Direct Evidence for Dynamical Evolution of Luminosity Functions of Globular Cluster Systems: HST/ACS observations of the 3-Gyr-old merger remnant NGC 1316

Paul Goudfrooij

Space Telescope Science Institute, Baltimore, Maryland, USA

Abstract. Recent observations of globular clusters (GCs) in intermediate-age (2–4 Gyr old), early-type merger remnants have provided the hitherto ‘missing link’ between young merger remnants and ‘normal’ elliptical galaxies in the form of a GC subsystem with colors and luminosities consistent with population synthesis model predictions for those ages and ∼ solar metallicity. Here we present new, deep observations of the GC system of the intermediate-age merger remnant NGC 1316, using the ACS camera aboard Hubble Space Telescope, which allowed us to create luminosity functions (LFs) as a function of galactocentric radius. We find that the inner 50% of the ‘red’ GC system shows a clear turnover in its LF, at about 1 mag fainter than that of the ‘old’ blue GCs. This constitutes direct, dynamical evidence that metal-rich GC populations formed during a gas-rich merger can evolve into the ‘red’, metal-rich GC populations that are ubiquitous in ‘normal’ giant ellipticals.

1. Galaxy Mergers and Globular Cluster Formation

Over the last decade, the importance of young massive star clusters as signposts to major star formation events has been recognized. In particular, the discovery of young globular clusters (GCs) in galactic mergers and young merger remnants using Hubble Space Telescope (HST) imaging (e.g., Schweizer 2002 and references therein) has generated a great deal of excitement. This is hardly surprising, as these clusters have provided previously unexpected opportunities including (i) the chance to study the formation and evolution of GCs in the local universe rather than trying to derive how they formed ∼ 14 Gyr ago; (ii) the possibility to age-date merger events (i.e., major star formation epochs) in galaxies from star clusters with simple, single-burst stellar populations.

In many cases, follow-up spectroscopy of these young clusters confirmed their nature as star cluster and their ages, and in one case even their high masses predicted from their colors and luminosities (Maraston et al. 2004). The metallicities of the young clusters have been found to be near solar, as expected for clusters formed out of enriched gas in spiral disks. Such metal-rich clusters are now known in merger remnants at essentially all ages, ranging from birth (e.g., NGC 4038/4039, Whitmore et al. 1999) through youth (several $10^8$ yrs, e.g. NGC 7252, Schweizer & Seitzer 1998) to middle age, when only faint ripples and loops reveal their merger history (e.g. NGC 1316, Goudfrooij et al. 2001a).

It should also be emphasized that the cluster systems of young merger remnants were also found to contain fainter, redder objects with colors and luminosities consistent with those of old, metal-poor halo GCs that are very
common in nearby galaxies such as the Milky Way. It is commonly believed that
these fainter GCs in merger remnants probably belonged to the (now merged)
progenitor spirals. This bimodality in star cluster systems of young merger
remnants is rather interesting in the context of formation scenarios for normal
elliptical galaxies, since the latter are also well known to generally host GC
systems with bimodal color distributions (Kundu & Whitmore 2001; Larsen
et al. 2001 to name a few). Deep HST imaging of ‘normal’ ellipticals shows
that roughly half of their GCs are blue (metal-poor) and half are red (metal-
rich, typically roughly solar or somewhat less). Spectroscopy with 10-m class
telescopes revealed that both ‘blue’ and ‘red’ GC subpopulations of ‘normal’
ellipticals are typically old (≥8 Gyr, Cohen, Blakeslee & Côté 2003; Puzia
et al. 2004). A natural interpretation of these data is that the metal-rich GCs in
‘normal’ ellipticals formed in gas-rich mergers at z ≥ 1, and that the formation
process of galaxies with significant populations of metal-rich GCs was similar to
that in galaxy mergers observed today.

One might think “now don’t get carried away” at this point, and indeed it
is important to examine this scenario in detail. If correct, one should be able
to (i) find ellipticals with second-generation GCs of intermediate age (i.e., 2–5
Gyr) and (ii) study the evolution of second-generation GC systems from young
through intermediate to old ages, and compare their properties with theoretical
predictions. These two issues are addressed in the remainder of this paper.

2. Intermediate-Age Globular Cluster Systems

The existence of intermediate-age GC systems has been argued for several years
already, based on GC colors and luminosities from deep optical photometry of
ellipticals with high fine structure such as ripples and tidal features (e.g., Whit-
tmore et al. 1997). The breakthrough in identifying intermediate-age GCs came
by using methods that break the age-metallicity degeneracy present in optical
colors, namely the use of optical-to-near-IR colors and spectroscopy with large
telescopes. Goudfrooij et al. (2001a,b) used both methods to discover a major
∼3 Gyr old, metal-rich GC population in the merger remnant NGC 1316, dis-
cussed further below. Soon afterward, Puzia et al. (2002) identified a significant
population of intermediate-age GCs in the elliptical galaxy NGC 4365 (featur-
ing a counter-rotating core) using V, I, and K-band photometry. Follow-up
Keck spectroscopy of a subset of the Puzia et al. GCs by Larsen et al. (2003)
confirmed the effectiveness of the optical-to-near-IR technique, which was sub-
sequently used by Hempel et al. (2003) who identified intermediate-age GCs in
NGC 5846 as well. Other investigations using this method are ongoing.

Now that the presence of intermediate-age GC systems has been established,
time has come to test whether or not properties of GC systems formed in mergers
are compatible with those of ‘red’ GCs in old ellipticals. If so, this would render
them a definite evolutionary link between young remnants and ‘normal’ ellipti-
cals with bimodal GC color distributions. One of the most important tracers of
such systematic evolution is the luminosity function (LF) of second-generation
GCs. The LF of ‘old’ GC systems is a Gaussian in magnitude units, with a peak
(‘turnover’) at $M_V = -7.3$ (e.g., Harris 1996), while that of GCLF’s in young
merger remnants is a power law with index $\alpha \sim -2$ (e.g., Whitmore et al. 1999).
Deep Luminosity Function of an Intermediate-Age GC System

The transition from power law to Gaussian LF has been predicted theoretically (Fall & Zhang 2001), being a consequence of preferential erosion of low-mass GCs due to various disruption mechanisms, of which the main ones are internal two-body relaxation and tidal shocking. If indeed the metal-rich GCs in ‘old’ giant ellipticals are evolved GCs formed during a gas-rich merger, this gradual erosion should be evident in observed LFs of second-generation GC systems that form an age sequence. This critical test of the ‘merger hypothesis’ was infeasible until recently, due to the necessity to reach $\sim 2$ mag beyond the turnover magnitude. However, the unprecedented sensitivity of the ACS camera, installed on HST in March 2002, made this possible.

3. Results

We observed NGC 1316 in March 2003 using the wide-field channel of HST/ACS through the F435W, F555W, and F814W filters, with total exposure times of 1860 s, 14560 s, and 4770 s, respectively. The supreme spatial resolution of the new ACS images allowed us to impose stringent size constraints on the list of detected compact objects so as to exclude extended background galaxies as well as foreground stars. Due to space restrictions, I will only show the main result here: *An observational confirmation of the predicted dynamical evolution of the LF of a second-generation, metal-rich GC system.* A paper containing a more detailed presentation and discussion of the results of this study has been submitted to a refereed journal.

The new ACS images allowed us to reach a factor of $\sim 4.5$ fainter in luminosity than with the WFPC2 observations presented in Goudfrooij et al. (2001b; hereafter Paper I), which resulted in a final GC candidate list of 1496 objects - almost four times as many as from the WFPC2 images (!). Metal-poor (blue) GCs were selected using $V - I < 0.95$ (just redward of the reddest halo GC in our Galaxy), whereas metal-rich (red) GCs were selected using $V - I > 1.05$. Correction for contamination by compact background galaxies was done in a statistical way, using WFPC2 F555W and F814W images that were taken in parallel with the ACS data. After this correction, the LFs of the blue and red subpopulations were produced: See panels (a) and (b) of Fig. 1. The blue GC system shows a Gaussian LF consistent with that of the GC system of ‘normal’, old ellipticals, as expected and as found by Paper I. The LF of the red GC system as a whole exhibits a power-law behavior with slope $\alpha \sim 1.7$ (as was found in Paper I using the earlier WFPC2 data). Although there is an indication of flattening out beyond $M_V \sim -5.8$, this does not seem to constitute strong evidence for the expected disruption of the low-mass end of the second-generation GCs. However, the effect of cluster disruption processes should show up first in the central regions of galaxies since the disruption timescale of GCs scales with galactocentric distance (e.g., Vesperini & Heggie 1997; Fall & Zhang 2001). With the huge number of detected GC candidates in the ACS data, we are now in a position to produce GC LFs in different radial intervals with adequate statistical significance. And indeed, as panels (c) and (d) of Fig. 1 show, the LF of the outer 50% of the red GCs reveals a power-law down to its 50% completeness limit, whereas the LF of the inner 50% of the red GCs does shows a turnover at $M_V \sim 6$, i.e. $\sim 1$ mag fainter than the turnover of ‘old’ GC systems.
Figure 1. $V$-band LFs of GC candidates from the ACS data. Panel (a): LF of the full ‘blue’ subpopulation. Panel (b): LF of the full ‘red’ subpopulation. Panel (c): LF of the outer 50% of the ‘red’ subpopulation. Panel (d): LF of the inner 50% of the ‘red’ subpopulation. The histograms are filled for magnitude bins brighter than the weighted mean 50% completeness limit (this limit depends strongly on the background level), and open beyond it. The smooth curve in panel (b) is a power-law fit to the LF. The dotted vertical lines represent the predicted turnover magnitude for ‘old’ GC systems.

Acknowledgments. It is a pleasure to thank the workshop organizers for a great workshop that brought together researchers from a variety of fields related to star cluster research. I thank my collaborators on this project: Diane Karakla, François Schweizer, and Brad Whitmore. Support for HST Proposal number GO-9409 was provided by NASA through a grant from the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5–26555.

References

Cohen, J. G., Blakeslee, J. P., & Côté, P., 2003, ApJ, 592, 866
Fall, S. M., & Zhang, Q., 2001, ApJ, 561, 751
Goudfrooij, P., Mack, J., Kissler-Patig, M., et al., 2001, MNRAS, 322, 643
Goudfrooij, P., Alonso, M. V., Maraston, C., & Minniti, D., 2001, MNRAS, 328, 237
Hempel, M., Hilker, M., Kissler-Patig, M., et al., 2003, A&A, 405, 487
Kundu, A., & Whitmore, B. C., 2001, AJ, 121, 1888
Larsen, S. S., Brodie, J. P., Huchra, J. P., et al., 2001, AJ, 121, 2974
Maraston, C., Bastian, N., Saggia, R. P., et al., 2004, A&A, 416, 467
Puzia, T. H., Zepf, S. E., Kissler-Patig, M., et al., 2002, A&A, 391, 453
Puzia, T. H., Kissler-Patig, M., Thomas, D., et al., 2004, A&A, 415, 123
Schweizer, F., 2002, in: “Extragalactic Star Clusters”, eds. D. Geisler, E. K. Grebel, & D. Minniti (ASP: San Francisco), 630
Schweizer, F., & Seitzer, P., 1998, AJ, 116, 2299
Vesperini, E., & Heggie, D. C., 1997, MNRAS, 289, 898
Whitmore, B. C., Zhang, Q., Leitherer, C., et al., 1999, AJ, 118, 1551