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Formation of M31 revealed from globular clusters

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Abstract. M31 is an ideal archetype for massive spiral galaxies in the local universe. From recent results on the structure and kinematics of the globular systems in M31 based on the largest sample of globular clusters we suggest a new view of the halo structure of M31: M31 has dual halos, metal-poor one and metal-rich one. This is consistent with the case of massive early-type galaxies. Then we propose that the M31 halo formed in dual mode: formation of metal-poor halo and formation of metal-rich halo.

Key words. galaxies: formation — galaxies: halos — galaxies: star clusters

1. Introduction

How massive spiral galaxies formed is a fundamental question on understanding galaxy formation. M31 is an ideal archetype of massive spiral galaxies to investigate this problem because of its proximity. Recent very wide field surveys of M31 found remarkable features on the large scale structure: giant streams, elongated and clumpy distribution of red giants, and vast thin disk of satellites (McConnachie et al. 2009; Ibata et al. 2013). In addition, M31 contains three times more globular clusters than the Milky Way Galaxy, although it is as massive as the Milky Way Galaxy. However, the structure of the M31 halo has been intriguing and controversial and several terms have been used to describe the structure of outer regions: a giant bulge, a halo, and an extended disk (Lee et al. 2008; Mould 2013). Globular clusters are an excellent tool to investigate structure and kinematics of various components in disk galaxies: disk, bulge and halo. We used recent results on the structure and kinematics of the globular systems in M31 to study how M31 formed.

2. The catalog of the globular clusters in M31

We used a master catalog of 612 globular clusters with velocity and age information in M31, compiled from various sources in the literature (Lee et al. 2008; Galleti et al. 2009; Caldwell et al. 2009, 2011; Lee et al. 2014). This is the largest sample for M31 ever used. It contains 156 young globular clusters with ages younger than 3 Gyr, and 456 old globular clusters with ages older than 3 Gyr. We divided the old cluster sample into two groups according to their metallicity: ∼290 metal-poor clusters ($[Fe/H] < -0.9$) and ∼130 metal-rich ($[Fe/H] \geq -0.9$) clusters. Here we used only old clusters for analysis.

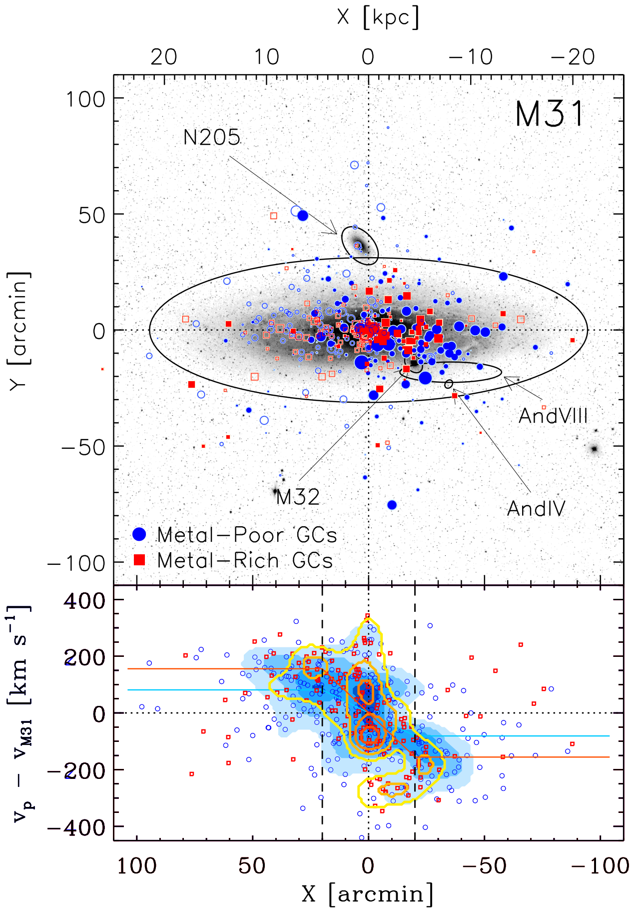

Fig. 1. (Upper panel) Spatial distributions of the metal-poor (blue circles) and metal-rich (red circles) old globular clusters in M31. (Lower panel) Radial velocity with respect to the M31 center versus distance along the major axis(X) of the metal-poor (blue circles) and metal-rich (red circles) old globular clusters. The blue color map and yellow contour map represent the number density of the metal-poor and metal-rich globular clusters, respectively.

3. Structure and kinematics of the globular cluster systems in M31

Figure 1 displays spatial distributions of the metal-poor and metal-rich old globular clusters in M31, and their radial velocity with respect to the M31 center versus the distance along the major axis (X). Several features on the structure and kinematics of the globular cluster systems are noted. First, while the metal-poor clusters are spread over a wide circular area with a recognizable central concentration, the metal-rich globular clusters show a distribution elongated along the major axis with a stronger and narrower central concentration. The latter corresponds to the bulge. Second, the metal-rich globular clusters show fast rotation and those in the bulge region show large

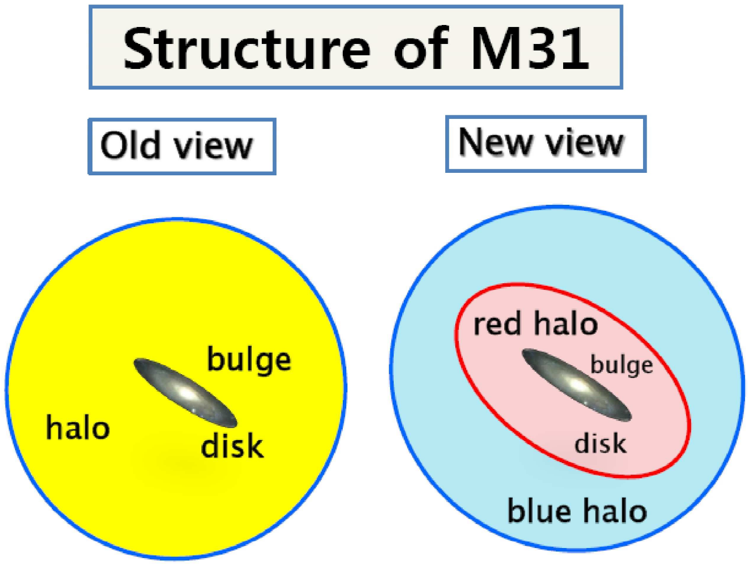

Fig. 2. A schematic picture of the structure of M31 in the old view (left panel) and new view based on the properties of the globular cluster systems derived in this study (right panel). Here blue and red halos represent, respectively, metal-poor and metal-rich halos.

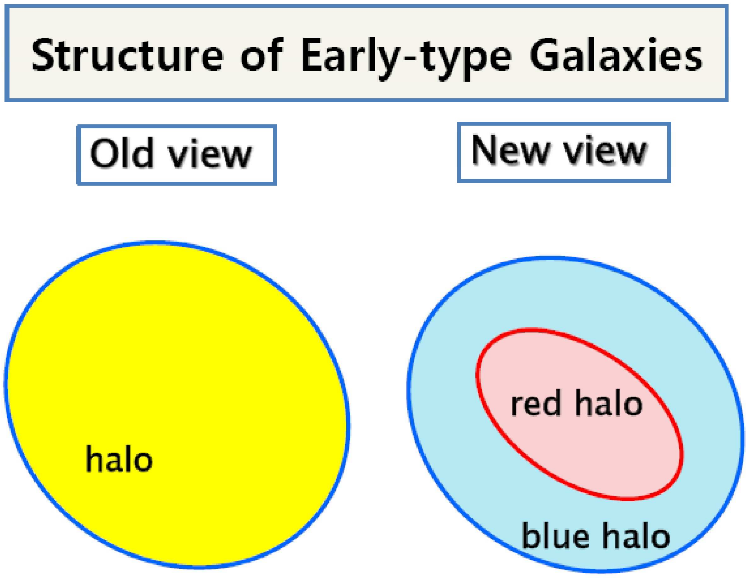

Fig. 3. A schematic picture of the structure of early-type galaxies in the old view (left panel) and new view derived from the study of globular cluster systems in massive early-type galaxies of the Virgo cluster by Park & Lee (2013) (right panel). Here blue and red halos represent, respectively, metal-poor and metal-rich halos.

velocity dispersion. The velocity dispersion of the metal-rich globular clusters is significantly larger than the value for the thin disk derived from the young globular clusters. Third, the metal-poor globular clusters also show significant rotation but with slower rotation velocity. Fourth, the velocity dispersion of the metal-poor globular clusters is much larger than that of the metal-rich globular clusters.

4. A new scenario for structure and formation of M31

From the results on the globular clusters as described above, we propose that M31 has dual halos: a metal-poor (blue) halo and a metal-rich (red) halo, as sketched schematically in Figure 2. Both halos show contrasting properties. The metal-rich halo is smaller, more elongated, rotating faster than the metal-poor halo which is much extended in almost an circular shape and supported primarily by pressure with significant rotation. We expect that most massive spiral galaxies have dual halos like M31.

The existence of dual halos in M31 is consistent with the case for massive early-type galaxies. Recently Park & Lee (2013) proposed that massive early-type galaxies have dual halos, a blue halo and a red halo, as sketched in Figure 3. Here blue and red halos represent metal-poor and metal-rich halos, respectively. This proposal is based on the analysis of the spatial distribution of the globular cluster systems in Virgo galaxies. The ellipticity of the red globular cluster systems shows a much stronger correlation with that of the stellar light in their host galaxies than that of the blue globular cluster systems. The ellipticity of the stellar light shows a strong correlation with the rotation parameter of the stellar light in their host galaxies. Therefore the red globular cluster systems may rotate much faster than the blue globular cluster systems. Thus the halo structures in the massive early-type galaxies and disk galaxies are basically similar in the sense that both have dual halos.

From this we propose a new scenario for the formation of M31 halo. M31 halo formed in dual mode: a metal-poor halo formation mode and a metal-rich halo formation mode. Halos of most massive disk galaxies as well as early-type galaxies might have formed in the similar way. The formation scenario of M31 can be summarized as below.The bulge formed via monolithic collapse or ancient major merger. The metal-rich halo formed via a major merger (Bekki 2010; Hammer et al. 2013). The outer part of the metal-poor halo grow via accretion of dwarfs and globular clusters. The inner part of the metal-poor halo form via a major merger. The disk formed after the bulge and halos formed.

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