Space-Based UV/Optical Wide-Field Imaging and Spectroscopy: Near-Field Cosmology and Galaxy Evolution Using Globular Clusters in Nearby Galaxies

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Abstract

Star formation plays a central role in the evolution of galaxies and of the Universe as a whole. Studies of star-forming regions in the local universe have shown that star formation typically occurs in a clustered fashion. Building a coherent picture of how star clusters form and evolve is therefore critical to our overall understanding of the star formation process. Most clusters disrupt after they form, thus contributing to the field star population. However, the most massive and dense clusters remain bound and survive for a Hubble time. These globular clusters provide unique observational probes of the formation history of their host galaxies. In particular, the age and metallicity can be determined for each globular cluster individually, allowing the *distribution* of ages and metallicities within host galaxies to be constrained.

We show how space-based UV-to-Near-IR imaging covering a wide field of view ($\gtrsim 20'$ per axis) and deep UV/Optical multi-object spectroscopy of globular cluster systems in nearby galaxies would allow one to place important new constraints on the formation history of early-type galaxies and their structural subcomponents (e.g., bulge, halo).

1 Globular Clusters as Fossil Records of the Formation History of Galaxies

Infrared studies of star formation within molecular clouds have shown that stars typically form in clusters or associations with initial masses $\mathcal{M}_{\rm cl,\,0}$ in the range $10^2 - 10^8\ M_\odot$ (e.g., Lada & Lada 2003; Portegies Zwart et al. 2010). While most star clusters with $\mathcal{M}_{\rm cl,\,0} \lesssim 10^4\ M_\odot$ are thought to disrupt and disperse into the field population of galaxies within a few Gyr, the surviving massive GCs constitute luminous compact sources that can be observed out to distances of several tens of megaparsecs. Furthermore, star clusters represent the best known approximations of a "simple stellar population", i.e., a coeval population of stars with a single metallicity[1], whereas the field stars in galaxies typically constitute a mixture of populations. Thus, studies of globular cluster systems can constrain the *distribution* of stellar ages and metallicities whereas measurements of the integrated light of galaxies can only provide luminosity-weighted averages of these key quantities. Consequently, globular clusters represent invaluable probes of the star formation rate and chemical enrichment occurring during the main star formation epochs within their host galaxy's assembly history (see, e.g., reviews of Ashman & Zepf 1998; Brodie & Strader 2006).

The study of extragalactic globular clusters was revolutionized by the Hubble Space Telescope (HST). The main reason for this is that the size of globular clusters is well-matched to diffraction-limited optical imaging with a 2-m class telescope: a typical globular cluster half-light radius of ~ 3 pc at a distance of 15 Mpc corresponds to $\sim 0\farcs05$ on the sky, which is roughly the diffraction limit (and detector pixel size) in the V band for HST. This yields very high quality photometry of globular clusters relative to ground-based optical imaging by beating down the high galaxy surface brightness in the central regions of galaxies. Furthermore, it also allows robust measurements of globular cluster radii, and hence of their dynamical status.

Notwithstanding the important progress that HST imaging has facilitated in this field, there is one critical property of globular cluster systems that HST imaging *cannot* address well. Globular cluster systems around massive early-type galaxies extend far into the galaxy halos, covering several tens of arcminutes on the sky (e.g., Goudfrooij et al. 2001; Rhode & Zepf 2001, 2004; Zepf 2005), while HST images only cover the central $\sim 3\farcm3 \times 3\farcm3$. This is illustrated in Figure 1. Obviously, *wide fields of view* ($\gtrsim 20'$ per axis) are required to accurately determine total properties of globular cluster systems (e.g., total numbers of clusters per unit galaxy luminosity, color or metallicity distributions, trends with galactocentric distance). Furthermore, the faint outer halos of galaxies are thought to hold unique clues regarding the early assembly history of galaxies, and bright globular clusters constitute one of the very few probes that can be studied in these environments. In the following we highlight a few key science questions in this growing field for which new space-based UV/Optical instrumentation can be expected to yield major steps forward in our understanding of the formation and evolution of galaxies.

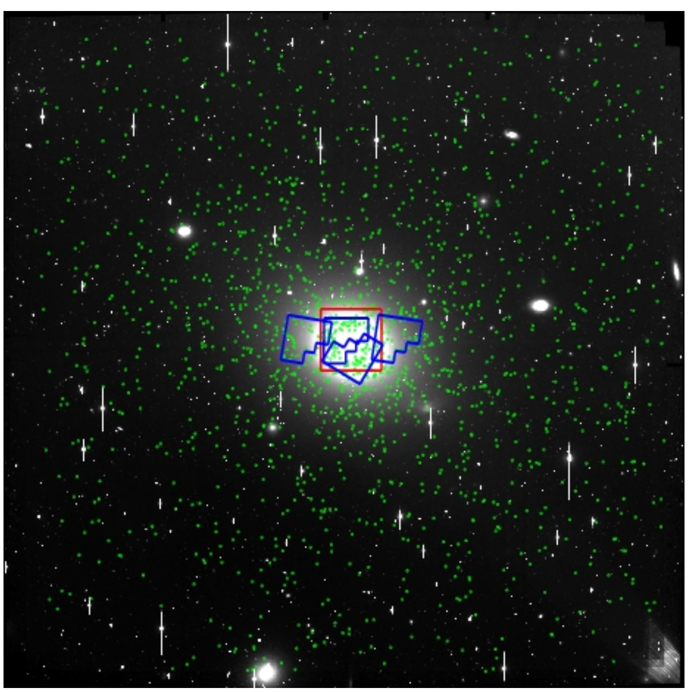

Figure 1. R-band KPNO 4-m/MOSAIC image of the giant elliptical galaxy NGC 4472 in the Virgo cluster of galaxies, covering a $36' \times 36'$ field of view. Footprints of available HST/ACS and HST/WFPC2 images are drawn in red and blue, respectively. Globular cluster candidates from Rhode & Zepf (2001) are indicated as green dots. Note the small fraction of globular cluster candidates covered by HST images, implying the need for large and uncertain extrapolations when trying to extend conclusions from the HST studies to the full systems of globular clusters. Figure taken from Zepf (2005).

[1]Massive star clusters in the Milky Way host secondary populations with varying relative light-element abundances (e.g., Gratton et al. 2012). However, the effect of these variations to optical and near-IR colors is negligible (Sbordone et al. 2011).

2 New Constraints on the History of Star Formation and Chemical Enrichment of Early-Type Galaxies

A key discovery of HST studies of globular cluster systems of luminous galaxies was that their optical color distributions are typically bimodal (e.g., Whitmore et al. 1995; Kundu & Whitmore 2001; Larsen et al. 2001; Peng et al. 2006). Figure 2 shows an example. Follow-up spectroscopy of bright globular clusters using 10-m-class telescopes has indicated that both "blue" and "red" populations are typically old (age $\gtrsim$ 8 Gyr), implying that the color bimodality is mainly due to differences in metallicity (e.g., Cohen et al. 2003; Puzia et al. 2005). In broad terms, the metal-rich globular cluster population features colors, metallicities, radial distributions, and kinematics that are similar to those of the spheroidal ("bulge") component of early-type galaxies. In contrast, the metal-poor globular cluster population has a much more radially extended distribution, and is likely physically associated with metal-poor stellar halos such as those found around nearby galaxies (e.g., Bassino et al. 2006; Goudfrooij et al. 2007; Peng et al. 2008).

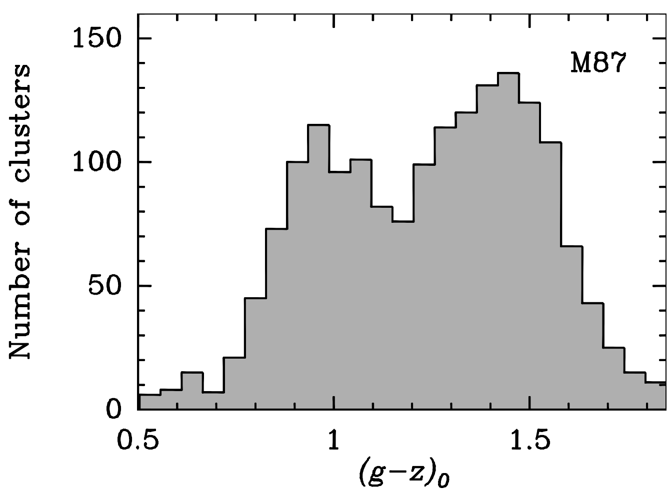

Figure 2. $g-z$ color distribution of globular clusters in the massive elliptical galaxy M87 from Peng et al. (2006). Note the obvious color bimodality, which has been confirmed to be mainly due to differences in metallicity, and which is common among massive early-type galaxies in the local universe.

The bimodality in optical colors of globular clusters constitutes one of the clearest signs that star formation in luminous early-type galaxies must have been episodic. However, we emphasize that the optical color distributions do not significantly constrain *when* these events occurred, or in what order. This is because optical colors alone cannot generally distinguish between different combinations of age and metallicity (the "age-metallicity degeneracy"). A general understanding of the age and metallicity distributions of globular cluster systems requires braking this degeneracy. There are two primary and complementary ways to do this, described below:

1. **The addition of near-infrared photometry to optical data**. The main power of this method (using color-color diagrams) is the ability to identify age differences (of order $\gtrsim$ 25% for high-quality data), due to the fact that near-IR colors are primarily sensitive to metallicity while optical colors are sensitive to both age and metallicity. This approach resulted in the identification of substantial populations of intermediate-age metal-rich globular clusters in several early-type galaxies (Goudfrooij et al. 2001; Puzia et al. 2002; Hempel et al. 2007; Georgiev et al. 2012). The current limitation of this method is twofold. While HST has a powerful near-IR channel in its WFC3 instrument, its use is limited to the *innermost regions* of nearby galaxies due to its relatively small footprint of $\sim 2' \times 2'$ (cf. Figure 1 above). The NIRCam instrument to be installed on the 6.5-m James Webb Space Telescope (JWST) will reach 2 mag fainter than HST in a given integration time, but its footprint is similarly small. Conversely, while near-IR imaging instruments with reasonably large fields of view are starting to become available on large ground-based telescopes (e.g., $7\farcm5 \times 7\farcm5$ for HAWK-I on

the VLT), contamination of globular cluster candidate samples by compact background galaxies is a major concern for ground-based spatial resolution (see, e.g., Rhode & Zepf 2001). As demonstrated by HST, imaging at $\sim 0\farcs1$ resolution effectively eliminates this concern due to the marginally resolved nature of globular clusters (cf. Section 1). Thus, the study of galaxy formation and evolution by means of accurate globular cluster photometry will benefit tremendously from space-based wide-field UV/Optical imaging. A relatively simple multi-chip UV/optical camera installed on one of the two 2.4-m telescopes recently donated to NASA by the National Reconnaissance Office would be ideal for this (and many other) purpose(s). Their fast (f/1.2) primary mirror could easily yield a useful field of view of hundreds of square arcminutes per exposure at a resolution of $\sim 0\farcs1$, providing accurate photometry of virtually *all* globular clusters associated with nearby galaxies with very little contamination. Along with a relatively standard suite of broad-band and narrow-band filters from the near-UV through the near-IR, such an instrument would place important constraints on the formation and assembly history of massive early-type galaxies, particularly in their outer regions for which there currently are few other constraints.

2. **Optical multi-object spectroscopy with large telescopes**. The main strength of this technique lies in the presence of intrinsically strong absorption lines of several key elements in the optical region, which facilitates accurate determinations of overall metallicities and element abundance ratios that can be used to infer typical timescales of star formation (e.g., Puzia et al. 2005, 2006). However, this technique is currently only available from the ground and is therefore significantly hampered by the high surface brightness of the diffuse light of the inner regions of the host galaxies. In practice, this limits the application of this technique currently to mainly the *outer regions* of galaxies. This has caused a general lack of crucial spectroscopic information for the metal-rich globular clusters, which are located mainly in the inner regions. While future developments in the area of adaptive optics systems on large telescopes will enable high spatial resolution imaging and spectroscopy from the ground, they will do so only over a small ($\lesssim 1'$) field of view which is not useful for spectroscopy of extragalactic star clusters. This science would however advance dramatically with a 8-m class UV/Optical space-based telescope (such as the concepts proposed for ATLAST) equipped with a multi-object spectrograph with field of view of several arcmin per axis. Note that radial velocities resulting from such globular cluster spectra will also provide important kinematical probes in the outskirts of galaxies (where the diffuse light is too faint to give useful information).

3 From Star Clusters to the Field Star Population in Galaxies

Star clusters begin disrupting (losing mass) as soon as they are formed. Understanding how they do so as a function of cluster mass, time, and environment is key to many questions in the study of star clusters and their relation to galaxies. A main observable in this context is the star cluster mass function. HST studies have shown that among young cluster systems in star-forming galaxies, the mass function is well approximated by a power law ($\psi(M) \propto M^{\alpha}$ with $\alpha \simeq -2$, see, e.g., Fall et al. 2009 and references therein). On the other hand, cluster mass functions in ancient galaxies such as giant early-type galaxies and our Galaxy show a log-normal shape (e.g., Jordán et al. 2007). This stark difference (illustrated in Figure 3) is most likely due to dynamical evolution of the star cluster system. It is however not yet clear how this important process happens in detail, and the recent literature contains many different theoretical models and observational conclusions regarding this transition. Being able to distinguish between the various ideas will have relevant implications as to how, and to what extent, the field star population in galaxies is built up over time from disrupting star clusters.

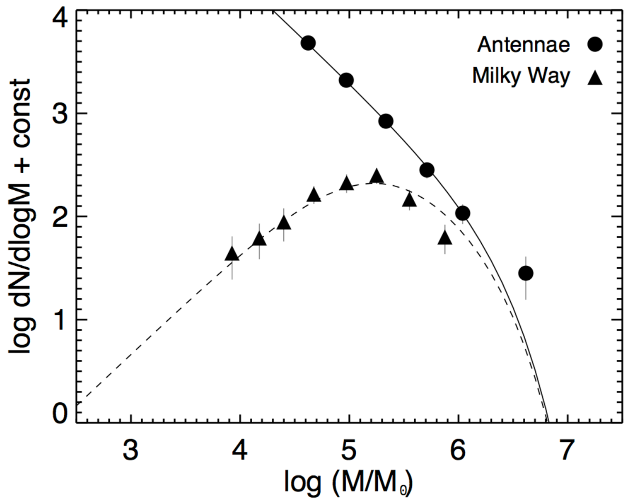

Figure 3. A comparison of the mass function of the young star cluster system of the Antennae galaxies (Fall et al. 2009) with that of the globular cluster mass function in the Milky Way. The stark difference between these mass functions illustrates the important effect of dynamical evolution of star clusters over time.

As to the early stages of the cluster disruption process, the number of clusters per unit log(age) in several star-forming galaxies appears to decline starting at very young ages, suggesting that many clusters dissolve easily (e.g., Whitmore et al. 2007; Fall & Chandar 2012). It is however not yet clear which mechanism is most responsible for this rapid dissolution. Longer-term mass loss of star clusters over a Hubble time is likely responsible for the very different shapes observed for young and ancient star cluster systems (cf. above). However, the disruption processes must also account for the observation that the mass function of old globular clusters appears to be similar among virtually all galaxies. Several different scenarios have been proposed to explain this observation, each advocating different disruption mechanisms that act on different time scales (e.g., Vesperini & Zepf 2003; Parmentier et al. 2008; McLaughlin & Fall 2008; Gieles et al. 2011).

It is likely that the variety of proposed explanations for the difference between mass functions of young and old star cluster systems is caused in large part by the small footprint of HST images on the sky. In the central few kpc of massive galaxies covered by HST images, the strong tidal field imposes a relatively small range of mass densities on globular clusters in order for them to survive tidal shocks for several Gyr (see, e.g., Gnedin 1997; Goudfrooij 2012). This means that the current distribution of globular cluster sizes and mass densities (derived from HST data) has no memory of the physical conditions occurring when the clusters were formed, or even when they may have been accreted from dwarf galaxies (if they were). This situation is quite different in the outer regions of galaxies, where the tidal limit imposed by the galaxy potential on star cluster sizes is much larger and observed star cluster sizes *do* constrain the conditions occurring when the star clusters were formed or accreted (e.g., Madrid et al. 2012). However, we simply do not have adequate size information for star clusters in the outer regions of massive galaxies at this time, and HST is not a suitable facility in this context.

The determination of accurate ages for globular clusters at different distances from the galaxy centers using space-based wide-field optical and near-IR photometry and optical multi-object spectroscopy (cf. Section 2 above) will also yield important information to sort out the relevance of various cluster disruption mechanisms (e.g., Goudfrooij 2012).

In summary, accurate, deep cluster mass functions and size information for the *full spatial extent of star cluster systems* will be key to our understanding of dynamical evolution of star clusters and the nature of the field star component in massive galaxies. Similar to the aforementioned study of the star formation history of galaxies using globular cluster photometry (cf. Section 2), this study requires wide-field optical imaging with spatial resolution of order 0.″1 for which one of the 2.4-m space telescopes donated to NASA by the National Reconnaissance Office would be a very well-suited platform.

4 Concluding Remarks

The increasing realization that the study of star clusters has direct relevance for the basic processes involved in how galaxies assemble and evolve over time has placed this field at the forefront of extragalactic research in recent years. We have described two fundamental questions that are of central importance in star cluster research, and identified two types of future UV/Optical space telescope facilities that would enable significant breakthroughs in these areas, providing important new constraints for galaxy formation, assembly, and evolution. These two types of facilities are:

1. A wide-field (of order $20' \times 20'$), multi-detector imaging camera on a moderate-size space telescope with small focal ratio. One of the two f/1.2, 2.4-m space telescopes recently donated to NASA by the National Reconnaissance Office would be very well-suited to host such an instrument.
2. A 8-m class space telescope that includes a multi-object spectrograph that supports observations of $\gtrsim 100$ targets per exposure, covering a field of view of several arcmin per axis. The concepts proposed for ATLAST seem compatible with these requirements.

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