Radial variation of optical and near-infrared colours in luminous early-type galaxies in A2199

Naoyuki Tamura1*† and Kouji Ohta2†

1Department of Physics, University of Durham, South Road, Durham DH1 3LE
2Department of Astronomy, Kyoto University, Kyoto 606-8502, Japan

ABSTRACT

We performed K-band surface photometry for luminous early-type galaxies in a nearby rich cluster A2199. Combining it with B- and R-band surface photometry, radial variations of B–R and R–K colours in the galaxies were investigated. It is found that the inner regions of the galaxies are redder in both B–R and R–K colours. Comparing the radial variations of both colours with predictions of simple stellar population models for a range of ages and metallicities, it is suggested that the cluster ellipticals have negative metallicity gradients, but their age gradients are consistent with zero, although our sample is small; the typical metallicity gradient is estimated to be −0.16 ± 0.09 in d log Z/d log r, while the age gradient is estimated to be −0.10 ± 0.14 in d log (age)/d log r. Considering that similar results have also been derived in the other recent studies using samples of ellipticals in the Coma cluster and less dense environments, it seems that there is no strong dependence on galaxy environment in the radial gradient of stellar population in an elliptical galaxy.

Key words: galaxies: clusters: individual: A2199 – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation – galaxies: fundamental parameters.

1 INTRODUCTION

Elliptical galaxies in a cluster show a tight colour–magnitude (CM) relation; colours of more luminous ellipticals are systematically redder (e.g. Bower, Lucey & Ellis 1992). It has been found that the relation still holds in distant rich clusters around z ~ 1 (e.g. Stanford, Eisenhardt & Dickinson 1998). Based on these observational results, galaxy evolution models taking into account chemical evolution claim that elliptical galaxies in rich clusters formed at, for example, z > 3 through a monolithic collapse of a gas cloud (e.g. Kodama & Arimoto 1997). In this monolithic formation, a radial variation of stellar population, in the sense that stellar metallicity is higher on average towards the galaxy centre (metallicity gradient hereafter), is expected to form as a result of initial starburst and subsequent blow of galactic wind; a more extended period of active star formation and thus more chemical enrichment is expected in the inner portions of a galaxy (e.g. Kawata 1999). Indeed, many elliptical galaxies are known to have radial gradients of colours and absorption-line strengths: colours are redder and metal absorption lines are stronger in the inner regions (e.g. Peletier et al. 1990a; Davies, Sadler & Peletier 1993), and the evolution of the colour gradients investigated by looking at distant ellipticals suggests that these gradients originate from the metallicity gradients (Saglia et al. 2000; Tamura et al. 2000; Tamura & Ohta 2000; La Barbera et al. 2003).

On the other hand, a bottom-up structure formation based on the cold dark matter (CDM) universe generally succeeds in reproducing many observational aspects of galaxies in the present-day Universe. In this scheme, an elliptical galaxy is considered to form via a major merger of galaxies. Accordingly, even if the progenitors of an elliptical galaxy have some radial variations of stellar population, the variations are more likely to be smeared out during the merger. It is also expected that the histories of mass assembly and star formation of an elliptical galaxy can be different from galaxy to galaxy, even if elliptical galaxies having similar masses at a given redshift are considered. Therefore, the radial gradient of stellar population in an elliptical galaxy would not be expected to correlate with the galaxy mass, although there is a possibility that the gradients in more massive ellipticals are less steep because they are likely to experience more merging events on average than less massive systems.

These considerations show that investigating colour or absorption-line strength gradients in elliptical galaxies in a statistical manner is a potentially powerful probe of the galaxy formation process (see also Kobayashi 2004). We recently performed B- and R-band surface photometry for elliptical and S0 galaxies (E/S0s) in A2199, which is one of the nearby rich clusters, to study their colour gradients (Tamura & Ohta 2003, hereafter Paper I). From...
these optical data, we find the following. (i) The average metallicity gradient in the ellipticals estimated from their colour gradients on the assumption of no age gradient is $\sim -0.3 \pm 0.1$ in $d\log Z/d\log r$, which can be reproduced by a recent model of the monolithic-like galaxy formation (e.g. Kawata 1999). (ii) For galaxies brighter than $R = 15$ mag ($L \sim L^*$ at the distance of A2199), more luminous galaxies tend to have steeper colour gradients (Fig. 1). These results are consistent with the monolithic collapse scenario rather than the bottom-up scheme (Larson 1974; Carlberg 1984; Kawata & Gibson 2003). Considering that almost all other previous studies have targeted ellipticals in environments less dense than A2199 and no such correlations have been found in the previous studies, our data may imply an environmental dependence of the formation process of an elliptical galaxy.

However, it is premature to conclude that the cluster E/S0s formed through the monolithic collapse scenario, and it needs to be confirmed that the galaxy luminosities correlate with the metallicity gradients. Although this requires us to disentangle the age–metallicity degeneracy, which is very hard in practice, one possible way to address this issue is to add another colour information including a near-infrared (NIR) band to the optical colour and seeing the radial variations of both colours (e.g. Peletier, Valentijn & Jameson 1990b). This will allow us to see whether the colour variation is consistent with a pure metallicity gradient or whether a significant contribution of age gradient is essential to explain it. In this paper, we present the results of $K$-band surface photometry for the E/S0 galaxies in A2199 to be combined with the optical surface photometry (Paper I). The $K$ band is chosen to make a baseline of wavelength longer in order to break the degeneracy more clearly. Among the luminous ellipticals plotted in Fig. 1, we observed eight galaxies. We briefly summarize the optical observation and then describe the NIR observation and data reduction in the next section. Data analysis and results are presented in Section 3. After discussing the results in Section 4, we summarize this paper in Section 5.

2 OBSERVATION AND DATA REDUCTION

2.1 Overall description of data acquisition

We started studying colour gradients in the cluster ellipticals with optical data, as described in Paper I in detail. We performed $B$- and $R$-band surface photometry for 40 early-type (E, E/S0 and S0) galaxies in A2199 selected from the catalogue by Lucey et al. (1997). The galaxy morphology listed by Lucey et al. (1997) is mostly taken from Butcher & Oemler (1985) and Rood & Sastry (1972). Although studying these morphologically selected early-type galaxies could be one option, it is known that there is a variety in spheroidal-to-total luminosity ratio among galaxies in each morphological type (Simien & de Vaucouleurs 1986) and some of them can be disc-dominated galaxies. In order to securely sample galaxies dominated by spheroidal components, we made azimuthally averaged radial surface brightness profiles of the galaxies and performed decompositions of the profiles into bulge and disc components to estimate the bulge-to-total luminosity ($B/T$) ratios. We sampled galaxies with $B/T$ ratios in the $B$ band larger than 0.6. This criterion isolates galaxies earlier than E/S0 or $T \leq -3$ according to Simien & de Vaucouleurs (1986), where $B/T$ ratios of nearby galaxies are also derived in the $B$ band. Eventually, 31 galaxies were sampled out of the 40 galaxies observed. The galaxies plotted in Fig. 1 are those brighter than $R = 15$ mag ($L \sim L^*$) and eight of these galaxies were observed in the $K$ band.

2.2 Optical observation

Because the details of the optical observation and data are described in Paper I, we briefly summarize them here. The imaging observations in the $B$ and $R$ bands were performed on 2001 June 20 and 21 with a Tektronix 2K × 2K CCD on the University of Hawaii 2.2-m telescope. One pixel of the CCD subtends 0.22 arcsec on the sky and thus each frame covers a field of view of $\sim 7.5 \times 7.5$ arcmin. A typical seeing size during the observing run was $\sim 0.9$ arcsec in the FWHM. A total exposure time at each field is typically 1800 s in the $B$ band and 750 s in the $R$ band, each of which was divided into three or four exposures with the telescope dithered. The imaging data were reduced with IRAF\(^1\) in the standard procedure. After bias subtraction and flat-fielding by dome-flat frames, sky subtraction was carried out in each frame and the sky-subtracted frames at each field were registered by subpixel shifts. The FWHMs

\(^{1}\) IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. under cooperative agreement with the National Science Foundation.
were de-registered to those in the unregistered frames and the pixels images were stacked with the 3σ clipping algorithm. Firstly, a sky-background in each frame was estimated, by calculating the modal pixel value after bright objects were masked, and was normalized the stacked image by its modal pixel value. An object frame was flat-fielded by the sky-flat frame constructed with the blank sky frame. This method allows us to correct for the complex pattern subtraction, we carried out flat-fielding using sky-flat frames. To make a sky-flat frame, we stacked exposures of adjacent blank sky regions with the same exposure time as that of the object frames. These sky-subtracted images were registered by subpixel shifts and, after the FWHMs of stellar objects in the sky-subtracted and registered frames were matched by convolutions of images with Gaussian kernels, they were stacked with the 3σ clipping algorithm. Finally, the K-band stacked image was aligned with the optical data by using stars in the field of view and a Gaussian convolution was employed to match the FWHMs of stellar objects with those in the optical images.

### 2.4 Calibration
For the optical data, the photometric calibration was performed using the standard stars in Landolt (1992). Several standard star fields were observed at the beginning and end of each night. Because the weather was slightly non-photometric, an external check of the accuracy of the calibration was performed using aperture photometry data and growth curves for several galaxies, which were taken from HYPERCAT. There seem to be zero-point offsets between our growth curves and those from HYPERCAT; the amounts of the offsets are 0–0.1 mag in each band. We will return to the treatment of these offsets later.

For the K-band data, the photometric calibration was carried out using UKIRT Faint Standard stars (Hawarden et al. 2001). About 10 standard stars were observed at the beginning and end of each night. The weather was clear and stable during the two nights and the photometric zero-point can be determined with an accuracy of ~0.02 mag from the data of standard stars.

It is found that some of the galaxies have B–R colours slightly inconsistent (~0.1 mag) with those of typical luminous ellipticals in the local Universe and this can be due to the calibration error in the B and R bands. We correct for these offsets using the CM relation. We assume that the CM relation in the Coma cluster also exists in A2199. Their ‘true’ colours are estimated using stellar populations modelled by Kodama et al. (1998) using a population synthesis model, so that the CM relations in U–V and V–K colours obtained in the Coma cluster by Bower et al. (1992) are well reproduced. We estimated B–R and R–K colours of the sample galaxies within an aperture of 12 arcsec (5 h⁻¹ kpc) in diameter (Table 1), which is equivalent to

| Galaxy | R (mag) | dB − R/d log r (mag dex⁻¹) | d(R − K)/d log r (mag dex⁻¹) | r_e (arcsec) | r_{in}/r_e | r_{out}/r_e | B−R (mag) | R−K (mag) | Δ(B−R) (mag) | Δ(R−K) (mag) |
|--------|--------|-----------------------------|-----------------------------|-------------|-----------|-----------|----------|----------|------------|------------|
| NGC 6158 | 13.6   | −0.12 ± 0.01                | −0.17 ± 0.01                | 10.4        | 0.1       | 1.6       | 1.72     | 2.78     | −0.01      | −          |
| RS 8    | 13.8   | −0.09 ± 0.02                | −0.22 ± 0.02                | 5.8         | 0.3       | 2.5       | 1.56     | 2.79     | 0.15       | −          |
| RS 72   | 13.9   | −0.10 ± 0.02                | −0.18 ± 0.02                | 5.5         | 0.3       | 2.5       | 1.71     | 2.81     | −0.01      | −          |
| RS 162  | 14.1   | −0.03 ± 0.01                | −0.13 ± 0.02                | 5.9         | 0.3       | 1.9       | 1.66     | 2.81     | 0.04       | −          |
| BO 24   | 14.3   | −0.06 ± 0.03                | −0.19 ± 0.03                | 3.6         | 0.4       | 2.9       | 1.72     | 3.00     | −0.04 −0.24 | −          |
| BO 26   | 14.6   | −0.13 ± 0.03                | −0.21 ± 0.02                | 3.0         | 0.5       | 2.8       | 1.70     | 2.70     | −0.02      | −          |
| BO 25   | 14.6   | −0.04 ± 0.02                | −0.06 ± 0.02                | 5.3         | 0.3       | 1.8       | 1.55     | 2.78     | 0.12       | −          |
| BO 34   | 15.0   | −0.08 ± 0.03                | −0.03 ± 0.09                | 6.4         | 0.2       | 1.3       | 1.53     | 2.69     | 0.12       | −          |

© 2004 RAS, MNRAS 355, 617–626

Table 1. List of the galaxies with K-band photometry. Columns 2, 3 and 5 are from Paper I. Effective radii (r_e) are estimated in the R band. Columns 6 and 7 give the inner and outer cut-off radii, which are indicated in units of effective radius. Columns 8 and 9 show the B−R and R−K colours estimated within an aperture of 12 arcsec (5 h⁻¹ kpc) in diameter, which is equivalent to that in Bower et al. (1992) for Coma ellipticals. Columns 10 and 11 give the amounts of the offsets applied to B−R and R−K colours, respectively.

of the point spread functions (PSFs) were matched by convolutions of images with Gaussian kernels and these images were combined with the 3σ clipping algorithm. Finally, a PSF size of the stacked image in one band was matched to that in another band by smoothing with Gaussian kernels. A resulting PSF size is 1.1 arcsec in the FWHM.

### 2.3 K-band observation
The K-band imaging observation was performed on 2003 June 20 and 21 with the UKIRT Fast Track Imager (UFTI) on the 3.8-m UKIRT. The UFTI has a 1 K × 1 K array and one pixel of the detector subtends 0.091 arcsec on the sky, yielding a field of view of 1.5 × 1.5 arcmin. A typical seeing size during the observing run was ~0.7 arcsec in the FWHM. The exposure time of each frame was 40 or 60 s and a total on-source integration time of typically 1200 s with the dither pattern of nine telescope pointings. Because the apparent size of a target is too extended to make flat-field frames from object frames themselves, the on-source exposures were interlaced by exposures of adjacent blank sky regions with the same exposure time as that of the object frames.

These K-band imaging data were reduced with IRAF. After dark subtraction, we carried out flat-fielding using sky-flat frames. To make a sky-flat frame, we stacked ~5 blank sky frames and normalized the stacked image by its modal pixel value. An object frame was flat-fielded by the sky-flat frame constructed with the blank sky frames, which were taken close in observation time to the object frame. This method allows us to correct for the complex pattern seen in the flat-field frame, whose contrast slightly varies with time. The flat-fielded blank sky frames have very uniform distribution of brightness across the field of view (global variation is ~0.1 per cent or even smaller, and pixel-to-pixel variation is ~1 per cent), which is reasonable for an image looking at such a small area of the sky.

Sky subtraction was performed by estimating a single background value in each object frame, where the following two steps were used. First, a sky-background in each frame was estimated, by calculating the modal pixel value after bright objects were masked, and was subtracted. The images taken with the telescope dithered around each target were registered by subpixel shifts and these registered images were stacked with the 3σ clipping algorithm. Secondly, because objects that are too faint to be found in the individual exposure but may cause a wrong estimation of sky-background are detectable in this stacked image, they were picked out using SExtractor version 2.2.2 (Bertin & Arnouts 1996). The coordinates of these objects were de-registered to those in the unregistered frames and the pixels where the objects should be were masked. The sizes and shapes of the masks were defined based on those measured in the stacked image. Then, a sky-background was re-estimated in each of the masked images and it was subtracted.

These sky-subtracted images were registered by subpixel shifts and, after the FWHMs of stellar objects in the sky-subtracted and registered frames were matched by convolutions of images with Gaussian kernels, they were stacked with the 3σ clipping algorithm. Finally, the K-band stacked image was aligned with the optical data by using stars in the field of view and a Gaussian convolution was employed to match the FWHMs of stellar objects with those in the optical images.
that in Bower et al. (1992). Also, we estimated the deviations of the colours from the CM relations at their luminosities and adopted the values as zero-point offsets of the colours. The amount of the offset applied to each object is listed in Table 1. These are corrected for in the following presentations of the colours. We note that the $R-K$ colour of BO 24 is $\sim$0.2 mag redder than the others. Because its $B-R$ colour is not unusual, we have also attributed this shift to an observational error and we have corrected for it using the CM relation in the same method as above. It should be stressed that these corrections are performed by shifting zero-points of colours and do not affect any spatial variations of colour in galaxies, which are focused on in this paper. We performed these corrections only for clarity in comparing the data with variations of colours predicted by population synthesis models, as described in the next section.

3 DATA ANALYSES AND RESULTS

3.1 Radial profiles of surface brightness and colours in galaxies

The radial surface brightness profiles of the galaxies in the $B$, $R$ and $K$ bands are indicated in Fig. 2. These profiles were obtained along ellipses fitted to the isophotes with the ELLIPSE task in the STSDAS package with a radial sampling of 0.22 arcsec (1 pixel) along the major axis. Because bright objects in the neighbour of a target galaxy may have serious effects on the fitted ellipses, the neighbours are masked out beforehand. In fitting an ellipse to an isophote, ellipticity is set to be a free parameter. The galaxy centre is fixed to a centroid within which half of the galaxy light is included. In the following analyses, all of the radial profiles and the parameters related to radius are expressed in terms of the equivalent radius of an ellipse, $\sqrt{ab}$, where $a$ and $b$ are the semimajor and semiminor axes of the ellipse.

Before obtaining radial colour profiles in the sample galaxies, we made $B-R$ colour maps of the galaxies after the seeing sizes in both $B$ and $R$ bands were matched (Paper I). These demonstrate that almost all the galaxies show axisymmetric colour distributions independent of morphology and luminosity, and that their radial colour profiles and the colour gradients well represent the two-dimensional colour distributions. We also made $R-K$ colour maps of the galaxies observed in the $K$ band and we have found that their trends are the same as those in $B-R$.

The radial profiles of the $B-R$ and $R-K$ colours of a sample galaxy are constructed by subtracting the surface brightness profile in the $R$ band from those in the $B$ and $K$ bands, both of which were made along the same ellipses fitted to isophotes in the $R$-band image. The results are shown in the bottom panels of Fig. 2. An error bar attached to each data point in the colour profile includes a local sky subtraction error and a standard deviation of colours along each elliptical isophote. To estimate the sky subtraction error, we construct a histogram of pixel values in blank regions of a fully reduced image where surface photometry of a galaxy is performed. Then we adopt the standard deviation around the modal value as an error of background estimation. In the optical data, the pixel values in an annulus around each target, whose inner radius and width are $\sim$3$R_h$ and 11 arcsec (50 pixel), respectively, were used to make the histogram. In the $K$-band data, pixels which remained after objects were masked were investigated in each object frame. In the following, we focus on the portions of the galaxies between the inner and outer cut-off radii, which were defined to avoid the regions where colour distributions are seriously affected by seeing effects and those where colours are rather poorly determined.

The outer cut-off radius is defined to be a radius where the $R$-band surface brightness of a galaxy is 22.5 mag arcsec$^{-2}$ (Paper I). At this radius, the typical error of $B-R$ colour amounts to $\sim$0.1 mag. Because the typical error of $R-K$ colour is also $\sim$0.1 mag at this radius, it is reasonable to adopt the same cut-off as that applied to the optical data in investigating the radial profiles of $R-K$ colour and estimating the gradients. The $R-K$ colour profile of BO 34 (Fig. 2) starts becoming noisy at a smaller radius than in the other galaxies due to the $\sim$40 per cent shorter integration time in the $K$ band.

The inner cut-off radius is necessary to mitigate seeing effects on colour gradients. In order to define this, we performed simulations using artificial elliptical galaxies added on the real images to investigate deviations of measured colour gradients from the intrinsic values caused by seeing effects. We also investigated their dependences on size, luminosity, ellipticity and intrinsic colour gradient of the model elliptical galaxy (see Paper I for details). Based on the simulations, we defined the inner cut-off radius to be 1.5 arcsec, which can reduce the deviation of a measured colour gradient from the intrinsic value down to the level comparable to a fitting error of the regression line. It should be mentioned that, because the FWHMs of stellar objects in the $K$-band images are smaller than those in the $B$- and $R$-band images and the $K$-band data were smoothed to match the FWHMs with those in the optical data, this inner cut-off is not required to be modified.

To summarize, the same inner and outer cut-offs defined in $B-R$ colour can be adopted to the radial colour profiles in $R-K$. In Table 1, the cut-off radii for each galaxy scaled by the effective radius are tabulated. Also listed are the $B-R$ and $R-K$ colour gradients calculated by fitting regression lines to the colour profiles between the inner and outer cut-off radii.

3.2 Spatially resolved $B-R$ and $R-K$ diagrams

Fig. 3 shows the $B-R$ and $R-K$ colours of each target galaxy within the region between the inner and outer cut-off radii. The colours at the outer radii are indicated with larger symbols and the radial sampling is the same as that in the radial colour profiles in Fig. 2 (0.22 arcsec). The two colour diagrams are ordered in decreasing luminosity from left to right and top to bottom (NGC 6158 is the most luminous and BO 34 is the least luminous). The data points in each panel show a basic trend of radial colour variation, such that colours are redder in both $B-R$ and $R-K$ at smaller radii. It is interesting to note that although the sample is small, there seems to be a variety in distribution of the colours on the diagram from galaxy to galaxy.

Although it is hard to disentangle the age–metallicity degeneracy, it is still possible to obtain some insight into how stellar age and metallicity vary across a galaxy by comparing the $B-R$ and $R-K$ colour variations with predictions from a simple stellar population (SSP) model. The grid superposed on the two colour diagrams indicates variations of $B-R$ and $R-K$ colours of an SSP model along with its age and metallicity. This is constructed using the SSP models by PEGASE version 2.0 (Fioc & Rocca-Volmerange 1997) with the Salpeter initial mass function (IMF). The details of the SSP models for the grid are indicated in Fig. 4. We sample the ages of 5, 10 and 18 Gyr and the metallicities of 0.008 (0.4 $Z_\odot$), 0.02 (Z$\odot$) and 0.03 (1.5 Z$\odot$). It is stressed that only relative values of age and metallicity from a model are discussed here, and determining their absolute values in a galaxy is beyond the scope of this paper.
Figure 2. $R$-band image (top), radial profiles of surface brightness (middle) and colour (bottom). In the middle panels, open triangles, solid triangles and circles indicate $B$-, $R$- and $K$-band surface brightness profiles, respectively. In the bottom panels, triangles and circles indicate $B-R$ and $R-K$ colours, respectively, and two vertical lines show the inner and outer cut-off radii.
Comparing the data points with the grid in Fig. 3, it is suggested that the colour distributions tend to be in parallel with the prediction for a constant age, and it seems to be dominated by a metallicity gradient in the sense that stars are more metal-rich in the inner regions. In most of the ellipticals, the data do not seem to support the fact that the primary origin of the colour gradients is an age gradient.

It is worth investigating how much the grid on the two-colour diagram can vary from model to model. We compare the grid by PEGASE with that by (Vazdekis et al. 1996, hereafter V96) and those by GALAXEV (Bruzual & Charlot 2003) with the Padova 1994 (P94) or Padova 2000 (P00) evolutionary tracks in Fig. 5, where the Salpeter IMF is adopted for all the models. The lower and upper mass cutoffs are 0.1 and 100 M⊙ in PEGASE, 0.0992 and 72 M⊙ in V96 and 0.1 and 120 M⊙ in GALAXEV. Note that for the GALAXEV model with the P94 evolutionary tracks, the metallicity of the most metal-rich SSPs is 2.5 times larger than the solar value, while it is 1.5 times larger than the solar value for all other models. By using PEGASE, the variation of the grid due to the choice of IMF is also investigated. The grids for three representative IMFs are indicated in Fig. 6: the Salpeter IMF, the Kroupa IMF (Kroupa, Tout & Gilmore 1993) and the Millar–Scalo IMF (Miller & Scalo 1979). As shown in Fig. 5, there is some discrepancy in the shape of the grid as well as its location on the two-colour diagram among the models. On the other hand, Fig. 6 suggests that both the shape and location of the grid are rather insensitive to the choice of IMF.

Considering contributions of both age and metallicity gradients, a colour gradient can be described as

\[
\frac{d(\text{colour})}{d \log r} = a \frac{d \log Z}{d \log r} + b \frac{d \log (\text{age})}{d \log r},
\]

where

\[
a \equiv \frac{\partial(\text{colour})}{\partial \log Z} \bigg|_{\text{age}},
\]

and

\[
b \equiv \frac{\partial(\text{colour})}{\partial \log (\text{age})} \bigg|_{Z}.
\]

Given the sensitivities of $B-R$ and $R-K$ colours to age and metallicity (i.e. $a$ and $b$), which can be estimated with an SSP model, the age and metallicity gradients can be worked out simultaneously using the $B-R$ and $R-K$ colour gradients derived with the data. A similar method has been applied to absorption-line strength gradients (Kobayashi & Arimoto 1999; Mehlert et al. 2003; see also Henry & Worthey 1999). The coefficient $a$ is determined within a range of metallicity ($0.4 < Z/Z_{\odot} < 1.5$) by using colours predicted with SSPs having a single age (10 Gyr). The coefficient $b$ is calculated within a range of age between 5 and 18 Gyr by using SSPs having the solar metallicity. We calculated these coefficients for each of the SSP models (PEGASE, V96 and GALAXEV with P94 and P00) with the Salpeter IMF assumed (Table 2) and derived age and metallicity gradients of a galaxy. The results from our data are shown in Table 3, indicating that negative metallicity gradients (stellar metallicity is higher towards the galaxy centre) are detected in all the cluster ellipticals but BO 34, while an age gradient is significantly detected only in NGC 6158. This suggests that the cluster ellipticals have metallicity gradients while their age gradients are consistent with zero; using PEGASE, the typical metallicity gradient is estimated to

\[3\] For GALAXEV with P94, the coefficient $a$ is determined for $0.4 < Z/Z_{\odot} < 2.5$. 

\[\text{Figure } 2 - \text{continued}\]
Radial variations of optical and NIR colours

Figure 3. $B-R$ and $R-K$ colour–colour diagrams. The galaxies are arranged in order of decreasing luminosity from left to right and top to bottom right (NGC 6158 is the most luminous and BO 34 is the least luminous). The grid superposed with the data points on each diagram shows variations of $B-R$ and $R-K$ colours of an SSP along with its age and metallicity predicted using PEGASE for the Salpeter IMF. A bold line indicates the colour variation predicted for a constant age, and a thin line depicts that for a constant metallicity. More details of the grid are explained in Fig. 4. Note that the same ranges of colours are shown in all panels.

Figure 4. Details of the SSP model grid with PEGASE superposed with the data in Fig. 3. The reddening vector for $A_V = 0.1$ mag is also shown for comparison.

be $-0.16 \pm 0.09$ in $d \log Z/d \log r$, while the age gradient is estimated to be $-0.10 \pm 0.14$ in $d \log (\text{age})/d \log r$. It is mentioned that although estimated values of age and metallicity gradients depend on the model, the qualitative trend that the cluster ellipticals have negative metallicity gradients but age gradients are not detected significantly can be seen in all the models.

4 DISCUSSION

It has also been suggested from other recent studies that nearby ellipticals have negative metallicity gradients while their age gradients are consistent with zero (Mehlert et al. 2003; Wu et al. 2004). The presence of a metallicity gradient and the absence of an age gradient are consistent with the monolithic collapse scenario. The typical metallicity gradient estimated from gradients of colours and metal absorption-line strengths in nearby ellipticals could be reproduced in a recent model of galaxy formation through a monolithic-like process (e.g. Kawata 1999). Because all stars are presumed to form nearly coevally at high redshift in this scenario, no significant variation in stellar age across a galaxy would be expected. On the other hand, it is less clear what type of radial variations of stellar populations can be formed in elliptical galaxies in the framework of hierarchical galaxy formation. However, it has recently been suggested by numerical simulations that metallicity gradients estimated in nearby ellipticals assuming no age gradients can be reproduced including its variety (Kobayashi 2004). It is intriguing to mention that, unlike the monolithic collapse scenario, an age gradient can be acquired due to star formation associated with mergers and/or accretions. Exploring what type of age gradients elliptical galaxies could possess in the hierarchical galaxy formation may provide clues to understanding their formation processes and evolutionary histories (Benson, Ellis & Menanteau 2002).

Our data also suggest that colour distributions on the two-colour diagram tend to be less scattered in less luminous cluster ellipticals. In other words, stellar populations may be spatially more uniform in less luminous cluster ellipticals. This is not because in less luminous elliptical colours are investigated within the smaller portions of galaxies; the outer cut-off radii scaled by effective radii are similar in all the galaxies (Table 1). If the colour gradients originate from
pure metallicity gradients, this trend would indicate that the metallicity gradients correlate with the galaxy luminosities and could support the monolithic collapse scenario (Larson 1974; Carlberg 1984; Kawata & Gibson 2003). However, the metallicity gradients estimated using both $B-R$ and $R-K$ colour gradients do not seem to correlate well with the luminosities. This may simply be due to the poor statistics and/or the fact that the individual measurements of the metallicity gradients may be too coarse. More precise estimations of age and metallicity gradients for a larger sample of galaxies will be necessary for detailed studies of the relationship between radial variation of stellar population and galaxy luminosity in the cluster ellipticals.

Figure 5. Grids constructed with different SSP models are shown. In each panel, the colour variation predicted with PEGASE (solid line) is compared with that predicted with V96 or GALAXEV (dashed line). The Salpeter IMF is adopted in all the models. For the grid from GALAXEV with the P94 tracks (right panel), the ages of 5, 10 and 18 Gyr and the metallicities of $Z = 0.008, 0.02$ and 0.05 are used. For the other grids, the ranges of age and metallicity are the same as those in Fig. 4; 5, 10 and 18 Gyr in age and $Z = 0.008, 0.02$ and 0.03 in metallicity. Note that slightly larger ranges of colours than those in Fig. 3 are used for the grids to be included entirely.

Figure 6. Variation of the grid due to choice of IMF is exemplified. In each panel, the colour variation predicted with the Salpeter IMF (solid line) is compared with that of the Kroupa IMF or the Miller–Scalo IMF (dashed line). All the grids are constructed using PEGASE.

Table 2. Sensitivities of $B-R$ and $R-K$ colours to age and metallicity. The coefficient $a \equiv \frac{\partial \text{colour}}{\partial \log Z_{\text{age}}}$ is determined within a range of metallicity ($0.4 < Z/Z_\odot < 2.5$ for GALAXEV with P94 and $0.4 < Z/Z_\odot < 1.5$ for the other models) by using SSPs with a 10-Gyr age. The coefficient $b \equiv \frac{\partial \text{colour}}{\partial \log \text{age}}Z$ is determined within a range of age between 5 and 18 Gyr by using SSPs with the solar metallicity.

| Model            | $B-R$ | $R-K$ |
|------------------|-------|-------|
| PEGASE           | 0.34  | 0.38  |
| V96              | 0.33  | 0.37  |
| GALAXEV (P94)    | 0.56  | 0.39  |
| GALAXEV (P00)    | 0.27  | 0.33  |

Age and metallicity gradients in nearby ellipticals have recently been investigated in a range of galaxy environment. In Mehlert et al. (2003), the age and metallicity gradients in 35 elliptical and S0 galaxies in the Coma cluster were estimated from the gradients of absorption-line indices (H$\beta$, Mg$b$ and $\langle$Fe$\rangle$). In Wu et al. (2004), the gradients in 36 elliptical and S0 galaxies in the Sloan Digital Sky Survey Early Data Release, which are sampled not from a specific cluster but from various environments, were estimated with multiband surface photometry from optical to NIR. Including our study of the luminous early-type galaxies in a rich cluster A2199, the presence of a metallicity gradient and the absence of an age gradient have been suggested in all of these studies. This may imply that there is no strong dependence on galaxy environment in the radial gradient of stellar population in an elliptical galaxy.

Finally, it should be mentioned that dust extinction may have some effects on a colour gradient in an elliptical galaxy (e.g. Goudfrooij & de Jong 1995). As a matter of fact, even if an elliptical galaxy consists of a mixture of stars without any radial gradients of stellar population and diffusely distributed dust, a calculation of the radiative transfer in the galaxy suggests that the colour gradients could be reproduced only by the dust effects (Witt, Thronson & Capuano 1992; Wise & Silva 1996). However, many elliptical galaxies show not only colour gradients but also metal absorption-line strength gradients, which are unlikely to be created by effects of dust extinction. It has also been suggested that, on average, metallicity gradients in elliptical galaxies as estimated by a population synthesis model from colour gradients are consistent with those estimated from absorption-line index gradients (e.g. Peletier et al. 1990a; Davies et al. 1993). Nevertheless, there are some exceptions.
Table 3. Gradients of age and metallicity estimated from the $B-R$ and $R-K$ gradients.

| Galaxy   | Model      | $d \log (age)/d \log r$ (dex$^{-1}$) | $d \log Z/d \log r$ (dex$^{-1}$) |
|----------|------------|-------------------------------------|----------------------------------|
| NGC 6158 | PEGASE     | $-0.24 \pm 0.07$                    | $-0.09 \pm 0.05$                 |
|          | V96        | $-0.15 \pm 0.08$                    | $-0.19 \pm 0.06$                 |
|          | GALAXEV (P94) | $-0.24 \pm 0.09$            | $-0.05 \pm 0.04$                 |
|          | GALAXEV (P00) | $-0.28 \pm 0.10$            | $-0.09 \pm 0.09$                 |
| RS 8     | PEGASE     | $+0.01 \pm 0.14$                   | $-0.28 \pm 0.09$                 |
|          | V96        | $+0.13 \pm 0.16$                   | $-0.42 \pm 0.11$                 |
|          | GALAXEV (P94) | $+0.07 \pm 0.17$            | $-0.21 \pm 0.09$                 |
|          | GALAXEV (P00) | $+0.08 \pm 0.20$            | $-0.44 \pm 0.18$                 |
| RS 72    | PEGASE     | $-0.12 \pm 0.14$                   | $-0.16 \pm 0.09$                 |
|          | V96        | $-0.03 \pm 0.16$                   | $-0.27 \pm 0.11$                 |
|          | GALAXEV (P94) | $-0.10 \pm 0.17$            | $-0.11 \pm 0.09$                 |
|          | GALAXEV (P00) | $-0.11 \pm 0.20$            | $-0.23 \pm 0.18$                 |
| RS 162   | PEGASE     | $+0.12 \pm 0.09$                   | $-0.22 \pm 0.07$                 |
|          | V96        | $+0.20 \pm 0.10$                   | $-0.31 \pm 0.09$                 |
|          | GALAXEV (P94) | $+0.18 \pm 0.11$            | $-0.18 \pm 0.06$                 |
|          | GALAXEV (P00) | $+0.21 \pm 0.13$            | $-0.37 \pm 0.13$                 |
| BO 24    | PEGASE     | $+0.10 \pm 0.21$                   | $-0.28 \pm 0.14$                 |
|          | V96        | $+0.20 \pm 0.23$                   | $-0.41 \pm 0.17$                 |
|          | GALAXEV (P94) | $+0.17 \pm 0.26$            | $-0.23 \pm 0.13$                 |
|          | GALAXEV (P00) | $+0.19 \pm 0.30$            | $-0.46 \pm 0.26$                 |
| BO 26    | PEGASE     | $-0.20 \pm 0.19$                   | $-0.16 \pm 0.12$                 |
|          | V96        | $-0.10 \pm 0.21$                   | $-0.28 \pm 0.14$                 |
|          | GALAXEV (P94) | $-0.19 \pm 0.23$            | $-0.10 \pm 0.11$                 |
|          | GALAXEV (P00) | $-0.23 \pm 0.27$            | $-0.20 \pm 0.22$                 |
| BO 25    | PEGASE     | $-0.07 \pm 0.14$                   | $-0.04 \pm 0.09$                 |
|          | V96        | $-0.04 \pm 0.16$                   | $-0.07 \pm 0.11$                 |
|          | GALAXEV (P94) | $-0.07 \pm 0.17$            | $-0.02 \pm 0.09$                 |
|          | GALAXEV (P00) | $-0.08 \pm 0.20$            | $-0.04 \pm 0.18$                 |
| BO 34    | PEGASE     | $-0.33 \pm 0.33$                   | $+0.13 \pm 0.27$                 |
|          | V96        | $-0.33 \pm 0.39$                   | $+0.12 \pm 0.35$                 |
|          | GALAXEV (P94) | $-0.39 \pm 0.43$            | $+0.13 \pm 0.24$                 |
|          | GALAXEV (P00) | $-0.46 \pm 0.49$            | $+0.27 \pm 0.50$                 |

and it is hard to isolate the effect of dust extinction on an individual galaxy basis. Future observation in the far-infrared with high spatial resolution may be able to give constraints on such a spatial variation of effects of dust extinction.

5 SUMMARY

We performed $K$-band surface photometry for luminous early-type galaxies in a nearby rich cluster A2199. Combining it with $B$- and $R$-band surface photometry, radial variations of $B-R$ and $R-K$ colours in the galaxies were investigated. It is found that the inner regions of the galaxies are redder in both $B-R$ and $R-K$ colours. Comparing the radial variations of both colours with predictions of SSP models for a range of ages and metallicities, it is suggested that cluster ellipticals have metallicity gradients but their age gradients are consistent with zero, although the sample is small. The typical metallicity gradient is estimated to be $-0.16 \pm 0.09$ in $d \log Z/d \log r$, while the age gradient is estimated to be $-0.10 \pm 0.14$ in $d \log (age)/d \log r$. Because similar results have also been obtained in other recent studies by investigating ellipticals in the Coma cluster and less dense environments, it seems that radial gradients of stellar populations in elliptical galaxies, and thus their evolutionary histories, are rather insensitive to galaxy environment.

Considering the trend found in our optical study that less luminous ellipticals have less steep colour gradients, it is suggested that they have spatially more uniform distributions of both $B-R$ and $R-K$ colours and thus probably stellar population. However, the metallicity gradients estimated using both $B-R$ and $R-K$ colours do not seem to correlate well with the galaxy luminosities. This may simply be due to the poor statistics and/or the fact that the individual measurements of the metallicity gradients may be too coarse. More precise estimations of age and metallicity gradients for a larger sample of galaxies will be necessary for detailed studies of the relationship between the radial variation of stellar population and galaxy luminosity in the cluster ellipticals.

ACKNOWLEDGMENTS

We are grateful to the staff of the Joint Astronomy Centre for its support of the UKIRT observation. We appreciate the support from the members of the University of Hawaii observatory. We also thank the referee, Dr Francesco La Barbera, for helpful comments and advice. This research made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

REFERENCES

Benson A. J., Ellis R. S., Menanteau F., 2002, MNRAS, 336, 564
Bertin E., Arnouts S., 1996, A&AS, 117, 393
Bower R. G., Lucey J. R., Ellis R. S., 1992, MNRAS, 254, 601
Bruzual G., Charlot S., 2003, MNRAS, 344, 1000
Butcher H. R., Oemler A. Jr., 1985, ApJS, 57, 665
Carlberg R. G., 1984, ApJ, 286, 403
Davies R. L., Sadler E. M., Peletier R. F., 1993, MNRAS, 262, 650
Fioc M., Rocca-Volmerange B., 1997, A&A, 326, 950
Goudfrooij P., de Jong T., 1995, A&A, 298, 784
Hawarden T. G., Leggett S. K., Letawsky M. B., Ballantyne D. R., Casali M. M., 2001, MNRAS, 325, 563
Henry R. B. C., Worthey G., 1999, PASP, 111, 919
Kawata D., 1999, PASJ, 51, 931
Kodama T., Arimoto N., Barger A. J., Aragón-Salamanca A., 1998, A&A, 334, 99
Kroupa P., Tout C. A., Gilmore G., 1993, MNRAS, 262, 545
La Barbera F., Busarello G., Massarotti M., Merluzzi P., Mercurio A., 2003, A&A, 409, 21
Landolt A. U., 1992, AJ, 104, 340
Lucey J. R., Guzmán R., Steel J., Carter D., 1997, MNRAS, 287, 899
Mehlert D., Thomas D., Saglia R. P., Bender R., Wegner G., 2003, A&A, 407, 423
Miller G. E., Scalo J. M., 1979, ApJS, 41, 513
Peletier R. F., Davies R. L., Illingworth G. D., Davis L. E., Cawson M., 1990a, AJ, 100, 1091
Peletier R. F., Valentijn E. A., Jameson R. F., 1990b, A&A, 233, 62
Rood H. J., Sastry G. N., 1972, AJ, 77, 451
Saglia R. P., Maraston C., Greggio L., Bender R., Ziegler, B., 2000, A&A, 360, 911

© 2004 RAS, MNRAS 355, 617–626
N. Tamura and K. Ohta

Simien F., de Vaucouleurs G., 1986, ApJ, 302, 564
Stanford S. A., Eisenhardt P. R., Dickinson M., 1998, ApJ, 492, 461
Tamura N., Ohta K., 2000, AJ, 120, 533
Tamura N., Ohta K., 2003, AJ, 126, 596 (Paper I)
Tamura N., Kobayashi C., Arimoto N., Kodama T., Ohta K., 2000, AJ, 119, 2134
Vazdekis A., Casuso E., Peletier R. F., Beckman J. E., 1996, ApJS, 106, 307 (V96)

Witt A. N., Thronson H. A. Jr, Capuano J. M. Jr, 1992, ApJ, 393, 611
Wu H., Shao Z., Mo H. J., Xia X., Deng Z., 2004, ApJ, submitted (astro-ph/0404226)

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.