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OPTICAL-NEAR INFRARED COLOR GRADIENTS OF ELLIPTICAL GALAXIES AND THEIR ENVIRONMENTAL DEPENDENCE

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ABSTRACT

We have studied the environmental effect on optical-NIR color gradients of 273 nearby elliptical galaxies. Color gradient is a good tool to study the evolutionary history of elliptical galaxies, since the steepness of the color gradient reflects merging history of early types. When an elliptical galaxy goes through many merging events, the color gradient can be get less steep or reversed due to mixing of stars. One simple way to measure color gradient is to compare half-light radii in different bands. We have compared the optical and near infrared half-light radii of 273 early-type galaxies from Pahre (1999). Not surprisingly, we find that r_e(V)s (half-light radii measured in V-band) are in general larger than r_e(K)s (half-light radii measured in K-band). However, when divided into different environments, we find that elliptical galaxies in the denser environment have gentler color gradients than those in the less dense environment. Our finding suggests that elliptical galaxies in the dense environment have undergone many merging events and the mixing of stars through the merging have created the gentle color gradients.

Key words : galaxies: clusters(Abell 2199 and Fornax) and field — galaxies: formation and evolution — galaxies: color gradients — galaxies: effective radii — galaxies: optical and infrared

I. INTRODUCTION

Many studies have shown that stars in an elliptical galaxy gradually become redder toward the center, and this is called "color gradient" (e.g., Franx & Illingworth 1990; Peletier et al. 1990; Tamura & Ohta 2003). It is known that the most dominant cause of the color gradient is a radial change of the stellar metallicity, i.e., metallicity gradient although there might be a small correction due to age gradient (e.g., Hinkley & Im 2001). The color gradient becomes more prominent when a long wavelength baseline is covered, such as the optical versus near-infrared bands (Hinkley & Im 2001; La Barbera et al. 2003).

Various galaxy formation models explain how the color gradient (or equivalently the metallicity gradient) arises. Models suggest that elliptical galaxies form largely in two ways — via monolithic collapse of the proto-galactic gas at high redshift ("monolithic collapse model"; Eggen, Lynden-Bell, & Sandage 1962; Larson 1975), or merging of gas-rich spiral galaxies at a more recent epoch ("merging model"; Kauffmann, White, & Guiderdoni 1993; Baugh, Cole, & Frenk 1996). Either way, the steep gravitational well in the inner part of the elliptical galaxies allow the metal-enriched interstellar gas stay there for successive star formation events, which enriches the metallicity of the surrounding gas even more. In contrast, supernovae explosions can easily blow away the surrounding ISM gas prohibiting more stars to form in the outer part. Therefore, the metallicity gets enriched more in the inner part than in the outer part, and this is considered to be the mechanism to produce the observed color-gradient in elliptical galaxies. Theoretical works suggest that the metallicity gradient can be as steep as $\Delta log(Z)/\Delta log(R) = -0.5$ to -1 under this kind of galaxy formation out of gas-rich systems (Larson 1974; Carlberg 1984). The observed steepness of the color gradients is broadly consistent with the theoretically computed values. If not many events happen after the initial formation of elliptical galaxies as the monolithic collapse model suggests, the color (or metallicity) gradient will stay at this initial state. However, under merging models, the situation changes. The merging activity complicates the color-gradient in many ways. When gas-poor elliptical galaxies merge, stars in the galaxies get mixed up, diluting the color-gradient. The collision between a gas-poor elliptical galaxy and gas-rich satellite galaxy can lead to sprinkling of young stars in the inner part of the elliptical galaxy, potentially creating a flat or a reversed color-gradient. There is already some observational evidences for the reversed color-gradient in elliptical galaxies (e.g., Im et al. 2001). However, it still remains as uncertain how significantly merging activities play in the evolution and the formation of elliptical galaxies.

Recently, hierarchical galaxy formation models put forward the environment-dependent galaxy formation

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picture, where elliptical galaxies in high density environment form early and go through more merging events than elliptical galaxies in low density environment. Interestingly, spectral properties and colors of nearby ellipticals from the Sloan Digital Sky Survey (SDSS) turned out not to be strongly dependent on environments (Bernardi et al. 2003). Such a finding, however, does not exclude a possibility that the present-day galaxies were assembled through merging of gas-poor galaxies or not - the hierarchical merging model is still viable. As an attempt to test the merging history of nearby early-type galaxies, we have studied optical-NIR color gradients of nearby elliptical galaxies in different environments.

II. DATA

Color gradient shows up as a change in half-light radii at different wavelengths. Half-light radii of early-type galaxies decrease systematically from a short wavelength to a long wavelength because of the color gradients. Furthermore, the difference in size can be substantial when the size in optical is compared with that in near infrared, i.e., when a long wavelength baseline is explored. Therefore, the comparison of the optical vs near infrared sizes can be a simple and powerful way to measure color gradients in many elliptical galaxies (Sparks & Jørgensen 1993; Pahre et al. 1998).

In order to investigate the optical-near infrared color gradient, we have compared the V-band and K-band effective radii of 273 elliptical galaxies from Pahre (1999). Pahre (1999) has compiled a list of 273 elliptical galaxies for which optical structural parameters and the velocity dispersion measurements are available from literatures. For these ellipticals, they have obtained NIR K-band images, and derived K-band structural parameters. Using these galaxies, they have studied the fundamental plane relation in NIR. For our study, we use the effective radii measured using circular apertures as listed in Pahre (1999) for both V-band sizes (hereafter, $r_e(V)$), K-band sizes (hereafter, $r_e(K)$).

III. RESULTS

First, we compare $r_e(V)$ vs $r_e(K)$ of 273 sample galaxies (Fig. 1). The median of the ratio of $r_e(V)$ and $r_e(K)$ is 1.33. In the other words, $r_e(V)$ is about 33% larger than $r_e(K)$ on average. Using the result of Sparks & Jørgensen (1993), the scale-length difference ($\Delta s = \Delta r_e/r_e$) can be converted into an isophotal color gradient of $\Delta(\mu_V - \mu_K) = \beta \Delta \log r$, with $\Delta s \sim \beta$ = -0.33 mag arcsec^{-2}. We find that some elliptical galaxies show a very large difference between optical effective radius and near infrared effective radius. The difference can be more than a factor of 2. Some elliptical galaxies show positive color gradients, which means that stars are redder toward the outer part as merging models suggest. The optical-NIR color gradient from our study seems rather steep, compared to the expected size difference of about 10-20 % using the observed metallicity gradient from the optical photometric and spectroscopic studies. There is a weak trend in Fig. 1 that galaxies with small apparent sizes have smaller $r_e(V)/r_e(K)$ values. This is probably due to the difficulty of determining sizes when galaxy sizes are similar to the seeing size.

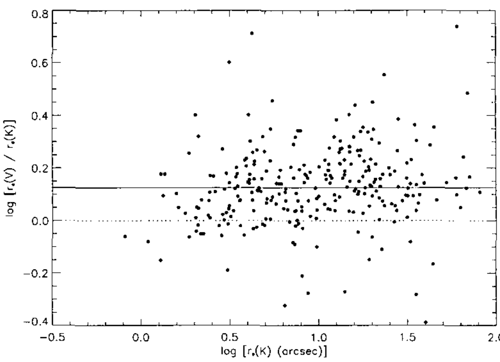

Fig. 1.— The ratio of effective radius in V-band versus K-band of 273 galaxies from Pahre (1999). The solid line represents the median value (0.125 dex).

Next, in Fig. 2, we compare color gradients of elliptical galaxies in different environments. Fig. 2 shows the ratio $r_e(V)/r_e(K)$ for elliptical galaxies in a rich cluster Abell 2199 (the top panel), in a poor cluster, Fornax (the middle panel), and in field (the bottom panel). The median effective radii ratio for elliptical galaxies in the nearby rich cluster Abell 2199 is smaller than the same quantity in a poor cluster, Fornax. Also, we find that color gradients of cluster galaxies are much smaller than field galaxies. These results suggest that there is a relationship between the steepness of color gradients and environment: elliptical galaxies in the lower density regions tend to have steeper color gradient than ellipticals in the higher density regions. We have examined other elliptical galaxies in field, group, or other clusters, and find a similar trend (Im & Ko 2005, in preparation).

IV. DISCUSSION AND FUTURE WORK

The cause of the environmental dependence can be understood as the following. Hierarchical galaxy formation models predict that galaxy evolution proceeds differently depending on the environment. Early-types, when they formed first, are expected to have steep color gradients, since star formation activities are longer in the inner parts by abundant cold gas. Such prolonged star-forming activities could make stars in the inner parts more metal-rich, i.e., redder. After undergoing merging events, the color gradient of the progenitor galaxy gets watered down as a consequence of mixing of stellar populations. Since early-types in the cluster environment have gone through more merger events than in the field environment in the hierarchical merging models, color gradients of cluster galaxies become gentler than those of field galaxies,

The large values for $r_e(V)/r_e(K)$ in Fig. 1 are harder to understand. There is no question that the metallicity gradient is contributing here. We find that some galaxies with extremely large $r_e(V)/r_e(K)$ show the evidence for dust, therefore dust-extinction is another possible contributing factor (e.g., Wise & Silva 1996). We have examined another possibility that our result might be caused by a measurement error in the literature. To check for such a possibility, we have used our own observation (imaging observation in optical bands using 1 m telescope at Lemmon and 1.5 m telescope at Maidanak) and archival data (2MASS), and derived half light radii independently. Our independent check finds no strong systematic bias in the published optical sizes of galaxies in Pahre (1999), although we find that the literature values of r_e for some ellipticals with large $r_e(V)/r_e(K)$ turned out to be inconsistent with our measurements. We plan to extend our analysis to a much larger sample using the SDSS data set. A more complete analysis of the SDSS work will be presented elsewhere (Ko & Im 2005, in preparation).

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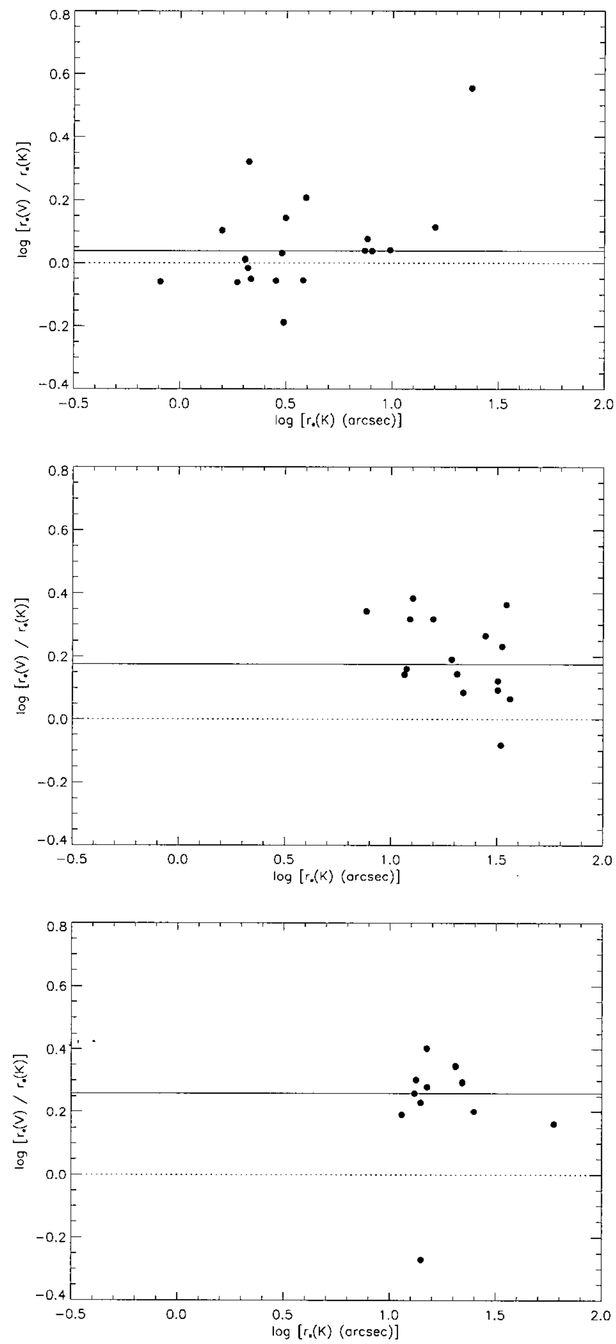

Fig. 2.— Comparison of the effective radius ratio in different environment. *Top*, the rich cluster Abell 2199 (the median is 0.037 dex); *middle*, the poor cluster Fornax (the median is 0.176); *bottom*, field galaxies (the median is 0.260)