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A PHOTOMETRIC STUDY ON THE FORMATION OF THE EARLY TYPE GALAXIES IN NEARBY GALAXY CLUSTERS

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ABSTRACT

We present a photometric study of galaxies in the central regions of six nearby galaxy clusters at redshift z=0.0231~ 0.0951. We have derived BVI photometry of the galaxies from the CCD images obtained at the Bohyunsan Optical Astronomical Observatory (BOAO) in Korea, and JHK_s photometry of the bright galaxies from the 2MASS extended source catalog. Comparing the galaxy photometry results with the simple stellar population model of Bruzual & Charlot (2003) in the optical & NIR color-color diagrams, we have estimated the ages and metallicities of early type galaxies. We have found that the observed galaxies had recent star-formation mostly 5 ~ 7 Gyrs ago but the spread in age estimation is rather large. The average metallicities are [Fe/H]=0.1~0.5 dex. These results support the hypothesis that large early type galaxies in clusters are formed via hierarchical merging of smaller galaxies.

Key words : galaxies: early type — galaxies: clusters — galaxies: age — galaxies: metallicity — galaxies: formation — galaxies: photometry

I. INTRODUCTION

When galaxies are formed and how they have evolved have always been our fundamental questions. There may be many approaches to solve that query, and to study elliptical galaxies is one of them. There are two major models which explain the formation of elliptical galaxies. One is a monolithic collapse model (Eggen *et al.* 1962; Partridge 1967; Tinsley 1972, *hereafter* MCM) and the other is a hierarchical merging model (Toomre 1977; Searl & Zinn 1978; Kauffmann et al. 1993, *hereafter* HMM). Because these two models suggest different star formation history, the ages and metallicities of the galaxies are expected to be different between the two models. Therefore any information of ages and metallicities on galaxies in clusters will lead us to understanding the formation and evolution mechanism of the galaxies and clusters.

The color of a galaxy reflects the integrated color of the member stellar population. Using color information, we can estimate ages and metallicities of galaxies, which can be used to study formation history of galaxies. In the optical band, the color of the stellar population becomes red as the average stellar population gets older or as it contains more metal-rich stars. It means the color of the galaxies depend upon the age as well as the metallicity. This problem is called *'age-metallicity degeneracy'*, or it is also known as '3/2−*rule*' (Worthey, 1994). This means that if two stellar populations differ in $\Delta log(age)/\Delta logZ \sim 3/2$, then their broad-band colors and most of the line indices look almost identical. However, Aaronson (1978), Vazdekis *et al.* (1997), Kodama & Arimoto (1997), and Bruzual & Charlot (2003) suggested that if we combine both the optical and the NIR information, it is possible to break 'age-metallicity degeneracy'. Smail *et al.* (2001) performed an optical & NIR photometric study of galaxies in Abell 2218 to present $BVIK_s$ photometry and they compared the observed colors of the galaxies with the theoretical values given by Bruzual & Charlot (1993). They also compared the results with those from spectroscopic study (Ziegler *et al.* ,2001) and confirmed the reliability of photometric analysis. They showed that we can discriminate between the effects of age and metallicity because the optical-infrared color of an old stellar population over 1 Gyr is primarily determined by the temperature of the red giant branch, which is more sensitive to the metallicity than the age of the stellar populations, while optical color, for example $(V-I)$ and $(B-I)$, is sensitive to both age and metallicity. So if we combine the information of optical and near infrared color, we can break *'age-metallicity degeneracy'*.

In this study we present a photometric research of galaxies in several nearby galaxy clusters, providing observational constraints to the models of galaxy formation. We compare photometric data with stellar population model to obtain age and metallicity of galaxies. Photometric data of spiral galaxies are significantly affected by dust in their spiral arms while elliptical galaxies suffer little from dust and have simple star formation history. Therefore we focus on early type galaxies including elliptical and lenticular galaxies in this study. Throughout this paper, we adopt

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TABLE 1.
BASIC INFORMATION OF THE GALAXY CLUSTERS

NAME	RA (J2000)	DEC (J2000)	Z	RICHNESS [CLASS]	BM-TYPE	DIAMETER (ARCMIN)	E(B-V)
A1656	12H59M48S	+27D58M48S	0.0231	[2]	II	319	0.008
A2061	15H21M15S	+30D39M18S	0.0784	[1]	III	40	0.021
A2065	15H22M43S	+27D43M21S	0.0726	[2]	III	44	0.040
A2175	16H20M23S	+29D54M54S	0.0951	[1]	II	40	0.040
A2199	16H28M37S	+39D31M28S	0.0301	[2]	I	182	0.011
A2256	17H03M44S	+78D43M03S	0.0581	[2]	II-III	140	0.053

the cosmological constants derived from the studies using Wilkinson Microwave Anisotropy Probe (WMAP), $H_0 = 71 km/s/Mpc$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$.

II. OBSERVATION AND DATA REDUCTION

We observed six clusters using 2K CCD with BOAO 1.8m telescope in B, V, I bands on June 2–5, 2003. The pixel scale of the CCD is 0.3438 arcsec/pixel. And the FOV is 11.7×11.7 $arcmin^2$. The basic information of the observed clusters is described in Table 1. The observed region was mainly selected from the central region of galaxy clusters.

We also used 2MASS All-Sky Extended Source Catalog released on March 2003. In this study, we used '20 $mag/arcsec^2$ isophotal fiducial elliptical aperture magnitude' where the aperture was defined in K_s band.

For the photometry of galaxies, we used Source Extractor (Bertin and Arnouts, 1996 : *hereafter* 'SExtractor'). Especially for calculation of galaxies' color, we need to integrate the flux in the same elliptical aperture in the three filter bands. So we ran SExtractor in a 'dual-image mode' taking V band image as a reference frame. We decided to use 'MAG_AUTO' as galaxy magnitude. Standard calibration for BOAO data was performed with Landolt's (1992) standard stars using IRAF/PHOTCAL package. SA92, SA107, SA110, SA112, PG1323, PG1633 region was observed at various airmasses.

We used the results of Schlegel *et al.* (1998) for the foreground galactic extinctions, and adopted the values of Poggianti (1997) for K-correction.

III. RESULTS

We obtain the color-color diagrams of the clusters with stellar population models, and translate measured colors into ages and metallicities of galaxies.

(a) Simple Stellar Population Model

'Simple stellar population' (*hereafter*, SSP) is a simple model constraining stellar population. SSP regards all stars were instantaneously formed with the same chemical composition. There are several studies carried out on SSP models; We compared some SSP

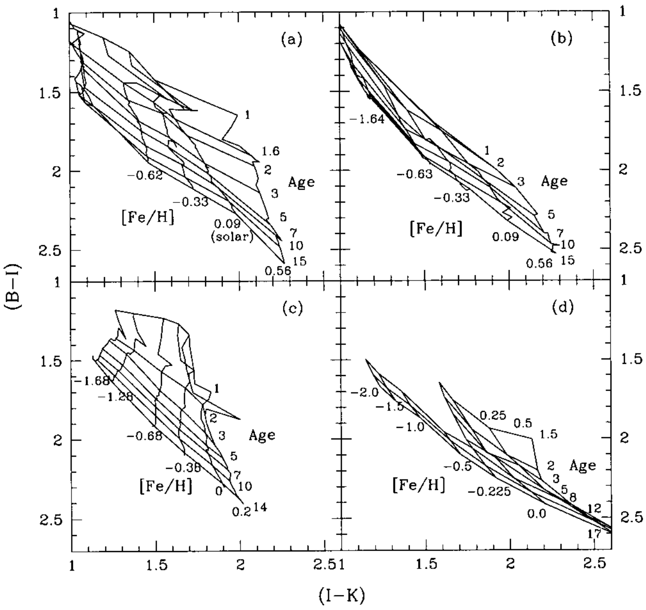

Fig. 1.— The comparison of SSP models in the color-color diagram. (a) Bruzual & Charlot (2003). (b) Kurth *et al.* (1999). (c) Vazdekis (1999), IMF of Kroupa Revised. (d) Worthey (1994). The age indices are in [Gyr].

models in Fig. 1. It can be seen that there are differences in each model. But this is due to the different input physical parameters on IMF, chemical enrichment law, and star-formation rate, stellar libraries and stellar evolutionary track. In this study, we used SSP models of Bruzual & Charlot (2003) for the comparison of our cluster sample observables. We used stellar evolutionary track of Padova 1994 model and Salpeter IMF of slope 1.35 with lower and upper mass cut-offs of $0.1 M_\odot$ and $100\ M_\odot$. (In Bruzual & Charlot 2003, they recommend using evolutionary track of Padova 1994 model rather than recent result of Padova 2000 model. See Section 3.1 of Bruzual & Chalot, 2003) This model provides stellar population at ages between 10^5 year and 2×10^{10} year and at 6 metallicities from Z=0.0001 to Z=0.05.

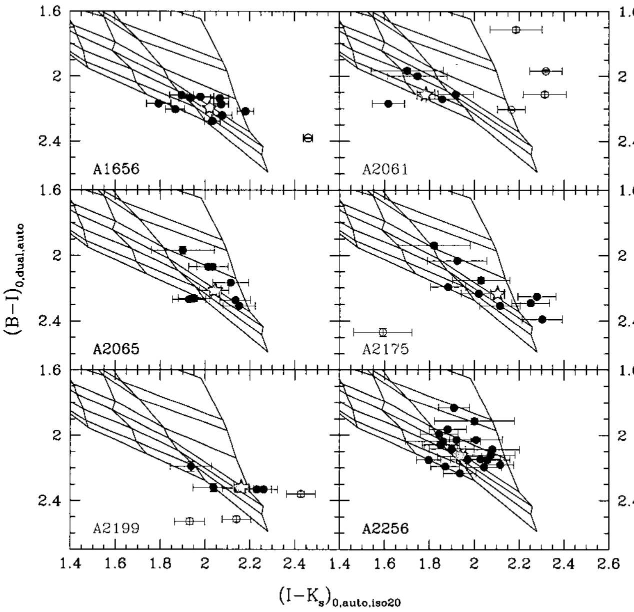

Fig. 2.— The $(B-I)-(I-Ks)$ color-color diagram of early type galaxies with the stellar population model grid of Bruzual & Charlot (2003). The distinct outlying galaxies were marked with open circles. The average value of selected galaxies (filled circle) are shown in star.

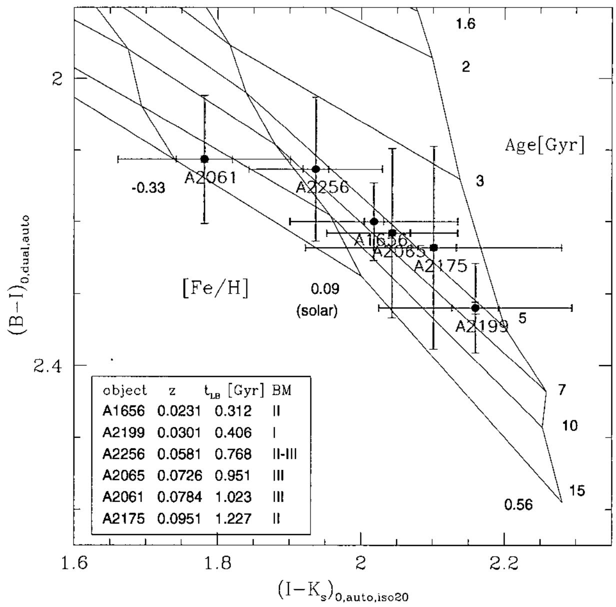

Fig. 3.— The $(B-I)-(I-Ks)$ color-color diagram which represent weighted mean color of early type galaxies of each cluster. The small error bar indicates variance of weighted mean, and the large error bar means standard deviation of early type galaxies in each cluster. In the small box, basic information of the galaxy clusters are presented; name, z, look back time, and Bautz-Morgan type (Bautz & Morgan, 1970.)

(b) Color-Color Diagram of Galaxies

We present the color-color diagrams of six clusters. Morphologies or galaxies are classified into early type and late type galaxies. In this study, age indicates the time when the last major star formation episode took place, not the mean age of the stellar population in a galaxy. Also the ages and metallicities we derive in this study are not absolute values but model dependent ones. Therefore those values are meant to be used as relative age & metallicity.

Average values of each cluster's colors are plotted with stellar population model in Fig. 3 including standard deviation of member early type galaxies. Then we estimated ages and metallicities of each galaxies interpolating the model grid. With these results, we present color-magnitude, age-magnitude with metallicity-magnitude diagrams in Fig. 4.

From our color-color diagram(Fig. 2,3), the variances of the member galaxies in some clusters are large, which means the formation epoch is different to some extent hence they are not co-eval. On that account, we can not explain the formation of galaxies in the context of MCM.

It is interesting that in each cluster, the variance of the member galaxies are large in ages and metallicities, but their weighted mean age of each clusters are very similar to one another. In Fig. 3, the weighted mean age of the four clusters out of six sample clusters are in 5 $\sim$ 7 Gyrs, and metallicities of all clusters except one cluster are in the range between 0.09 and 0.56 in $(B-I)-(I-K_s)$ color-color diagram.

It is hard to make direct comparisons between our study and other previous studies, because each study uses different SSP models. As shown in Fig. 1, each models are different in color-color diagram. Comparison of relative ages and metallicities is meaningful only when the result is obtained using the same SSP model.

By estimating ages and metallicities of galaxies, we can confirm whether the slope of color-magnitude relation (*hereafter* CMR) is originated from age or metallicity. Kodama & Arimoto (1997) suggested that CMR is primarily originated from the mean stellar metallicity effect. But Ferreras *et al.* (1999) argued that CMR is caused by combination of age and metallicity. From Fig. 4, we can see that the CMR is not originated from the metallicity-only effect nor the age-only effect. CMR may imply complex combination of the age and the metallicity effect.

IV. SUMMARY AND DISCUSSION

We present *BVI* photometry of galaxies in six nearby galaxy clusters, supplemented by 2MASS near-infrared extended source catalog. We have estimated ages and metallicities of bright early type galaxies using optical & NIR color-color diagrams in conjunction with simple stellar population models. Our six cluster sam-

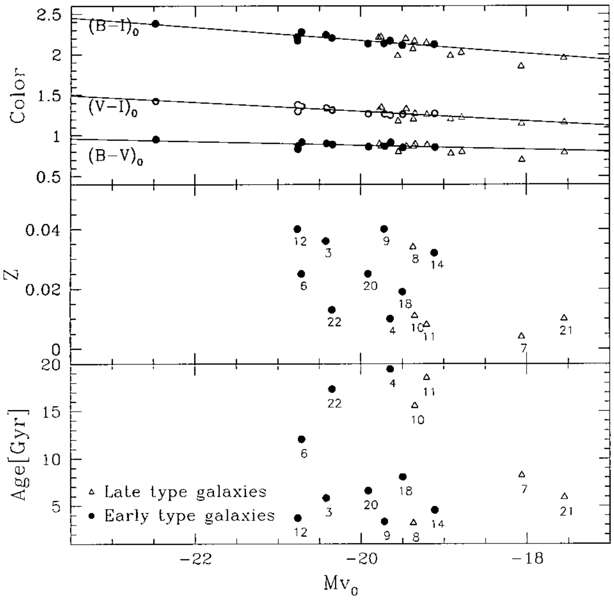

Fig. 4.— Color(top), Metallicity(middle), Age(bottom) vs. magnitude diagram of A1656, the COMA cluster. Ages and metallicities of galaxies were estimated with the SSP synthesis model of Bruzual & Charlot(2003). Galaxies falling out of the model grid are omitted in this diagram. The number under each point is the ID of the galaxies in corresponding cluster.

ples show tight color-magnitude relation for early type galaxies. Ages and metallicities of galaxies in each cluster show large variance, but the weighted mean of ages and metallicities for most of our sample clusters lie in a narrow region, that is weighted mean ages in $5 \sim 7$ Gyrs and weighted mean [Fe/H] in $0.09 \sim 0.56$.

In MCM, giant proto-galactic clouds collapse and then form stars in a short time. And then it becomes a primitive elliptical galaxy. After the main burst of star formation, the galaxy has evolved quiescently until now. But the variance of age and metallicity in early type galaxies of each cluster shows that early type galaxies are not formed in a short duration. Therefore, our results support that the elliptical galaxies are formed by merging. In the HMM, since galaxies are formed by merging, more massive galaxies should be younger and more metal rich. But in our results in Fig. 4, the prediction are not surely seen. Since our samples are not sufficient to conclude, we need more galaxy clusters of various properties to enhance our research. It would be useful to compare the age and metallicity estimated by color of photometric data and by line indices of spectroscopic data. If the two results show a good agreement, we can investigate the formation of galaxies very effectively by utilizing the photometric data which are quite more abundant than spectroscopic data. The SDSS data will give us the good opportunity in both photometric and spectroscopic methods. Through studies on more various galaxy clusters, we would get closer to the statistically more meaningful results to understand the formation and evolution history of galaxies.

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