Galactic Archaeology: Near-Field Cosmology and the Formation of the Milky Way
ASP Conference Series, Vol. 458
W. Aoki, M. Ishigaki, T. Suda, T. Tsujimoto, N. Arimoto, eds.

Galactic Archaeology Using Star Clusters in Nearby Galaxies

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Abstract. Star clusters are an excellent tool for archaeology of nearby galaxies. Recently the paradigm for star clusters is changing from simplicity to variety. With the advent of the Hubble Space Telescope and wide field imagers in large telescopes new types of star clusters and cluster-like objects have been discovered in the nearby universe. These objects must include significant clues for understanding the formation of their host galaxies and galaxy groups. However, their nature and origin is still too intriguing to explain. I review the current status of our understanding of globular clusters in nearby galaxies in terms of galactic archaeology. There are cumulating evidence that every galaxy has a different star formation history, although some of them look similar in their morphology. Galaxies are formed via several mechanisms rather than any single one.

1. Prologue: Archaeology and Astronomy

In 1907 Harlow Shapley, the pioneer in galaxy archaelogy, entered Missouri University, majoring in journalism. He opened the curriculum book to choose courses to take. "The first course was a-r-c-h-a-e-o-l-g-y. I couldn't pronounce it. The second course was a-s-t-r-o-n-m-y. I could pronounce it – and here I am." (in 'Through rugged ways to the stars' by Shapley 1969).

Here we get together to discuss galaxy archaeology in astronomy. While archaelogy traces the history of humans using ancient fossils or clues, galactic archaeology reveals the history of galaxies using astronomical clues. Star clusters are an excellent archaeological tool, because they are mostly made of simple populations allowing us to measure their age and metallicity.

I present an overview of recent findings on early history of galaxies based on the study of globular clusters in the nearby universe. These will be critical clues to answer big questions such as the formation of globular clusters and dwarf galaxies, the formation of halos, bulges, bars, and disks in disk galaxies, and the formation of giant elliptical galaxies.

2. Globular Clusters in the Milky Way Galaxy

There are about 160 globular clusters in the Milky Way Galaxy (MWG) (Harris 1996). They serve as the reference objects for understanding the nature of globular clusters in other galaxies. The MW globular clusters can be divided into three groups: the bulge/thick disk group, the inner halo group, and the outer halo group. Fig. 1 displays their age, [Fe/H], and half-light radii (r_h) versus galactocentric distance (R_{GC}). Reliable ages based on the main-sequence fitting are available for many of these (Marín-Franch et al. 2009; Carretta et al. 2010; Dotter et al. 2011). Most globular clusters are older than 10 Gyrs with a scatter of about 1 Gyr, and only a few at 10 kpc $< R_{GC} <$ 20 kpc (Pal 1, Pal 12, and Ter 7) are 7 to 9 Gyrs old, much younger than the others. Their mean age is slightly decreasing from 13 Gyr to 11 Gyr as R_{GC} increases from 1 kpc to 20 kpc and outward. Most globular clusters are located at $R_{GC} <$ 40 kpc, but several are found far out at 70 kpc $< R_{GC} <$ 130 kpc. These outer globular clusters are metal-poor and have large half-light radii. Their metallicity shows a large spread at $R_{GC} <$ 30 kpc. The mean values of the metallicity show an anti-correlation with R_{GC} at $R_{GC} <$ 30 kpc, while they shows no correlation in the outer area. The metallicity distribution is bimodal: the metal-rich component in the bulge/thick disk, and the metal-poor component in the halo. The mean size of the globular clusters increases as R_{GC} increases. The globular clusters in the bulge group ($R_{GC}8 <$ 8 kpc) shows a strong age-[Fe/H] relation, while those in the halo ($R_{GC}8 <$ 8 kpc) shows a much weaker relation (Dotter et al. 2011). The globular clusters in the outer areas are considered to have an accretion-origin. So the globular clusters in the MWG were formed mostly within a short period of time, but not simultaneously, in the early days. The oldest globular clusters are located in the inner region of the MWG.

3. Globular Clusters in Nearby Disk Galaxies

Recent wide field surveys found four extended globular clusters in the remote halos of NGC 6822 (Hwang et al. 2011). These clusters are probably old and metal-poor. Interestingly all they are located along the major axis of the NGC 6822 halo which is almost perpendicular to the disk. IC 10 is a famous starburst galaxy in the Local Group. The existence of young clusters in its main body has been known for long. Lim & Lee (2012, this conference) found a dozen of compact star clusters in the remote halo of this galaxy. Some of these clusters may be old and metal-poor. Similarly these old and metal-poor clusters were found in another famous starburst galaxy M82 in the M81 group (Lim et al. 2012, in preparation).

M31 has about 650 globular clusters (Lee et al. (2008), Lee et al. (2012, in preparation)). Ages and [Fe/H] for many of these were derived from the Lick line indices in comparison with the simple stellar population models. The kinematics of the M31 GCs in Fig. 2 show that both the metal-poor and metal-rich globular clusters show significant rotation and that the latter rotates faster than the former. So the halo of M31 is rotating, in contrast to the little rotating halo of the MWG. It is also noted that several globular clusters are not following the rotation, indicating that they have an external origin.

The age distribution of M31 globular clusters in Fig. 3 shows a strong peak at about 12 Gyr, similar to the case of the MW globular clusters. However it shows also a long tail in the young age range, which is not seen in the MWG. Both metal-poor and metal-rich globular clusters show a similar distribution. The metallicity distribution of the M31 globular clusters in Fig. 3 shows a broad distribution, while the MW globular clusters show a bimodal metallicity distribution. Younger globular clusters ($<$ 10 Gyr) have higher metallicity. These show that the globular clusters in M31 were formed in a much more extended period than the MW globular clusters.

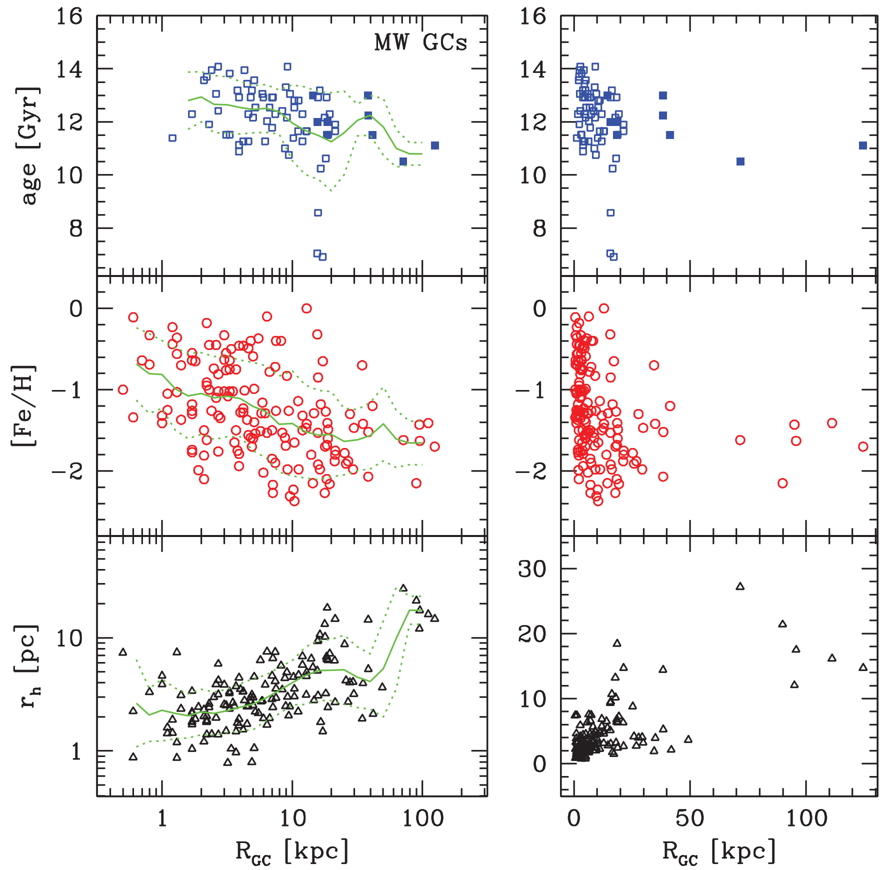

Figure 1. Age, [Fe/H], and half-light radii (r_h) versus galactocentric distance (R_{GC}) in logarithmic (left panels) and linear (right panels) scales for MW globular clusters. Solid lines and dotted lines represent the mean values and 1σ, respectively.

4. Globular Clusters in Giant Elliptical Galaxies

Giant elliptical galaxies (gEs) are rich in globular clusters. It has been known long that the globular clusters in gEs show a bimodal color distritribution, invoking several interesting scenarios to explain it. However the ages and metallicities of these globular clusters are relatively less known because of the difficulty in obtainging their spectra. Recently the data for age and [Fe/H] for globular clusters in several gEs in the literature were compiled by Park et al. (2012, ApJ, submitted), as shown in Fig. 4. The age distribution of metal-poor GCs in the combined sample shows a strong peak at about 12 Gyr and a weaker tail to the younger age. In contrast the metal-rich globular clusters show no old peak, but a much broader distribution. The metallicity distribution is clearly bimodal. Younger globular clusters (< 10 Gyr) shows a stronger metal-rich component, while older globular clusters (> 10 Gyr) shows a stronger metal-poor components. These show that globular clusters in gEs were formed in a much more extended period compared with the MWG globular clusters, and that the metal-rich ones were formed together with the stars, later than the metal-poor ones.

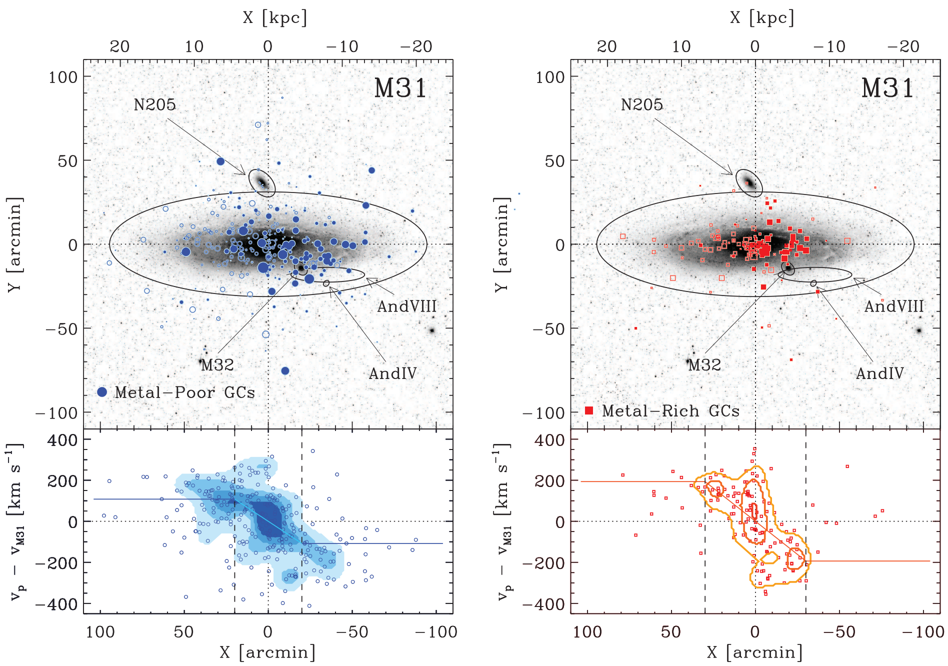

Figure 2. Spatial distribution (upper panel) and radial velocity versus major axis of M31 (lower panel) for metal-poor (left) and metal-rich (right) globular clusters in M31. Contours in the lower panel represent the number density.

5. Wandering Globular Clusters

Globular clusters are found not only in galaxies but also between galaxies in the M81 Group (Jang et al. 2012, in preparation), Virgo cluster (Lee et al. 2010a), Coma cluster (Peng et al. 2011), and Abell 1185 (West et al. 2011). Most of the intragroup/ intracluster or wandering globular clus are probably old and metal-poor, indicating that their origin may be dwarf galaxies (Lee et al. 2010a).

6. Summary

Major recent findings are summarized as below. The Milky Way Galaxy is not typical, but unique in that its globular clusters are mostly very old and it lacks of young massive globular clusters. Starburst galaxies have not only young star clusters but also old globular clusters in their halo showing that they are also old. The kinematics of the metal-poor globular clusters in M31 show that the M31 halo is rotating. The globular clusters in gEs show a bimodal metallicity distribution and a broad age distribution. Intracluster globular clusters are mostly blue indicating that they are metal-poor. These observational clues for globular clusters are consistent with the mixture model (the bibimbap model) (Lee et al. 2010b). Every galaxy has a different evolution history, although they sometimes look similar in their morphology.

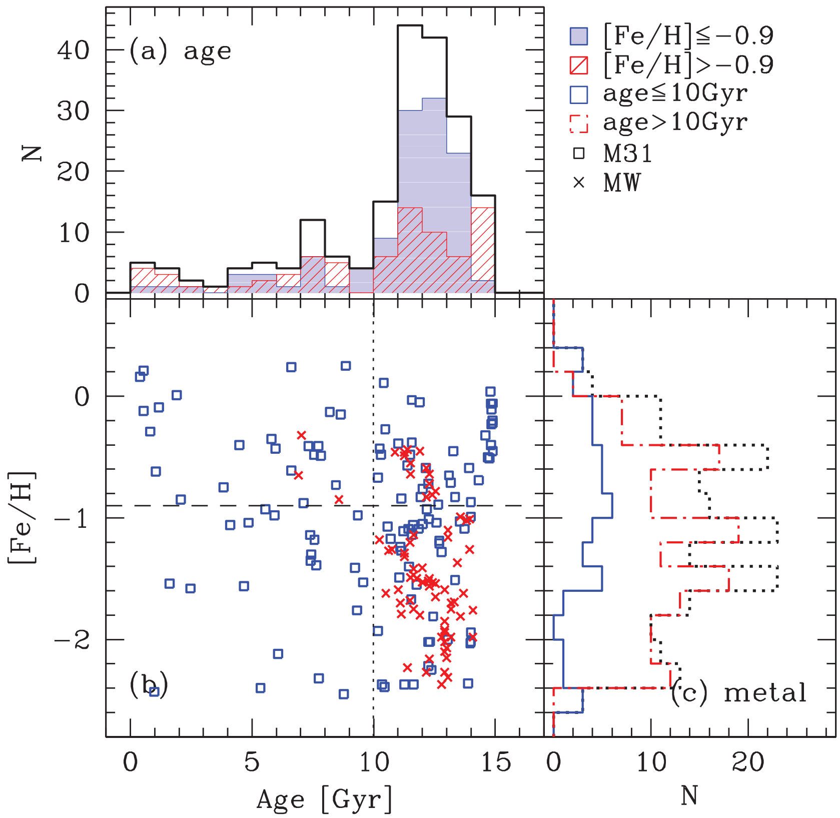

Figure 3. Age-[Fe/H] relation for globular clusters in M31. (a) Age distribution for metal-poor (filled histogram), metal-rich (hatched histogram), and all GCs (empty histogram) in M31. (b) Age-[Fe/H] relation for the globular clusters in M31 (open squares) and the MWG (crosses). (c) [Fe/H] distribution for young (solid line), old (dot-dashed line), and all GCs (dotted line).

Discussion

Ferguson: Could you comment on how you are finding globular clusters in the M81 Group since these objects must be almost unresolved from the ground?

Lee: Its hard to find them with the images taken with the ground-based telescopes. We used the HST images in the archive to find them.

Cohen: Two papers on globular clusters are about to be submitted: a) Jay Strader is leading a study of M87 globular clusters with about 750 spectroscopic velocities, and b) Janet Coluccis study of high dispersion spectra of about 20 globular clusters, including abundances of about 15 elements.

Lee: Thats wonderful.

Hensler: Super star clusters (SSCs) are formed in mergers's central peaks. They are supposed to develop to globular clusters. Do you see a possibility that SSCs are also formed in the tidal tails of mergers?

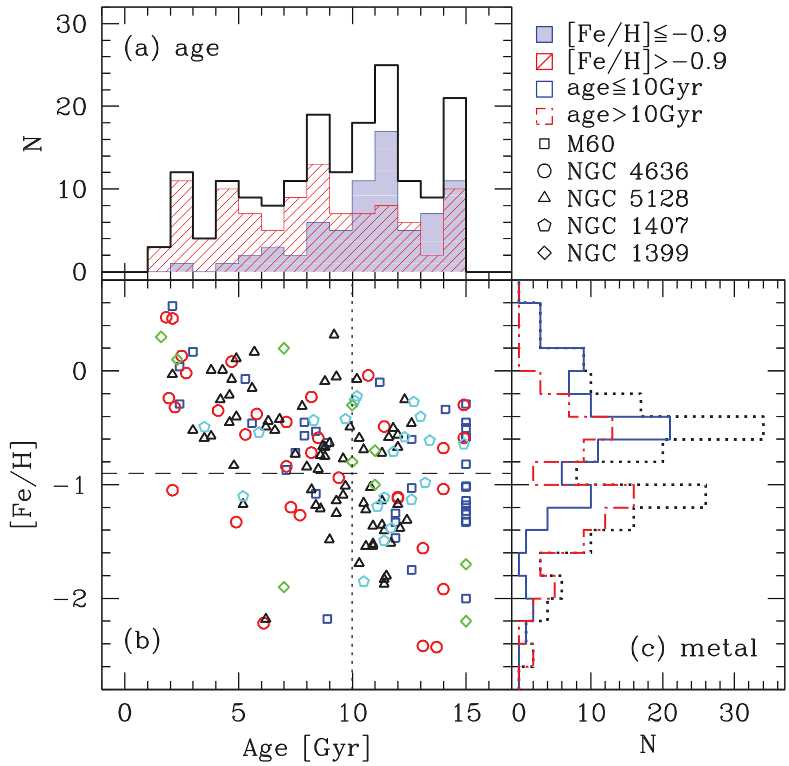

Figure 4. Age-[Fe/H] relation for globular clusters in gEs a) Age distribution for metal-poor (filled histogram), metal-rich (hatched histogram), and all GCs (empty histogram). (b) Age-[Fe/H] relation for globular clusters in gEs. (c) [Fe/H] distribution for young (solid line), old (dot-dashed line), and all GCs (dotted line) in gEs.

Lee: We do not have mergers with tidal tails in the sample of our study. However, I think that SSCs will evolve to globular clusters when they get old.

Acknowledgments. The author is grateful to his collaborators including Hong Soo Park, Sungsoon Lim, Insung Jang, Ho Seong Hwang, Narae Hwang, and Nobuo Arimoto. This was supported in part by Mid-career Research Program through the NRF grant funded by the MEST (no.2010-0013875).

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