Star clusters: basic galactic building blocks
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A new era for the globular cluster system in M31

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Abstract. The globular cluster system in M31 is an ideal laboratory for studying the formation and evolution of M31 as well as the globular clusters themselves. There have been numerous surveys and studies of the globular clusters in M31. However, only recently has the entire body of M31 been searched for globular clusters using wide-field CCD images by our group. A new era for the M31 globular cluster system has begun with the advent of wide-field CCD surveys of M31. We have discovered more than 100 new globular clusters in M31. Our catalog currently includes more than 500 globular clusters confirmed either based on spectra or *HST* images, many more than in the Milky Way. We present the structure, kinematics and chemical abundance of the M31 globular cluster system based on this large sample, and the implications for the formation and evolution of M31.

Keywords. galaxies: spiral, Local Group, galaxies: stellar content, galaxies: evolution, galaxies: star clusters

1. Introduction

M31, the great spiral galaxy in Andromeda, has long been considered a twin of our Galaxy. Since Hubble's seminal work in 1932 (Hubble 1932), numerous surveys of globular clusters in M31 have appeared (see Galleti *et al.* 2006; and references therein). Some examples of extensive studies of M31 globular clusters based on these surveys include Barmby *et al.* (2000), Perrett *et al.* (2002) and Puzia *et al.* (2005). Yet, these surveys were based on photographs or small-field CCD images, and many globular clusters in M31 remain to be discovered.

We recently finished a wide-field survey covering a $3^\circ \times 3^\circ$ field centered on M31, using CCD images obtained at the *KPNO 0.9m* and spectra taken with the Hydra multi-fiber spectrograph at the *WIYN 3.5m* telescope. We found 113 new globular clusters, 258 probable globulars, and confirmed the nature of 383 globular clusters known from previous studies (Kim *et al.* 2007). At present, the total number of known globular clusters in M31 is greater than 500. Combining our results with those from the literature, we produced a master catalog of ~500 globular clusters with velocity data, and ~400 globulars with spectroscopically measured metallicities (Lee *et al.* 2008; Lee *et al.*, in prep.). This is the first survey of the entire M31 system based on CCD imaging, opening up a new era for the study of M31 globular clusters. Our survey was followed by several new surveys (e.g., Huxor *et al.* 2008; Caldwell *et al.* 2009; Alves–Brito *et al.* 2009).

2. Kinematics and metallicity of the M31 globular cluster system

Figure 1 shows a map of the globular clusters in M31, and rotation curves for the entire sample, the disk sample (located closer than 1 kpc from the major axis) and the halo sample (located farther than 5 kpc from the major axis). The disk sample follows the galaxy's rotation very well. Surprisingly, the halo sample shows weak but measurable rotation, while it has a much larger velocity dispersion.

The existence of a halo in M31 has long been controversial. From analysis of the kinematic data we showed that there is indeed a dynamically hot halo in M31 that is rotating but primarily pressure supported. We derived a dynamical mass of $(5.5 \pm 0.4) \times 10^{11}$ $M_{\odot}$ out to a radius of 55 kpc, and $(1.9 \pm 0.1) \times 10^{12}$ $M_{\odot}$ out to 100 kpc, using the projector and tracer mass estimators, respectively.

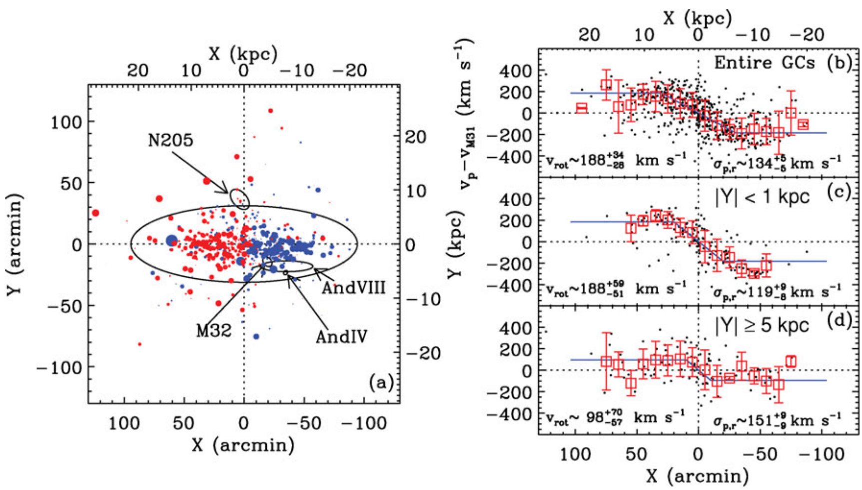

Figure 1. *(a)* Map of the globular clusters in M31. The symbol size is proportional to the velocity deviation. *(b)* Relative velocity with respect to the M31 center versus X, representing distance along M31's major axis for the entire globular cluster system. *(c)* Same as *(b)* but for the globular clusters located closer than 1 kpc from the major axis. Y represents the distance from the major axis. *(d)* Same as *(b)* but for the globular clusters in the halo of M31 located farther than 5 kpc from the major axis. Squares represent the mean values, and the solid lines represent the reference rotation curve (Lee *et al.* 2008).

In addition, we have identified 50 'friendless' globular clusters that are distinct from neighbors in space and kinematics, as shown in Figure 2. These probably have a different origin from the other globular clusters.

Figure 3 displays spatial distributions and rotation curves for the metal-rich and metal-poor globular clusters in M31. It is found that not only the metal-rich but also the metal-poor globular clusters show strong rotation in the inner region, and that the metal-rich globular clusters in the central region exhibit a large velocity dispersion, indicating that they belong to the galactic bulge. The rotation curve for the metal-poor globular clusters

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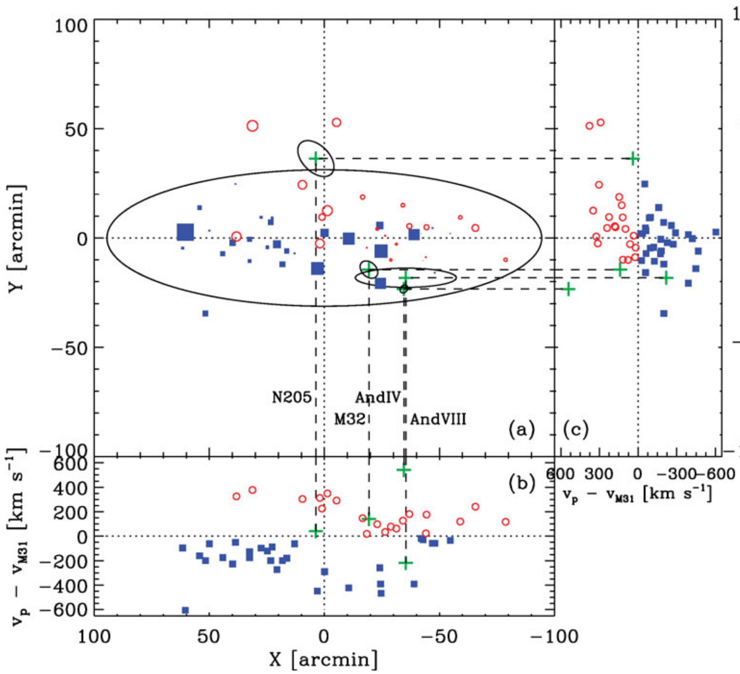

Figure 2. *(a)* Spatial distribution of friendless globular clusters in M31. The symbol size is proportional to the velocity deviation. Radial velocities versus projected radii along the *(b)* major and *(c)* minor axis. Filled squares and open circles represent the approaching and receding 'friendless' globular clusters, respectively. The large ellipse represents the optical extent of M31, i.e., R_{25} (Lee *et al.* 2008).

shows an asymmetric feature at $X < -30'$, with a maximum velocity much greater than the expected value from the opposite side.

We derived metallicities and ages for the globular clusters from the line indices measured in the Hydra spectra, using both the Brodie & Huchra (1990) method and the Lick-index grid method following Puzia *et al.* (2005). Figure 4 displays Lick line indices for hydrogen Balmer lines (Hβ, Hγ and Hδ) versus [MgFe]$'$ and $\langle$Fe$\rangle$ versus Mg_2, compared with the simple stellar population models for various values of [Z/H] and age given by Thomas *et al.* (2004). Balmer lines are sensitive to age and [MgFe]$'$ is sensitive to metallicity. We also plotted the data for M31 and Galactic globular clusters from the literature (see for details, Lee *et al.*, in prep.). Most of the M31 globular clusters are very old, although some are much younger. Old globular clusters show a wide range in metallicity. Most have $[\alpha/\mathrm{Fe}] \approx 0.2$ dex.

Figure 5 displays the metallicity distribution of the entire sample, the bulge, thin-disk, thick-disk and halo samples. The metallicity distribution of the entire M31 globular cluster system can be fit by two or three Gaussian components. The M31 globular cluster system shows an excess of intermediate-metallicity globular clusters with $-1.5 < [\mathrm{Fe/H}] < -1.0$ dex, compared with the Galactic globular clusters. Most of the bulge sample are metal-rich, while most of the halo sample are metal-poor. The intermediate-metallicity component is distinguishable only in the thin- and thick-disk samples, and it has no counterpart in our Galaxy.

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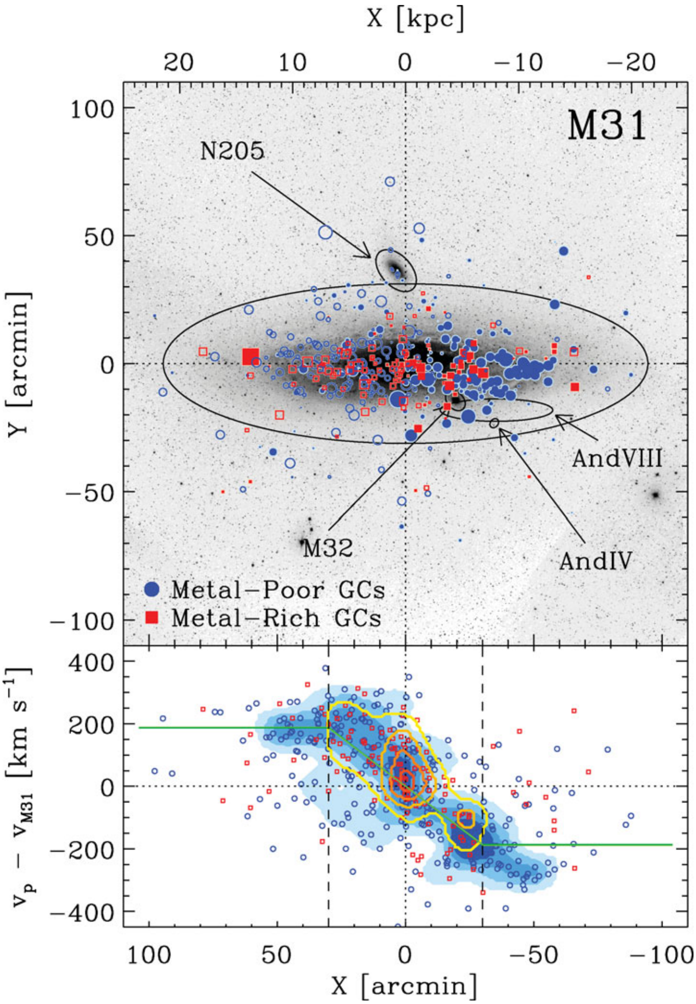

Figure 3. *(top)* Spatial distribution of the metal-rich (squares) and metal-poor (circles) globular clusters in M31. Open and closed symbols represent globular clusters receding and approaching with respect to M31, respectively. Their size represents relative velocity. *(bottom)* Radial velocity with respect to the center of M31 versus projected distance along the major axis for the metal-poor (pseudo-color map) and metal-rich globular clusters (contours).

3. Formation and evolution of M31

Our findings for the structure, kinematics and metallicity of the M31 globular cluster system provide very useful clues to understanding the formation and evolution of M31. The existence of a rotating, metal-rich central bulge, the radial metallicity gradient and the extended, smooth, metal-poor halo in M31 can be explained by the rapid dissipative collapse of a protogalactic cloud. On the other hand, the extended bulge, substructure and friendless globular clusters are evidence of accretion and merging of small-scale filaments. This is also consistent with the recent finding that the distribution of red giants in the outer parts of M31 is remarkably extended with complicated structures, and may even be connected to M33 (McConnachie *et al.* 2009).

The structure of the metal-poor halo and extended bulge in M31 is similar to the double-halo structure recently found in our Galaxy, consisting of an outer and inner halo

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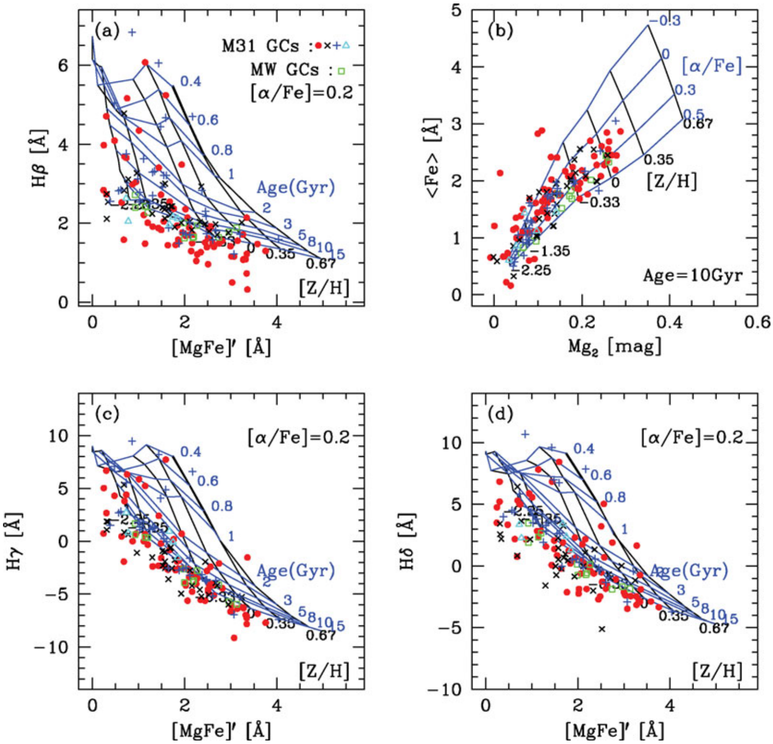

Figure 4. Lick line indices for hydrogen Balmer lines (Hβ, Hγ and Hδ) versus [MgFe]$'$ *(a, c* and *d)*, and $\langle$Fe$\rangle$ versus Mg_2 *(b)* for M31 globular clusters measured in this study (circles) and from the literature (crosses: Puzia *et al.* 2005; pluses: Beasley *et al.* 2004; triangles: Trager *et al.* 1998). Open squares represent Galactic globular clusters. Grids represent the simple stellar population models for various values of [Z/H] and age (Gyr) given by Thomas *et al.* (2004).

(Carollo *et al.* 2007). This double-halo structure was also found from the spectroscopic study of red giants in M31 (Koch *et al.* 2008). However, the uniqueness of the M31 halo globular system is that it is rotating faster than the Galactic halo, although it is mainly pressure supported. The presence of a metal-poor halo in M31 rotating faster than that of our Galaxy is a mystery. It indicates that the galaxy probably suffered a major merger in the past.

Therefore, it is concluded that the formation of M31 is likely linked to three processes, including (i) a rapid monolithic collapse in the early phase, (ii) a major merger in the middle phase and (iii) sporadic accretion and minor mergers throughout its entire evolution.

Acknowledgements

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References

Alves–Brito, A., Forbes, D. A., Mendel, J. T., Hau, G. K. T., & Murphy, M. T. 2009, *MNRAS* (Letters), 395, L34

Barmby, P., Huchra, J. P., Brodie, J. P., Forbes, D. A., Schroder, L. L., & Grillmair, C. J. 2000, *AJ*, 119, 727

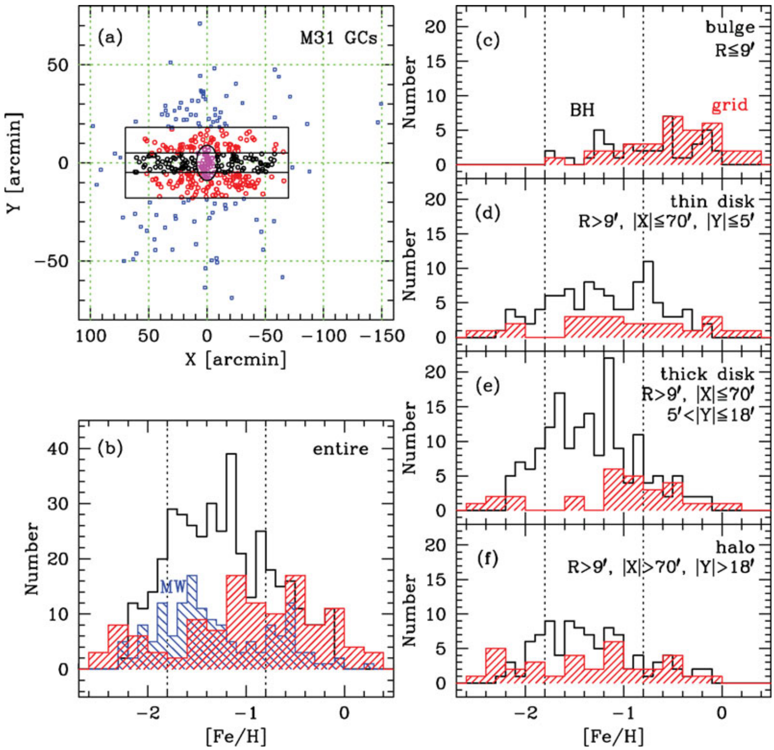

Figure 5. Metallicity distribution of M31 globular clusters. *(a)* Map of the globular clusters. Lines represent the boundaries for each sample of the bulge, thin disk, thick disk and halo in M31. *(b), (c), (d), (e) and (f)* represent the metallicity distribution of the entire sample, the bulge, thin-disk, thick-disk and halo samples, respectively. Empty and hatched histograms represent data derived using the Brodie & Huchra (1990) method and the Lick-index grid method, respectively. In *(b)*, Galactic globular clusters are shown as the hatched histogram labeled 'MW.'

Brodie, J. P. & Huchra, J. P. 1990, *ApJ*, 362, 503

Beasly, Brodie, J. P., Strader, J., Forbes, D. A., Proctor, R. N., Barmby, P., & Huchra, J. P. 2004, *AJ*, 128, 1623

Caldwell, N., Harding, P., Morrison, H., Rose, J. A., Schiavon, R., & Kriessler, J. 2009, *AJ*, 137, 94

Carollo, D., *et al.* 2007, *Nature*, 450, 1020

Galleti, S., Federici, L., Bellazzini, M., Buzzoni, A., & Fusi Pecci, F. 2006, *A&A*, 456, 985

Hubble, E. 1932, *ApJ*, 76, 44

Huxor, A. P., Tanvir, N. R., Ferguson, A. M. N., Irwin, M. J., Ibata, R., Bridges, T., & Lewis, G. F. 2008, *MNRAS*, 385, 1989

Kim, S. C., Lee, M. G., Geisler, D., Sarajedini, A., Park, H. S., Hwang, H. S., Harris, W. E., Seguel, J. C., & von Hippel, T. 2007, *AJ*, 134, 706

Koch, A., *et al.* 2008, *ApJ*, 689, 958

Lee, M. G., Hwang, H. S., Kim, S. C., Park, H. S., Geisler, D., Sarajedini, A., & Harris, W. E. 2008, *ApJ*, 674, 886

McConnachie, A. W., *et al.* 2009, *Nature*, 461, 66

Perrett, K. M., Bridges, T. J., Hanes, D. A., Irwin, M. J., Brodie, J. P., Carter, D., Huchra, J. P., & Watson, F. G. 2002, *AJ*, 123, 2490

Puzia, T., Perrett, K. M., & Bridge, T. J. 2005, *A&A*, 434, 909

Thomas, D., Maraston, C., & Korn, A. 2004, *MNRAS* (Letters), 351, L19

Trager, S. C., Worthey, G., Faber, S. M., Burstein, D., & Gonzalez, J. J. 1998, *ApJS*, 116, 1