EVOLUTION OF GALAXIES IN CLUSTERS

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ABSTRACT

We use new models of stellar population synthesis to estimate the fraction of stars formed during the last major bursts of star formation in E/S0 galaxies in low-redshift clusters ($z \lesssim 0.4$) from the spectral signatures of intermediate-age stars. We find that the mass fraction of stars formed in late bursts in early-type galaxies in clusters must have decreased smoothly with time, from about 8% at $z \approx 1$ to less than 1% at $z \approx 0$. This result, which we interpret as a constraint on stellar mass added in mergers, is nearly independent of the assumed ages and morphological types of the progenitor galaxies prior to the last major bursts of star formation. We then compute the implied color and 4000 Å break evolution for progenitors of E/S0 galaxies in clusters at redshifts $z \lesssim 1$. We investigate a conservative model in which all present-day E/S0 galaxies are assumed to be initially elliptical galaxies and then to undergo bursts of star formation at the rate estimated from the signatures of intermediate-age stars at low redshifts. This model predicts that the progenitors of present-day E/S0 galaxies could be among the galaxies with the bluest colors and smallest 4000 Å breaks observed in high-redshift clusters. However, the predicted fraction of blue galaxies at high redshifts is significantly lower than is observed. The most natural explanation for this shortfall is an increase with redshift of the fraction of blue spiral galaxies in clusters, as suggested independently by recent high-resolution observations of intermediate-redshift clusters.

Subject headings: galaxies: clustering — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: stellar content — stars: formation

1. INTRODUCTION

Clusters are valuable laboratories for studying galaxy evolution over large lookback times because they are more readily identifiable than field galaxies at high redshifts. The extent to which galaxy evolution differs between cluster and field environments is not clear. Present-day clusters are rich in elliptical galaxies, whereas the field population is rich in spiral galaxies. Many galaxies in distant clusters have red colors consistent with the hypothesis that these galaxies formed coevally at a redshift $z > 2$ and evolved passively to become the E/S0 galaxies which dominate present-day clusters such as Coma (e.g., Bower, Lucey, & Ellis 1992; Aragón-Salamanca et al. 1993). However, there is also strong evidence for the evolution of galaxies in clusters. Butcher & Oemler (1978, 1984) pointed out that the fraction of blue galaxies in the cores of rich clusters increases with redshift, from about 2% at $z \approx 0$ to nearly 20% at $z \approx 0.4$—the "Butcher-Oemler" effect (see also Dressler & Gunn 1983, 1992; Couch & Sharples 1987; Lavery & Henry 1988). These blue galaxies are generally interpreted as star-forming galaxies which have disappeared today, either because they merged or because they were only temporarily blued by interaction-induced starbursts (Dressler & Gunn 1983; Lavery & Henry 1988; Evrard 1991). Recently, high-resolution ground-based and *Hubble Space Telescope* (*HST*) observations have revealed that many blue galaxies in several clusters at $z \approx 0.4$ are normal spiral or at least "disky" galaxies which

often show signs of interactions and bursts of star formation (Lavery, Pierce, & McClure 1992; Couch et al. 1993, 1994; Dressler 1993).

The evidence for evolution of cluster galaxies also comes from absorption-line studies of E/S0 galaxies in low-redshift clusters ($z \lesssim 0.4$). Many of the galaxies which were observed exhibit spectral signatures consistent with the presence of intermediate-age stellar populations (Couch & Sharples 1987; Lavery & Henry 1988; Pickles 1989; Dressler & Gunn 1992). This would indicate that the galaxies were forming stars, and hence were bluer, only a few billion years ago. However, the fact that many blue galaxies in distant clusters appear to be normal spiral galaxies suggests that morphological evolution of spiral into E/S0 galaxies could also have played a significant role over the last few billion years. The situation is complicated by the fact that present-day clusters contain a significant fraction of gas-poor, spiral galaxies with colors nearly as red as E/S0 galaxies (with $B - V \approx 0.9$; see the recent review by Oemler 1992). On average, about 10%–20% of galaxies in the cores of nearby rich, concentrated clusters are of late type (Dressler 1980; Butcher & Oemler 1978), whereas only 2%–5% are blue (where a blue galaxy is defined as having a $B - V$ color at least 0.2 mag bluer than the E/S0 sequence at the same absolute magnitude; see Butcher & Oemler 1984). In this context, the absorption-line signatures of intermediate-age stars in E/S0 galaxies at low redshifts constitute a powerful means of estimating the minimum fraction of blue galaxies in high-redshift clusters which should have evolved into E/S0 galaxies today, regardless of morphological evolution.

In this paper we use stellar population synthesis models to estimate the implications of the signatures of intermediate-age stars in E/S0 galaxies in low-redshift clusters for the photometric evolution of these galaxies at high redshifts, when the

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stars formed. Our main purpose is to evaluate the minimum color evolution implied by the low-redshift spectral analyses, and hence to infer the additional evolution (of colors or morphology) needed to explain the blue galaxy content of high-redshift clusters. We first describe in § 2 the signatures of the past history of star formation in the spectra of passively evolving galaxies using new models of stellar population synthesis. We use these arguments in § 3 to interpret the results of absorption-line studies of E/S0 galaxies in low-redshift clusters ($z \lesssim 0.4$) in terms of the average rate of star formation as a function of redshift in progenitors of E/S0 galaxies ($z \lesssim 1$). We then compute in § 4 the implied spectrophotometric evolution for progenitors of E/S0 galaxies at high redshift, and find that they could be among the galaxies with the bluest colors and smallest 4000 Å breaks observed in distant clusters. We show by a quantitative analysis in § 5 that only a small fraction of the observed blue galaxies in high-redshift clusters can be accounted for by late bursts of star formation superimposed on old elliptical galaxies, and we discuss the implications of these results for the color and morphological evolution of galaxies in clusters. Most of the arguments presented throughout this paper pertain to the evolution of galaxies in the cores of rich, concentrated clusters.

2. PREDICTIONS FROM POPULATION SYNTHESIS MODELS

Wɘ first describe the signatures of the past history of star formation in the spectra of passively evolving galaxies using the Bruzual & Charlot (1993) models of stellar population synthesis. The models have solar metallicity and include all phases of stellar evolution from zero-age main sequence to supernova explosion (for progenitors more massive than 8 $M_\odot$) or the end of the white-dwarf cooling sequence (for less massive progenitors). Most of the stellar spectra were taken directly from observations of Galactic stars at near-ultraviolet, optical, and near-infrared wavelengths and were extended into the far-ultraviolet using model atmospheres. The main adjustable parameters in the population synthesis models are the star formation rate and the initial mass function (IMF). Here, we are primarily interested in the evolution of galaxies which stop forming stars after a last burst of star formation. We consider two extreme histories of star formation for the underlying galaxy: a burst of duration 5×10^8 yr (model elliptical galaxy) and a constant star formation rate (model spiral galaxy). In each case, we assume that star formation stops when the galaxy undergoes a last burst of star formation, of duration 10^8 yr. The age of the underlying elliptical or spiral galaxy at this time and the mass fraction of the burst—defined throughout this paper as the fraction of the final mass in stars of the galaxy which is formed during the burst—are kept as free parameters. We further adopt in all models the Salpeter IMF with lower and upper cutoffs of 0.1 and 100 $M_\odot$, respectively.

Figure 1 shows the evolution of the optical/infrared colors and 4000 Å break of the model spiral and elliptical galaxies when the burst of star formation occurs at an age of 6 Gyr and involves 10% of the total mass (we have adopted here the definition of the 4000 Å break given by Bruzual 1983, i.e., the dimensionless ratio of the fluxes in two bands just redward and blueward of the 4000 Å discontinuity). Before the burst, the colors of the model elliptical galaxy redden rapidly as the most massive stars leave the main sequence, and the 4000 Å break becomes strong (the red phase around 1 Gyr, which is mostly visible in the $I - K$ color, is produced when stars on the asymp-
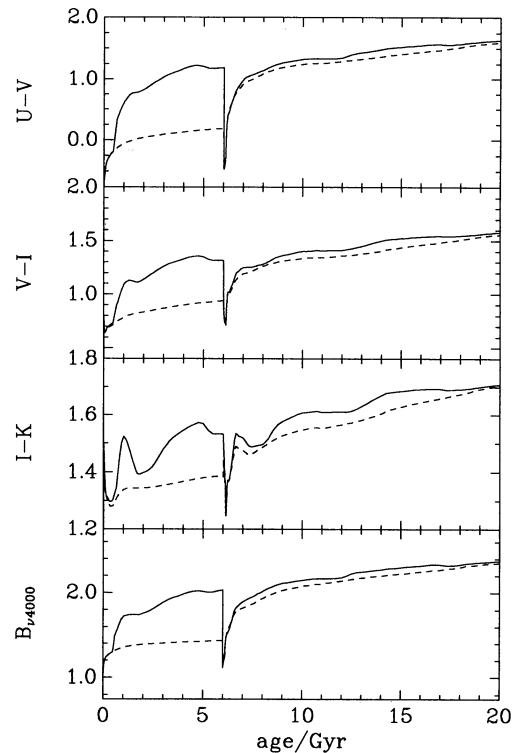

Fig. 1.—Evolution of the $U - V$, $V - I$, and $I - K$ colors and 4000 Å breaks of two model galaxies undergoing a last burst of star formation which involves 10% of their final mass at an age of 6 Gyr. The solid line corresponds to a 0.5 Gyr burst stellar population (model elliptical galaxy), and the dashed line to a stellar population with constant star formation rate for the first 6 Gyr (model spiral galaxy). The models have solar metallicity and the Salpeter IMF from 0.1 to 100 $M_\odot$. The filter response functions correspond to the RGO CCD U (which includes the atmosphere), V, and Kron-Cousins I filters and the UKIRT IRCAM K filter.

totic giant branch dominate the spectrum; see Bruzual & Charlot 1993). Meanwhile, the colors and 4000 Å break of the model spiral galaxy remain almost constant, since they are dominated by massive stars that are continuously replenished on the main sequence. During the burst, at an age of 6 Gyr, the new input of massive stars blues the colors and reduces the 4000 Å break temporarily in both models. From then on, the evolution of the colors and 4000 Å break depend only weakly on the past history of star formation. The difference between the two models in Figure 1 is less than 0.1 mag in all colors and less than 10% in the 4000 Å break at all ages after 6 Gyr. Moreover, the colors and 4000 Å break at ages greater than 6.5 Gyr are nearly the same as those of the model elliptical galaxy before the burst. Hence, we conclude from Figure 1 that the age and history of star formation of a galaxy which has evolved passively for several billion years cannot be determined from only the observed continuum emission. The situation is even further complicated when corrections for reddening have to be made.

Fortunately, more precise information on the past history of star formation in passively evolving galaxies can be learned from the absorption lines of hydrogen and of other prominent atoms and molecules such as Mg, Mg_2, Fe, Ca, Na, Sr, and CN (O'Connell 1980, 1986; Burstein et al. 1984; Rose 1985; Couch & Sharples 1987; Pickles 1985; Worthey, Faber, & Gonzalez

1992; Jablonka & Alloin 1994). We now illustrate this. The medium wavelength resolution and unique metallicity of the models used here restrict our analysis to only a few absorption lines. Two suitable examples are the equivalent width of the Hδ absorption line and the ratio of the central intensity of the combined Ca II H and Hϵ lines to the central intensity of the Ca II K line, referred to as the "Ca II H + Hϵ/Ca II K index" (Rose 1985). These features both hardly depend on metallicity (Rose 1984, 1985). The Ca II H + Hϵ/Ca II K index, which is constant in F, G, and K stars, drops significantly in A and B stars as the Ca II lines weaken and the H-Balmer lines strengthen. Therefore, a strong Hδ absorption equivalent width indicates the presence of stars younger than about 2 Gyr, and a strong Ca II H + Hϵ/Ca II K index that of older, longer lived stars.

We show in Figure 2 the evolution of the Hδ absorption equivalent width and the Ca II H + Hϵ/Ca II K index as a function of $U-V$ and $V-K$ colors for the two models of Figure 1. The evolution is shown starting from the age of 6 Gyr, when the burst occurs (triangles). At this age, the model spiral galaxy has a stronger Hδ equivalent width and a weaker Ca II H + Hϵ/Ca II K index than the model elliptical galaxy because it contains some A and B stars. Shortly after the burst, at an age of 6.5 Gyr, the $U-V$ and $V-K$ colors of both models already approach those characteristic of passively

evolving galaxies (see Fig. 1). However, the Hδ equivalent width and Ca II H + Hϵ/Ca II K index continue to evolve significantly for about 1.5 Gyr, with a weak dependence on the past history of star formation in the underlying galaxy. In particular, from 6.5 to 8 Gyr, the Hδ absorption equivalent width of the model galaxies drops by an order of magnitude and the Ca II H + Hϵ/Ca II K jumps by more than 50%, while the colors redden by less than 0.1 mag. Therefore, stellar absorption lines can reveal recent bursts of star formation in galaxies with colors otherwise typical of old, passively evolving stellar populations. We have considered here only the cases of the Hδ equivalent width and Ca II H + Hϵ/Ca II K index, whose sensitivities are limited to roughly 2 Gyr after a burst of star formation. However, other combinations of prominent metallic features can help detect bursts of star formation which are several billion years old (e.g., Pickles 1985).

Absorption-line strengths can also be used to untangle the competing effects of metallicity and age on the spectra of passively evolving galaxies. Stars of increasing metallicity have redder colors and evolve more slowly (e.g., Schaller et al. 1992). Thus, the age assigned to a stellar population from its observed colors is a strong function of metallicity. Pickles (1985; 1989; see also Pickles & van de Kruit 1988) has investigated the effects of age and metallicity on galaxy spectra by using isochrone spectra of instantaneous-burst stellar populations for
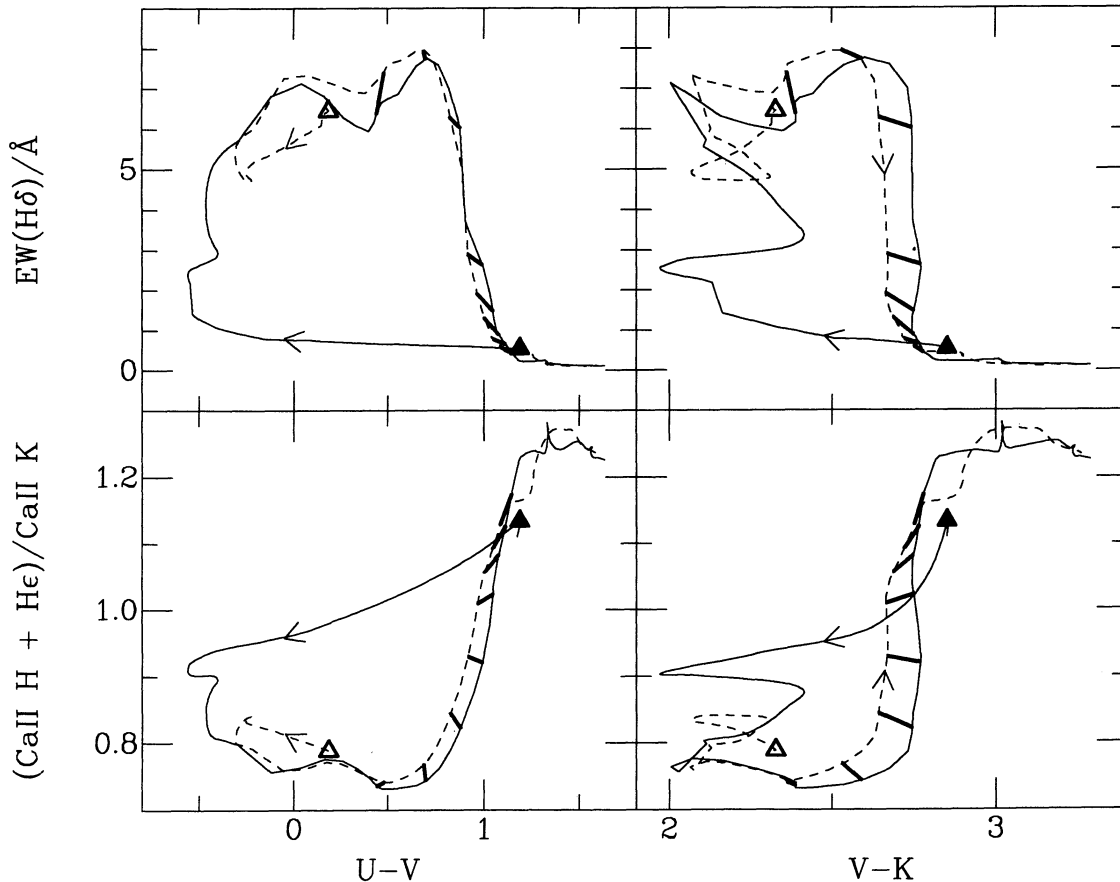

FIG. 2.—Evolution of the Hδ absorption equivalent widths and Ca II H + Hϵ/Ca II K indices as a function of $U-V$ and $V-K$ colors for the model galaxies of Fig. 1. The evolution is shown from an age of 6 Gyr, when the bursts occur (triangles). The tick marks indicate the positions of the models at successive steps of 0.25 Gyr, until the age of 8 Gyr. The filled triangle and solid line correspond to the case of an underlying elliptical galaxy, and the open triangle and dashed line to that of an underlying spiral galaxy. The filter response functions are the same as in Fig. 1.

six different ages between 2 and 15 Gyr and four metallicities between 0.0017 and 0.06. He showed that tight constraints on the age and metallicity of the various generations of stars in a galaxy can be obtained by requiring the observed spectrum to be fitted with a combination of isochrone spectra which reproduces the prominent metallic lines in addition to the continuum emission. One then infers the fraction of light, generally in the optical region of the spectrum, produced by stars of a given age. Unfortunately, we cannot illustrate this method here because our population synthesis models are restricted to solar metallicity. We refer the reader to the studies by Pickles (1985), Worthey (1993), and Jablonka & Alloin (1994).

We also emphasize here that the contribution to the optical light by the youngest stars in a galaxy provides valuable information on the fraction of the galaxy mass involved in the last major burst of star formation. Figure 3 shows the evolution of the fractional contribution to the visual luminosity of various model galaxies by stars created in a last burst. As expected, the fraction of V light produced by new stars in a model elliptical galaxy scales with the fraction of the galaxy mass involved in the last burst of star formation (Fig. 3a). The contribution peaks during the burst, when new massive stars occupy the main sequence, and then drops to a nearly constant value. For example, when 2% and 10% of the stars are created during the burst, their contribution to the V light 2 Gyr later is 5% and 24%, respectively. The reason for the nearly constant contribution at late ages is that the visual luminosity of a passively evolving stellar population changes only slowly after a few billion years (see Fig. 1 of Bruzual & Charlot 1993). In fact, this
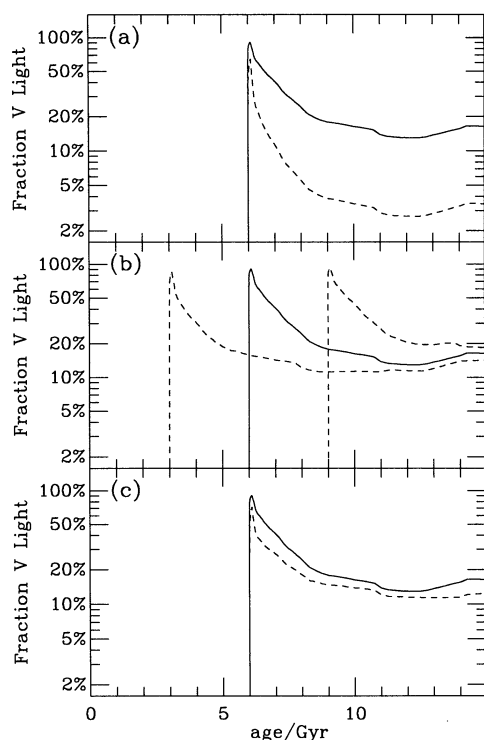
also implies that the fraction of V light produced by young stars depends only weakly on the age of the underlying population at the time of the burst, as Figure 3b shows. Figure 3c further indicates that the predicted contribution by stars formed in a last burst to the visual luminosity is only about 20% lower when the underlying galaxy is a model spiral instead of elliptical galaxy. Hence, the contribution by young stars to the visual luminosity of a passively evolving galaxy can be used to estimate the fraction of mass involved in the last burst of star formation, almost independently of the age and past history of star formation of the underlying galaxy when the burst occured.

3. RATE OF RECENT STAR FORMATION IN EARLY-TYPE GALAXIES

In this section, we estimate the rate of recent star formation in early-type galaxies at low redshifts ($z \lesssim 0.4$) from the absorption-line signatures of intermediate-age stars, using the models and arguments presented in the previous section. Since we cannot directly perform spectral analyses based on many spectral lines and include the effects of varying metallicity, we use here the results of several detailed absorption-line studies of low-redshift E/S0 galaxies that were published over the last few years. These results are conveniently expressed in terms of the fraction of the optical light of the galaxies accounted for by stars formed in the last few billion years. From the fractional contributions to the optical light, we can then securely estimate the mass of stars formed (§ 2). The galaxies studied at low redshifts were mostly selected from the field, but the few examples in clusters present similar characteristics (O'Connell 1980; Burstein et al. 1984; Rose 1985; Gonzalez 1993). At higher redshifts, spectral analyses have mainly been performed on cluster galaxies (Dressler & Gunn 1982, 1983, 1992; Couch & Sharples 1987; Lavery & Henry 1988; Mellier et al. 1988; Pickles 1989; Jablonka & Alloin 1994). Most of the galaxies in question have luminosities around L_*, which correspond to masses in the range 0.5–$1.5 \times 10^{11} h^{-2} M_\odot$. We do not consider here the first-ranked, giant cD galaxies observed in some rich clusters, which have typical luminosities $\gtrsim 10 L_*$ and are believed to accrete up to 40%–75% of their mass in a Hubble time by cannibalizing other cluster galaxies (e.g., Lauer 1988). We now interpret these observations.

Rose (1985) has analyzed the absorption lines of a sample of 12 nearby E/S0 galaxies with luminosities in the range $0.01 L_* \lesssim L \lesssim L_*$. He found that the Ca II H + Hϵ/Ca II K indices of the galaxies have a sharp distribution (except for one outlier, NGC 205) around a mean value corresponding to the index of the prototypical elliptical galaxy M32.[3] This dwarf galaxy is one of the best studied nearby E/S0 galaxies, and it exhibits several signatures of recent star formation (Spinrad & Taylor 1969; Faber 1972; Pritchet 1977; O'Connell 1980, 1986; Burstein et al. 1984; Rose 1985; Freedman 1992). The common value of the Ca II H + Hϵ/Ca II K index in nearly all the galaxies studied is significantly lower than the value expected from the proportions of main-sequence dwarfs and red giants indicated by the Sr II/Fe I indices. Rose concludes

FIG. 3.—Evolution of the fractional contribution to the V luminosity by stars produced in a last burst of star formation in a galaxy: (a) for a burst involving 10% (solid line) and 2% (dashed line) of the final mass, occuring in a 6 Gyr old elliptical galaxy; (b) for a burst involving 10% of the final mass, occuring in a 3, 6, and 9 Gyr old elliptical galaxy; and (c) for a burst involving 10% of the final mass, occuring in a 6 Gyr old elliptical (solid line) and spiral (dashed line) galaxies.

[3] The weak dependence of the Ca II H + Hϵ/Ca II K index on luminosity does not contradict the increasing strength of prominent metallic lines (Mg$_2$, Fe, etc.) of E/S0 galaxies with luminosity. In fact, the latter is generally attributed to a change in metallicity (e.g., Worthey, Faber, & Gonzalez 1993). The Ca II H + Hϵ/Ca II K index, on the other hand, depends only weakly on metallicity (Rose 1985).

that the discrepancy between the Ca II H + Hε/Ca II K and Sr II/Fe I indices implies that roughly 2% of the light at 4000 Å in the galaxies is produced by extra populations of A and B stars. Since the evolutionary phase of the stars is not known, this sets an upper limit on the contribution by main-sequence A and B stars with lifetimes less than 2.5 Gyr. Using diagrams similar to those shown in Figure 2, we infer that typically less than 0.5% of the mass in stars in nearby E/S0 galaxies have formed within the last 2.5 Gyr.

The observed color dispersion of nearby E/S0 galaxies provides another upper limit on their young star content, although this requires accurate photometry (see Fig. 1). Early-type galaxies follow a color-magnitude relation, which is generally attributed to an increase in metallicity from faint to bright luminosities (e.g., Faber 1977; Bower, Lucey, & Ellis 1992). Schweizer & Seitzer (1992) show that the departure of the $U - B$ and $B - V$ colors of nearby E/S0 galaxies from the mean color-magnitude relation correlates with their "fine-structure index" (a measure of dynamical youth) and absorption-line strengths. Thus, the dispersion of E/S0 galaxies around the mean color-magnitude relation could originate, at least in part, from an age difference. Schweizer & Seitzer (1992) consider a model in which they assume that E/S0 galaxies result from equal-mass mergers of two spiral galaxies of the same type (Sb-Sb or Sc-Sc). They adopt three main parameters: the star formation timescale, τ, of the model spiral galaxies (6 Gyr for Sb galaxies and 10 Gyr for Sc galaxies); the mass fraction ϵ of the available gas converted into stars at the time of the merger (typically, 10%); and the age of the spiral galaxies (15 Gyr). Schweizer & Seitzer then use population synthesis models to interpret the relative blueing of each of the 69 galaxies of their sample in terms of the time t_m elapsed since the merger. The results range from $4 \lesssim t_m \lesssim 10$ Gyr for Sb-Sb mergers to $5 \lesssim t_m \lesssim 11$ Gyr for Sc-Sc mergers. The galaxy mass fraction converted into stars during the merger can then be expressed as $\epsilon \exp([t_m - 15]/\tau)$, where t_m and τ are in Gyr.

E/S0 galaxies at higher redshifts also show many signs of recent star formation. Dressler & Gunn (1983, 1992), Lavery & Henry (1988), and Jablonka & Alloin (1994) have discovered many red galaxies in clusters at $0.3 \lesssim z \lesssim 0.6$ with strong Balmer absorption lines characteristic of post-starburst spectra. Pickles (1989, see § 2 of the present paper) has spectroscopically evaluated the ages of young stellar populations and their contribution to the visual luminosity in bright ($R \lesssim 20$ mag), red ($B - R \gtrsim 2.0$ mag) galaxies in clusters at redshifts between 0.18 and 0.39 (with absolute luminosities $0.4 L_* \lesssim L \lesssim 2.5 L_*$). To increase the signal-to-noise ratio in the observations, he coadded the spectra of the galaxies observed in each of the six clusters in his sample, distinguishing between a faint ($\lesssim L_*$) and a bright ($\gtrsim L_*$) class. This procedure is justified by the small differences in colors and line strengths of individual spectra in a given class. In fact, the inferred fraction of V light accounted for by young (2–6 Gyr) stars appears to be roughly comparable for the two luminosity classes in each cluster. Therefore, we adopt here the average over faint and bright galaxies of the fraction of visual luminosity contributed by young stars as a measure of the rate of recent star formation in E/S0 galaxies in each cluster. This fraction appears to increase with redshift, from about 7% at $z = 0.18$ to about 12% at $z = 0.39$. The population synthesis models indicate that the corresponding fraction of the galaxy masses transformed into stars 2–6 Gyr earlier ranges from roughly 4% at $z = 0.18$ to 8% at $z = 0.39$.

Couch & Sharples (1987) have also analyzed the stellar content of bright ($R \lesssim 20$ mag), red ($B_J - R \gtrsim 2.0$ mag) galaxies in three rich clusters at $z = 0.31$. Unlike Pickles (1989), they identified marked differences in the signatures of recent star formation among the galaxies, which they classified into "normal" E/S0 galaxies (62 objects) and E/S0 galaxies with strong Hδ absorption equivalent widths (11 objects with EW[Hδ] ≥ 3 Å). Couch & Sharples measured the Ca II H + Hε/Ca II K indices of the coadded spectra of the two types of galaxies, but did not determine the relative contributions to the light by main-sequence dwarfs and red giants. An upper limit on the number of young A and B stars, however, may be obtained from the difference between the observed indices and the value corresponding to the case of a red giant-dominated stellar population. The result is that less than 10% of the light at 4000 Å in the normal E/S0 galaxies is produced by A and B stars. This implies that less than 1.8% of the stars formed in the last 2.5 Gyr. The coadded spectrum of the strong-lined galaxies, on the other hand, is well fitted by a population synthesis spectrum in which 50% of the light at 4000 Å is produced by 1.0–1.5 Gyr old stars. Allowing for the observed dispersion in Hδ equivalent widths, this would imply that about 8.3($\pm$5)% of the stars formed between 1 and 1.5 Gyr ago. The relative fractions of normal and strong-lined galaxies then suggest that, on average, E/S0 galaxies in clusters at $z = 0.31$ formed less than about 1.5% of their stars in the last 2.5 Gyr and roughly 1.25($\pm$1)% between 1.0 and 1.5 Gyr ago.

Figure 4 summarizes the results of the previous paragraphs. For consistency, we have reexpressed all the observational limits on the fraction of luminosity of E/S0 galaxies produced by young stars as limits on the contribution in the V band (Fig. 4a). The ages of the stars, which vary from one observation to another, are indicated in billion years. Figures 4b and 4c show the resulting limits on the mass fraction of stars formed in early-type galaxies as a function of redshift. We have reexpressed constraints on the age of stellar populations as constraints on their redshift of formation for two cosmological models: a flat universe with $q_0 = 0.5$ and $h = 0.45$ and an open universe with $q_0 = 0.1$ and $h = 0.55$ (where $h = H_0/100$ km s^{-1} Mpc^{-1}). Both correspond to a present age of the universe of about 15 Gyr and lead to similar predictions. Figure 4 shows that the mass fraction of stars formed in E/S0 galaxies increases with redshift, from less than 1% at $z \approx 0$ to about 8% at $z \approx 1$. This result was anticipated earlier by Pickles (1989) on the basis of his data. Moreover, the upper limits set by Schweizer & Seitzer (1992) on the past rate of star formation in nearby field galaxies for their two assumptions of Sb-Sb mergers and Sc-Sc mergers, obtained with an earlier version of the population synthesis models used here (Charlot & Bruzual 1991), bracket the results for cluster galaxies in Figure 4. Thus, recent star formation might be a generic feature of E/S0 galaxies both in clusters and in the field.

We show two other limits in Figure 4. One is the lower limit on the mass accretion rate by L_* galaxies in a standard model of hierarchical clustering (dashed line in Fig. 4b). This is the minimum mass fraction accreted by an L_* galaxy to a given redshift in a cold dark matter-dominated universe (Carlberg 1990a, b; Tóth & Ostriker 1992). The steep rise of this limit at high redshift is not in contradiction with our results because some of the accreted material might already be in the form of old stars. In a low-density universe (Fig. 4c), the crude limit on the mass accreted by an L_* galaxy obtained using the scaling formulae of Carlberg (1990b) is much lower. Tóth & Ostriker
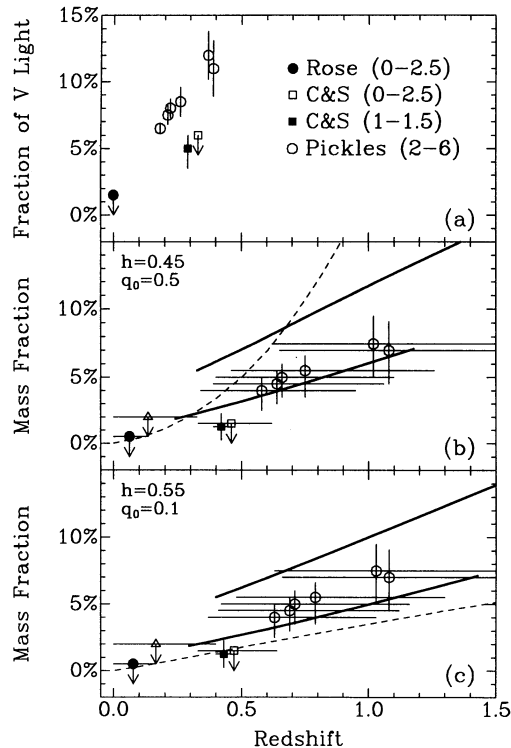
Fig. 4.—(a) Observed contributions by intermediate-age stars to the V luminosity of E/S0 galaxies in low-redshift clusters inferred from stellar absorption-line studies. The corresponding ranges of stellar ages are indicated next to the sources (see text for details). (b) Mass fraction of new stars in the progenitors of E/S0 galaxies as a function of redshift derived from (a) for the cosmology $h = 0.45$ and $q_0 = 0.5$. The solid lines indicate the upper limits on the past star formation rate in nearby E/S0 field galaxies set by the merger models of Schweizer & Seitzer (1992), for Sb-Sb type (lower curve) and Sc-Sc type (upper curve) mergers. The dashed line is a lower limit on the mass accretion rate by an L_* galaxy in a standard model of hierarchical clustering (Carlberg 1990a, 1990b). The open triangle is a comparative upper limit on the mass recently accreted by spiral galaxies from Tóth & Ostriker (1992; see § 3 of the present paper). The horizontal error bars correspond to the uncertainties on the ages of intermediate-age stars detected in low-redshift E/S0 galaxies. The vertical error bars represent the uncertainties on the observed fraction of V light contributed by these stars and the uncertainties on the determination of their contribution to the mass for the allowed ranges of ages. (c) Same as (b) for the case $h = 0.55$ and $q_0 = 0.1$.

(1992) also derived an upper limit on the mass of material accreted recently by spiral galaxies from the thinness and coldness of their disks. Although spiral and elliptical galaxies are generally found in different environments, it is interesting to see how this limit compares to that on the mass of stars formed recently in E/S0 galaxies. According to Tóth & Ostriker, a typical giant spiral galaxy must have accreted less than 4% of its disk mass in the last 5 Gyr. This is roughly 2% of the mass of a typical, L_*, E/S0 galaxy, since elliptical galaxies have an average mass-to-light ratio twice that of spiral galaxies (e.g., Faber & Gallagher 1979). This upper limit therefore compares with that obtained by Rose (1985) for E/S0 galaxies and is indicated by an open triangle in Figures 4b and 4c.

The evolution of the star formation rate in E/S0 galaxies obtained in Figure 4 is in reality a mean evolution averaged over large redshift intervals, as the horizontal error bars indicate. This result does not imply that E/S0 galaxies should form stars at all times. In fact, the ages of intermediate-age stars estimated from the absorption-line strengths in the spectra of

galaxies at low redshifts are uncertain by a few billion years (Fig. 4a). As Figure 1 shows, after a galaxy undergoes a last burst of star formation, the colors reach the values characteristic of old, passively evolving stellar populations in less than 1 Gyr. Thus, although galaxies in a cluster at low redshift may present similar signatures of recent star formation, there should be a dispersion in the ages and hence colors of the progenitor galaxies at high redshift around the values corresponding to the mean epoch of star formation estimated in Figure 4b or Figure 4c.

4. IMPLICATIONS FOR THE SPECTROPHOTOMETRIC EVOLUTION AT HIGH REDSHIFTS

The star formation rates obtained in the previous section imply that E/S0 galaxies in clusters have undergone spectrophotometric evolution at redshifts $z \lesssim 1.1$. We now evaluate this evolution using the population synthesis models and compare our results with observations of high-redshift clusters. In particular, Dressler & Gunn (1983, 1990, 1992) have obtained g, r, and i photometry of 15 rich clusters at redshifts $0.04 \leq z \leq 0.94$. They also measured the 4000 Å breaks of bright ($r \lesssim 22$ mag) galaxies in each cluster. This spectroscopic subsample may be slightly incomplete but is thought to include galaxies in the full range of colors in representative proportions. More recently, Aragón-Salamanca et al. (1993) obtained V, I, and K photometry of 10 rich clusters at redshifts $0.55 \leq z \leq 0.92$, two of which belong to the Dressler & Gunn (1990) sample. They selected the galaxies in the K band, as opposed to the r-band selection by Dressler & Gunn (1990), to reduce the chances of biasing the sample toward blue objects. However, unlike Dressler & Gunn (1990), Aragón-Salamanca et al. (1993) do not have redshifts for their galaxies; hence the most distant clusters may be significantly contaminated by foreground objects. The clusters themselves in these samples were selected from various catalogues, for which the reddest filter corresponds to the photographic N band ($\lambda_{eff} \approx 8000$ Å). The main results of these studies are that the fraction of starforming galaxies in clusters increases with redshift (the Butcher-Oemler effect) and that beyond a redshift of about 0.7, the reddest galaxies in clusters show evidence for evolution consistent with passive evolution (the "blueing of the red envelope"). In the following, we examine how the evolution of the colors and 4000 Å break expected from recent star formation in E/S0 galaxies compares with the ranges of colors and 4000 Å breaks of galaxies in these observations. The distributions of the spectrophotometric properties among galaxies in a cluster will be addressed in the next section.

The history of star formation prior to the last major burst of star formation in model galaxies is a free parameter, since it has little influence on the subsequent evolution (Fig. 3). We recall that our main purpose in this paper is to evaluate the minimum amount of evolution implied for E/S0 galaxies in clusters by the signatures of recent star formation. We therefore consider a conservative model, in which all E/S0 galaxies are assumed to be initially elliptical galaxies formed at a redshift $z_F = 5$, and then to undergo bursts of star formation at various redshifts at the rate estimated previously from the lowredshift signatures of intermediate-age stars (we adopt throughout this section $q_0 = 0.5$ and $h = 0.45$). We will also discuss later the case of progenitor spiral galaxies and the effect of changing z_F. The evolution of the $V - K$ and $I - K$ colors of the model elliptical galaxy in the absence of late bursts of star formation is shown by the dashed lines in Figure 5. The colors
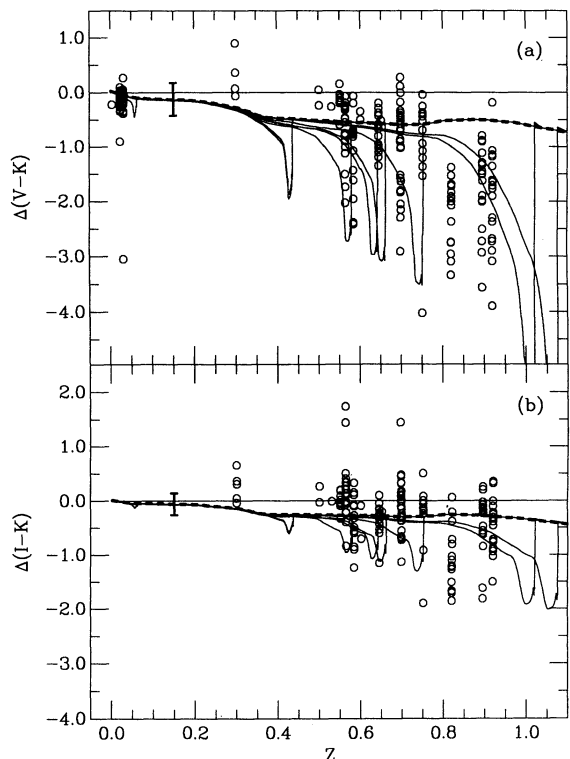
FIG. 5.—Evolution of the (a) $V - K$ and (b) $I - K$ colors of model galaxies forming at $z_F = 5$ as a function of redshift for $h = 0.45$ and $q_0 = 0.5$. The colors are zero-pointed to the k-corrected colors of a nonevolving, present-day elliptical galaxy. The thick dashed line corresponds to a model elliptical galaxy, and the solid lines to the effect of adding bursts of star formation to this model with the mass fractions of new stars taken from Fig. 4b. The data are the observed colors of galaxies in high-redshift clusters from Aragón-Salamanca et al. (1993). The associated uncertainties are typically less than 0.2 mag in both the $V - K$ and $I - K$ colors. The error bars on the figure indicate the effect on the predicted colors of increasing and decreasing the metallicity by a factor of 2 in the models. The filter response functions are the same as in Fig. 1.

are zero-pointed to the k-corrected colors of a non-evolving, bright elliptical galaxy (which has $V - K = 3.25$ and $I - K = 1.87$ at $z \approx 0$ for the filter response functions adopted in Fig. 5; Bruzual & Charlot 1993). As expected, the model elliptical galaxy is bluer at high redshifts than a non-evolving elliptical galaxy but has $\Delta(V - K) \approx 0$ and $\Delta(I - K) \approx 0$ at $z \approx 0$ (i.e., at an age of about 13.5 Gyr for our adopted parameters). Also shown in Figure 5 are the observed colors of galaxies in high-redshift clusters from the sample of Aragón-Salamanca et al. (1993) and, in Figure 5a, the $V - K$ colors of galaxies in the Virgo and Coma Clusters from Bower et al. (1992). The Butcher-Oemler effect and the blueing of the red envelope at high redshift are mostly apparent in the $V - K$ color, which is more sensitive than the $I - K$ color to variations of the rest-frame blue light.

The solid lines in Figure 5 show the effects of new bursts of star formation on the color evolution of the model elliptical galaxy. Again, this is the minimum color evolution expected for E/S0 galaxies in clusters from the signatures of intermediate-age stars at low redshifts. The different curves on the figure correspond to the estimates at different redshifts of the mean mass fraction of new stars in the progenitors of E/S0 galaxies from Figure 4b. As expected, the bursts of star formation temporarily blue the galaxies, which then rapidly recover the red colors characteristic of passively evolving stellar popu-

lations (see Fig. 1). Figure 5 shows that the modest amount of star formation predicted for E/S0 galaxies at high redshifts is sufficient to explain the full range of blue colors seen in the data. We have checked that the increase of the color range with redshift is primarily caused by the shift of the filters into the rest-frame ultraviolet, which is more sensitive to the presence of young stars than the optical and infrared light, rather than by the increase of the star formation rate. The reason for this is that elliptical galaxies have modest ultraviolet luminosities. Thus, for any amount of star formation, blue massive stars dominate the ultraviolet spectrum. The strong dependence of the color range on redshift is common to the models and data in Figure 5. However, some of the observed blue objects may be foreground galaxies (Aragón-Salamanca et al. 1993).

We compare in Figure 6a the 4000 Å break evolution of the model galaxies of Figure 5 with the observed 4000 Å breaks of galaxies in high-redshift clusters by Dressler & Gunn (1990). For reference, we also show the 4000 Å breaks of field E/S0 galaxies from Hamilton (1985) and Spinrad (1986). Again, the Butcher-Oemler effect and blueing of the red envelope are manifest in the cluster data. In this case, however, the cluster memberships of all galaxies are secure. At $z \approx 0$, the model elliptical galaxy has the standard $B_{v4000} \approx 2.2$ of present-day E/S0 galaxies (Hamilton 1985; Spinrad 1986). Furthermore, the bursts of star formation at various redshifts produce small
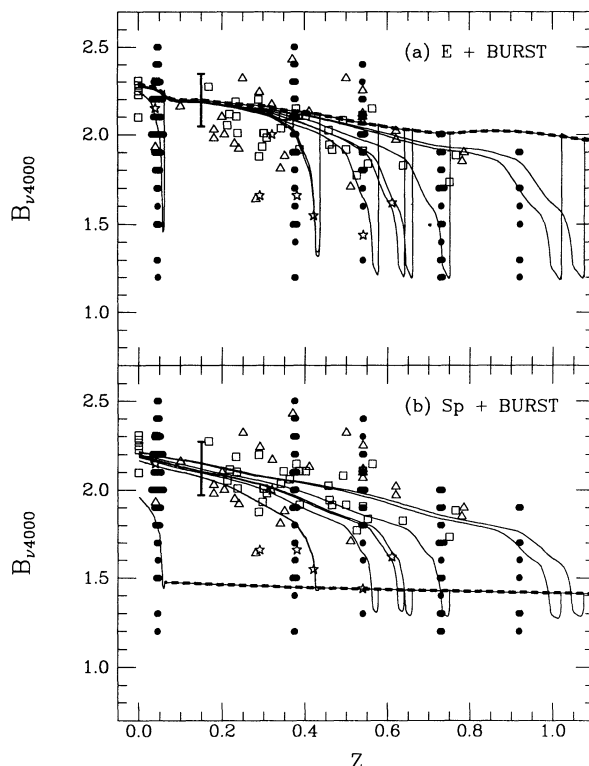

FIG. 6.—(a) Evolution of the 4000 Å break for the model galaxies of Fig. 5. The data are the observed 4000 Å breaks of galaxies in high-redshift clusters from Dressler & Gunn (1990) (filled circles) and of field galaxies from Hamilton (1985); (triangles: program galaxies; stars: serendipitous galaxies) and Spinrad (1986) (squares). The observational uncertainties are of the order of 5%. (b) Same as (a) but in the case where the progenitor galaxies are assumed to be spiral instead of elliptical galaxies. The error bars on the figure indicate the effect on the predicted B_{v4000} of increasing and decreasing the metallicity by a factor of 2 in the models.

4000 Å breaks that can match the observations. The range of B_{v4000}, however, does not depend on redshift as sensitively as the range of colors considered previously because the 4000 Å break samples the rest frame spectra of the objects. In fact, galaxies with 4000 Å breaks of about 1.2 are found at all redshifts. Hence, if the signatures of intermediate-age stars in low-redshift E/S0 galaxies are interpreted as recent bursts of star formation superimposed on old elliptical galaxies, the bluest colors and weakest 4000 Å breaks observed for galaxies in high-redshift clusters can be explained. However, the same range of spectrophotometric properties could be obtained for much different amounts of star formation. This emphasizes again the usefulness of constraints from absorption-line studies of low-redshift cluster galaxies.

Several galaxies in Figures 5 and 6a appear to have observed colors that are much redder, and 4000 Å breaks that are much stronger, than the model elliptical galaxy at $0.1 \lesssim z \lesssim 1$. This deserves comment because old, passively evolving stellar populations are generally expected to generate the reddest spectra. Extinction by dust is unlikely to be the explanation for these red objects because the $I - K$ color appears to be at least as reddened as the $V - K$ color. Furthermore, dust has little influence on the 4000 Å break, with B_{v4000} increasing by less than 0.15 for an extinction $A_B = 1$. Another possible source of reddening is metallicity. The population synthesis models used here are limited to solar metallicity. However, present-day elliptical galaxies are observed to have an average metallicity of nearly twice solar with a dispersion of about 50% (Gonzalez 1993). We have evaluated the effect of increasing and decreasing the metallicity by a factor of 2 in the models using recent stellar evolutionary tracks and model atmospheres for non-solar metallicities by Schaerer et al. (1993) and Kurucz (1992; see Charlot et al. 1993 for details). The results, indicated by the error bars in Figures 5 and 6, show that most of the red galaxies can be understood as early-type galaxies with less than twice solar metallicities. The few galaxies with very red colors in Figure 5 could be background galaxies, even though similar objects do not seem to appear in control field samples (Aragón-Salamanca et al. 1993). A possible explanation may be that these galaxies recently underwent a burst of star formation with an IMF deficient in low-mass stars (Charlot et al. 1993). This, in fact, could also explain the very large 4000 Å breaks of some cluster galaxies in Figure 6a.

The predicted spectral evolution after the last major burst of star formation is similar if cluster galaxies are assumed to be initially spiral instead of elliptical galaxies. In Figure 6b we show the evolution of the 4000 Å break for models in which bursts of star formation are added to progenitor spiral galaxies which formed stars continuously since $z_F = 5$. In this case, B_{v4000} remains nearly constant as long as star formation is maintained in the underlying spiral galaxy (*dashed line*). Then, when a final burst occurs and star formation stops, the 4000 Å break increases rapidly, as in the case of a progenitor elliptical galaxy. In fact, as in Figure 6a, the model galaxies in Figure 6b have at $z \approx 0$ the typical $B_{v4000} \approx 2.2$ of present-day E/S0 galaxies. Hence, we conclude from Figures 5 and 6 that the signatures of intermediate-age stars in low-redshift E/S0 galaxies imply that these galaxies could have been some of the objects with the bluest colors and weakest 4000 Å breaks observed in high-redshift clusters. This conclusion does not depend on the exact fraction of stars thought to have formed recently in E/S0 galaxies, since similar ranges of colors and 4000 Å breaks could be obtained for different predictions. Finally, we note that

Figures 5 and 6 alone do not allow us to determine whether the progenitors of E/S0 galaxies were preferentially spiral or elliptical galaxies in distant clusters.

5. DISCUSSION

The main result of the previous sections is that a few billion years ago, the progenitors of E/S0 galaxies in present-day clusters were at least temporarily blued by modest amounts of star formation. Their colors and 4000 Å breaks were then indistinguishable from those of galaxies which make up the Butcher-Oemler effect. We can use this result to set constraints on the global evolution of galaxies in clusters in the following way. The conservative model considered in § 4, in which the progenitors of all E/S0 galaxies are assumed to be old elliptical galaxies undergoing late bursts of star formation, provides a lower limit to the fraction of blue galaxies expected to be found in clusters at high redshifts for two reasons: firstly, E/S0 galaxies could equally well be the products of blue, spiral progenitor galaxies (Fig. 6b); and secondly, E/S0 galaxies represent on average only 80%–90% of the galaxy population in the cores of rich, concentrated nearby clusters (see § 1). The remaining galaxies are spiral and irregular galaxies, whose colors are systematically redder in clusters than in the field ($\Delta[B-V] \approx 0.2$ mag), implying that many early-type spiral galaxies in clusters have colors nearly as red as E/S0 galaxies ($B-V \approx 0.9$). However, the galaxies were presumably bluer in the past. Hence, by modeling the evolution of only E/S0 galaxies and assuming that these were old elliptical galaxies which underwent late bursts of star formation, one obtains a lower limit on the fraction of blue galaxies in high-redshift clusters. Any excess of blue galaxies in the observed color distribution with respect to this prediction may then be identified as spiral progenitors of E/S0 galaxies, or the progenitors of present-day spiral galaxies, or even galaxies which have since faded away.

To quantify this, we now compute the expected distribution in a cluster at a redshift z of the spectrophotometric property C (for example, a color) of progenitors of present-day E/S0 galaxies, under the conservative assumption that these were initially elliptical galaxies formed at $z_F = 5$. The mean mass fraction of stars added to the galaxies at z can be inferred from the observed trend in Figure 4b. This fraction, however, could have been added at any redshift in an interval $[z + \sigma_+(z), z - \sigma_-(z)]$ corresponding to the uncertainties of a few billion years on the ages of young stellar populations in low-redshift E/S0 galaxies (Fig. 4a). Therefore, the distribution of property C at a mean redshift $\langle z \rangle$ can be expressed as

$$N(C) \propto \int_{z + \sigma_+(z)}^{z - \sigma_-(z)} dz' \Sigma t(C, z, z') , \qquad (1)$$

where $\Sigma t(C, z, z')$ is the total time between $z + \sigma_+(z)$ and $z - \sigma_-(z)$ during which a galaxy undergoing a burst at z' is observed to have the property C. Figure 4 indicates that $\sigma_+(z)$ and $\sigma_-(z)$ correspond typically to uncertainties on the age of about 1 Gyr at $z \lesssim 0.5$ and 2 Gyr at $z \gtrsim 0.5$.

In the remainder of this paper, we identify the spectrophotometric property C as the 4000 Å break for three main reasons: (1) color distributions of distant cluster galaxies are more difficult to interpret, since they generally are subject to foreground contamination (e.g., Aragón-Salamanca et al. 1993); (2) the 4000 Å break has the advantage of sampling directly the rest frame spectra of galaxies, while the interpretation of observed colors involves k-corrections, which depend on the unknown

morphological types of the galaxies; and (3) the 4000 Å break is much less sensitive than colors to the presence of dust in the galaxies (Charlot et al. 1993). Figure 7 shows the expected distribution at different redshifts of the 4000 Å break of progenitors of low-redshift E/S0 galaxies calculated using the results of the previous section and equation (1) above. We indicate for reference the expected distribution of B_{v4000} in the absence of late bursts of star formation, i.e., for elliptical galaxies evolving passively since $z_F = 5$ (Fig. 7a). As expected, the inclusion of new bursts of star formation produces a tail at small B_{v4000} in the histograms (Fig. 7b). The fraction of galaxies in the tail increases with redshift, from about 12% at $z = 0.05$ to almost 30% at $z = 0.5$. The reason for this is that the mass fraction of new stars, and hence the time during which these dominate the spectra of the galaxies, increases with redshift (Figs. 3a and 4b). The fraction of objects with 4000 Å breaks smaller than passively evolving galaxies drops again under 20% at redshifts $z \gtrsim 0.7$ because the model elliptical galaxy still has a small 4000 Å break at these early ages. We note that shortening the timescale of new bursts of star formation from our adopted value of 0.1 Gyr to 0.01 Gyr would reduce the fraction of galaxies in the tail of the distribution by less than 1%.

In reality, the 4000 Å break of early-type galaxies also correlates with luminosity, an effect similar to the color-magnitude relation (§ 3). Thus, the distribution of 4000 Å breaks for E/S0 galaxies in a cluster is expected to be broadened by their spread in luminosity. The most natural way to compare our predictions with observations would be to normalize the 4000 Å breaks of a sample of observed galaxies to a fixed absolute

magnitude using the mean B_{v4000}-magnitude relation in the sample (e.g., Butcher & Oemler 1984). Unfortunately, we cannot use this approach here because the magnitudes of individual galaxies in the Dressler & Gunn (1990) sample under consideration are not available. Therefore, we must include in the models the influence of the luminosity function of E/S0 galaxies on the distribution of 4000 Å breaks. We evaluate this effect using observations of galaxies in the Virgo Cluster. We adopt the Gaussian approximation of the B-band luminosity function of E/S0 galaxies in this cluster given by Sandage, Binggeli, & Tamman (1985). We may ignore dE/dS0 galaxies, since all galaxies in the Dressler & Gunn (1990) sample have luminosities larger than $0.1 L_*$ (Gunn 1989). Furthermore, we estimate the B_{v4000}, V-magnitude relation for E/S0 galaxies in Virgo using the recent determination of the $U - V$, V color-magnitude relation by Bower et al. (1992) and the tight correlation between B_{v4000} and $U - V$ color (Aragón-Salamanca et al. 1993). The B_{v4000}, B-magnitude relation can then be evaluated using the $B - V$, V color-magnitude relation (Sandage 1972). This is the least certain step because the $B - V$, V color-magnitude relation is not very tight. Finally, we obtain the relative number of E/S0 galaxies with a given 4000 Å break from the B_{v4000}, B-magnitude relation and B luminosity function.

The distribution of B_{v4000} obtained in this way for E/S0 galaxies in the Virgo Cluster is close to a Gaussian distribution with a mean of 2.13 and a standard deviation of about 0.15. For comparison, the mean and standard deviation of the 4000 Å breaks of field galaxies observed at $\langle z \rangle = 0.05$ are 2.19 and 0.13, respectively (Hamilton 1985; Spinrad 1986). Here, we are primarily interested in the dispersion of the B_{v4000} distribution, which we include in the models by assuming that the distribution of 4000 Å breaks of early-type galaxies has the same shape at all redshifts as determined for E/S0 galaxies in the Virgo Cluster. The mean of the distribution, on the other hand, is taken to be the value predicted by the models. In particular, at $z = 0.05$ the model elliptical galaxy considered above has $B_{v4000} = 2.21$. We note that the similarity of the color-magnitude relations in Virgo, Coma, and Abell 370 indicates that the dispersion in B_{v4000} for early-type galaxies may, in fact, not change significantly out to at least $z \approx 0.4$ (Aragón-Salamanca, Ellis, & Sharples 1991). Since the dispersion in B_{v4000} only pertains to E/S0 galaxies, we do not apply a correction to model galaxies which have just undergone a new burst of star formation, so long as the amplitude of their 4000 Å break is more than 0.2 smaller than the expected value for a passively evolving galaxy at the same redshift.

Figure 8a (heavy solid lines) illustrates the broadening by the B_{v4000}-magnitude relation of the predicted distributions of 4000 Å breaks for the progenitors of E/S0 galaxies from Figure 7b. Also shown are the observed distributions of 4000 Å breaks for galaxies in clusters at the same redshifts from the sample of Dressler & Gunn (1990) (dotted lines); these include the spiral galaxy population. It appears that, as expected, high-redshift clusters contain significantly more galaxies with small 4000 Å breaks than predicted by our conservative model. To quantify this result, we first estimate the characteristics of the dominant population of early-type galaxies with large 4000 Å breaks at the various redshifts in both the models and data. We use the "biweight" central location and scale estimators, which are particularly suited for non-Gaussian distributions with tails such as those investigated here (Beers, Flynn, & Gebhardt 1990). The resulting estimates of the central locations are
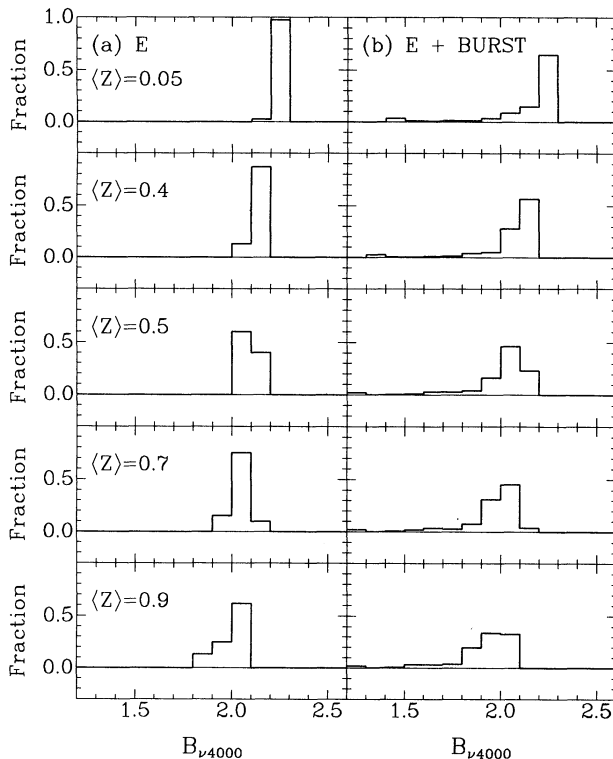

FIG. 7.—Model distributions of the 4000 Å break for progenitors of E/S0 galaxies in clusters at different redshifts (top to bottom) computed using eq. (1); (a) for passively evolving elliptical galaxies forming at $z_F = 5$; and (b) when including bursts of star formation at the rate predicted by the results of Fig. 4b.
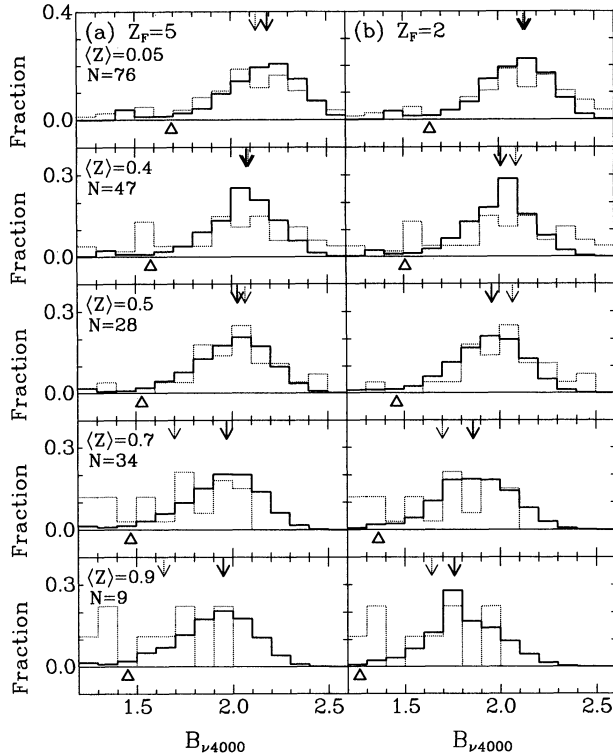
FIG. 8.—(a) The heavy histograms correspond to the broadening by the B_{v4000}-magnitude relation of the model histograms of Fig. 7b (see text). The dotted histograms show the observed distributions of 4000 Å breaks of galaxies in clusters at the different redshifts (from Dressler & Gunn 1990). In each panel, the number of galaxies defining the observed histogram is indicated. The down arrows show the central locations of the model and observed distributions calculated using the biweight estimator (see text). The open triangle indicates the value of the 4000 Å break 0.5 away from the central location of the model distribution. This is the limit under which a galaxy is classified as having a small 4000 Å break. (b) Same as (a) for the case $z_F = 2$.

shown by arrows above the histograms in Figure 8a. At $z \lesssim 0.5$, the predicted and observed distributions of B_{v4000} for early-type galaxies have similar central locations. However, the scale—an estimate of width—of the observed distributions (~ 0.25) is larger than that of the predicted distributions (~ 0.15). This difference appears to result from an excess both of galaxies with unusually large breaks and of galaxies with small breaks in the observed distributions.

At $z \gtrsim 0.7$, galaxies with large 4000 Å breaks are not observed, and the early-type population is no longer well defined. This is the blueing of the red envelope discussed by Dressler & Gunn (1990) and Aragón-Salamanca et al. (1993). In the models, however, the distribution of early-type galaxies is still well defined at these high redshifts, and the central location decreases much more weakly. The absence of galaxies with strong 4000 Å breaks may not be common to all clusters at $z \gtrsim 0.7$. In fact, this result has been challenged by the recent discovery by Dickinson (1994) of several galaxies in two clusters at $z \approx 1.2$ with red $R - K$ colors consistent with those predicted by our model elliptical galaxy. For reference, we also show in Figure 8b the results obtained when the progenitor elliptical galaxies of present-day E/S0 galaxies are assumed to form at $z_F = 2$ instead of $z_F = 5$. In this case, the central locations of the observed and predicted histograms are in slightly better agreement at high redshift and remain in good agree-

ment at low redshift. The paucity of the observed sample at $\langle z \rangle = 0.9$, however, does not allow us to favor a low z_F.

We can now investigate the fraction of galaxies with 4000 Å breaks significantly smaller than E/S0 galaxies in the histograms of Figure 8. We define here the fraction of galaxies with small 4000 Å breaks in a cluster to be the fraction of the total cluster population with B_{v4000} at least 0.5 smaller than the central location of the model B_{v4000} distribution. This appears to be the minimum significant difference with respect to the 4000 Å breaks of early-type galaxies common to all model histograms in Figure 8 (triangles). In this definition, we have used the central location of the predicted distribution because it agrees with the observed one for $z \lesssim 0.4$ and is more clearly defined at higher redshift. We find that, for $z_F = 5$, the predicted fractions of galaxies with small B_{v4000} are 6%, 4%, 4%, 3%, and 3%, and the fractions observed are 10%, 19%, 4%, 27%, and 33%, at $\langle z \rangle = 0.05$, 0.4, 0.5, 0.7, and 0.9, respectively (the model predictions are naturally lower than those obtained previously without including the B_{v4000}-magnitude relation). The prediction for $\langle z \rangle = 0.5$ is probably not representative of most clusters, since the observed sample at this redshift includes the cluster 0016 + 16, which is known to be particularly deficient in blue galaxies (Koo 1981; Butcher & Oemler 1984). Also, the prediction for $\langle z \rangle = 0.05$ follows from only an upper limit by Rose (1985) on the mass fraction of stars formed over the last 2.5 Gyr in nearby E/S0 galaxies, and hence may be overestimated. Despite these uncertainties, there appears to be a trend of increasing fraction of galaxies with small 4000 Å breaks in high-redshift clusters, which cannot be explained by the single occurence of bursts of star formation in old elliptical galaxies. According to the crude modelling performed above, this unaccounted fraction would represent at least 4% of the galaxy population in clusters at $\langle z \rangle = 0.05$, increasing to roughly 15% at $\langle z \rangle = 0.4$, and 24% at $(z) = 0.7$.

The most natural explanation for the excess population of galaxies with small 4000 Å breaks in distant clusters is to invoke spiral galaxies. About 10%–20% of galaxies in the cores of rich, concentrated nearby clusters are of late type (Butcher & Oemler 1978). However, few of these galaxies are blue, as many Sa and Sb galaxies have colors and 4000 Å breaks comparable to those of E/S0 galaxies (Dressler & Schectman 1987; Oemler 1992). Hence, if only 4% of red spiral galaxies in present-day clusters were blue at $\langle z \rangle = 0.05$, and if most of them (about 15% of the total galaxy population) were still blue at $\langle z \rangle = 0.4$, the discrepancy between the predicted and observed fractions of galaxies with small 4000 Å breaks at $z \lesssim 0.4$ in Figure 8a could be explained without having to invoke morphological evolution of spiral into E/S0 galaxies (Fig. 6b shows that star-forming spiral galaxies at $z \approx 0.4$ can have today a 4000 Å break as strong as E/S0 galaxies). In fact, recent high-quality ground-based and *HST* observations indicate that many of the blue galaxies in clusters at $0.3 \lesssim z \lesssim 0.4$ are normal spiral or "disky" galaxies (Lavery et al. 1992; Couch et al. 1993, 1994; Dressler 1993; Jablonka & Alloin 1993). At a redshift of 0.7, however, the unaccounted fraction of galaxies with small B_{v4000} in Figure 8a is too high to be explained by the simple color evolution of spiral galaxies. A possible explanation would be for these excess galaxies to be spiral progenitors of present-day E/S0 galaxies, implying that morphological evolution has played a major role early on in clusters. Alternatively, the excess star-forming galaxies at $z \gtrsim 0.7$ could have faded away by the present epoch (dynamical disruption, top-heavy IMF, etc.).

Hence, the spectral signatures of intermediate-age stars in low-redshift E/S0 galaxies and the 4000 Å break distributions of galaxies in distant clusters suggest that the Butcher-Oemler effect mainly originates from enhancement of the population of blue spiral galaxies at high redshift. Out to a redshift $z \sim 0.4$, the available data do not seem to require morphological evolution and can be understood if the star formation efficiency of spiral galaxies has declined substantially by the present epoch. Several processes have already been proposed for causing such a decline (see the review by Oemler 1992): ram pressure stripping of the interstellar medium of the galaxies through interactions with the hot intracluster medium; galaxy-galaxy interactions and mergers; tidal interaction with the cluster gravitational potential; and removal of the external gas supply of galaxies by the dense cluster environment. At $z \gtrsim 0.7$, on the other hand, more than simple color evolution seems to be required to explain the large fraction of galaxies with small 4000 Å breaks in the clusters observed by Dressler & Gunn (1990). A natural explanation would be to invoke morphological evolution of spiral into E/S0 galaxies, but the excess population of star-forming galaxies could also have faded away by the present time. It appears, therefore, that direct morphological studies at high redshifts will be the most secure way to draw more definite conclusions about the evolution of galaxies in clusters.

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