Observational Properties of Extragalactic Globular Cluster Systems

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Abstract. The superior resolution of HST and the light gathering power of large 8-10m class telescopes are now providing information on distant globular clusters (GCs) that is comparable to that obtained in early 1990s for Local Group systems. Here I summarise what has been learnt from the imaging and limited spectroscopy of GCs in other galaxies. The GC systems of spirals and ellipticals reveal remarkable similarities. The vast bulk of GCs appear to have formed at early epochs, with mergers making a limited contribution to the overall GC system at later epochs. These observational findings are placed in the context of galaxy formation.

1. Introduction

Much has been learnt about the formation and evolution of our Milky Way Galaxy from the system of globular clusters (GCs). It is natural to extend such studies to the GC systems of other galaxies. There are several advantages in doing this:

- Greater numbers, e.g. the MW has only 150 known GCs, M31 has a total population of $\sim 400$ and M87 $\sim 10,000$.
- Probing to higher metallicity GCs.
- The Local Group has no giant ellipticals.
- No foreground stars in the GC spectra.
- Discover something new!

For Local Group studies ($D \sim 1$ Mpc), 3-6m telescopes have collected optical and IR colours, and measured sizes for large numbers of GCs. Spectra also exist in large numbers for $V \sim 16$ GCs, giving metallicities, abundances, relative ages and system kinematics. Classic papers for Local Group GCs are those of Brodie & Huchra in 1990s (e.g. Brodie & Huchra 1990, 1991) More recently the 0.1” resolution of HST has provided CMD morphologies for several Local Group GCs (see various posters at this conference).

Further afield (e.g. Virgo/Fornax distance of 15 Mpc) 8-10m telescopes are starting to obtain similar information for more distant GC systems. Optical colours have now been measured for $\sim 50$ systems. IR colours are lagging behind but quickly catching up (see posters by Puzia and Hempel). At 15 Mpc, GCs are partially resolved by HST allowing sizes to be measured (e.g. Larsen et al. 2001). Typical mags of $V \sim 22$ have made obtaining high quality spectra (for ages,
abundances etc) and large numbers for system kinematics slow going. Only a handful of systems have good quality spectra for individual GCs (the vast majority coming from the SAGES project.) A database of imaging and spectral information for extragalactic GCs can be found at: astronomy.swin.edu.au/dforbes

2. Bulge GCs in Spirals

In our Galaxy, the inner metal-rich GCs are now thought to be associated with the bulge rather than the disk (Minniti 1995). Recently Forbes et al. (2001) extended this view to other spiral galaxies. In particular, they showed that the mean metallicity, velocity dispersion, rotation velocity and spatial distribution of the inner metal-rich GCs in M31 and M81 supported a bulge origin. HST imaging of the GCs in the Sombrero galaxy (M104) revealed a large number of metal-rich GCs (Larsen, Forbes & Brodie 2001). It seems highly unlikely that they are associated with the tiny disk but instead with the dominant bulge. A comparison of the number of metal-rich GCs with the bulge luminosity (called ‘bulge’ specific frequency) in the MW, M31 and M104 suggests a near constant value of 1.0. This can be compared to the specific frequency of red (metal-rich) GCs in field ellipticals which is 0.5–1.5 (assuming that the elliptical is simply a large bulge). Thus the ‘bulge specific frequency’ for spirals and ellipticals are similar.

3. The Local Group Elliptical

Some, perhaps all, large ellipticals are thought to have formed via the merger of spirals. It is thus interesting to ‘merge’ together the GC systems of the Local Group galaxies to simulate a dissipationless (ie no new GCs are formed) merger. This merger is of course dominated by M31 (Sb) and MW (Sbc). Forbes et al. (2000) carried out this exercise and found the total GC system of the LG elliptical to be 700 ± 125. The total luminosity was estimated to be $M_V = -22.0$, giving $S_N = 1.1$. After correcting for the presence of young stellar populations this value rises to $S_N \sim 2$, so still a relatively low $S_N$ elliptical. The GC luminosity function revealed a peak at the universal value (ie $M_V \sim -7.5$) and the metallicity distribution was bimodal with peaks $[\text{Fe/H}] \sim -1.5$ and $-0.5$. The ratio was $2.5:1$ for metal-poor to metal-rich. Any models of merging spirals should take into account not only the pre-existing metal-poor GCs but also the metal-rich ones (which could be a significant fraction in the case of early-type spiral progenitors).

4. Overview of GC imaging

- Metallicity distributions. All galaxies, irrespective of Hubble type, appear to have a population of metal-poor ($[\text{Fe/H}] \sim -1.5$) GCs. Galaxies with bulges have a metal-rich ($[\text{Fe/H}] \sim -0.5$) population also. Some particular exceptions may exist (eg Woodworth & Harris 2000).
- Metallicity-mass relation. The mean metallicity of the metal-poor GCs is almost constant at $[\text{Fe/H}] \sim -1.5$, whereas the mean value for the metal-rich ones
varies with host galaxy mass (i.e., luminosity or velocity dispersion). This suggests that the metal-poor ones formed slightly pre-galactic while the metal-rich ones know about the potential that formed they in (Forbes & Forte 2001).

- Size trend. Metal-poor GCs are, on average, 20\% larger than metal-rich ones irrespective of Hubble type (Larsen et al. 2001). This effect may be due to conditions at formation or subsequent dynamical evolution due to different orbits.
- Spatial distribution. In general, the metal-rich GCs in ellipticals are centrally concentrated and appear to follow the ‘bulge/spheroid’ light. Whereas the metal-poor GCs are more extended and are associated with the halo.

5. Overview of GC Spectroscopy

- Metallicities. Spectra have confirmed the bimodality seen in optical colours and the metallicity range of less than one hundredth solar to twice solar.
- Ages. Relative ages, from Lick indices, are now available for a number of GCs in ellipticals. These suggest that most GCs are old ($\sim 12$ Gyrs) although there is tentative evidence that the red GCs may be a few Gyrs younger than the blue ones. There are also cases now of some intermediate (Puzia et al. 2002; Larsen et al. 2002) and young age GCs in otherwise ‘old’ ellipticals (Forbes et al. 2001). It is not yet clear how significant this younger subpopulation is compared to the total. One caveat is the possible presence of blue horizontal branches which may affect the age determinations based on the $H\beta$ line (Lee et al. 2000).
- Abundances. To date most GCs in ellipticals are consistent with supersolar abundances, i.e., $[\text{Mg/Fe}] \sim +0.3$ (although Maraston et al. 2001 found solar ratios for GCs in the ongoing merger NGC 7252). This indicates the dominance of SN II over SN Ia in their formation, which is probably due to a short time scale for star formation. Further abundance studies will reveal important chemical evolution clues.

Currently all high quality spectra (i.e., $H\beta$ errors of $< \pm 0.3\AA$) of GCs beyond the Local Group come from the Keck telescope. These include:

- NGC 1399 Forbes et al. (2001)
- M81 Schroder et al. (2002)
- M104 Larsen et al. (2002)
- NGC 524 Beasley et al. (2003)
- NGC 4365 Larsen et al. (2002)

In the near future, spectra from the VLT and Gemini telescopes will add to this list.

An example of three GCs in NGC 1399 observed by Keck + LRIS is shown in Fig. 1. Here the exposure time was 3.5 hours and the typical $H\beta$ error was $\pm 0.2-0.4\AA$. For NGC 1399 we found (Forbes et al. 2001) that the GCs covered the full metallicity range, i.e., $-2.2 < [\text{Fe/H}] < 0.3$, and that most of the blue and red GCs were old ($\sim 12$ Gyrs). However we also found two young ($\sim 2$ Gyrs) GCs. All of the GCs were consistent with having supersolar $[\text{Mg/Fe}]$ abundance ratios.

GC system kinematics have only been measured for a small number of elliptical galaxies (e.g., Kissler-Patig & Gebhardt 1988; Zepf et al. 2000), and each
Figure 1. Examples of Keck spectra for globular clusters in NGC 1399. These spectra represent 3.5 hours of Keck/LRIS time, and have H$\beta$ errors of $\sim 0.25$ Å (about $\pm 4$ Gyrs in age).

system appears to have slightly different kinematic trends. So it is difficult to draw general conclusions. This situation should change rapidly with new spectrographs coming online which have hundreds of slits (eg DEIMOS, GMOS, VIMOS). As well as constraining galaxy formation models, it will be interesting to compare mass estimates from GCs (which require assumptions about orbits) with those from X-ray measurements (which requires the assumption of hydrostatic equilibrium).

6. The Formation and Evolution of GCs

Three scenarios had been proposed to understand the observations of extragalactic GC systems in the context of galaxy formation. They are late stage mergers (Ashman & Zepf 1992), two-phase collapse at early epochs (Forbes, Brodie & Grillmair 1997) and accretion (Cote, Marzke & West 1998). Galaxy formation itself is often interpreted using a semi-analytic code (eg Cole et al. 2000) within a ΛCDM universe. Recently we simulated the formation of GCs around ellipticals using the GALFORM semi-analytic code (eg Cole et al. 2000) in such a universe for the first time. This model involves elements of mergers, collapse and accretion.
Figure 2. Specific frequency vs ratio of blue to red globular clusters. The small open circles represent the model galaxies from GALFORM, the filled circles with error bars are observed galaxies for which the imaging covers a wide area (so this excludes most HST studies), and the solid line shows the spiral-spiral merger simulations of Bekki et al. (2002) for various impact parameters. As suggested by the merger simulations, the expectation is that high $S_N$ galaxies will have low blue-to-red ratios. This is contrary to the general trend seen in the data and in the GALFORM model galaxies.
Details of this work can be found in Beasley et al. (2002). Briefly, GCs are formed in two modes of star formation. In the first, or ‘quiescent’ mode, metal-poor GCs form in proto-galactic clouds. These gaseous clouds collapse/merge, giving rise to a burst of star formation. During this ‘burst’ mode, the vast bulk of the galaxy stars form along with the metal-rich GCs. The final GC system depends on the local galaxy environment and its mass (luminosity). For example, low luminosity field ellipticals tend to have a more extended star formation history which is more bursty in nature. We would expect such galaxies to reveal metal-rich GCs that are 3-5 Gyrs younger in the mean than the metal-poor ones which are \( \sim 12 \) Gyrs old in all ellipticals. More high quality spectra with 8-10m class telescopes should be able to test this prediction.

We had to make two key assumptions in order to produce bimodal GC colour distributions. The first was to fix the efficiency of forming GCs vs field stars (this was chosen to match observations of M49). The second was to stop the formation of metal-poor GCs at redshift \( z = 5 \). There was no physical basis for this, but such a redshift may be associated with the epoch of reionisation (see Cen 2001). The model ellipticals have GC systems that can reproduce the diversity seen in HST studies (eg Larsen et al. 2001) and the relation between number of GCs and galaxy luminosity (ie typical \( S_N = 5 \)).

In Fig. 2 we plot \( S_N \) (number of GCs per unit galaxy starlight) vs the ratio of blue (metal-poor) to red (metal-rich) GCs. We compare the model predictions of 450 ellipticals with galaxies for which wide field imaging data is available. We also show the range of parameters for the major merger model of Bekki et al. (2002). The GALFORM model and the data both show a weak trend for the higher \( S_N \) galaxies to have relatively more blue GCs, ie it is the number of blue GCs that drives \( S_N \). Examination of the evolution of \( S_N \) with time in individual galaxies also indicates that most of the change in \( S_N \) occurs at early epochs and late stage mergers have only a minor effect on \( S_N \) (see Fig. 3).

On the other hand, major mergers would require a different trend. To form a high \( S_N \) system via mergers one needs many red GCs. The major merger predictions of Bekki et al. (2002) are clearly at odds with the data, suggesting that such mergers are not the dominant process in creating high \( S_N \) galaxies. Indeed observations of young (few Gyr old) ellipticals suggest \( S_N \) values close to 2–3 (after correction for the M/L ratio of the younger stellar populations).

### 7. Summary and Predictions

The observations of extragalactic GC systems indicate that:

- The inner metal-rich GCs in the Milky Way and other spirals has a bulge (not disk) origin.
- The GC systems of spirals and ellipticals show remarkable similarities.
- Blue and red GCs have similar ages \( \sim 12 \) Gyrs (but red GCs could be younger by 2–4 Gyrs).
- Some young (\( \sim 2-8 \) Gyrs) GCs have been found in ‘old’ ellipticals.
- Blue and red GCs appear to have supersolar alpha ratios.
- Red GCs trace elliptical galaxy star formation.
Figure 3. Evolution of galaxy luminosity and globular cluster specific frequency $S_N$ with look back time for two different galaxy models from GALFORM. The dotted line shows the evolution of $S_N$ for the red clusters, the dashed line for blue clusters, and the solid line for the total cluster system. The lower luminosity galaxy undergoes a merger at $\sim 5$ Gyr ago, which causes only a small increase in the overall $S_N$.

The modelling of GC formation in a $\Lambda$CDM universe indicates that:

- Blue GCs formed $\sim 12$ Gyrs ago in all ellipticals.
- Red GCs have a mean age of 8–10 Gyrs in field ellipticals.
- $S_N$ is driven by the number of blue GCs in a galaxy and is largely determined at early epochs; late stage mergers have little effect on $S_N$.
- In general, spirals and ellipticals have similar GC systems.

Areas of research that we will no doubt hear more about in the near future are:

- 8m wide field K band imaging studies (eg Puzia et al. 2002).
- Age structure within the red GCs (Beasley et al. 2002).
- Nature of the large ($R_{eff} \sim 10$ pc) red low luminosity ($M_V \sim -6$) clusters (Brodie this meeting).
- Importance of shredded dwarf galaxies (eg Bekki et al. 2001).
- HST+ACS CMDs for Local Group GCs (eg Rich this meeting).
- Halo mass estimates, GC kinematics vs Xrays (eg Kissler-Patig et al. 1998).
- Continued improvements in SSP grids (eg Maraston this meeting).
8. References

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