sum are overplotted.

Dip statistics (Hartigan & Hartigan 1985; Gebhardt & Kissler-Patig 1999) indicate the probability that the distribution is not unimodal. For the magnitude interval $22 < V < 24$, the dip value is 99.1%, for $22 < V < 25$, it is 98.7%, and for $22 < V < 26$, it is 98.1%. The 50% completeness limit for the data is at $\sim 26.5$ mag in $V$, but the observational scatter clearly increases substantially below $V = 25$.

3.2. Metallicities

To convert our $V-I$ colors to metallicities, we use the relations derived by Couture, Harris, & Allwright (1991) and Kissler-Patig et al. (1998a). These relations provide the best calibrations for the low- and high-metallicity ranges, respectively. Using the $V-I$ values for our brighter magnitude interval (i.e., 0.91 and 1.09), the conversion relations yield metallicities of $[\text{Fe/H}] \sim -1.50$ and $-0.59$ dex and $[\text{Fe/H}] \sim -1.52$ and $-0.94$ dex, for the blue and red peaks, respectively. The errors introduced by the internal uncertainties of the conversion relations are around 0.3 dex. Note that if we used the reddening value adopted by Secker et al. (1995), the peak colors would redden to $(V-I) \sim 0.96$ and 1.14, corresponding to metallicity shifts of only $\sim 0.2$ dex. These values that we derive are typical for bright elliptical galaxies (Forbes et al. 1997). In particular, the peaks in M87 are found at $V-I = 0.95$ and 1.20 mag (Kundu et al. 1999), corresponding to $[\text{Fe/H}] \sim -1.4$ and $-0.6$ dex (using the Kissler-Patig et al. 1998a relation). The peaks in NGC 1399 occur at $V-I = 0.99$ and 1.18 (Kissler-Patig et al. 1998a), corresponding to $[\text{Fe/H}] \sim -1.3$ and $-0.6$ dex. If anything, the metal-rich peak in NGC 3311 may have somewhat lower metallicity than the metal-rich peaks in the central cD galaxies of the Virgo and Fornax Clusters.

The data of Seeker et al. (1995) were obtained under nonphotometric conditions. As described in their text, these authors clearly made every attempt to calibrate their frames correctly using conventional and appropriate techniques. However, given that our $HST$ colors agree well with those for other central cD galaxies’ globular cluster systems, it seems likely that the Seeker et al. results suffer from a zero-point error.

4. Discussion

4.1. Do Systems Exist with No Metal-poor Globular Clusters?

Zepf, Ashman, & Geisler (1995) studied the globular clusters in NGC 3923 and reported an exceptionally red color distribution for this galaxy’s luminosity. We note, however, that these observations were made on the same CTIO 4 m telescope, nonphotometric, observing run as NGC 3311 and were calibrated a posteriori with the same data. We suggest that these observations be revisited in light of the differences found for NGC 3311.

In the Coma Cluster, Woodworth & Harris (2000) found, from $HST$ data, that IC 4051 has a high mean globular cluster metallicity ([Fe/H] $\sim -0.3$ dex). The color distribution appears to be unimodal with a narrow dispersion, although Woodworth & Harris were not able to exclude the possibility of a bimodal distribution with two close peaks and a metal-poor population around $[\text{Fe/H}] \sim -1.0$ dex. The specific frequency of IC 4051 is high ($S_\beta = 12 \pm 3$), comparable to those of cluster central cD galaxies, although IC 4051 is neither the central galaxy in this rich galaxy cluster nor is it exceptionally luminous ($M_V = -21.9$).

In their survey of archival $HST$ data, Gebhardt & Kissler-Patig (1999) found evidence for systems dominated by metal-rich globular clusters. However, none of these cases were as extreme as NGC 3311 was previously thought to be. The existence of a blue (metal-poor) population in these galaxies is not excluded by these data (because of small sample statistics), but Gebhardt & Kissler-Patig suggest that it is not likely to be significant, as in IC 4051.

In summary, no system has yet been observed to have a globular cluster color distribution as extremely red as the previous claim for NGC 3311. In particular, no galaxy has yet been convincingly shown to be entirely lacking globular clusters with metallicities below $[\text{Fe/H}] \sim -1.0$ dex.

4.2. Implications for Formation Models of Globular Cluster Systems

NGC 3311 represented the best case of an almost exclusively metal-rich globular cluster population. As such, it raised serious questions about our understanding of globular cluster and galaxy formation since the existence of a metal-poor population is implicit in all the current scenarios.

In the merger picture, an elliptical galaxy is formed from the merger of two gas-rich spiral galaxies. The resultant galaxy contains a blue, metal-poor population of globular clusters from the progenitor spiral galaxies and a metal-rich population formed during the merger. In this scenario, the metal-poor population should peak at the median metallicity of the globular cluster systems of spiral galaxies, i.e., $[\text{Fe/H}] \sim -1.5$ dex. It is generally recognized, though, that mergers are unlikely, by themselves, to result in high specific frequency galaxies, such as NGC 3311 (Ashman & Zepf 1998; Forbes et al. 1997). In the multiphase picture, the blue population is formed in a pregalaxy phase, or during galaxy assembly, from relatively unenriched gas and therefore, by definition, is metal-poor. The red globular cluster population and the bulk of the galaxy stars are formed later from enriched material. In the accretion model, the original elliptical galaxy (formed in a single burst) accretes smaller (lower metallicity) galaxies, with their retinues of low-metallicity globular clusters. Giant galaxies at the centers of rich galaxy clusters may also be expected to strip metal-poor
globular clusters from the outskirts of neighboring galaxies. Because of the globular cluster mean metallicity–parent galaxy luminosity relation (Brodie & Huchra 1991; Forbes et al. 1996), accreted/stripped globulars must be, on average, of lower metallicity than those belonging to the “seed” elliptical. Côté et al. (1998) show how accretion processes and the luminosity function of galaxies will lead to bimodal globular cluster systems in bright galaxies with blue and red peaks at [Fe/H] ~ −1.5 and ~−0.5 dex, as generally observed.

Sketchy arguments can be imagined to accommodate an absence of metal-poor clusters within any of the above formation scenarios. To produce only, or predominantly, metal-rich clusters under the “in situ” scenario would require rapid star formation prior to cluster formation in the same star formation event. In a deep gravitational potential, the metals produced by the stars are retained, and the average metallicity of the system is driven to a high value (see also Woodworth & Harris 2000), conceivably before any clusters are formed. In accretion scenarios, the metal-poor population in the final galaxy would be minimized if small fragments/dwarf galaxies were absent from the galaxy’s environment. Note, though, that such a situation is less likely for a central cD galaxy. Late mergers are expected to provide a significant population of metal-poor globular clusters originating in the progenitor galaxies, but predominantly metal-rich systems could be explained if the progenitors were rich in gas but poor in clusters (see also Gebhardt & Kissler-Patig 1999). Stripping can result in the preferential removal of metal-poor clusters if the metal-poor population is more extended than the metal-rich one. Since stripping will act more efficiently on the more extended population, it could result in systems that are biased toward high metallicities. In this context, it is interesting to note that the halo light of IC 4051 appears truncated beyond ~30 kpc (Jørgensen, Franx, & Kjærgaard 1992).

 Preferentially metal-rich globular cluster systems can be accommodated by adjusting the existing scenarios. An exclusively metal-rich globular cluster population, should one be discovered, would probably be most easily accommodated in a single-collapse model—an in situ galaxy formation scenario with rapid star formation preceding cluster formation.

5. SUMMARY

We have shown that the color distribution of globular clusters in NGC 3311 is normal for bright elliptical galaxies. It is bimodal with peaks at V − I = 0.91 and 1.09, corresponding to metallicity peaks at around [Fe/H] ~ −1.5 and ~−0.75 (the precise values being dependent on the choice of the conversion relation between color and metallicity). This range of metallicities is normal for bright elliptical galaxies, a result that contradicts an earlier claim that NGC 3311 might host an extremely metal-rich globular cluster system.

We suggest that it is worth revisiting the globular cluster system of NGC 3923 whose globular cluster system was reported to be very red on the basis of observations made on the same run that produced the NGC 3311 results. Although the evidence for exclusively metal-rich globular cluster systems has been weakened, there are still cases of galaxies whose globular cluster systems may lack a significant metal-poor component. We have briefly discussed the implications of such systems for our understanding of globular cluster and galaxy formation and have concluded that, with some adjustments, they can be explained under existing scenarios.

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