Origin of the colour-magnitude relation of elliptical galaxies

Tadayuki Kodama[1] **and Nobuo Arimoto**[1,2,3]

[1] Institute of Astronomy, University of Tokyo, Mitaka, Tokyo 181, Japan

[2] Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge, CB3 0HA, UK

[3] Department of Physics, University of Durham, South Road, Durham, DH1 3LE, UK

Abstract. Evolutionary models of elliptical galaxies are constructed by using a new population synthesis code. Model parameters are calibrated to reproduce the observed colour-magnitude (CM) relation of Coma ellipticals in $V - K$ vs. M_V diagram. The SEDs are degenerated in stellar age and metallicity. An attempt is performed to break this degeneracy, by simulating evolution of the CM relation of elliptical galaxies, based on the two alternative interpretations; *i.e.,* the CM relation reflects different mean stellar age or various stellar metallicity. A confrontation with the CM diagrams of E/S0 galaxies in the two distant clusters Abell 2390 ($z = 0.228$) and Abell 851 ($z = 0.407$) reinsures previous contentions that the CM relation is primarily a metallicity effect. This conclusion does not depend either on the model parameters, or on the cosmological parameters adopted.

Key words: galaxies: elliptical – galaxies: evolution – galaxies: formation – galaxies: photometry – galaxies: stellar content

1. Introduction

The integrated colours of elliptical galaxies become progressively bluer towards fainter magnitudes (Faber 1973, 1977; Visvanathan & Sandage 1977; Frogel et al. 1978; Persson, Frogel, & Aaronson 1979; Bower, Lucey, & Ellis 1992a; 1992b). With an accurate photometry of a large sample of elliptical galaxies in Virgo and Coma clusters of galaxies, Bower et al. (1992a, b) have shown that the colour-magnitude (CM) relations of two clusters are identical within observational uncertainties, suggesting that the CM relation is universal for cluster ellipticals. The rms scatter about the mean CM relation is typically ~ 0.04 mag, a comparable size to observational errors, and implies a virtually negligible intrinsic scatter. If the scatter is due to age dispersion among cluster ellipticals, the photometric data by Bower et al. (1992a, b) suggest that cluster ellipticals are unlikely to have formed below a redshift of 2 ($q_0 = 0.5$), which

Send offprint requests to: T. Kodama

sets an upper limit of ~ 2 Gyrs for the age dispersion of the bulk stellar populations of cluster ellipticals. An identical upper limit to the age dispersion of such galaxies is also suggested by their small dispersion about the so-called fundamental plane (Renzini & Ciotti 1993). These findings are in excellent agreement with a scenario for the formation of elliptical galaxies dominated by protogalactic collapse and dissipational star formation early in the evolution of the universe (Larson 1974; Saito 1979a, b; Arimoto & Yoshii 1986, 1987, hereafter AY87; Matteucci & Tornambé 1987; Yoshii & Arimoto 1987; Bressan, Chiosi, & Fagotto, 1994; Tantalo et al. 1996). The CM relation itself is also quite naturally established in collapse/wind model of galaxy formation; a galactic wind is induced progressively later in more massive galaxies owing to deeper potential and stellar populations in brighter galaxies are much more enhanced in heavy elements and as a result redder in colours.

This *conventional* interpretation of the CM relation of ellipticals, however, has been questioned by Worthey (1996) who points out, based on his population synthesis model (Worthey 1994), that the sequence of colours and line strengths among ellipticals can be almost equally well explained by a progressive decrease of either a mean stellar metallicity or an effective stellar age. Recently, Bressan, Chiosi, & Tantalo (1996) have performed a detailed analysis of the CM relation of elliptical galaxies. In addition to broad band colours, the authors have considered absorption line strengths and their radial gradients, abundance ratios, spectral energy distribution in UV-optical region, and stellar velocity dispersion, all of which might be tightly coupled with the CM relation itself, and have suggested that the history of star formation in elliptical galaxies has probably been more complicated and heterogeneous than the galactic wind scenario mentioned above.

The dual interpretations of the CM relation are now well known as the *age-metallicity degeneracy* of old stellar populations. Arimoto (1996) have distributed the spectral templates of nearby ellipticals (E1 for giants and E4 for dwarfs; Bica 1988) to about dozen groups of population synthesis (E.Bica & D.Alloin; A.Pickles; R.W.O'Connell & B.Dorman; W.Kollatschny & W.Goerdt; G.Bruzual & S.Charlot; M.Fioc & B.Rocca-Volmerange; G.Worthey; B.Poggianti & G.Barbaro; U.Fritz-

v.Alvensleben; J.-H.Park & Y.-W.Lee; R.F.Peletier, A.Vazdekis, E.Casuso, & J.E.Beckman; N.Arimoto & T.Yamada), both evolutionary and optimizing, and have asked to report their best fit solutions. The results are surprising: for E1 exercise most groups come to the same conclusion; *i.e.,* nuclei of giant ellipticals are old (10-19) Gyrs and mean metallicities are at least solar or more. However, for E4 exercise, they do not agree at all. They find that nuclei of dwarf ellipticals are either 1) old $(11 - 15)$ Gyrs and metal-rich $(2.5 - 3Z_\odot)$, or 2) old $(10 - 16)$ Gyrs and solar metallicity or metal-poor $(0.15 - 0.7Z_\odot)$, or 3) young $(3 - 5)$ Gyrs and solar metallicity or metal-rich $(2Z_\odot)$ [see Arimoto (1996) for more details]. This confusing results for E4 exercise come from the age-metallicity degeneracy and not from different approach (evolutionary or optimizing), nor from different techniques and ingredients adopted in the models.

All in all, the previous interpretation that the CM relation is primarily a metallicity effect looks less secured today. It is not clear anymore whether fainter ellipticals are bluer because stellar populations are younger or because stars are more metal-deficient in average. Indeed an alternative scenario for the formation of elliptical galaxies suggests that ellipticals result from the merging of lesser stellar systems taking place mostly at later times and involving substantial star formation (Toomre & Toomre 1972; Schweizer & Seitzer 1992; Fritz-von Alvensleben & Gerhard 1994). This scenario is in good agreement with fine structures and kinematic anomalies of some elliptical galaxies (eg., Kormendy & Djorgovski 1989). In addition to this, the optimizing synthesis tend to pick up finite fraction of light from intermediate age populations, which also supports recent episodes of star formation in ellipticals (O'Connell 1976; Pickles 1985b; Rose 1985; O'Connell 1986; Bica 1988; see also Arimoto 1996).

Although several attempts have been made to disentangle the age and metallicity effects on the line strengths as well as on the broad band colours (Buzzoni, Gariboldi, & Mantegazza 1992; Buzzoni, Chincarini, & Molinari 1993; Gonzales 1993; Worthey 1994; Worthey et al. 1994), it is still very difficult to break the age-metallicity degeneracy of elliptical galaxies so far as one sticks to photo-spectroscopic data of galaxies at the present epoch. However, it is comparatively easier to show that the CM relation is indeed primarily due to the stellar metallicity effect if one studies evolution of the CM relation as a function of look-back time. If the CM relation is an age sequence, it should evolve rapidly and should disappear beyond certain redshift, because fainter galaxies are approaching to their formation epoch. Contrary, if the CM relation is a metallicity sequence and ellipticals are essentially old, it should evolve *passively* and should be still traced at significantly high redshifts. In this paper, we compare the theoretical evolution of the CM relation with the CM relations of cluster ellipticals at cosmological distances $(z \simeq 0.2 - 0.4)$ and show that the bulk of stars were probably formed early in elliptical galaxies, and that the CM relation takes its origin at early times from galactic wind feedback, thus reinsuring confirmation of previous contentions.

In Sect. 2, we outline our population synthesis model, and in Sect. 3 we present the theoretical evolution of the CM relation

and confront it with the CM diagrams of elliptical/S0 galaxies of two distant clusters Abell 2390 ($z = 0.228$) and Abell 851 ($z = 0.407$). We discuss implications of several effects, such as dynamical disturbance, intermediate age stars, and new star formation, on the formation of elliptical galaxies in Sect. 4. Our conclusions are given in Sect. 5.

2. Model

2.1. Stellar population synthesis code

The basic structure of our new code follows Arimoto & Yoshii's (1986) stellar population synthesis prescription that takes into account the effects of stellar metallicity on integrated colours of galaxies for the first time. New stellar evolutionary tracks are incorporated comprehensively, and late stellar evolutionary stages are fully taken into account. The code uses the so-called *isochrone synthesis* technique (cf. Charlot & Bruzual 1991) and gives the evolution of synthesized spectra of galaxies in a consistent manner with galaxy chemical evolution, and the details of the code will appear in Kodama & Arimoto (1996). A brief description for essential techniques and the ingredients are given below (see also Table 1).

2.1.1. Stellar evolutionary tracks

Original tracks: By using the stellar evolution code provided by Saio & Nomoto (1994; private communication), we have calculated a grid of stellar evolutionary tracks for low mass stars $(0.6 \leq m/M_\odot \lesssim 2.4)$ from zero-age main sequence (ZAMS) to tip of red giant branch (RGB), and for intermediate mass and massive stars $(2.4 \lesssim m/M_\odot \leq 60)$ from ZAMS to onset of carbon ignition. These tracks are calculated for low stellar metallicities $Z = 0.0001, 0.0002, 0.0005, 0.001$, and 0.002 with helium abundance $Y = 0.23 + 2.5Z$. The revised radiative opacities by Iglesias (1993) are used and a mixing length parameter ℓ/H_p is set to be 1.5 throughout. For the RGB evolution, the mass loss law of Reimers (1977) with an efficiency parameter $\eta = 1/3$ is assumed and those given by Nieuwenhuijzen & de Jager (1990) are adopted for the rest of evolutionary stages. We have compared our stellar evolutionary tracks for $Z = 0.0005$ with those of Padua group (see below) for $Z = 0.0004$. The appearance on the HR diagram is nearly identical for all masses, but the evolutionary time of our tracks is systematically $\sim 10\%$ longer than the Padua tracks. This is essentially due to a difference in the program structure and the input physics between the two codes, and we do not try to adjust the evolutionary time of our tracks.

Padua tracks: For stars of higher metallicities $Z = 0.004$, 0.008, 0.02, and 0.05, we adopt Padua stellar evolutionary tracks from the ZAMS to the tip of RGB for low mass stars $(0.6 \leq m/M_\odot \lesssim 2.4)$ and to the onset of carbon ignition to the rest $(2.4 \lesssim m/M_\odot \leq 60)$, with $Y = 0.23 + 2.5Z$ (Bressan et al. 1993; Fagotto et al. 1994a; 1994b). Padua tracks are calculated with the revised radiative opacities by Iglesias et al. (1992) and

with $\ell/H_p = 1.63$. Stellar mass loss is considered for massive stars ($m/M_\odot \geq 12$).

Lower main sequence: Lower main sequence stars ($0.1 \leq m/M_\odot \leq 0.5$) are assumed to stay on the ZAMS over the Hubble time. Tracks are taken from VandenBerg (1983) for $0.0001 \leq Z \leq 0.02$ and are extrapolated for $Z = 0.05$. $Y = 0.25$ is adopted regardless of Z. Opacities are adopted from Cox & Stewart (1970a; 1970b), Cox & Tabor (1976) and Alexander (1975). A low value of $\ell/H_p = 1.0$ is assumed but the location of ZAMS on the HR diagram for lower main sequence stars is rather insensitive to a mixing length parameter since convective energy is transported almost adiabatically in these stars (VandenBerg 1983).

Horizontal branch: We adopt the revised Yale tracks for low mass horizontal branch (HB) evolution which are kindly provided by S.Yi & P.Demarque (1995; private communication). The tracks are calculated with the revised OPAL opacities (Iglesias & Rogers 1991; Rogers & Iglesias 1992) and $\ell/H_p = 1.7$ for a full range of Z and Y. For our use, 9 sets of HB tracks are interpolated from the original grid for $Z = 0.0001$ to 0.05 and Y at the ZAMS. For details of the input physics, see Yi (1996). HB stars are distributed on the HR diagram by using the same method developed by Rood (1973) with a total mass dispersion $\sigma_M = 0.025M_\odot$.

Asymptotic giant branch, post-AGB, and white dwarf: Evolutionary tracks of low mass asymptotic giant branch (AGB) stars are taken from Vassiliadis & Wood (1993) and those of post-AGB stars (H-burning tracks) and white dwarfs are taken from Vassiliadis & Wood (1994). These tracks are calculated for $0.001 \leq Z \leq 0.02$, thus tracks for lower and higher metallicities are extrapolated. $Y = 0.25$ is assumed throughout. Opacities are taken from Huebner (1977) and Bessell et al. (1989). The mixing length parameter is set to be $\ell/H_p = 1.6$. A formula of mass loss rate is applied for AGB stars according to the empirical relation between mass loss rate and pulsational period.

2.1.2. Stellar spectra

Kurucz's (1992) stellar flux library is adopted for the metallicity $0.0001 \leq Z \leq 0.05$, the effective temperature $4000K \leq T_{\rm eff} \leq 50000K$, and the surface gravity $0.0 \leq \log g \leq 5.0$. The library covers the wavelength range from UV to near IR with spectral resolutions $\Delta\lambda = 10 - 20$Å for $\lambda \leq 1\mu m$ and $\Delta\lambda = 50 - 100$Å for $\lambda \geq 1\mu m$. We interpolate linearly a logarithm of the flux F_λ in $\log Z$, $\log T_{\rm eff}$ and $\log g$, if necessary.

Below $4000K$, empirical stellar spectral libraries of Pickles (1985a) are employed with a supplemental use of Gunn & Stryker (1983). The former covers the wavelength range from $\lambda = 3600$Å to 10000Å with the resolution $\Delta\lambda = 10 - 17$Å, while the latter covers from $\lambda = 3130$Å to 10800Å with the resolution $\Delta\lambda = 20 - 40$Å. Fluxes are extended towards the near IR region using empirical colours in $JHKL$ bands for M stars by Bessell & Brett (1988): Effective temperatures are allocated according to Ridgway (1980) and Pickles (1985a). Since spectra of M stars with non-solar metallicity are hardly available, the line blanketing effects of metallicity are ignored. This could

be justified partly by the fact that there are very few M giants with $Z \leq 1/3Z_\odot$. Bolometric corrections for M stars are taken from Bessell & Wood (1984) and Johnson (1966).

Above $50000K$, spectra are almost featureless, and black body spectra are assumed.

2.1.3. Simple stellar population (SSP) model

SSP is defined as a single generation of coeval and chemically homogeneous stars of various masses (Renzini & Buzzoni 1986; Buzzoni 1989). The SSP is a building block of galactic population synthesis model and any stellar system of composite age and metallicity, like a galaxy, can be constructed as a linear combination of the SSPs (Charlot & Bruzual 1991; Bruzual & Charlot 1993). SSP spectrum is constructed as follows. Isochrone is first constructed from the stellar evolutionary tracks for the specified age and metallicity. Stellar spectra are assigned for each point on the isochrone and the SSP spectrum is synthesized by integrating stellar spectra along the isochrone with the number of stars, estimated from the initial mass function (IMF), as a weight.

Broad band colours are calculated by applying the filter response functions to the SSP spectrum. The resulting colours are confronted with the observed colours of star clusters in the Milky Way (Harris 1996) and the Magellanic Clouds (van den Berg 1981) and are confirmed to reproduce the observed ones. The $B - V$ evolution of the solar metallicity SSPs is nearly identical to that of Bruzual & Charlot (1995), while the $V - K$ are slightly redder than Bruzual & Charlot (1995) for the SSPs older than 13 Gyrs and approach progressively towards Bertelli et al.'s (1994; see Charlot, Worthey, & Bressan 1996).

2.1.4. Chemical evolution

The stellar populations of any galactic model can be described by a linear combination of the SSP models, provided that a mass weight of each SSP model specified with a single set of age and metallicity is known *a priori*. The fractional contributions of SSP models should come from the detailed history of star formation and nucleosynthesis, or in other words, a modelling of galactic chemical evolution is of vital importance in synthesizing a galaxy spectrum.

Since our major concern in the present study is the colour evolution of elliptical galaxies, we hereafter consider the so-called infall model instead of the simple model of galaxy chemical evolution (see Sect. 2.2). We assume that the galactic gas is supplied from the surrounding gas reservoir trapped in the gravitational potential of a galaxy, and that the gas is always well-mixed and distributes uniformly. Then time variations of the gas mass M_g and the gas metallicity Z_g are given by the following equations (Tinsley 1980):

$$\frac{dM_g(t)}{dt} = -\psi(t) + E(t) + \xi_{in}(t), \tag{1}$$

$$\frac{dZ_g(t)}{dt} = \frac{1}{M_g(t)} \left\{ E_Z(t) - \psi(t)Z_g(t) + \xi_{in}(t)Z_{in}(t) \right\}, \tag{2}$$

Table 1. Characteristics of Stellar Population Synthesis Code.

Stellar evolutionary tracks	this work, Bressan et al. (1994), Fagotto et al. (1994a,b), VandenBerg (1983), Yi & Demarque (1995), Vassiliadis & Wood (1993,1994)
Interior opacities	Iglesias et al. (1992), Iglesias (1993)
Mixing length (ℓ/H_p)	$1.5 - 1.7$
Mass loss rate	Nieuwenhuijzen & de Jager (1990), Reimers (1977) ($\eta = 1/3$), empirical formula (AGB)
Flux library	Kurucz (1992)
M giants spectra	Pickles (1985a), Gunn & Stryker (1983)
near IR colours	Bessell & Brett (1988)
effective temperature	Ridgway et al. (1980)
bolometric correction	Bessell & Wood (1984)
Metallicity range	$0.0001 \leq Z \leq 0.05$
Mass range	$0.1 \leq m/M_\odot \leq 60$

where $\psi(t)$ and $\xi_{in}(t)$ are the star formation rate (SFR) and the gas infall rate, respectively. As for the initial conditions, we assume that there was no gas in a galaxy before the onset of star formation; ie., $M_g(0) = 0$ and $Z_g(0) = 0$. The SFR $\psi(t)$ is assumed to be proportional to the gas mass (Schmidt law):

$$\psi(t) = \frac{1}{\tau} M_g(t), \tag{3}$$

where τ gives the star formation time scale in Gyrs. $\xi_{in}(t)$ is assumed to be expressed with the initial total mass of gas reservoir M_T and the gas infall time scale τ_{in} as,

$$\xi_{in}(t) = \frac{M_T}{\tau_{in}} \exp(-\frac{t}{\tau_{in}}) \tag{4}$$

(cf. Köppen & Arimoto 1990). Z_{in} is the metallicity of the infalling gas and assumed to be zero. $E(t)$ and $E_Z(t)$ in Eqs.(1)-(2) are the ejection rate of the gas and the metals from dying stars, respectively, and are calculated from the following integrals:

$$E(t) = \int_{m_t}^{m_u} (1 - w_m)\psi(t - \tau_m)\phi(m)dm, \tag{5}$$

$$E_z(t) = \int_{m_t}^{m_u} \{(1 - w_m - p_{zm})Z_g(t - \tau_m) + p_{zm}\}$$
$$\times \psi(t - \tau_m)\phi(m)dm, \tag{6}$$

where w_m and τ_m are the remnant mass fraction and the lifetime of stars with mass m, respectively. p_{zm} is the mass fraction of newly synthesized and ejected metals. Lower mass limit m_t for both integrals is the stellar mass with lifetime $\tau_m = t$. Nucleosynthesis data w_m and p_{zm} are taken from Nomoto (1993; private communication) for $m \geq 10M_\odot$ and from Renzini & Voli (1981) for $m < 10M_\odot$.

The IMF $\phi(m)$ is defined by mass fraction and assumed to have a single power law of mass:

$$\phi(m)dm = Am^{-x}dm, \qquad m_l \leq m \leq m_u, \tag{7}$$

where m_l and m_u are lower and upper limits of initial stellar mass, respectively. The Salpeter (1955) mass function has a slope $x = 1.35$ in this definition. The coefficient A is determined by,

$$\int_{m_l}^{m_u} \phi(m)dm = 1. \tag{8}$$

The IMF is assumed to be time invariant.

Recent chemical evolution analyses of disc dwarfs and halo giants in the solar neighbourhood suggest that the mean lifetime of progenitors of type Ia supernovae (SNIa) that are responsible for iron production is not an order of 10^8 yrs as previously believed but as long as $(1.5 - 2.5)$ Gyrs (Ishimaru & Arimoto 1996; Yoshii, Tsujimoto, & Nomoto 1996). This implies that SNIa's start to explode longer after when the bulk of stars formed in ellipticals as we will see in Sect. 2.2. Therefore, we ignore SNIa in this study.

Finally, the synthesized spectrum F_λ of a model as a function of galaxy age T can be given by,

$$F_\lambda(T) = \int_0^T \psi(t)f_\lambda(T - t, Z(t))dt, \tag{9}$$

where $f_\lambda(T - t, Z(t))$ is the SSP spectrum with age $T - t$ and metallicity $Z(t)$.

2.2. Evolution model of elliptical galaxies

A formation picture of elliptical galaxies by Larson (1974) and AY87 assumes that initial bursts of star formation occurred during rapidly infalling stage of proto-galactic gas clouds and that the gas was expelled when the cumulative thermal energy from supernova explosions exceeded the binding energy of the remaining gas. No stars formed afterwards and a galaxy has evolved passively since then.

Following AY87, we assume that star formation abruptly terminates at the epoch of galactic wind $t = t_{gw}$; i.e.,

$$\psi(t) = 0 \quad for \quad t \geq t_{gw}. \tag{10}$$
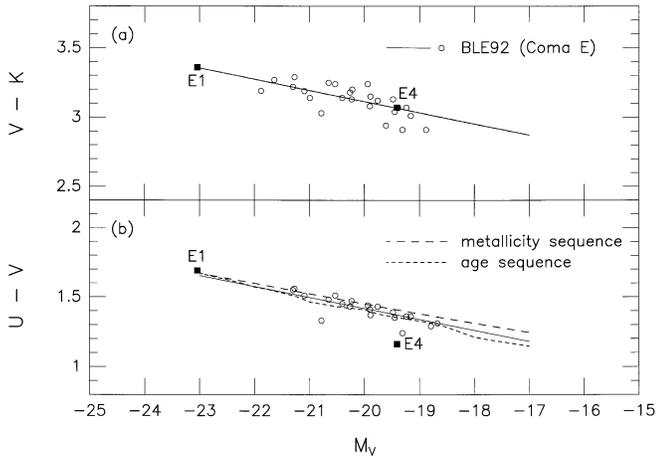
Fig. 1. a CM relation of Coma ellipticals in $V - K$ vs. M_V diagram. Open circles are Coma ellipticals and a regression line is given by a solid line taken from Bower et al.(1992a,b) (BLE92). Filled squares gives Bica's (1988) E1 and E4 templates. Dashed and dotted lines represent loci of models defined as the metallicity sequence and the age sequence, respectively. **b** The same as **a**, but in $U - V$ vs. M_V diagram.

A precise value of t_{gw} is rather difficult to evaluate, because it would depend strongly on how much dark matter is involved in defining a gravitational potential as well as on the change of galactic radius during the gravitationally collapsing phase. Instead, we determine t_{gw} empirically in such a way that models can reproduce $V - K$ of nearby elliptical galaxies in Coma cluster. Open circles in Figs. 1a and 1b give the CM relations of Coma ellipticals in $V - K$ vs. M_V and $U - V$ vs. M_V diagram, respectively (Bower et al. 1992a). Observational errors are estimated to be 0.035 mag and 0.037 mag in $V - K$ and $U - V$, respectively. Absolute magnitudes M_V are calculated with a help of the distance modulus of Coma cluster $(m - M)_0 = 34.6$. This value is obtained from the relative distance modulus between Coma and Virgo, $\Delta(m - M)_0 = 3.6$ (Bower et al. 1992b), and Tully-Fisher distance of Virgo core $(m - M)_0 = 31.0$ (Jacoby et al. 1992). Two filled squares indicate Bica's (1988) E1 and E4 spectral templates of nearby ellipticals adapted from Arimoto (1996).

In Figs. 1a and 1b, the CM relations can be clearly identified with surprisingly small scatter. It is now well recognized that the CM relations can be interpreted alternatively either by a decrease of mean stellar metallicity towards fainter galaxies (AY87; Matteucci & Tornambè 1987; Bressan, Chiosi & Fagotto 1994) or by a decrease of mean stellar age towards dwarf ellipticals (Worthey 1996). This happens because metallicity difference $\Delta \log Z$ or age difference $\Delta \log$ Age in two old stellar populations gives almost identical change in any colours and spectral indices if $\Delta \log \text{Age}/\Delta \log Z = -3/2$ is kept (The 3/2 rule of Worthey 1994). This is the so-called *age-metallicity degeneracy* for old stellar populations (cf. Arimoto 1996).

To break the age-metallicity degeneracy, Arimoto (1996) suggests to verify if the theoretical CM relation, defined ei-

ther by the metallicity or by the mean age, is consistent with the empirical CM relations of cluster ellipticals at cosmological distances. Therefore, we have simulated the evolution of the CM relation of elliptical galaxies for the two alternative scenarios. The resulting CM relations are then confronted with observational data, in the observer's frame, of elliptical galaxies in two distant clusters Abell 2390 ($z = 0.228$) and Abell 851 ($z = 0.407$) (Sect. 3.2).

We regard the CM relation in the $V - K$ vs. M_V diagram of Coma ellipticals (Fig. 1a) as a standard sequence of nearby ellipticals to which models for present day ellipticals should be fitted. Model parameters are chosen as $x = 1.20$, $m_l = 0.1 M_\odot$, $m_u = 60 M_\odot$, $\tau = 0.1$ Gyrs, and $\tau_{in} = 0.1$ Gyrs. $m_l = 0.1 M_\odot$ is chosen to give a mass-to-light ratio $M/L_B \simeq 8$ for giant ellipticals (Faber & Jackson 1976; Michard 1980; Schechter 1980). Although the choices of x, τ, and τ_{in} are somewhat arbitrary, we note that our analysis is rather insensitive to these parameters due to the following reasons: 1) Colour evolution of the old SSPs depends negligibly on x (Tinsley 1980), because stars that determine the synthesized colours of the old SSPs are main sequence stars near the turnoff and red giants; mass difference among them is negligibly small. 2) Relative dispersion of stellar ages within a galaxy is very small in our formation picture of elliptical galaxies. 3) Since t_{gw} is determined so as to reproduce $V - K$ at $z = 0$ (in the case of metallicity sequence introduced below), the mean stellar metallicity of a galaxy is adjusted automatically for any set of x, τ, τ_{in}, and T_G. Thus, nearly identical stellar contents for each galaxy is realized in terms of the mean stellar age and the metallicity, even if different set of parameters is chosen.

(a) *metallicity sequence* : The colour change along the CM relation in $V - K$ is explained simply by a difference of mean stellar metallicities of galaxies (AY87). Following this interpretation, we construct a sequence of models with different mean metallicities. All ellipticals are assumed to have an equivalent age $T_G = 15$ Gyrs. In galactic wind model, the metallicity difference can be produced by assigning different t_{gw}. A standard CM relation in $V - K$ is, then, reproduced with $t_{gw} = 0.52$ Gyrs at $M_V = -23$ mag and $t_{gw} = 0.10$ Gyrs at $M_V = -17$ mag. In total 13 models are calculated for 0.5 magnitude interval in M_V and properties of some models at the present epoch are summarized in the upper part of Table 2: M/L_B is given in solar units, galaxy mass M_G is calculated from M_V and M/L_V. Luminosity-weighted mean stellar metallicity is defined as:

$$< \log Z/Z_\odot >= \frac{\Sigma(\log Z/Z_\odot)L_{\text{BOL}}}{\Sigma L_{\text{BOL}}}, \qquad (11)$$

where summation is taken for all stars in a galaxy (cf. AY87). The solar metallicity $Z_\odot = 0.019$ is taken from Anders & Grevesse (1989). We note that t_{gw} is always less than the lifetime of SNIa (cf. Sect. 2.1.4) and that $< \log Z/Z_\odot >$ ranges from -0.014 to -0.596 from the brightest end to the faintest

end. Alternatively, the luminosity-weighted mean stellar metal-licity can be defined as (Greggio 1996):

$$\log < Z/Z_\odot >= \log \left\{ \frac{\Sigma(Z/Z_\odot)L_{BOL}}{\Sigma L_{BOL}} \right\}. \qquad (12)$$

The resulting metallicities are also given in Table 2 for comparison. Eq.(12) gives $\sim +0.15$ dex higher values than Eq.(11).

(b) *age sequence* : The CM relation can be explained alternatively by a progressive decrease of galaxy age towards fainter ellipticals (Worthey 1996). This can be represented by a sequence of models with fixed t_{gw} and various galaxy ages. A wind time is fixed to be the same as the brightest model of the metallicity sequence; ie., $t_{gw} = 0.52$ Gyrs. A standard CM relation in $V - K$ is, then, reproduced with $T_G = 15$ Gyrs at $M_V = -23$ mag and $T_G = 2.3$ Gyrs at $M_V = -17$ mag. In total 25 models are calculated for 0.25 magnitude interval in M_V and properties of some models at the present epoch are summarized in the lower part of Table 2. All models have $< \log Z/Z_\odot >\simeq 0$ in this sequence.

Models given in Tables 2 are all calculated under the context of the infall model of galaxy chemical evolution. A simple model approach is also attempted, but a resulting $U - V$ is bluer by 0.15 mag than the observed CM relation of Coma ellipticals at brightest end ($M_V = -23$ mag), while the model gives a good fit to $V - K$. This implies that the simple model predicts too many metal deficient stars (G-dwarf problem of elliptical galaxies). As is in the solar neighbourhood, infall model is effective in solving the G-dwarf problem and the observable properties of infall model were extensively discussed by Arimoto & Jablonka (1991).

The metallicity sequence and the age sequence are shown in Figs. 1a and 1b with dashed and dotted lines, respectively. The same filter systems as Bower et al. (1992a) are adopted. Since both sequences are calibrated to the CM relation in $V - K$ vs. M_V diagram, these two lines are identical to Bower et al.'s (1992b) regression (solid) line in Fig. 1a. On the contrary, $U - V$ of the metallicity sequence are systematically redder than the regression line of Bower et al. (1992b), amounting $\Delta(U - V) \simeq 0.06$ at the faintest end. Fig. 15 of Charlot et al. (1996) suggests that this is partly due to our use of Kurucz (1992) spectra, but it is also possible that this is due to the neglect of binary stars in our population synthesis code. Binary main sequence stars will give rise of blue stragglers which have brighter magnitudes than the turnoff stars, thus will increase the flux in U-band. Alternatively, the $U - V$ discrepancy can be attributed to an aperture effect. Bower et al. (1992a; b) adopted the same small aperture size for all galaxies, and if elliptical galaxies have metallicity gradient decreasing outward (e.g., Davies, Sadler, & Peletier, 1993), the fixed aperture photometry should get progressively more light from metal-poorer stars in smaller galaxies. However, such a detailed modeling of 2D and/or 3D metallicity gradient is beyond a scope of the present study. We therefore do not use $U - V$ to calibrate the models. Conclusions of this work is entirely free from this $U - V$ mismatch.

Recently Bressan, Chiosi, and Tantalo (1996) have conducted a detailed study of stellar populations in elliptical galaxies. The authors also adopt the infall model of chemical evolution. Table 3 compares the models on the metallicity sequence of this work with those of Bressan et al. (1996) at galaxy age $T_G = 15$ Gyrs. The Salpeter IMF with $m_l \simeq 0.16 M_\odot$ (we calculate this value from their parameter $\zeta = 0.5$ by assuming the turnoff mass $m_t = 0.9 M_\odot$) and $m_u = 120 M_\odot$ and constant $\tau_{in} = 0.1$ are assumed in their models. The definitions and the units of model properties are the same as those given in Table 2. τ and M/L_B of Bressan et al. (1996) are re-scaled to our definition. Bressan et al. define the mean stellar metallicity as:

$$< Z >= \frac{\int_0^{T_G} \psi(t)Z(t)dt}{\int_0^{T_G} \psi(t)dt}, \qquad (13)$$

which gives the mass-weighted mean metallicity of stars ever formed. We therefore re-calculate $< Z >$ for the models of this study according to Eq.(12). The model comparison has been done for two typical galaxies which have different mass along the CM relation. Table 3 shows that chemical and photometric properties are almost similar between the two models.

Although it is not explicitly shown in Table 3, their model predicts higher [Mg/Fe] ratios for more massive galaxies, while ours would give virtually the same values. This is because their model assumes shorter time scale of star formation for massive galaxies, while our model assumes it constant for all galaxies. As a result, their model achieves an earlier occurrence of galactic wind in more massive galaxies. Indeed, there is an observational trend that ellipticals with stronger Mg_2 indices tend to have larger line strengths of iron (Fe5270 and Fe5335), but the increase in iron is less than the prediction given by a population synthesis model with solar [Mg/Fe] (Worthey et al. 1992). However, the scatter is large and real. Moreover, it is not clear if this means an increase of [Mg/Fe] towards luminous ellipticals, because unlike single star spectroscopy these lines come from many stars of different age, metallicity, and probably abundance ratios, and a population synthesis approach is required to interpret [Mg/Fe] from these line strengths. However, the present day population synthesis models are not yet matured to conduct such analysis because behaviours of neither stellar evolutionary tracks nor stellar model atmosphere are fully investigated with various elemental abundance ratios. Thus, we believe that the trend of [Mg/Fe] with galaxy luminosity needs to be confirmed and that one need not necessary take it as a strong constraint for modeling elliptical galaxies. We should also note that the galactic wind time in Bressan et al.'s (1996) models is in the range of $0.31 - 0.43$ Gyrs, this would give [Mg/Fe] in the "right" direction if the mean lifetime of SNIa progenitors is 0.25 Gyrs (Matteucci 1994). However, recent studies suggest that the mean lifetime of SNIa progenitors that are most responsible to the iron enrichment could be as long as $(1.5 - 2.5)$ Gyrs (Ishimaru & Arimoto 1996; Yoshii et al. 1996). If that is the case, much longer time scale of star formation would be required for less massive galaxies than Bressan et al.'s (1996) models.

Table 2. Model sequences of elliptical galaxies at $z = 0$.

	M_V(mag)	−23.00	−21.98	−20.98	−20.04	−18.99	−17.97	−16.96
	$M_G(10^9 M_\odot)$	812	291	108	42.0	14.8	5.35	1.98
	T_G(Gyr)	15.00	15.00	15.00	15.00	15.00	15.00	15.00
metallicity	t_{gw}(Gyr)	0.515	0.320	0.235	0.185	0.147	0.120	0.100
sequence	$< \log Z/Z_\odot >$	−0.014	−0.116	−0.213	−0.304	−0.404	−0.502	−0.596
	$\log < Z/Z_\odot >$	0.147	0.025	−0.079	−0.173	−0.273	−0.368	−0.458
	M/L_B	8.406	7.568	6.846	6.240	5.652	5.144	4.700
	$U - V$	1.671	1.596	1.521	1.452	1.378	1.308	1.242
	$V - K$	3.355	3.273	3.192	3.116	3.032	2.949	2.868
	M_V(mag)	−23.00	−22.00	−21.00	−20.00	−19.00	−18.00	−17.00
	$M_G(10^9 M_\odot)$	812	232	68.5	22.2	6.20	1.86	0.693
	T_G(Gyr)	15.00	9.97	6.88	5.57	3.68	2.54	2.30
age	t_{gw}(Gyr)	0.515	0.515	0.515	0.515	0.515	0.515	0.515
sequence	$< \log Z/Z_\odot >$	−0.014	0.002	0.013	0.004	0.013	0.060	0.039
	$\log < Z/Z_\odot >$	0.147	0.160	0.176	0.160	0.166	0.207	0.189
	M/L_B	8.406	5.856	4.190	3.334	2.266	1.635	1.483
	$U - V$	1.671	1.571	1.465	1.408	1.326	1.211	1.146
	$V - K$	3.355	3.274	3.194	3.113	3.033	2.952	2.871

Table 3. Model comparison

	M_V	x	t_{gw}	τ	τ_{in}	T_G	M_G	$< Z >$	$V - K$	$U - V$	M/L_B
this	−22.49	1.20	0.39	0.10	0.10	15	485	0.025	3.314	1.633	7.974
work	−16.96	1.20	0.10	0.10	0.10	15	1.98	0.007	2.868	1.242	4.700
Bressan et al.	−22.56	1.35	0.31	0.14	0.10	15	648	0.031	3.280	1.588	9.682
(1996)	−16.82	1.35	0.43	1.00	0.10	15	2	0.008	2.793	1.215	5.265

3. Comparison with observations

3.1. Age-metallicity degeneracy

Figs. 2 and 3 compare E1 and E4 models to E1 and E4 spectral templates (see Arimoto 1996 for the details). E1 model has parameters $T_G = 15$ Gyrs and $t_{gw} = 0.52$ Gyrs. In Fig. 2a, the lower solid line gives E1 model and the upper one shows the E1 template, respectively. Residuals between the two spectra are shown in Fig. 2b. E1 model reproduces the E1 template very well except for $\lambda < 3000$Å.

Two E4 models (E4M and E4A) are confronted with the E4 template. E4M is one of the metallicity sequence with $T_G = 15$ Gyrs and $t_{gw} = 0.17$ Gyrs (lower solid line in Fig. 3a). E4A is taken from the age sequence with $T_G = 4.0$ Gyrs and $t_{gw} = 0.52$ Gyrs (dotted line in Fig. 3a). Both E4M and E4A models have almost identical spectrum and give excellent fits to the E4 template except for $\lambda = 3000 - 4000$Å, where the observational data might have systematic errors (the E4 template spectrum in this wavelength range is indeed an amalgam of several different galaxies taken from different sources; see Arimoto 1996). This possible error is suggested from the fact that the E4 template is 0.2 magnitude bluer in $U - V$ compared to Bower et al.'s (1992b) regression line, as seen in Fig. 1b.

From Figs. 2 and 3, one cannot tell which is the key factor, age or metallicity, that brings a systematic difference in the spectral energy distributions between the E1 and E4 templates. This is the so-called *age-metallicity degeneracy*.

To disentangle the degeneracy, luminosity and colour evolution of distant cluster ellipticals are crucial. Figs. 4a and 4b show the luminosity and colour evolutions of E1, E4M, and E4A models in the observer's frame. Filters are chosen for Gunn's system g ($\lambda_{\rm eff} = 4930$Å) and r ($\lambda_{\rm eff} = 6550$Å) bands. Transmission functions are taken from Thuan & Gunn (1976). Photometric zeropoints are defined by Thuan & Gunn (1976) in such a way that the star BD+17°4708 of spectral type F6V has $g = 9.5$ and $g - r = 0.0$, and its spectral energy distribution is obtained by K.Shimasaku (private communication). Adopted cosmological parameters are $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$.

E4A model brightens rapidly in r-band as a function of redshift from $z = 0$ to $z \simeq 0.24$, beyond of which E4A model dims abruptly as it is approaching to the formation epoch $z_f \simeq 0.26$ (Fig. 4). $g - r$ of E4A model is kept nearly constant to $z \simeq 0.16$ but becomes significantly bluer at higher redshifts since a galaxy is mainly composed of young massive stellar populations. Evolutionary behaviour of E4M model is almost similar to E1 model which becomes fainter and redder almost monotonically towards higher redshifts (Fig. 4) as a result of spectral reddening by redshift which is larger than intrinsic bluing of spectral shape by galaxy evolution. Such a conspicuous difference between E4A and E4M models clearly indicates that the colour and luminosity evolution must have definitive informations for *breaking* the age-metallicity degeneracy.

We note that $g - r$ of E1 and E4M models in the observer's frame become redder in $0 \leq z \leq 0.35$ due to the passage of g-
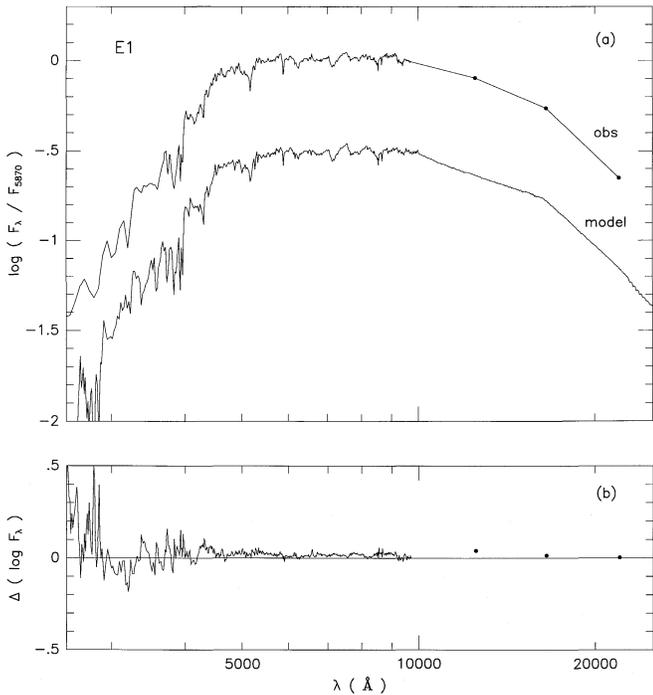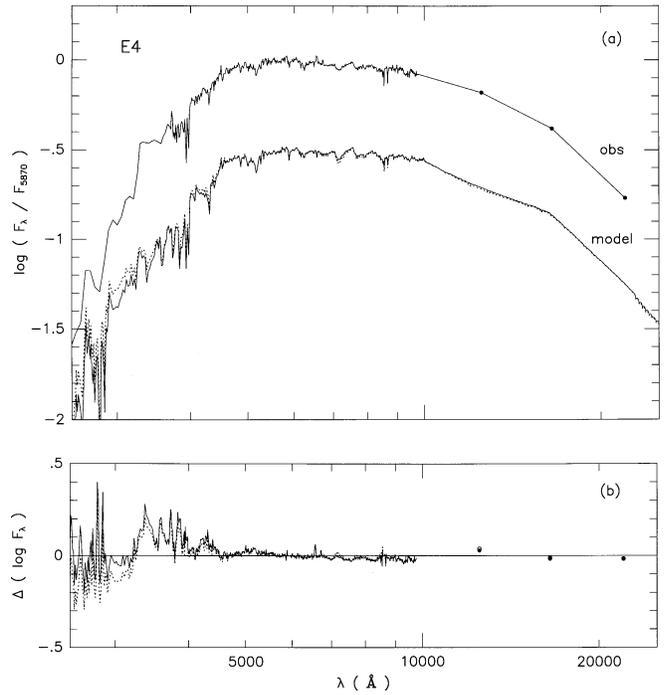
Fig. 2. a Comparison of E1 model with the E1 spectrum template. Filled circles correspond to the fluxes at the effective wavelengths of J, H and K bands. **b** Residuals of the fluxes between E1 model and E1 template.

Fig. 3. a Comparison of E4M (lower solid line) and E4A (lower dotted line) models with the E4 spectrum template. **b** Residuals of the fluxes between E4M (solid line and filled circles) and E4A (dotted line and open circles) models and E4 template (obs − model).

band through 4000Å break, remain nearly unchanged in $0.35 \leq z \leq 0.7$, and become redder again in $z \geq 0.7$. Stagnation at $z \sim 0.5$ happens because a decrease of g-band flux is balanced by rapid dimming of r-band flux caused by its passage through CH G-band (~ 4300Å) to 4000Å break; thus the feature is characteristic in Gunn's $g - r$.

3.2. Distant clusters

Evolutions of the CM relation in $g - r$ vs. M_r diagram are presented in Figs. 5 and 6 for the metallicity sequence and the age sequence, respectively. Cosmological parameters are again $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$. The age of the universe is then about 16.5 Gyrs, and a galactic age $T_G = 15$ Gyrs corresponds to the formation redshift $z_f \simeq 5.4$, and $T_G = 2.3$ Gyrs to $z_f \simeq 0.14$. Crosses on each line indicate the position of each model defined at $z = 0$. Galaxy masses at $z = 0$ are indicated for some models.

Observational data of E/S0 galaxies in two distant clusters Abell 2390 ($z = 0.228$; triangles) and Abell 851 ($z = 0.407$; circles) are superposed in Fig. 5. For Abell 2390, data are taken from Yee et al. (1996). The membership is confirmed by redshift measurement and E/S0 morphologies are classified spectroscopically. Galaxies in the central field of the cluster $(7.3' \times 9.1')$ are represented by filled triangles. Since photometric data by Yee et al. (1996) are taken by CCD detector which reduces blue light, the transmission functions should be different from those of original system of Thuan & Gunn (1976).

According to Schneider, Gunn & Hoessel (1983), we convert their data to the original Gunn's system by using conversion formula given by Schneider et al. (1983) : $r = r_c + 0.044(g - r)_c$ and $g - r = 1.199(g - r)_c$, where subscript c indicates the CCD magnitude. For Abell 851, galaxies classified as E/S0 with HST images are taken from Dressler et al. (1994). Filled circles indicate cluster members confirmed spectroscopically. Absolute magnitudes M_r are calculated from the redshift of each cluster with a help of the adopted cosmological parameters.

Both clusters Abell 2390 and Abell 852 show well-defined CM relations of E/S0 galaxies over $3 \sim 4$ magnitude range, and that these CM relations are almost in parallel to the CM relation at $z = 0$ which is calculated from model sequences calibrated with the CM relation of Coma in $V - K$ vs. M_V diagram. This trend is very well reproduced by the metallicity sequence (Fig. 5). In the observer's frame, the CM relation evolves almost in parallel towards redder colours and is well defined even at $z = 1$. Indeed, Stanford, Eisenhardt and Dickinson (1995) recently analyzed the optical$-K$ CM relation of elliptical galaxies in Abell 370 ($z = 0.374$) and Abell 851 ($z = 0.407$) and showed that these two clusters have almost identical slopes and dispersions of the CM relations to those of Coma ellipticals. They therefore concluded that the CM relations of the two clusters are fully consistent with a picture of old passive evolution with age more than 10 Gyrs.

Due to the reason given at the end of Sect. 3.1, the CM relations at $z = 0.4$ and $z = 0.6$ are nearly identical. This is the characteristic in this photometric system and there will be no

wonder if clusters in this redshift interval do not show any sign of evolution in their CM relations. As pointed out by Yee et al. (1996) and Dressler et al. (1994), their photometric data have uncertainties of the zeropoint calibration, which amount to $\sim$ 0.1 mag, but the slopes of CM relation should be much reliable.

For the age sequence, on the contrary, the CM relation changes drastically (Fig. 6). Galaxies *finally* on the CM relation at $z = 0$ become rapidly brighter and bluer as a function of lookback time, because smaller galaxies become considerably young as they approach to their formation epoch. For example, galaxies smaller than $2.2 \times 10^{10} M_\odot$ at $z = 0$ no longer exist in the universe at $z = 0.4$. As a result, at $z = 0.2$, the CM relation holds only for 2.4 mag from the brightest end, and virtually disappears at $z \geq 0.6$. We note that the slope of the CM relation becomes progressively steeper towards higher redshifts, which is in high contrast to the metallicity sequence whose CM relation keeps its slope nearly constant from $z = 0$ to 1.

The CM relations of the two clusters Abell 2390 and Abell 851 extend to much fainter magnitudes than the theoretical loci predicted by the age sequence models. This is a clear evidence that the CM relation cannot be simply attributed to the age difference alone. Thus, it can be concluded that the metallicity is the key factor that accounts for the CM relation of elliptical galaxies.

Our conclusion does not depend on the cosmological parameters chosen. Fig. 7 shows the evolution of CM relation of age sequence computed with $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. Here the age of the brightest galaxies are assumed to be 12 Gyrs instead of 15 Gyrs because the universe is younger ($\simeq 13$ Gyrs). $T_G = 12$ Gyrs corresponds to $z_f \simeq 4.5$, which is nearly the same as that of the brightest galaxy in Fig. 6. Galactic wind epoch t_{gw} is set to 1.25 Gyrs. The situation is worse than the $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$ cosmology; the CM relation is deformed even at lower redshift, The same situation is realized when smaller formation redshift, such as $z_f = 1$ or 2, is adopted for a given set of cosmological parameters.

4. Discussion

Galaxies defining the CM relation at high redshifts may not be simply the progenitors of those defining the CM relation at $z \simeq 0$, since galaxies undergoing star formation at moderate to high redshifts could well enter the CM relation at lower redshifts, or alternatively, since galaxies in the CM relation at high redshift may leave it if they undergo new episode of star formation (e.g., Barger et al. 1996). However, if galaxies suffered star formation at moderate and high redshifts and if the light of the intermediate-age stellar populations dominate the luminosities of the present day ellipticals, these galaxies should deviate considerably from the CM relation, unless the star formation episodes occurred beyond a redshift of 2 (Bower et al. 1992b). In other words, the light from the intermediate-age stars cannot be a primary cause of the CM relation of cluster ellipticals today. Fig. 5 shows that the CM relations were already established in Abell 2390 at $z = 0.228$ (in particular, E/S0 in the central field) and Abell 851 at $z = 0.407$. This implies that these galaxies
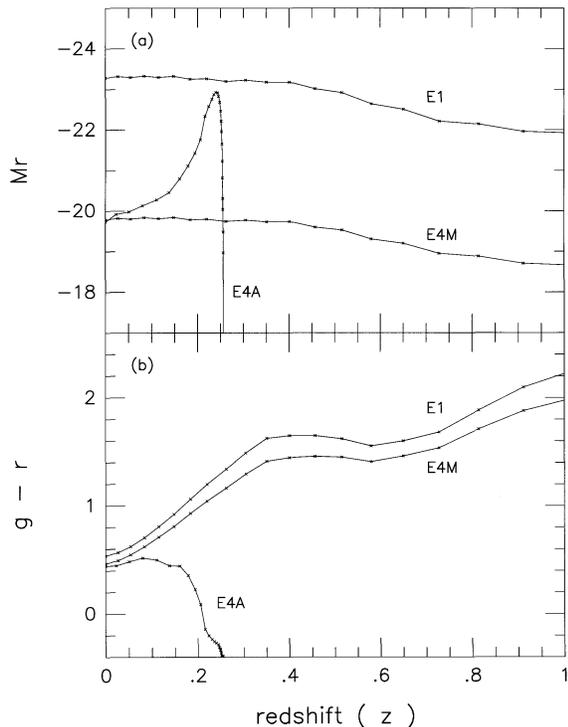

Fig. 4. a $r-$luminosity evolution of E1, E4M, and E4A models in the observer's frame. $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.1$. **b** The same as **a**, but for $g - r$ colour evolution.

had evolved *passively* down to these redshifts, and if the CM relations at these redshifts are due to the age effect, the epoch of galaxy formation must have been very precisely tuned for each specified galaxy mass. We believe this is very unlikely.

Based on a hierarchical clustering model of galaxy formation, Kauffmann (1995) demonstrated that some elliptical galaxies could be assembled and enter the CM relation even from $z = 0.4$ to now, but she also indicated that most of the stars even in such elliptical galaxies formed fairly in early epoch such as $z > 1.9$ and the resulting CM relation could keep the small dispersion of Bower et al. (1992b) (Kauffmann 1996). Kauffmann (1995) did not obtain the CM relation for ellipticals, probably because she did not include any metal enrichment in the models. She mentioned that it is likely that the observed CM relation is due to higher degree of metal enrichment in luminous galaxies.

As suggested by dynamical disturbances in elliptical galaxies such as shells/ripples, multiple nuclei, and rapidly rotating and/or counter rotating cores (e.g., Kormendy & Djorgovski 1989), or by the intermediate-age stellar populations suggested by the optimizing population synthesis (O'Connell 1976; Pickles 1985b; Rose 1985; O'Connell 1986; Bica 1988; Rose et al. 1994), some ellipticals, especially those in less dense environment, must have undergone recent star formation, possibly by interaction with other galaxies. Schweizer & Seitzer (1992) analized E/S0 galaxies in the field and groups and found that their $U - B$ and $B - V$ become systematically bluer as the amount of fine structure increases, which might spread the
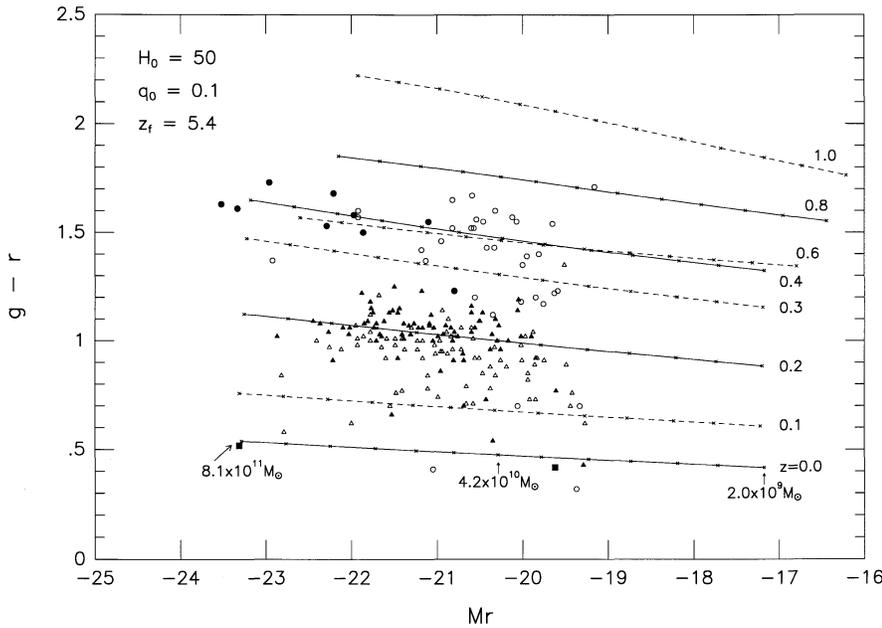
Fig. 5. Evolution of the CM relation for the metallicity sequence in the observer's frame (solid and dashed lines). Triangles and circles indicate E/S0 galaxies in Abell 2390 ($z = 0.228$) and Abell 851 ($z = 0.407$) clusters, respectively. Two filled squares give the E1 (left) and the E4 (right) templates, respectively.
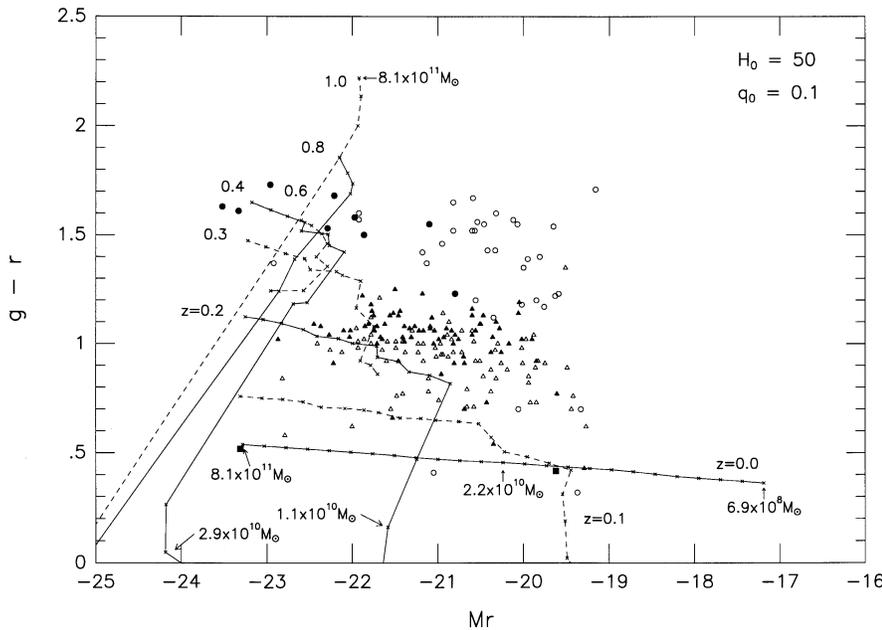

Fig. 6. The same as Fig. 5, but for the age sequence.

colour dispersion, though still small, compared to those of cluster ellipticals. This in turn suggests that the interaction with other galaxies causing these dynamical disturbances cannot be the major cause of the CM relations in clusters, as otherwise the CM relations should exhibit much larger dispersions than Bower et al. (1992b) found.

In distant clusters ($z = 0.31$) also, Barger et al. (1996) showed that upto 30 per cent of cluster members could undergo recent star bursts based on the high fraction of Hδ-strong galaxies, though many of them are regular spheroidals (*i.e.,* E/S0s). But we think these recent star formation should be secondary, with bulk of stars formed in early epoch, otherwise it must violate the small dispersion of Bower et al (1992b). Thus, some ellipticals might turn blue away from CM relation owing to the

recent secondary star formation and come back again to the relation later, but in terms of the origin of CM relation, we could well push back the formation epoch far into the past.

The results obtained in this paper are in excellent agreement with other, independent lines of evidence of an early completion of star formation in elliptical galaxies. The tightness of the correlation of galaxy colours with central velocity dispersion sets indeed an upper limit of ~ 2 Gyrs for the age dispersion of the bulk of stars in ellipticals (Bower et al. 1992b). An identical upper limit to the age dispersion of such galaxies is also established by the small dispersion on the fundamental plane (Renzini & Ciotti 1993). The most plausible interpretation of these evidences is that the bulk of star formation in cluster ellipticals was basically completed at $z \geq 2$, which is also suggested
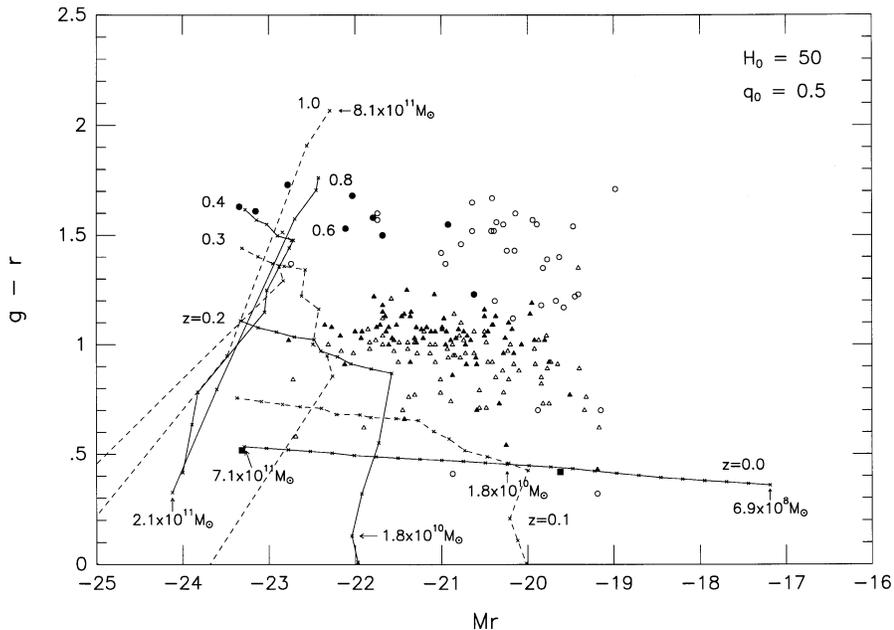
Fig. 7. The same as Fig. 6, but with the alternative cosmology ($H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$).

by the Mg$_2$ vs velocity dispersion relation of elliptical galaxies in Abell 370 ($z = 0.37$) (Bender, Ziegler, & Bruzual 1996). Fully consistent with this picture is also the detection of *passive* evolution of cluster ellipticals out to $z \simeq 1$, that seemingly requires a formation redshift in excess of ~ 2 (Aragón-Salamanca et al. 1993; Dickinson 1996). Finally, we note that the Fe II (UV+optical)/Mg II $\lambda 2798$ flux ratios of quasars B1422+231 at $z = 3.62$ (Kawara et al. 1996) and PKS 1937-101 (Taniguchi et al. 1996) at $z = 3.79$ indicate that the majority of stars in the host galaxies of these quasars, presumably ellipticals, have formed much earlier than these redshifts.

Fairly good agreements between the theoretical CM relations and the empirical ones of the two clusters are encouraging us to conduct a detailed study of cluster CM relations at intermediate and high redshifts. A confrontation of the model and the HST photometry of about dozen clusters will be given in a subsequent paper (T.Kodama, N.Arimoto, A.Aragón-Salamanca, & R.S.Ellis, 1996, in preparation).

Finally we should comment on our definition of the epoch of galaxy formation. Quite often the epoch of galaxy formation is defined to be the time when the protogalaxy decouples from the Hubble expansion to the formation of the dark halo of the galaxy. However, this process is virtually invisible and difficult to observe. Instead, as is often done by observational cosmologists, we identify the epoch of galaxy formation with observable events, or more precisely, the time when protogalaxies (normal massive ellipticals and bulges of spiral galaxies) are undergoing their first major episode of star formation. Then, the arguments given in this paper suggest that stars formed during this episode, at $z \geq 2$, dominate the light of the elliptical galaxy and the CM relation was established at that epoch. Since only the galactic wind model has so far been successful in explaining the observed CM relation, we are led to reach a conclusion that the CM relation takes its origin at early times from galactic

wind feedback. However, we should also mention that an alternative scenario of galaxy formation, the hierarchical clusrtering model discussed by Kauffmann (1995), could well satisfy the observational constraints we have used here. Indeed, Tinsley & Larson (1979) were able to reproduce the metallicity–mass relation of the form $Z_s \propto M_s^{0.25}$ (Tinsley 1978) with a model of hierarchical sequence of mergers among subsystems in which stars are assumed to form in bursts induced by galaxy–galaxy collisions. However, possible age effect on line indices which Tinsley (1978) used to derive the stellar metallicity was entirely ignored. The age effect on the CM relation was fully taken into account in Kauffmann's (1995) model, but the stellar metallicity effect was ignored instead. Therefore, there is no successful hierarchical clustering model that can reasonably reproduce the observed CM relation. Whether or not the hierarchical clustering model can account for the CM relation is yet to be fully investigated.

5. Conclusions

Evolutionary models for elliptical galaxies are constructed by using a new population synthesis code. The dissipative collapse picture by Larson (1974) is adopted and model parameters are adjusted to reproduce the CM relation of Coma ellipticals. Two evolutionary sequences are calculated under the contexts of *metallicity hypothesis* and *age hypothesis*, both can equally explain the CM relation at the present epoch. The confrontation with the observational CM diagrams of E/S0 galaxies in the two distant clusters Abell 2390 ($z = 0.228$) and Abell 851 ($z = 0.407$) rejects the *age hypothesis*, and strongly suggests that the bulk of stars were formed early in elliptical galaxies with a possibly minor contamination of the intermediate-age stars, and give a reinsuring confirmation of many previous contentions that the CM relation takes its origin at early times probably from

galactic wind feedback. This conclusion does not depend on the IMF nor the SFR, cosmological parameters, neither.

References

Alexander D. R., 1975, ApJS 29, 363

Anders E., Grevesse N., 1989, Geochim. Cosmochim. Acta 53, 197

Aragón-Salamanca A., Ellis R. S., Couch W. J., Carter D., 1993, MN-RAS 262, 764

Arimoto N., 1996, in: From Stars to Galaxies, eds. C. Leitherer, U. Fritz-von Alvensleben, J. Huchra (ASP Conf. Ser. Vol. 98), p.287

Arimoto N., Yoshii Y., 1986, A&A 164, 260

Arimoto N., Yoshii Y., 1987, A&A 173, 23 (AY87)

Arimoto N., Jablonka P., 1991, A&A 249, 374

Barger A. J., Aragón-Salamanca A., Ellis R. S., Couch W. J., Smail I., Sharples R. M., 1996, MNRAS 279, 1

Bertelli G., Bressan A., Chiosi C., Fagotto F., Nasi E., 1994, A&AS 106, 275

Bica E., 1988, A&A 195, 76

Bender R., Ziegler B., Bruzual A., 1996, ApJ 463, L51

Bessell M. S., Wood P. R., 1984, PASP 96, 247

Bessell M. S., Brett J. M., 1988, PASP 100, 1134

Bessell M. S., Brett J. M., Scholz M., Wood P. R., 1989, A&AS 77, 1

Bower R. G., Lucey J. R., Ellis R. S., 1992a, MNRAS 254, 589

Bower R. G., Lucey J. R., Ellis R. S., 1992b, MNRAS 254, 601

Bressan A., Chiosi C., Fagotto F., 1994, ApJ 94, 63

Bressan A., Chiosi C., Tantalo R., 1996, A&A 311, 425

Bruzual A. G., Charlot S., 1993, ApJ 405, 538

Bruzual A. G., Charlot S., 1995, ApJ, in preparation

Buzzoni A., 1989, ApJS 71, 817

Buzzoni A., Chincarini G., Molinari E., 1993, ApJ 410, 499

Buzzoni A., Gariboldi G., Mantegazza L. 1992, AJ 103, 1814

Charlot S., Bruzual A. G., 1991, ApJ 367, 126

Charlot S., Worthey G., Bressan A., 1996, ApJ 457, 625

Cox A. N., Stewart J. N., 1970a, ApJS 19, 243

Cox A. N., Stewart J. N., 1970b, ApJS 19, 261

Cox A. N., Tabor J. E., 1976, ApJS 31, 271

Davies R. L., Sadler E. M., Peletier R. F., 1993, MNRAS 262, 650

Dickinson M., 1996, in: Fresh Views of Elliptical Galaxies, eds. A. Buzzoni, A. Renzini, A. Serrano (ASP Conf. Ser. Vol. 86), p.283

Dressler A., Gunn J. E., 1992, ApJS 78, 1

Dressler A., Oemler A., Butcher H. R., Gunn J. E., 1994, ApJ 430, 107

Faber S. M. 1973, ApJ 179, 731

Faber S. M. 1977, in: The Evolution of Galaxies and Stellar Populations, eds. B. M. Tinsley, R. B. Larson, (Yale Observatory, New haven), p.157

Faber S. M., Jackson R. E., 1976, ApJ 204, 668

Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994a, A&AS 104, 365

Fagotto F., Bressan A., Bertelli G., Chiosi C., 1994b, A&AS 105, 29

Fritz-von Albensleben U., Gerhard O. E., 1994, A&A 285, 751

Frogel J. A., Persson S. E., Aaronson M., Matthews K., 1978, ApJ 220, 75

Gonzales J. J., 1993, Ph.D. Thesis, Univ. California, Santa Cruz

Greggio L., 1996, preprint

Gunn J. E., Stryker L. L., 1983, ApJS 52, 121

Harris W. E., 1996, Catalog of parameters for Milky Way globular clusters, McMaster University

Huebner W. F., Merts A. L., Magee N. H. Jr., Argo M. F., 1977, Astrophysical Opacity Library (Los Alamos Scientific Laboratory, LA-6760-M)

Iglesias C. A., 1993, private communication

Iglesias C. A., Rogers F. J., 1991, ApJ 371, 408

Iglesias C. A., Rogers F. J., Wilson B. G., 1992, ApJ 397, 717

Ishimaru Y., Arimoto N., 1996, submitted to A&A

Jacoby G. H., Branch D., Ciardullo R., Davis R. L., Harris W. E., Pierce M. J., Pritchet C. J., Tonry J L., Welch D. L., 1992, PASP, 104, 599

Johnson H. L., 1966, ARA&A 4, 193

Jones L. A., 1996, in: Fresh Views of Elliptical Galaxies, eds. A. Buzzoni, A. Renzini, A. Serrano (ASP Conf. Ser. Vol. 86), p.207

Kauffmann G., 1995, MNRAS 274, 161

Kauffmann G., 1996, submitted to ApJL

Kawara K., Murayama T., Taniguchi Y., Arimoto N., 1996, ApJL in press

Kormendy J., Djorgovski S., 1989, ARA&A 27, 235

Kurucz R. L., 1992, in: The Stellar Populations of Galaxies, eds. B. Barbuy, A. Renzini (Dordrecht: Kluwer), p.225

Köppen J., Arimoto N., 1990, A&AS 240, 22

Larson R. B., 1974, MNRAS 166, 686

Matteucci F., 1994, A&A 288, 57

Matteucci F., Tornambè F., 1987, A&A 185, 51

Michard R., 1980, A&A 91, 122

Nieuwenhuijzen H., de Jager C. A., 1990, A&A 231, 134

O'Connell R. W., 1976, ApJ 206, 370

O'Connell R. W., 1986, in: Spectral Evolution of Galaxies, eds. C.Chiosi, A.Renzini, (Dordrecht: Reidel), p.195

Persson S. E., Frogel J. A., Aaronson M., 1979, ApJS 39, 61

Pickles A. J., 1985a, ApJS 59, 33

Pickles A. J., 1985b, ApJ 296, 340

Reimers D., 1977, A&A 61, 217

Renzini A., Voli M., 1981, A&A 94, 175

Renzini A., Buzzoni A., 1986, in: Spectral Evolution of Galaxies, eds. C. Chiosi, A. Renzini (Dordrecht: Reidel), p.195

Renzini A., Ciotti, L., 1993, ApJ 416, L49

Ridgway S. T., Joyce R. R., White N. M., Wing R. F., 1980, ApJ 235, 126

Rogers F. J., Iglesias C. A., 1992, ApJ 401, 361

Rood R. T., 1973, ApJ 184, 815

Rose J. A., 1985, AJ 90, 1927

Rose J. A., Bower R. G., Caldwell N., Ellis R. S., Sharples R. M., Tegue P., 1994, AJ 108, 2054

Saito M., 1979a, PASJ 31, 181

Saito M., 1979b, PASJ 31, 193

Salpeter E. E., 1955, ApJ 121, 161

Schechter P., 1980, AJ 85, 801

Schneider D. P., Gunn J. E., Hoessel J. E., 1983, ApJ 264, 337

Schweizer F., Seitzer P., 1992, AJ 104, 1039

Stanford S. A., Eisenhardt P. R. M., Dickinson M., 1995 ApJ, 450, 512

Taniguchi Y., Murayama T., Kawara K., Arimoto N., 1996, submitted to ApJL

Tantalo R., Chiosi C., Bressan A., Fagotto F., 1996, A&A 311, 361

Thuan T. X., Gunn J. E., 1976, PASP 88, 543

Tinsley B.M., 1978, ApJ 222, 14

Tinsley B. M., 1980, Fundamentals of Cosmic Physics, Vol.5, p.287

Tinsley B.M., Larson, R.B., 1979, MNRAS 186, 503

Toomre A., Toomre J., 1972, ApJ 178, 623

VandenBerg D. A., Hartwick F. D. A., Dawson P. Alexander D. R., 1983, ApJ 266, 747

van den Berg S., 1981, A&AS, 46, 79

Vassiliadis E., Wood P. R., 1993, ApJ 413, 641

Vassiliadis E., Wood P. R., 1994, ApJS 92, 125

Visvanathan N., Sandage A., 1977, ApJ 216, 214

Worthey G., 1994, ApJS 95, 107

Worthey G., Faber S. M., Gonzalez J. J., 1992, ApJ 398, 69

Worthey G., Faber S. M., Gonzalez J. J., Berstein D., 1994, ApJS 94, 687

Worthey G., 1996, in: Fresh Views of Elliptical Galaxies, eds. A. Buzzoni, A. Renzini, A. Serrano (ASP Conf. Ser. Vol. 86), p.203

Yee H. K. C., Abraham R. G., Gravel G., Carlberg R. G., Smecker-Hane T. A., Schade D., Rigler M, 1996, ApJS 102, 289

Yi S., 1996, Ph.D. Thesis, Yale University

Yoshii Y., Arimoto N., 1987, A&A 188, 13

Yoshii Y., Tsujimoto T., Nomoto K., 1996, ApJ 462, 266