ORIGIN OF COLOR GRADIENTS IN ELLIPTICAL GALAXIES

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Received 1999 August 8; accepted 2000 January 7

ABSTRACT

The origin of color gradients in elliptical galaxies is examined by comparing model gradients with those observed in the Hubble Deep Field. The models are constructed so as to reproduce color gradients in local elliptical galaxies either by a metallicity gradient or by an age gradient. By looking-back a sequence of the color gradient as a function of redshift, the age-metallicity degeneracy is solved. The observed color gradients in elliptical galaxies at $z = 0.1$ to 1.0 agree excellently with those predicted by the metallicity gradient, while they deviate significantly from those predicted by the age gradient even at $z \sim 0.3$, and the deviation becomes larger with increasing redshift. This result does not depend on cosmological parameters and parameters for an evolutionary model of an elliptical galaxy within a reasonable range. Thus our results clearly indicate that the origin of color gradients is not age but stellar metallicity.

Key words: galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Stellar populations in an elliptical galaxy are not uniform. Stars at a galaxy center are redder than those in the outer region, and colors in a galaxy become progressively bluer with increasing radius (see, e.g., Vader et al. 1988; Franx, Illingworth, & Heckman 1989; Peletier et al. 1988; Franx, Illingworth, & Heckman 1989; Peletier et al. 1988a; Peletier, Valentijn, & Jameson 1990b). Peletier et al. (1990a) made surface photometry in the $U$, $B$, and $R$ bands for a sample of 39 nearby elliptical galaxies and examined their color gradients in $U-R$ and $B-R$. They found that typical color gradients $\Delta(U-R)/\Delta \log r$ and $\Delta(B-R)/\Delta \log r$ are $-0.20$ and $-0.09$ mag dex$^{-1}$, respectively, and demonstrated that dispersion of the color gradients is small, i.e., only 0.02 mag dex$^{-1}$ in both colors. Since many elliptical galaxies show radial gradients in line strengths, such as Mg$_b$, Fe$_1$ (5270 Å), and Fe$_2$ (5335 Å) (see, e.g., Carollo, Danziger, & Buson 1993; Davies, Sadler, & Peletier 1993; Gonzalez 1993; Kobayashi & Arimoto 1999), the color gradients have been naively assumed to originate from a metallicity gradient inside a galaxy.

However, such an interpretation for the origin of the color gradient is premature, because stellar populations of either higher metallicity or older age can make a galaxy redder. This problem, which is called the age-metallicity degeneracy, was first pointed out by Worthey, Trager, & Faber (1996) and then discussed by Arimoto (1996). For example, the degeneracy makes it difficult to interpret the origin of the tight correlation between colors and magnitudes of elliptical galaxies; brighter elliptical galaxies tend to have redder colors. This correlation, called the color-magnitude (CM) relation, can be excellently reproduced by a metallicity sequence with a galactic wind model based on a monolithic collapse (see, e.g., Arimoto & Yoshii 1987), where more massive elliptical galaxies should be more enriched in metals and thus become redder. However, Worthey et al. (1996) claimed that an age sequence of elliptical galaxies can equivalently reproduce the CM relation if brighter elliptical galaxies are older and thus redder. To break this degeneracy, Kodama & Arimoto (1997) built up two model sequences (metallicity and age sequences) that are normalized to reproduce the CM relation of elliptical galaxies in the Coma Cluster by using their evolutionary synthesis model. They compared the evolution of the model CM relation with the observed relations of elliptical galaxies in distant clusters. The CM relations produced by a metallicity sequence agree with the observed relations to $z \sim 1$, while those produced by an age sequence deviate from the observed ones significantly, even at $z \sim 0.2$–0.3, showing that the origin of the CM relation is primarily a metallicity variation with galaxy mass. The CM relation can also be reproduced in a hierarchical galaxy formation (Kauffmann & Charlot 1998). Although a model of Kauffmann & Charlot (1998) allows a more extended period of star formation in elliptical galaxies, it shows that the CM relation is produced by a metallicity variation. It is thus worth emphasizing that the interpretation of the CM relation with a metallicity sequence is robust and independent of detailed assumptions on galaxy formation processes.

Recently, the origin of color and line strength gradients in elliptical galaxies has been discussed with elaborate models. Martinelli, Matteucci, & Colafrancesco (1998) tried to reproduce the color gradients by assuming that a galactic wind blows later in the inner part of a galaxy because of a deeper potential well defined mainly by dark matter. Adopting a multizone model that takes into account gas dynamics, local star formation, and chemical evolution, Tantalo et al. (1998) reproduced radial gradients of colors and line strengths to some extent. Nevertheless, these detailed modelings are not fully successful; the inner part of a galaxy becomes too iron-enriched because of an extended period of star formation there.

In this paper, adopting a much simpler approach without entering into details of physical processes of galaxy formation and evolution, we try to depict essential aspects of the origin of color gradients. Our approach is similar to that adopted by Kodama & Arimoto (1997) for studying the origin of the CM relation. By using a population synthesis model, we first make two different model galaxies, each of
which can reproduce a typical color gradient of elliptical galaxies at $z = 0$ by changing either mean stellar metallicity or age, and let them evolve back in time. The evolution of color gradients thus predicted are then compared with the observed ones in distant elliptical galaxies extracted from the Hubble Deep Field North (HDFN; Williams et al. 1996). As was demonstrated by Kodama & Arimoto (1997), the best way to disentangle the age and metallicity effects on galaxy colors is to look-back galaxies at high redshift.

It should be noted that dust extinction in elliptical galaxies may have some effect on the color gradients (Goudfrooij & de Jong 1994; Wise & Silva 1996). Witt, Thronson, & Capuano (1992) calculated a radiative transfer within elliptical galaxies by assuming a diffuse distribution of dust and suggested that surface brightness profiles and color gradients could be well reproduced by dust effects. In fact, it has been believed that $IRAS$ detected far-infrared emission for about half the elliptical galaxies observed. However, since many of the detections were made with an $\sim 3 \sigma$ threshold, a significant fraction of the previously claimed detections may be spurious. Only 12%--17% of the observed elliptical galaxies are detected with a sufficiently high confidence level (Bregman et al. 1998). Therefore, in this paper, we have chosen to focus on age and metallicity effects only. The effects of dust extinction on the color gradients are still open and will be studied in our subsequent paper.

This paper is organized as follows: The model description is given in § 2. The sample selection and data reduction of elliptical galaxies in the HDFN are described in § 3. The observed color gradients are compared with the models in § 4. Discussion and conclusions are presented in §§ 5 and 6, respectively. The cosmological parameters adopted throughout this paper are $H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_0 = 0.2$, and $\Lambda = 0$ unless otherwise noted.

2. MODELS

The color gradients can be reproduced by either a metallicity gradient or an age gradient, but these effects are degenerate at $z = 0$. We attempt to break up such degeneracy by comparing model color gradients with the observed ones of ellipticals at high redshifts in the HDFN. We have built two sequences of evolutionary models under the alternative assumptions that (1) the color gradients originate from the metallicity gradient of old stellar populations or (2) the color gradients arise from the age gradient of stars that have the same metallicity within the galaxy.

The metallicity sequence is constructed as follows: We assume that star formation lasted progressively longer toward the galaxy center; i.e., the galactic wind blew later in the inner region, so that the mean stellar metallicity became higher and the colors became redder. Even at the galaxy center, however, the star formation stopped at early times ($t_{gw} = 0.83 \text{ Gyr}$), and the stellar ages are almost the same everywhere within a galaxy, 15 Gyr at $z = 0$ (see Tables 1 and 2). This assumption seems to be justified, because the duration of star-forming activity is determined from the local dynamic potential (Larson 1974) and should be longer in the inner region. To build a metallicity gradient, however, this hypothesis is not unique; other hypotheses, such as higher star formation efficiency, a larger yield (i.e., a flatter initial mass function [IMF] slope), or higher metallicity of infalling gas toward the galaxy center can also produce the metallicity gradient. However, such details are not essential in the present study, because as long as the mean stellar metallicity increases in the inner part of a galaxy while stars are uniformly old, the resulting evolution of the color gradient is essentially the same. We should stress this, because this paper aims to show how color gradients of stellar populations behave as a function of look-back time, not to seek the best model to explain the observed color gradients of sampled galaxies in the HDFN. The galactic wind is conventionally introduced to build up the metallicity gradient, and it might be possible that such gradients can also be established if elliptical galaxies formed by hierarchical clustering.

The age sequence is constructed as follows: Star formation started earlier in the inner regions but lasted equally long ($t_{gw} = 0.83 \text{ Gyr}$) everywhere in a galaxy. The period chosen here is the same as that assumed for the center-of-metallicity sequence model. In this way, the mean stellar ages $t_{age}$ become older and colors become redder in the inner regions, while the mean stellar metallicities are almost the same everywhere (see Tables 1 and 2). It is hard to comprehend the physical process that produce such an age gradient, although it may occur if a series of young dwarf
TABLE 2

Properties of Model Galaxies at $z = 0$

| $\log r/r_e$ | $-1$ | $-0.875$ | $-0.75$ | $-0.625$ | $-0.5$ | $-0.375$ | $-0.25$ | $-0.125$ | $0$ |
|-------------|------|----------|--------|----------|--------|--------|--------|--------|-----|
| Metallicity Sequence ($t_{\text{age}} = 15$ Gyr) |
| $\log Z/Z_O$ | 0.254 | 0.240 | 0.219 | 0.201 | 0.182 | 0.168 | 0.142 | 0.123 | 0.101 |
| $\pm 0.004$ |
| $[\text{Fe/H}]$ | $-0.069$ | $-0.088$ | $-0.112$ | $-0.131$ | $-0.151$ | $-0.181$ | $-0.213$ | $-0.245$ | $-0.273$ | $-0.307$ |
| $\pm 0.006$ |
| $[\text{Mg/Fe}]$ | 0.467 | 0.473 | 0.475 | 0.476 | 0.478 | 0.479 | 0.481 | 0.483 | 0.486 |
| $\pm 0.004$ | $-0.069$ | $-0.115$ | $-0.155$ | $-0.199$ | $-0.245$ | $-0.290$ | $-0.336$ | $-0.384$ | $-0.431$ |
| $U-R$ | 2.166 | 2.158 | 2.144 | 2.132 | 2.118 | 2.109 | 2.089 | 2.055 | 2.026 |
| $\pm 0.021$ | $2.166$ | 2.152 | 2.134 | 2.115 | 2.098 | 2.076 | 2.055 | 2.055 | 2.014 |
| $B-R$ | 1.632 | 1.627 | 1.620 | 1.615 | 1.606 | 1.599 | 1.589 | 1.572 | 1.563 |
| $\pm 0.004$ | $1.632$ | 1.619 | 1.606 | 1.593 | 1.587 | 1.578 | 1.566 | 1.552 | 1.539 |
| $V_{606} - I_{814}$ | 0.576 | 0.574 | 0.572 | 0.569 | 0.567 | 0.565 | 0.562 | 0.559 | 0.556 |
| $\pm 0.004$ | $0.576$ | 0.573 | 0.570 | 0.566 | 0.564 | 0.562 | 0.560 | 0.559 | 0.556 |
| Age Sequence ($t_{\text{age}} = 0.8$ Gyr) |
| $t_{\text{age}}$ | 15.00 | 14.35 | 13.65 | 13.00 | 12.40 | 11.20 | 10.20 | 9.75 | 9.20 |
| $\pm 0.004$ | $15.00$ | 14.00 | 13.10 | 12.20 | 10.60 | 9.75 | 9.00 | 8.60 | 7.80 |
| $\log Z/Z_O$ | 0.254 | 0.254 | 0.254 | 0.254 | 0.254 | 0.254 | 0.254 | 0.254 | 0.254 |
| $\pm 0.004$ | $[\text{Fe/H}]$ | $-0.069$ | $-0.069$ | $-0.070$ | $-0.070$ | $-0.070$ | $-0.070$ | $-0.070$ | $-0.070$ | $-0.070$ |
| $\pm 0.004$ | $[\text{Mg/Fe}]$ | 0.467 | 0.467 | 0.467 | 0.467 | 0.467 | 0.467 | 0.467 | 0.467 | 0.467 |
| $U-R$ | 2.167 | 2.154 | 2.140 | 2.126 | 2.114 | 2.109 | 2.099 | 2.082 | 2.068 |
| $\pm 0.021$ | $2.167$ | 2.147 | 2.129 | 2.112 | 2.089 | 2.068 | 2.047 | 2.031 | 2.012 |
| $B-R$ | 1.633 | 1.627 | 1.615 | 1.608 | 1.604 | 1.595 | 1.589 | 1.572 | 1.563 |
| $\pm 0.004$ | $1.633$ | 1.618 | 1.603 | 1.586 | 1.579 | 1.567 | 1.553 | 1.538 | 1.522 |
| $V_{606} - I_{814}$ | 0.577 | 0.575 | 0.573 | 0.570 | 0.569 | 0.566 | 0.564 | 0.561 | 0.560 |
| $\pm 0.004$ | $0.577$ | 0.573 | 0.568 | 0.562 | 0.559 | 0.562 | 0.557 | 0.557 | 0.557 |

Note.— The first, second, third, and fourth rows of each physical quantity correspond to those for the color gradient $\Delta(B-R)/\Delta \log r = -0.05, -0.07, -0.11, \text{and} -0.13 \text{mag dex}^{-1}$, respectively.
galaxies accrete onto a massive galaxy and are tidally disrupted at the outer region of the galaxy before falling into the center. However, it is not our aim anyway to construct a physically motivated age-sequence model.

Although we do not discuss in this paper in detail, we have tried to build an alternative age-sequence model in which star formation began everywhere 15 Gyr ago and lasted longer at the outer parts of the galaxy, keeping the same metallicity everywhere as that at the galaxy center. As a result, the mean stellar ages become younger from the galaxy center toward the outer region. However, this model fails to reproduce the observed color gradients in nearby ellipticals. If old stellar populations are contained in the outer regions and if the mean metallicity is as rich there as that at the center, there is no way by making their mean ages young to build up the color gradients as steep as the observed ones.

Both metallicity and age sequences are constructed to reproduce typical color gradients observed for nearby elliptical galaxies; $\Delta(B-R)/\Delta \log r = -0.09 \pm 0.02$ mag dex$^{-1}$ (i.e., $-0.07$ and $-0.11$ mag dex$^{-1}$) and $B-R = 1.633$ magnitudes at $r = r_e/10$ ($r_e$ refers to an effective radius), which is derived from the mean $B-R$ color at $r_e/2$ and $\Delta(B-R)/\Delta \log r = -0.09$ mag dex$^{-1}$ (Peletier et al. 1990a). We also construct models that reproduce the color gradients of $-0.09 \pm 0.04$ mag dex$^{-1}$ (i.e., $-0.05$ and $-0.13$ mag dex$^{-1}$), which include the gradients of almost all the sample ellipticals in Peletier et al. (1990a). Thus we have a set of four model sequences each for the age sequence and the metallicity sequence.

To calculate gradients of photochemical properties of a galaxy, we construct a galaxy model consisting of a shell at each radius and assume that each shell evolves independently. The star formation rate (SFR) in a shell is proportional to the gas fraction (Schmidt law), with a timescale of 0.1 Gyr. A primordial gas is supplied to the shell at the rate $\exp[-t/(0.1 \text{ Gyr})]$. An infall of primordial gas onto the shell may seem rather strange, since it is more likely that the inner shells suffer from the infall of enriched gas from the outer shells. However, a proper modeling of such an effect is beyond our scope. Since the infall rate we employed in the present study is significantly high, the resulting evolutionary behavior of the color gradient remains almost the same even if we adopt the “simple” model prescription instead of the infall model. For an IMF, a power-law mass spectrum with a slope of $x = 1.10$ is assumed in the range $0.05 M_{\odot} \leq M \leq 50 M_{\odot}$. We note that this IMF slope is the same as in Kodama et al. (1998) and was introduced to increase chemical yields to reproduce the reddest end of the Coma CM relation. The nucleosynthesis yields of SNe Ia and SNe II are taken from Tsujimoto et al. (1995). The chemical enrichment by SNe Ia is calculated with a metallicity-dependent SN Ia rate, for which a detailed formulation is given by Kobayashi, Tsujimoto, & Nomoto (2000). The spectral evolution is calculated using a spectral synthesis database of Kodama & Arimoto (1997). The adopted parameter values for the galactic wind epoch $t_{gw}$ and stellar age $t_{*}$ at each radius for the four color gradients are listed in Table 1.

The resulting photochemical properties of a galaxy at $z = 0$ are summarized in Table 2, including gas abundances and colors at each radius. It should be noted that our models have an SN II-like abundance pattern, though the value $[\text{Mg}/\text{Fe}]$, about $+0.4$, is slightly larger than that suggested by the observational estimates (Worthey, Faber, & Gonzalez 1992; Kobayashi & Arimoto 1999); a larger $[\text{Mg}/\text{Fe}]$ ratio is a result of the assumed flat IMF ($x = 1.10$).

3. GALAXIES FOR COMPARISON

3.1. Sample Elliptical Galaxies

To compare theoretical color gradients with those of elliptical galaxies at high redshifts, the archival data of the HDFN (Williams et al. 1996) are used. Our sample galaxies are selected from those brighter than $I_{814,AB} = 22$ mag, in such a way that we can derive reliable surface brightness profiles and color gradients. All these galaxies have spectroscopic redshifts. Elliptical galaxies are identified by using a bulge-to-total-luminosity ratio $B/T$ derived by Marleau & Simard (1998), who obtained the $B/T$ ratios in the $I_{814}$ band of HDF galaxies brighter than $I_{814} = 26$ mag by quantitatively decomposing the surface brightness profile into the bulge and the disk components. We define galaxies with $B/T > 0.5$ as ellipticals according to Marleau & Simard (1998). Our resulting sample consists of 10 elliptical galaxies with redshifts from $z = 0.089$ to 1.015, as listed in Table 3. It is important to note here that our sample selection does not rely on any color information. Franceschini et al. (1998) also made a sample of elliptical galaxies in the HDF using surface brightness profiles. Their selection, however, is not based on the bulge/disk decomposition. Consequently, within $I_{814,AB} < 22$ mag, our sample is smaller than that of Franceschini et al. (1998), except for galaxy 4-241.1 at $z = 0.318$. The sample of Franceschini et al. includes several galaxies having $B/T$ smaller than 0.5, which are presumably disk-dominated galaxies and thus are not included in our sample (see also Kodama, Bower, & Bell 1999). It should be noted that the value $B/T > 0.5$ in the $I_{814}$ band may be slightly loose to isolate elliptical galaxies. The value $B/T > 0.5$ in the $B$ band roughly corresponds to local early-type galaxies (see, e.g., Simien & de Vaucouleurs 1986). By using the bulge and disk models of Kodama et al. (1999), we found that the $I_{814}$-band $B/T$ ratios of ellipticals are larger than ~0.7 at $z = 0$ and change little from $z = 0$ to 1 in the observer's frame.

Thus our sample may include galaxies as late as Sa, though they must be a minority because most $B/T$ ratios of our sample galaxies are larger than 0.7 (Table 3).
We measured the $V_{606} - I_{814}$ colors of our sample galaxies and present them in Table 3 and Figure 1. These colors are obtained for a 10 kpc aperture. Seven of the sample galaxies have red colors consistent with those for ellipticals with passive evolution as shown in Figure 1 (hereafter we call these galaxies “red ellipticals”), and the other three galaxies (4-241.1, 2-251.0, and 4-928.0) have blue colors (hereafter referred to as “blue ellipticals” for convenience; see also Fig. 2). Azimuthally averaged radial surface brightness profiles of the sample ellipticals in the $I_{814}$ band are shown in Figure 2. The average is taken along an ellipse fitted to an isophote of the $I_{814}$-band image. These profiles are well represented by an $r^{1/4}$ law for both the red ellipticals and the blue ellipticals. Effective radii ($r_e$) of the sample ellipticals are obtained by the $r^{1/4}$ fitting, and the results are shown in Table 3. The fitting is done by removing data points in the inner and outer regions, since they are unreliable because of an effect of a point-spread function (PSF) and low signal-to-noise ratios (S/Ns), respectively. The obtained effective radii range from $r_e = 1.4$ to 7.9 kpc, which is typical for near giant ellipticals (see, e.g., Bender, Burstein, & Faber 1992).

![Figure 2a](image-url)
3.2. Color Gradients

To examine color gradients of our sample galaxies, the images in the F606W and F814W bands were used, because the S/Ns of the images are better in these bands than in the other bands (F300W and F450W). First, the sky value around each object was determined by using the PHOT task in the IRAF APPHOT package (MODE in an annulus with an inner radius mostly of about 3'–4' and a width of 0.4 is adopted) and subtracted. Next, the angular resolutions of the blue images and the red images were adjusted and a $V_{606} - I_{814}$ color map of each galaxy was made. Figure 3 shows the resulting color maps. Most of the color maps for the red ellipticals show symmetric structure and an ordinary color gradient. In two cases (2-456.0 and 2-121.0), slight asymmetry in the color distribution is seen. This does not seem to be caused by a misalignment of the images. For the blue ellipticals, a variety in the color distribution is seen, which we will discuss in §5.1. Next, a color profile is derived with the azimuthally averaged radial profiles as a function of semimajor radius.

![Color Gradient Diagram](image)

**TABLE 3**

**Sample Elliptical Galaxies**

| Galaxy   | $z$  | $I_{814}$ (mag) | $M_{F450W,AB}$ (mag) | $V_{606} - I_{814}$ (mag) | $r_e$ (kpc) | $B/T$ | $\Delta(V_{606} - I_{814})_{AB}$ (mag) |
|----------|-----|----------------|----------------------|--------------------------|-------------|-------|-------------------------------------|
| 2-456.0  | 0.38| 18.2$^a$       | -19.20$^b$           | 0.610                    | 1.4         | ...   | -0.02                               |
| 4-241.1  | 0.35| 20.33          | -20.94               | 0.422                    | 3.1         | 0.66  | ...                                 |
| 2-121.0  | 0.475| 20.03         | -20.94               | 1.071                    | 3.5         | 0.87  | 0.10                                |
| 3-790.0  | 0.562| 20.93         | -21.92               | 1.152                    | 2.8         | 0.63  | 0.21                                |
| 3-321.0  | 0.677| 20.92         | -22.17               | 1.490                    | 7.0         | 0.81  | 0.09                                |
| 4-744.0  | 0.764| 20.41         | -23.12               | 1.609                    | 5.1         | 0.79  | 0.06                                |
| 4-493.0  | 0.847| 21.17         | -22.89               | 1.670                    | 4.0         | 0.81  | 0.02                                |
| 2-251.0  | 0.960| 20.86         | -23.65               | 1.055                    | 7.9         | 1.00  | ...                                 |
| 4-752.0  | 1.013| 20.88         | -24.10               | 1.855                    | 6.9         | 0.87  | -0.14                               |
| 4-928.0  | 1.015| 21.75         | -23.03               | 1.347                    | 3.7         | 0.81  | -0.4                                |

$a$ Williams et al. 1996.

$b$ Cohen et al. 1996.

$^a$ Abraham et al. 1999. We converted the $M_{F450W,AB}$ magnitudes into those in the adopted cosmology.

$^b$ Bulge-to-total-luminosity ratio in the $I_{814}$ band taken from Marleau & Simard 1998.

$^c$ Zero points to compare the model color gradients for typical elliptical galaxies with the observed ones (see §4).

$^d$ The $B/T$ of this object is not in Marleau & Simard 1998. However, we include it in our sample because its spectrum (Hawaii Active Catalog$^d$), as well as its morphology, show this galaxy is clearly a typical E or S0 galaxy.

$^e$ Bouwens, Broadhurst, & Silk 1998.

$^f$ The $B/T$-band absolute magnitude calculated by Bouwens et al. 1998. We also converted the magnitude to that in the adopted cosmology.
Fig. 3.—$V_{606} - I_{814}$ color maps for (a) the red galaxies whose colors are consistent with that of a passively evolving galaxy and (b) the “blue” ellipticals. The cross on each object denotes the centroid of the galaxy in the $I_{814}$-band image. The circle represents an effective radius centered on the centroid. Object identifier, redshift, and effective radius are also shown. Note that the color bar differs from galaxy to galaxy to show the color distribution clearly.
from the galaxy center. The resulting color profiles are shown in Figures 4 and 5 for the red ellipticals and in Figure 7 for the blue ellipticals. It should be noted that in the plots of the observed color profiles the zero point of the observed color for each galaxy is shifted for comparing with those for the models. These shifts are listed in the last column of Table 3. Most of the shifts are less than 0.2 mag; for intrinsically luminous objects, the colors tend to be shifted to bluer colors and less luminous objects to redder colors. Thus, the color differences are presumably caused by an effect of the CM relation of elliptical galaxies. The zero-point offsets could also come from photometric errors in the HST data (see, e.g., Holtzman et al. 1995; Ellis et al. 1997; Kodama et al. 1998) and from uncertainty in the population synthesis model. Needless to say, zero-point offsets do not affect the color gradients. Error bars attached to each data point in the color profile include a photometric error, a local sky subtraction error, and the dispersion of colors along each elliptical isophote. The data points of 2-456.0 and 2-121.0 have relatively large error bars in the middle region of the profiles; these objects have asymmetric color distributions, which result in the relatively large dispersions of colors in the regions.

Finally, slopes of the color profiles $\Delta(V_{606} - I_{814}) / \Delta \log(r/r_e)$ of the sample galaxies are derived by applying a least-squares fit to the color profiles. This fit was done after removing the unreliable data points in the outer region ($r > r_e$) and in the innermost region. The removed data points in the innermost regions are shown by crosses in the color profiles (Fig. 4 and 5); they clearly deviate from the $r^{1/4}$ fits, presumably because of the effect of a PSF, as seen in Figure 2. The slopes of the color profiles for the blue ellipticals presented in Figure 7 are not derived.

4. ORIGIN OF COLOR GRADIENTS

After the spectra are calculated at various radii of a model galaxy in such a way that they reproduce the color gradient $\Delta(B-R)/\Delta \log(r/r_e) = -0.09$ mag dex$^{-1}$ at $z = 0$, the model gradient in any colors at any redshifts can be predicted to compare with the observed gradients. The model color gradients at the redshift of each sample elliptical galaxy are overplotted in each panel of Figures 4 and 5 for the age gradient and the metallicity gradient models, respectively. Solid and dotted lines in each panel show the gradients in the $V_{606} - I_{814}$ color corresponding to the gradients of $-0.09 \pm 0.02$ and $-0.09 \pm 0.04$ mag dex$^{-1}$ in the $B-R$ color at $z = 0$, respectively.

It is clearly shown that the model gradient made using the age gradient begins to deviate from the observed ones at redshift $z \sim 0.3$, and the deviation becomes worse as the redshift increases (Fig. 4). In contrast, the model gradient made using the metallicity gradient agrees well with the observed color gradients within the effective radius at any redshift from $z \sim 0.1$ to about 1 (Fig. 5). Considering that the model gradients are calibrated only at $z = 0$, we insist that the agreement between the model and the observed gradients is excellent. Such agreement is more clearly seen
Figure 4.—Observed color gradients of the red elliptical galaxies together with the model gradients made using the age gradient. Circles represent the data points. Crosses refer to data points that are not used in deriving slopes of color profiles. The models show the predicted color gradients seen at each object’s redshift. Solid lines correspond to \( \Delta(B-R)/\Delta \log(r/r_e) = -0.09 \pm 0.02 \) mag dex\(^{-1}\) at \( z = 0 \), and the dotted lines correspond to \( \Delta(B-R)/\log(r/r_e) = -0.09 \pm 0.04 \) mag dex\(^{-1}\) at \( z = 0 \). Zero points of the observed colors are slightly shifted by \( \Delta(V_{606} - I_{814}) \) in Table 3 to compare the observed gradients with the models.

DISCUSSION

5.1. Blue Galaxies in Our Sample

Since our sample is selected independently of galaxy colors, relatively blue elliptical-like galaxies are included (three of 10). Among these three, 4-241.1 (\( z = 0.318 \)) has a nearly flat color profile with a slightly bluer color in the inner part (Fig. 3b and Fig. 7, top panel). The spectrum of this galaxy (from the Hawaii Active Catalog\(^5\)) shows Balmer absorption lines shortward of 4000 Å in the rest frame, as well as emission lines such as \([\text{O II}] \lambda \lambda 3727, \ H\beta, \ [\text{O III}] \lambda \lambda 4959, 5007, \) and \( \text{Hz} \). Thus this galaxy is expected to have some young stellar populations. Galaxy 2-251.0 (\( z = 0.960 \)) has a color gradient in the opposite sense to those of ordinary ellipticals; i.e., the inner region of the galaxy is bluer than the outer region (Fig. 3b and Fig. 7, middle panel). Since this galaxy has been suggested as an active galactic nucleus (AGN; Franceschini et al. 1998), this opposite gradient is probably caused by AGN and/or associated starburst activity in the central part of the galaxy. Although both galaxies seem to have younger ages, our model by the age gradient cannot reproduce their color gradients. Accordingly, neither the metallicity gradient nor the age gradient can explain their observed color gradients. These galaxies presumably have ongoing star formation (or are poststarburst) in the inner part of the galaxies, which

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\(^5\) Available at http://www.ifa.hawaii.edu/~cowie/tts/tts.html.
may be caused by a galaxy interaction, as expected from their rather disturbed morphology. Our model cannot apply to these cases. The other galaxy, 4-928.0 ($z = 1.015$), has a rather steep color gradient, as seen in Figure 3b and the bottom panel of Figure 7. The observed color profile of the galaxy is shifted by 0.4 mag for comparison with the model color gradients (solid and dotted lines). The observed color gradient of this galaxy may be explained by the age gradient if we tune the ages of stellar populations in the model galaxy. However, the mean age is set to be 0.2 Gyr at $r_e$ and 9 Gyr at the innermost point. Such a large age at the center cannot be realized at this redshift ($z = 1.015$) unless a different set of cosmological parameters is adopted. Finally, note that the colors of these galaxies are not consistent with those of passively evolving ellipticals formed at high $z$. A much larger sample is needed to determine whether the population of the blue elliptical galaxies is really the minority in the population of elliptical galaxies.

5.2. Gradients of Metal Absorption Line Strengths

Kobayashi & Arimoto (1999) showed that central velocity dispersions of elliptical galaxies correlate well with their mean metallicities. They found, however, that this correlation has a significant scatter. They also showed that Mg$_2$ gradients do not correlate with any physical parameters, including galaxy mass. Such a large dispersion and an absence of correlation are contrary to what monolithic collapse simulations predicted. As the common cause of the large dispersion and absence of correlation, they suggested...
Fig. 7.—Color gradients of the galaxies that have relatively blue colors. The color gradient of 4-928.0, which has a rather steep color gradient, is plotted with a model color gradient made by fitting the age gradient to the observed one by tuning ages of stellar populations in the model galaxy. (See text for the model.) The observed color for 4-928.0 is shifted by 0.4 mag to compare the model gradients.

There seems to be a problem that color gradients in elliptical galaxies do not correlate with their gradients, though only a small number of elliptical galaxies have been studied both for color gradient and Mg$_2$ gradient (Peletier 1989). However, the absence of this correlation may be a spurious result caused by a difference in the way the color and Mg$_2$ gradients are derived. Some effects of dust extinction and/or, possibly, observational errors for both gradients might suppress the true correlation. In any case, this problem will be investigated in detail in our forthcoming paper.

Worthey et al. (1992) suggested that the color-magnitude relation of elliptical galaxies may originate from the fact that the more luminous ellipticals tend to contain more Mg relative to Fe. One can claim that possibly the same holds for the internal gradients. However, Kobayashi & Arimoto (1999) have recently carried out a careful study of line strength gradients of 80 elliptical galaxies with the best quality spectra, but they find no evidence supporting a [Mg/Fe] gradient. Therefore, we conclude that the color gradients are not caused by the gradient of the [Mg/Fe] ratio.

6. CONCLUSIONS

The origin of color gradients in elliptical galaxies is examined. A typical color gradient of nearby elliptical galaxies is reproduced by two alternative model sequences, the metallicity gradient and age gradient. This age-metallicity degeneracy is broken by looking-back the evolution of the color gradient toward high redshifts; the predicted color gradients at high redshifts are compared with the observed color gradients of 10 elliptical galaxies in the HDFN out to $z \sim 1$. We find that the observed color gradients of the seven red galaxies, whose colors are consistent with those of passively evolving galaxies, are in excellent agreement with the metallicity gradient at any redshift.

These conclusions are independent of cosmological parameters and parameters for an evolutionary model of galaxies (such as IMF and SFR) within a reasonable range. Thus, we conclude that the primary origin for the color gradient in elliptical galaxies is the metallicity gradient in old stellar populations.

This work was financially supported in part by grants-in-aid for scientific research 0940311 and 09740173 by the Japanese Ministry of Education, Science, Sports and Culture. C. K. and T. K. are thankful for research fellowships for young scientists from the Japanese Society for the Promotion of Science.

REFERENCES

Abraham, R. G., Ellis, R. S., Fabian, A. C., Tanvir, N. R., & Glazebrook, K. 1999, MNRAS, 303, 641
Arimoto, N. 1996, in ASP Conf. Ser. 98, From Stars to Galaxies, ed. C. Leitherer, U. Fritze-von Alvensleben, & J. Huchra (San Francisco: ASP), 287
Arimoto, N., & Yoshii, Y. 1987, A&A, 173, 23
Bender, R., Burstein, D., & Faber, S. M. 1992, ApJ, 399, 462
Bouwens, R., Broadhurst, T., & Silk, J. 1998, ApJ, 506, 557
Bregman, J. N., Snider, B. A., Grego, R., & Cox, C. V. 1998, ApJ, 499, 670
Carollo, C. M., Danziger, I. J., & Buson, L. 1993, MNRAS, 265, 553
Cohen, J. G., Cowie, L. L., Hogg, D. W., Songaila, A., Blanford, R., Hu, E. M., & Shopbell, P. 1996, ApJ, 471, L5
Davies, R. L., Sadler, E. M., & Peletier, R. F. 1993, MNRAS, 262, 650
Ellis, R. S., Smail, I., Dressler, A., Couch, W. J., Oemler, A., Jr., Butcher, H., & Sharples, R. M. 1997, ApJ, 483, 582
Franceschini, A., Silva, L., Fasano, G., Granato, G. L., Bressan, A., Arnouts, S., & Danese, L. 1998, ApJ, 506, 600
Frant, M., Illingworth, G., & Heckman, T. 1989, AJ, 98, 538
Gonzalez, J. J. 1993, Ph.D. thesis, Univ. California
Goudroop, P., & de Jong, T. 1994, A&A, 298, 784
Holmes, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995, PASP, 107, 1065
Kaukaif, G., & Charlot, S. 1998, MNRAS, 294, 705
Kobayashi, C., & Arimoto, N. 1999, ApJ, 527, 573
Kobayashi, C., Tsuchimoto, T., & Nomoto, K. 2000, ApJ, submitted (astro-ph/9908005)
Kodama, T., & Arimoto, N. 1997, A&A, 320, 41
Kodama, T., Arimoto, N., Barger, A. J., & Aragón-Salamanca, A. 1998, A&A, 334, 99
Kodama, T., Bower, R. G., & Bell, E. F. 1999, MNRAS, 306, 561
Larson, R. B. 1974, MNRAS, 169, 229
Marleau, F. R., & Simard, L. 1998, ApJ, 507, 585
Martinelli, A., Matteucci, F., & Colafrancesco, S. 1998, MNRAS, 298, 42
Peletier, R. F. 1989, Ph.D. thesis, Univ. Groningen
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
Simien, F., & de Vaucouleurs, G. 1986, ApJ, 302, 564
Tantalo, R., Chiosi, C., Bressan, A., Marigo, P., & Portinari, L. 1998, A&A, 333, 419
Tsujimoto, T., Nomoto, K., Yoshii, Y., Hashimoto, M., Yanagida, S., & Thielemann, F.-K. 1995, MNRAS, 277, 945
Vader, J. P., Vigroux, L., Lachièze-Rey, M., & Souviron, J. 1988, A&A, 203, 217
Williams, R. E., et al. 1996, AJ, 112, 1335
Wise, M., & Silva, D. R. 1996, ApJ, 461, 155
Witt, A. N., Thronson, H. A., Jr., & Capuano, J. M. 1992, ApJ, 393, 611
Worthey, G., Faber, S. M., & Gonzalez, J. J. 1992, ApJ, 398, 69
Worthey, G., Trager, S. C., & Faber, S. M. 1996, in ASP Conf. Ser. 86, Fresh Views of Elliptical Galaxies, ed. A. Buzzoni, A. Renzini, & A. Serrano (San Francisco: ASP), 203