

Dual Stellar Halos in Early-type Galaxies and Formation of Massive Galaxies

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Abstract. M105 in the Leo I Group is a textbook example of a standard elliptical galaxy. It is only one of the few elliptical galaxies for which we can study their stellar halos using the resolved stars. It is an ideal target to study the structure and composition of stellar halos in elliptical galaxies. We present photometry and metallicity of the resolved stars in the inner and outer regions of M105. These provide strong evidence that there are two distinct stellar halos in this galaxy, a metal-poor (blue) halo and a metal-rich (red) halo. Then we compare them with those in other early-type galaxies and use the dual halo mode formation scenario to describe how massive galaxies formed.

Keywords. galaxies: halos, galaxies: stellar content, galaxies: abundances, galaxies: elliptical and lenticular, cD galaxies: formation, etc.

1. Introduction

It has been long considered that radial surface brightness profiles of massive elliptical galaxies can be described in general by one component (for example, by the de Vaucouleurs $R^{1/4}$ law), indicating that each of them is composed of a single halo. However, deeper imaging in recent studies finds often much fainter substructures in the outskirts of these galaxies, indicating that there may be more than one components (for example, Watkins *et al.*(2014)).

On the other hand, the color distribution of the globular clusters in massive early-type galaxies (ETGs) is found to be bimodal, indicating the presence of two distinguishable populations: blue and red globular cluster systems. These two populations show significant differences in their spatial distribution in the sense that the distribution of the blue population is more extended and circular compared with the red population, and the distribution of diffuse stellar light is closer to that of the red population.

From these differences between the blue and red globular cluster systems Park & Lee(2013) suggested that massive ETGs may host dual halos and that the formation of massive ETG can be described by the dual halo mode formation scenario. The reality of dual halos in massive galaxies can be tested by studying the metallicity and spatial distribution of the resolved stars in nearby ETGs.

2. Dual Stellar Halos in ETGs

In 1997 Elson (1997) obtained photometry of resolved stars in a halo field of NGC 3115 (S0), finding that the $(V - I)$ color distribution of the resolved red giant is clearly bimodal. From this she suggested that NGC 3115 has two distinct halo populations: a metal-poor halo ($[\text{Fe}/\text{H}] \approx -1.3$) and a metal-rich halo ($[\text{Fe}/\text{H}] \approx -0.0$). Recently Peacock *et al.*(2015) confirmed it later in the study of the outer fields in NGC 3115 using deeper photometry.

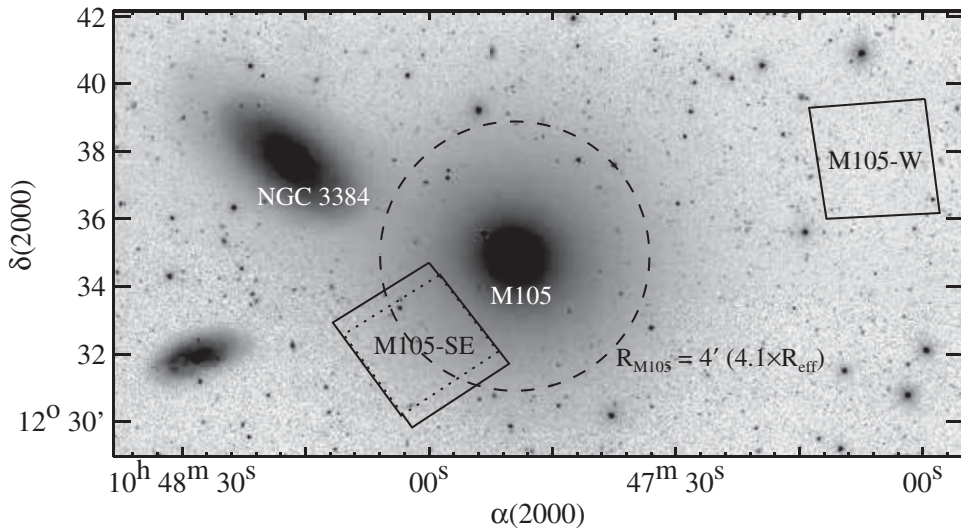


Figure 1. Locations of the two HST fields (SE and W) for M105 on the gray scale map of the Sloan Digital Sky Survey *i*-band image.

Since then photometry of resolved stars in several ETGs provided hints for the presence of dual stellar halos (see Peacock *et al.*(2015) and references therein): some examples are NGC 5128 (S0 pec), NGC 3377 (E5), and M105 (NGC 3379, E1) (Harris & Harris(2002), Harris *et al.*(2007a), Harris *et al.*(2007b), Rejkuba *et al.*(2011), Crnojević *et al.*(2013), and Bird *et al.*(2015)).

M105 in the Leo I Group is a textbook example of a standard elliptical galaxy. Old red giant stars in the halo of M105 are easily resolved in the HST images so that it is an ideal target to study the structure and composition of stellar halos in elliptical galaxies. It is only one of the few elliptical galaxies for which we can study their stellar halos using the resolved stars. In this study we present the current progress of our work on the resolved stellar populations in M105. We derive photometry and metallicity of the resolved stars in the inner and outer regions of M105. Then we compare them with those in other ETGs and suggest a dual halo mode formation scenario for massive ETGs (see Lee & Jang(2015) for details).

2.1. Resolved Stars in the Standard Elliptical galaxy M105

We derived deep photometry of the resolved stars from the F606W and F814W images of two fields available in the Hubble Space Telescope (HST) archive, as marked in Fig. 1. One field is located at $R \sim 4R_{\text{eff}}$ and the other is at $R \sim 12R_{\text{eff}}$. The resolved stars in the outer field were studied previously by Harris *et al.*(2007b). We used DAOPHOT (Stetson(1994)) for detection and point-spread-function-fitting photometry of the stars.

The color-magnitude diagrams (CMDs) of the resolved stars in the inner and outer regions in Fig. 2 show a broad red giant branch (RGB). Comparison with the theoretical isochrones for 12 Gyr age in the Dartmouth model (Dotter *et al.*(2008)) shows that the RGB stars have a large range of metallicity. The distance to M105 is estimated to be $d = 10.23 \pm 0.09$ Mpc using the tip of the RGB method (Lee *et al.*(1993)). The $(V - I)$ color histograms of the bright RGB stars ($M_{\text{bol}} \leq -3.0$ mag) in the lower panels of Fig. 2 show the presence of two distinguishable components, as pointed by Elson(1997) in the case of NGC 3115. However, they show a significant difference between the inner and outer regions, in the sense that the outer region shows a much stronger narrow blue peak

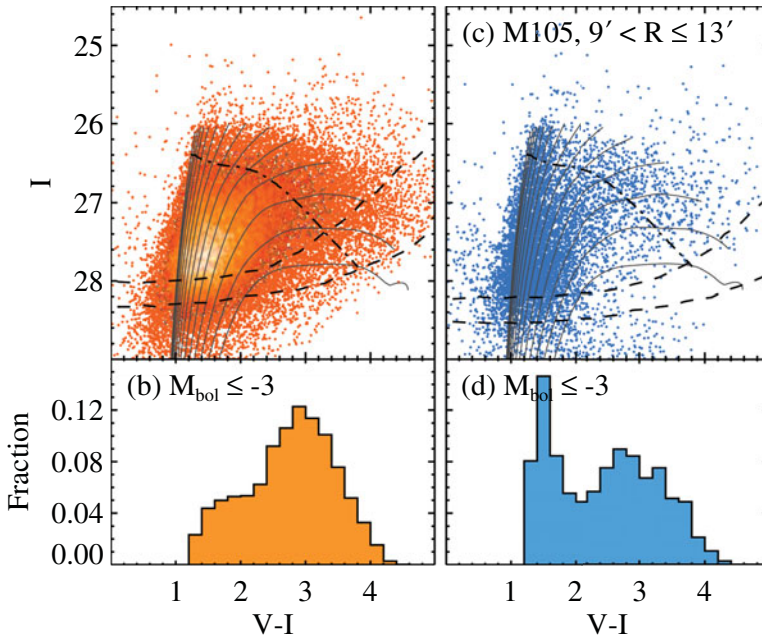


Figure 2. Color-magnitude diagrams (upper panels) of the resolved stars and $(V - I)$ color histograms (lower panels) of the bright RGB stars ($M_{\text{bol}} < -3.0$) in the inner and outer regions of M105. Curved solid lines denote theoretical isochrones for 12 Gyr age in the Dartmouth models Dotter *et al.* (2008). They cover a range of metallicity ($[\text{Fe}/\text{H}] = -2.4$ to $+0.2$ ($[\text{M}/\text{H}] = -2.2$ to $+0.4$)). The 50% and 20% completeness limits are shown by the dashed lines. Dot-dashed lines represent $M_{\text{bol}} < -3.0$.

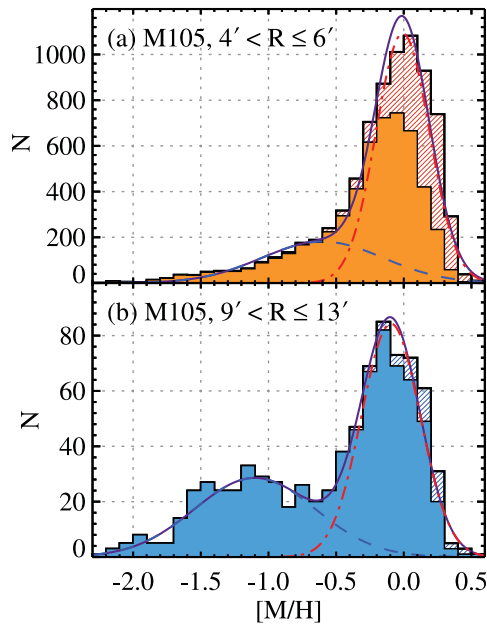


Figure 3. Metallicity distribution functions for the bright RGB stars ($M_{\text{bol}} \leq -3.0$) in the inner and outer regions of M105. The filled and hatched histograms represent the MDFs before and after completeness correction. Note that the MDFs can be fitted well by double Gaussian components (curved lines).

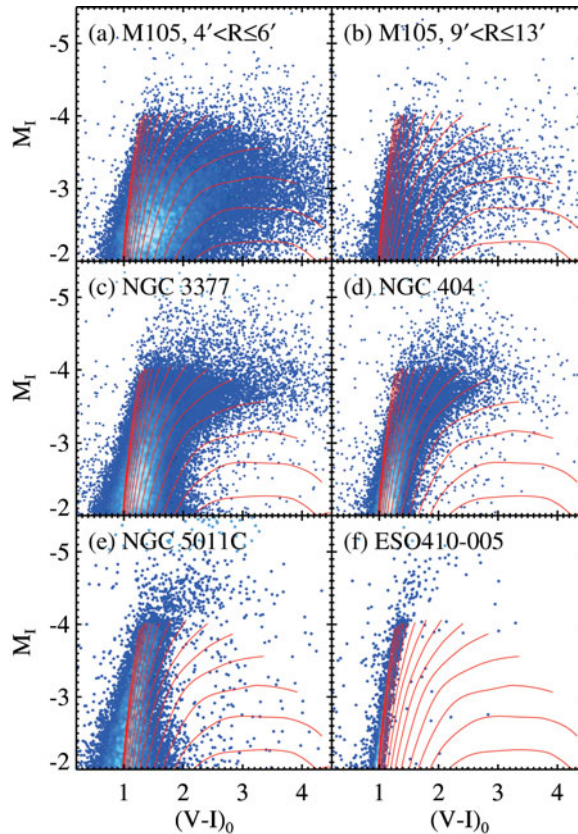


Figure 4. A comparison of the CMDs of the resolved stars in M105, NGC 3377 (E5, $M_V = -19.89$ mag), NGC 404 (S0, $M_V = -17.35$ mag), NGC 5011C (S0, $M_V = -14.74$ mag), and ESO410-005 (dE3, $M_V = -12.45$ mag). Same 12 Gyr isochrones as in Fig. 2 are also plotted (curved lines). Note the diversity of the RGBs.

than the inner region. We estimate the metallicity of the stars from the comparison with the theoretical isochrones and the positions of the stars in the CMDs. Fig. 3 shows the metallicity distribution functions (MDFs) of the bright RGB stars ($M_{\text{bol}} < -3.0$ mag) in M105. The MDFs in Fig. 3 shows two distinguishable components as in the case of the color histograms, which can be fit reasonably well by double Gaussian functions. The metallicity of the metal-rich peak change little between the inner and outer regions, but the metal-poor component is more significant in the outer region than in the inner region. This shows that there are dual halos in M105: a dominant metal-rich (red) halo and a weaker metal-poor (blue) halo. Radial number density profiles of the resolved stars show that the metal-poor halo is significantly more extended than the metal-rich halo. It is noted that the MDF of each halo can be described by accretion box models.

2.2. Resolved Stars in Bright to Faint ETGs

We compare the CMDs of M105 with those in other ETGs with bright to faint luminosity in Fig. 4: NGC 3377 (E5, $M_V = -19.89$ mag), NGC 404 (S0, $M_V = -17.35$ mag), NGC 5011C (S0, $M_V = -14.74$ mag), and ESO410-005 (dE3, $M_V = -12.45$ mag). We obtained photometry of these stars from the HST images in the archive. Fig. 4 shows that the RGBs vary significantly depending on the luminosity of the galaxies. The RGBs get broader and mean RGB colors get redder as their host galaxies become brighter.

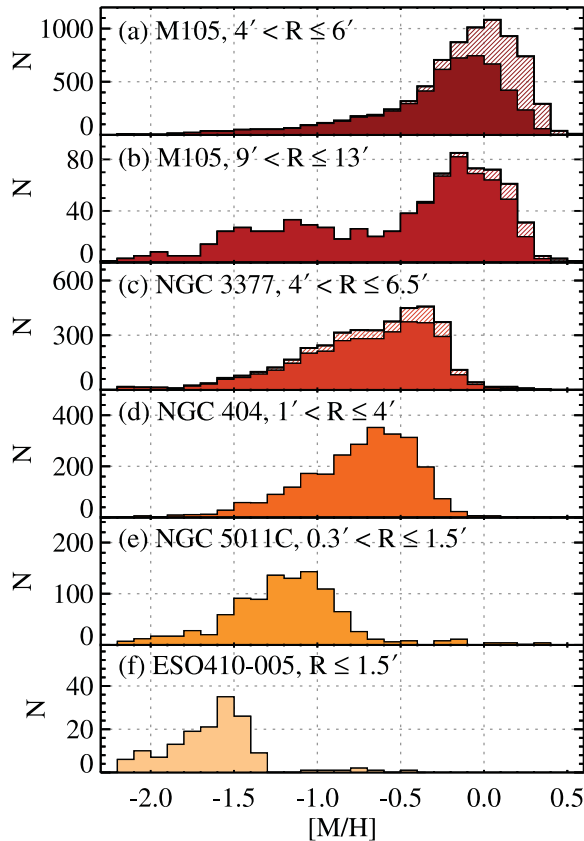


Figure 5. A comparison of the MDFs of the bright RGB stars in the same ETGs as in Fig. 4. Note that the metallicity of the metal-poor peak of the outer region in M105 is similar to that of NGC 5011C.

The MDFs of the resolved stars in these galaxies show two notable features. First, the peak metallicity decreases as the luminosity of their host galaxies decreases. Second, the MDF of the metal-poor component in the outer region of M105 is similar to that of NGC 5011C which has a magnitude of $M_V = -14.74$ mag. This implies that the origin of the metal-poor halo in M105 is probably a dwarf galaxy with $M_V \approx -15$ mag, and while the origin of the metal-rich halo in M105 is a massive galaxy which may be an outcome of major merging or monolithic collapse.

3. A Scenario for Formation of Massive Galaxies: Dual Halo Mode Formation

Considering the MDFs of the resolved stars depending on the galactocentric distance and the distinguishable properties of the blue and red globular cluster systems, we suggest a scenario to explain how massive ETGs might have formed, updating the previous version based on the study of the globular clusters in Park & Lee (2013). In this scenario, massive galaxies form through the metal-rich halo mode followed by the metal-poor halo mode.

First, a massive progenitor formed through in situ rapid collapse of a massive protogalactic cloud or wet merging of less massive galaxies with gas. It will be dominated by

metal-rich stars with a minor fraction of metal-poor stars so that it will correspond to a metal-rich halo. At the similar time numerous dwarf galaxies with low metallicity form in and around the massive galaxies. They will be the major source of low metallicity stars later. Second, the metal-rich massive galaxy grows further via dry merging/or accretion of less massive galaxies (mostly dwarf galaxies) so that its outer part will be dominated by metal-poor stars (originated from low mass stellar systems including dwarf galaxies and globular clusters). The resulting system corresponds to the metal-poor halo. Thus the metal-poor halo will consist mostly of the remnant stars from dwarf galaxies, and some of low metallicity stars from the original massive progenitor. This scenario can be tested further with simulations in the future (for example, Cooper *et al.*(2015)).

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