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SPECTRA OF GALAXIES IN CLUSTERS. II. MODELS FOR THE SPECTRA OF POSTBURST AND STRIPPED GALAXIES

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ABSTRACT

We have computed models for the spectral evolution of early-type galaxies undergoing starbursts and for a model of a late-type galaxy where stripping halts star formation. The goal of this work is to investigate the peculiar combination of mean Balmer absorption strengths, $\langle H \rangle = 7$–8 Å, and relatively red color, $B-V = 0.74 \pm 0.1$, observed in the "E+A" spectra of galaxies in 3C 295 and other high-redshift rich clusters. We find that bursts consuming $\sim$3%–8% of the luminous mass of the underlying galaxy match the observed $\langle H \rangle$ and $B-V$ quite well. These values are also produced by a stripped model which terminates star formation over a time of $\sim$0.1 Gyr or less. Since both types of models match the data, there is no strong reason to reject the stripping picture in favor of starbursts occurring in the densest clusters.

We have computed a number of line and band absorption and continuum indices which can be measured in the optical spectra of faint high-redshift galaxies. Bursts having a constant star formation rate of $\sim$0.5 Gyr duration cannot be distinguished from the stripped model in any of the indices that were compared. However, bursts that do not form O–B2 stars and have "delayed" star formation can be distinguished from the stripped model in comparisons between $\langle H \rangle$ and the 4000 Å break, H+K, and G band indices. Since the 4000 Å break is affected by the internal reddening in a galaxy, the H+K and G band indices are the best discriminators of star formation history. The separation between the various models is not large in any indices and a measurement precision of at least 5% is required to discriminate between them. We suggest that many of the E+A galaxies observed in high-redshift clusters might be recently stripped, while those in the high-redshift field are experiencing starbursts.

Subject headings: galaxies: clustering — galaxies: evolution — galaxies: stellar population

I. INTRODUCTION

Butcher and Oemler (1978*a*, *b*) measured the colors of galaxies in the rich, dense clusters Cl 0024+1654 ($z = 0.38$) and 3C 295 ($z = 0.46$), finding a higher fraction of blue galaxies in these clusters than in their low-redshift counterpart, the Coma Cluster at $z = 0.023$. They tentatively identified these blue galaxies as spirals. To arrive at the spiral-poor red galaxy population observed in Coma and other dense clusters near the present epoch would then require that spirals and other blue star-forming galaxies have been removed from dense clusters over a time scale of $\sim$5–6 Gyr. This surprising result was widely discussed: some authors claimed that either the data and its analysis were faulty (DeGioia-Eastwood and Grasdalen 1980; van den Bergh 1983), and others argued that these clusters were simply extreme examples of the overall cluster population (Mathieu and Spinrad 1981; Koo 1981; see Newberry, Kirshner, and Boroson 1988 for a discussion of the properties of Butcher-Oemler clusters). To examine the galaxy population of the 3C 295 cluster in more detail, Dressler and Gunn (1982, 1983, hereafter DG) obtained spectra for some of its brighter members. Although a number of these spectra were similar to those of normal luminous ellipticals and a few were strangely featureless, many showed extraordinarily high mean Balmer absorption of $\langle H \rangle = \frac{1}{3}(H\alpha + H\beta + H\gamma) \approx 7$–8 Å equivalent width. Since the galaxies having strong Balmer line spectra also showed strong metallic absorption features and a moderately red color of $B-V \approx 0.7$, they appeared to be a superposition of light from an E or S0 galaxy and a large population of A stars, which DG termed "E+A" spectra. Such spectra are not typical of the low-redshift luminous galaxy population (Dressler and Gunn 1982, 1983).

To investigate the nature of the objects producing the E+A spectra, DG constructed simple models which predicted the evolution of $B-V$ and $\langle H \rangle$ for a number of different stellar populations. Even the most extreme models having the constant star formation rate characteristic of luminous late-type galaxies at low redshift (Searle, Sargent, and Bagnuolo 1973, hereafter SSB; Bruzual 1981, 1983 and references therein) did not achieve Balmer absorption strengths larger than 5.4 Å. This suggested that the stellar populations of E+A galaxies were substantially different from those of any luminous galaxies observed near the present epoch. Since ram pressure stripping (Gunn and Gott 1972) has been proposed to act effectively in terminating star formation for galaxies in the cores of dense clusters, DG examined a model in which a late-type galaxy stopped forming stars. This model also did not achieve sufficient Balmer strength, and they turned to models in which the star formation rate near the epoch of observation was significantly higher than the galaxy's long-term average—that is, for a burst of star formation occurring in an old stellar population, possibly in an elliptical or S0 galaxy.

Two of DG's starbursting models proved an excellent match to the $\langle H \rangle$ and $B-V$ of the E+A spectra: one in which the burst consumed $\sim 20\%$ of the galaxy's gas in stars over the full range of stellar mass, and another that consumed $\sim 2\%$ of the galaxy's mass but produced only O and B stars. In both models the burst lasted ~ 0.5 Gyr and occurred ~ 1 Gyr before the epoch of observation. DG concluded that the E+A spectra correspond to "postburst" galaxies, and proposed that the ram pressure theory might be refashioned so that a galaxy's interaction with the dense intracluster medium ("ICM") of the cluster core might lead to large bursts of star formation instead of just a loss of gas to the ICM. This postburst galaxy picture has since been used to explain E+A and emission-line galaxy spectra observed in other dense clusters at redshifts $z \geq 0.2$ (Lavery and Henry 1986, hereafter LH; Couch and Sharples 1987; Henry and Lavery 1987, hereafter HL; Dressler 1987; Gunn 1988; Gunn and Dressler 1988; Lilly 1988), and in the Coma Cluster (Bothun and Dressler 1986, hereafter BD).

There are many reasons for carrying further the analysis of DG. First, their results suggested abandoning the ram pressure stripping mechanism in favor of a starbursting one. The stellar population models that led them to this conclusion used a simple treatment of post–main-sequence stellar evolution and were not based upon recent stellar data; the stellar evolutionary tracks and the transformations between the theoretical ($\log T_e$, $\log L$) and observational ($B-V$, M_v) H-R diagrams have been substantially revised relative to those used in their models. DG also assumed an idealized rectangular burst of star formation which may or may not be a good approximation to starbursts in galaxies. In the present paper we address these issues through a detailed investigation of the spectroscopic properties of models for starbursting and stripped galaxies. In § II, we describe the mechanics of our models, which we then use in § III to evaluate whether the $\langle H \rangle$ and $B-V$ coordinates of the E+A galaxies are consistent with postburst galaxies but not with stripped ones. We go further in § IV to explore a variety of other spectroscopic indices which might be useful discriminators between these two alternative star formation histories. The paper is concluded with a discussion in § V and a summary in § VI. In a subsequent paper (Newberry, Kirshner, and Boroson 1990), we will use these results to interpret our own spectra of galaxies in seven dense clusters at redshifts $0.2 < z < 0.38$.

II. EVOLUTIONARY SPECTRAL SYNTHESIS MODELS

a) Overview

Assuming a prescription for the star formation history of a stellar population, we seek to predict the time dependent behavior of features in its optical spectrum. The evolutionary synthesis method (Tinsley 1967) rather than the optimization method of population synthesis (see, for example, O'Connell 1970; Spinrad and Taylor 1971; Faber 1972) serves as a basis for these models. Here we will sketch the method; a more complete description is given by Newberry (1987). To model a spectrum for a stellar population, we adopt analytic forms for the initial mass function ("IMF") and the star formation rate ("SFR"). These are used to compute the gas consumption of the system as a function of time. A library of stellar evolutionary tracks then determines the distribution of stars of all ages over each "cell" of spectral type and luminosity class on the H-R diagram. Since the tracks are discrete in time and mass, this distribution is smoothed backward and forward over time near each model age of interest. The integrated spectrum of the stellar population is finally computed using this distribution to weight a library of stellar spectra. Spectral indices for the composite stellar population are then measured from this integrated spectrum.

Depending upon stellar mass, we have used main-sequence evolutionary tracks from Iben (1967), Ciardullo and Demarque (1977, 1979), and Chiosi, Nasi, and Sreenivasan (1978). We include a mass dependence for main sequence contraction time (Iben 1967) and consider all evolutionary phases through the end of the asymptotic giant branch ("AGB") phase. Giant branch tracks have been adjusted to nominally solar metal abundance, and to $\alpha = 1.6$ for the ratio of convective mixing length to pressure scale height (VandenBerg 1985). In contrast to much of the prior work in evolutionary synthesis models, we have not used the Tinsley and Gunn (1976) mean giant luminosity function; we have instead combined the red giant branch ("RGB") isochrones from the "new" Yale isochrone grid of Green, Demarque, and King (1987) as interpolated to Solar metal abundance by Pickles (1985) with an RGB luminosity function from the models of Sweigart and Gross (1978). To this, we have added an evolving horizontal branch extrapolated to Solar metal abundance from the models of Sweigart and Gross (1977) and AGB tracks which are a function of mass (Iben and Renzini 1983). Using photometry from Lee (1977), the luminosity function of the AGB was adjusted to be consistent with the relative RGB and AGB luminosity functions above the horizontal branch of 47 Tuc. For most of the models, we use stellar mass limits of 0.1 $M_\odot$ and 75 $M_\odot$; for one starburst model we use an upper limit of 7 $M_\odot$. We consider a number of simple analytical forms for the SFR of the various models and use the half-Gaussian fit to the IMF of the solar neighborhood (Miller and Scalo 1979). We assume that this choice of IMF is appropriate also to the luminous galaxies we aim to model. The SFR used in specific models is discussed in §§ II*b* and II*c*, below.

Our 282 stellar reference spectra are taken from the spectrophotometric atlases of Jacoby, Hunter, and Christian (1984) and Pickles (1985), and have spectral resolutions of approximately 4 Å and 10 Å, respectively. Each of the spectra in Pickles's atlas is an average of those of many different stars of nominally similar spectral class, and contain a small amount of Galactic reddening. Conversely, the individual spectra in the Jacoby *et al.* atlas are "dereddened" to their proper reddening-free values of $U-B$ and $B-V$. For both atlases, the spectra produce synthetic $B-V$ and $V-R$ that are correct for their spectral type. In our models, one reference spectrum is needed for each occupied cell of the H-R diagram, and an evolutionary track can populate a cell for which there is no corresponding spectrum in either atlas. In such cases we obtained a reference spectrum by interpolation in $\log T_e$ between adjacent spectral types and luminosity classes using conversion tables given by Landolt-Börnstein (1982).

To simplify the models, we have made the following assumptions: (1) The system is closed and has no gas infall from the outside. Gas infall is most likely inhibited in the dense cluster environment (Larson, Tinsley, and Caldwell 1984), and is accommodated by the normalization of the SFR function. (2) There is no recycling of the gas ejected by dying stars. To first order, accounting for recycling is also accommodated by adjusting the SFR. (3) There is no chemical evolution. This approximation follows a number of lines of evidence: the mean metal abundance of a system rapidly approaches the yield (Searle and Sargent 1972), and more complex models of chemical-photometric evolution (Arimoto and Yoshii 1986) find that the mean metal abundance of a stellar population older than about 5 Gyr converges rapidly to a value similar to that of the solar neighborhood. We do not expect that a starburst occurring in a luminous galaxy of 10 Gyr or greater age would make a substantial change in the mean chemical abundance of the galaxy. Twarog (1980) also shows that the abundance in the solar neighborhood has been approximately constant during the past 6 Gyr, corresponding to the maximum look-back time over which we will apply the models. Furthermore, the spectra of high-redshift galaxies show the strong metallic features characteristic of an old metal-rich population. (4) We neglect the gas emission spectrum (see, for example, the models of Huchra 1977). Cluster E+A spectra do not show [O II] λ3727 emission characteristic of H II regions. Also, for Balmer absorption to reach its very high observed strength in E+A spectra, no significant emission component can be present.

Model age was converted to look-back time and redshift using $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$ (these values were adopted by Butcher and Oemler and by DG), and an assumed redshift of galaxy formation $z_f = 5$. The adopted cosmology is important only in the connection between redshift and model age—this choice gives the models a present age of $\sim$16 Gyr. Changing z_f by ± 1 or increasing q_0 to 0.1 has negligible effect upon the properties of the models we will investigate.

It is noteworthy that our single-burst population models do not reproduce the $B-V$ of the classic models of SSB—our models are $\sim$0.1–0.2 mag redder near 10 Gyr age. This discrepancy results from a number of factors: (1) we use the Miller-Scalo IMF while they use the Salpeter form, (2) we use different sources for the log T_e–$B-V$ calibration used to transform theoretical evolutionary tracks to $B-V$ and thence to the spectral types of dwarfs and giants, and (3) SSB neglects post–RGB evolution. The temperature scale for late-type stars has changed considerably since that of their calibration (Harris 1963). For example, log $T_e = 3.666$ corresponds to a K0 giant in their models and in ours. However, log $T_e = 3.544$ corresponds to M3 III on the newer scale but only K5 III on the Harris scale. A similar effect also exists for dwarfs cooler than about mid-K. Thus the revised temperature scale alone would make SSB's models substantially redder using their same set of evolutionary tracks. To investigate the importance of the temperature scale, we computed a series of Salpeter IMF models based upon the evolutionary tracks used in our models, but adopted the Harris calibration for the log T_e–spectral type conversion. This made our models $\sim$0.15 mag bluer in $B-V$, and less than 0.05 mag redder than the values computed by SSB.

Beyond those parameters necessary to describe the spectrum of a "normal" galaxy, a complete description of a stripped or starbursting galaxy would require numerous others—for example, relative spectral contributions of the old and young stellar components, the amount of gas consumed in the burst of star formation, the burst parameters (SFR, IMF, stellar mass range), and similar details for all such prior events in the galaxy. Clearly, the number of variables makes the problem intractable, so we have investigated only the most extreme cases: a starburst occurring in an old stellar population, and a late-type galaxy which is rapidly stripped of gas and stops forming stars. These choices result in models having the largest difference in spectroscopic properties, with intermediate cases falling between them. As we shall show in § II*b*(iii), the differences between the spectra of these extreme models are not large enough to warrant producing models for intermediate cases.

b) Starbursts

The time over which significant star formation might take place in a galaxy in which star formation is induced by interaction with the ICM is not well understood, but we can make a crude guess from the Butcher-Oemler effect (Butcher and Oemler 1984). Since the radial distribution of blue galaxies in Butcher-Oemler clusters like 3C 295 peaks near the R_{30} radius containing 30% of the cluster's galaxy population, and the fraction of blue galaxies within this radius increases with redshift, we posit that an environmental mechanism which might have led to the present epoch paucity of blue star forming galaxies inside R_{30} operates over a time scale similar to the R_{30} crossing time (Lynden-Bell 1967). Using values of R_{30} and velocity dispersions tabulated in Newberry, Kirshner, and Boroson (1988), we adopted 0.5 Gyr for this time scale. Fortunately, the spectral characteristics of the postburst galaxy models are not highly sensitive to this timescale.

The E+A galaxies do not show the signatures of H II regions through Balmer line filling or [O II] λ3727 emission. This can be explained in two ways: either the full range of stellar mass was populated by the burst but star formation has abated by the epoch of observation, or star formation is occurring at the epoch of observation but the O–B2 stars that excite H II regions do not exist in significant numbers. In the former case, the population must be observed longer than $\sim 3 \times 10^7$ yr (the lifetime of a B2 star) after the SFR of the burst has declined to zero. These alternatives naturally lead to two varieties of starburst model, which we introduce below.

i) *Bursts Which Produce O–B2 Stars*

We have considered two different models which allow the formation of stars covering the full range of stellar mass. For the first, we adopt a rectangular (constant) SFR of 0.5 Gyr duration. This constant-burst model turns star formation on and off instantaneously as in the model computed by DG. However, we have chosen a Miller-Scalo IMF whereas DG used a Salpeter (1955) IMF with slope $s = -2.35$. As a second type of burst model, we use a Gaussian SFR of 0.2 Gyr FWHM. This convenient analytical form considers a more physically reasonable alternative to the constant burst model simply by having a gradual rise and fall in star formation rate. Its FWHM has been selected such that $\pm 3\ \sigma$ corresponds to 0.5 Gyr duration.

ii) *Bursts Which Do Not Produce O–B2 Stars*

Although the spectra of E+A galaxies do not show [O II] emission, this does not imply that star formation has ended by the epoch of observation. Extraordinary Balmer absorption strength such as that observed in E+A spectra can only be achieved if A stars dominate the main-sequence contribution near the epoch of observation. To accommodate this and allow substantial star formation to have occurred before the epoch of observation requires a model in which the SFR rises, falls, and gradually levels off. Hence, for this model, we adopt a delayed exponential SFR of the form SFR$(t) = (t/\tau) \exp(-t/\tau)$. Using 0.5 Gyr as the lifetime of significant star formation, we have set the peak of the SFR to occur at $\tau = 0.25$ Gyr; it then decays for times $t > \tau$, dropping to only a few percent of maximum by

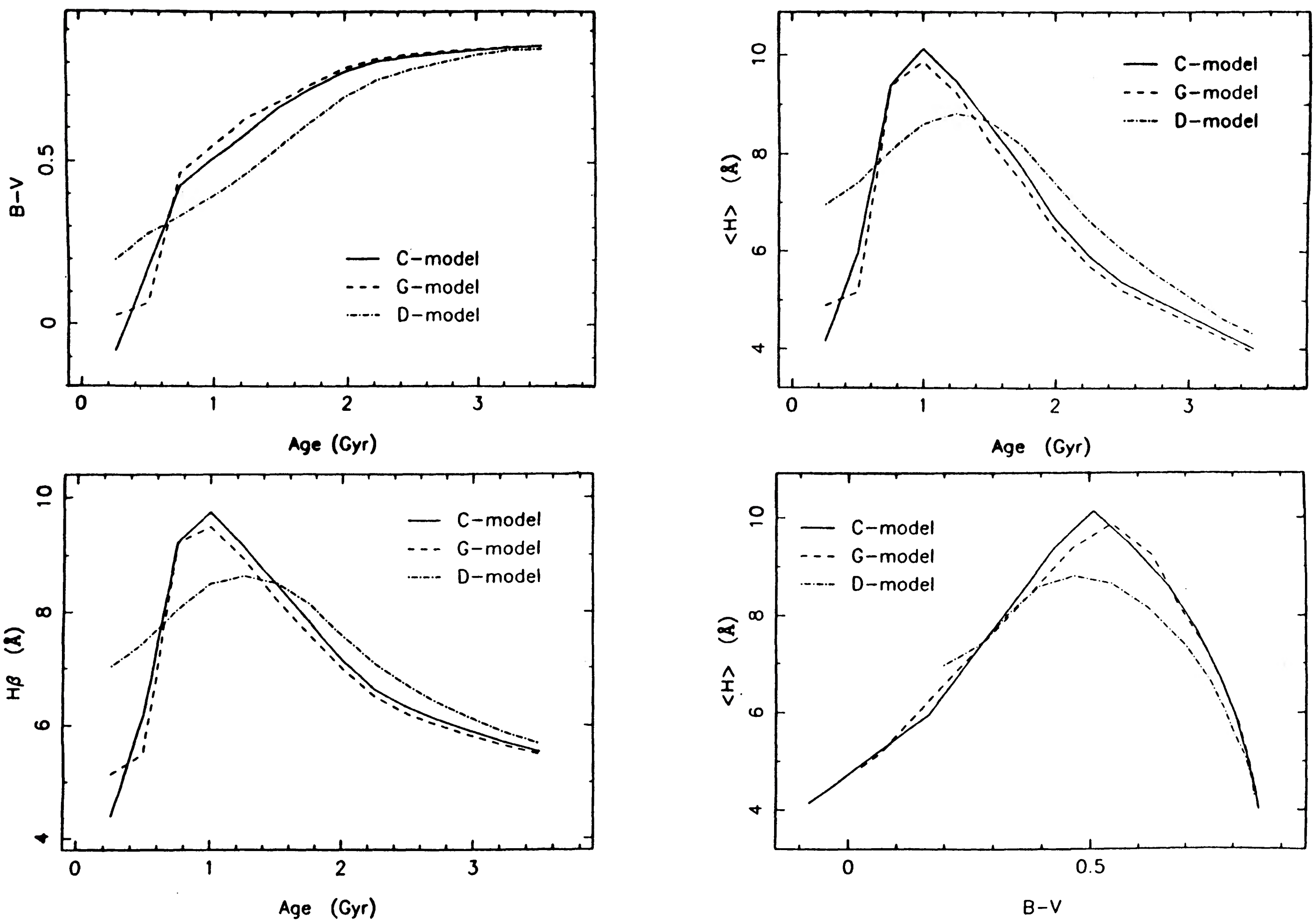

FIG. 1.—Evolution of spectral indices for three starburst models. The "C-", "G-", and "D-models" refer to constant, Gaussian, and delayed burst models, respectively.

$t = 1$ Gyr. To prevent the formation of H II regions we adopt a 7 $M_{\odot}$ upper limit, corresponding to a B2 star. We henceforth refer to this prescription as the delayed-burst model.

iii) Comparison of Burst Model Properties

Figure 1 shows the behavior of a variety of spectral indices during the first 3.5 Gyr of evolution of the three burst models. The rest frame $B-V$ was synthesized by convolving the model spectra with the standard Johnson B and V response functions revised by Buser (1978). The mean Balmer strength $\langle H \rangle$ is defined according to DG as $\langle H \rangle = \frac{1}{3}(H\alpha + H\beta + H\gamma)$, where the mean Balmer strength and other spectral indices have been measured as discussed in § IV*a*. All comparisons in Figure 1 show that the constant- and Gaussian-burst models follow similar tracks with time. Thus the difference between an instantaneous rise to constant SFR lasting 0.5 Gyr (as used by DG) and one having a more graceful rise and fall over a similar time scale does not yield substantially different behavior in spectral indices. As a result of this similarity and the relative difficulty of computation for the Gaussian model, we have not considered the Gaussian model further.

Since $\langle H \rangle$ and Hβ give similar information about the evolution of the stellar population, the increased measurement precision of $\langle H \rangle$ makes it more useful than Hβ in low S/N spectra. Furthermore, since the Balmer emission decrement of H II regions rises faster with wavelength than Balmer absorption from the stellar component, the $\langle H \rangle$ index is more robust in the presence of a small amount of Balmer emission which the galaxy spectra may have but the models do not consider. However, at spectral resolutions of $\sim$10 Å, the benefit of higher information content in $\langle H \rangle$ is mitigated by the difficulty in separating the G band from Hγ and the Fe II λ4046 line from Hδ. We will use $\langle H \rangle$ below and in § III because of its use by DG, but switch to Hβ for our investigation of other indices in § IV.

iv) Composite Models for Postburst Galaxies

We have considered only cases in which a starburst occurs in a previously dormant galaxy—one which would have an elliptical- or S0-like spectrum. This gives the spectrum of the burst the maximum contrast with that of the underlying galaxy. We have modeled the occurrence of a starburst in such a galaxy by adding the constant- or delayed-burst model to an evolving model of an old stellar population ("OSP"). Our OSP model is a single-burst population which uses a decaying exponential SFR with an e-folding time $\tau = 0.83$ Gyr. This SFR is identical to that of the $\mu = 0.7$ model of Bruzual (1981, 1983). The properties of the OSP model near 10 Gyr age change very slowly with time, so altering the burst epoch by ± 1 Gyr has negligible effect upon the composite spectrum of the postburst galaxy. For comparison with 3C 295 galaxies at $z = 0.46$, bursts were started in the OSP model at an age of either 9 Gyr (constant-burst models) or 8.75 Gyr (delayed-burst models) in order to reach maximum Balmer strength near a common age of 10 Gyr. For each of the two burst prescriptions, a family of postburst models was obtained by adding bursts in proportions 1%, 2%, 4%, 8%, ..., 64% of the mass of the underlying OSP model.

c) *The Stripped Galaxy Model*

As an alternative environmental effect, we consider stripping of gas from an active star-forming galaxy. This is assumed to terminate star formation without a burst of star formation being induced by the event. Only the case leading to the strongest observable effect has been considered: a system which has been forming stars at a constant rate since birth and has negligible light from an additional old stellar population. Again, for the most extreme effect, we assume that stripping terminates star formation activity over a time of $\sim$0.1 Gyr or less. In general, a galaxy having a decreasing SFR, a non-negligible contribution from an old stellar population, or one that was stripped over a much longer time scale would show smaller spectral changes than this model. We have sampled the model at intervals ranging from 5×10^7 yr during the rapid spectral evolution immediately after stripping up to 0.25 Gyr intervals 2 Gyr later. The spectral evolution of a constant SFR model near 10 Gyr age is slow prior to stripping, so that changing the stripping epoch by ± 1 Gyr has negligible effect upon its poststripped evolution.

d) *Comparisons between the Models*

Figures 2 and 3 show the $B-V$ evolution of the stripped model (*curve with dots*) with families of postburst models based upon constant SFR bursts (Fig. 2) and delayed SFR bursts (Fig. 3) of various masses. Note the rapidity with which $B-V$ increases in the stripped model after the termination of star formation—it would be quite improbable to observe such a galaxy in its blue phase ($B-V < 0.6$) immediately after stripping. By comparison, the delayed burst models exhibit less rapid changes in $B-V$ because they continue to form stars in significant numbers even 1–2 Gyr after the beginning of the burst. This sustained blueness results from the ongoing production of blue stars having masses lower than $\sim 7\ M_\odot$. In general, the constant-burst models are bluer than the delayed bursts during the first 0.5 Gyr but redden more rapidly after the disappearance of massive blue stars.

III. ARE E+A SPECTRA EXPLAINED BY POSTBURST MODELS?

As a first application of the constant- and delayed-burst models and the stripped model, we have investigated DG's result that the E+A spectra in the 3C 295 cluster are inconsistent with a stripped galaxy and thus require a poststarbursting description. We find that it is not necessary to reject a rapidly stripped model in favor of a starburst to explain all of the E+A spectra.

For a direct comparison with DG's results, we show model grids of $\langle H \rangle$ vs. $B-V$ in Figures 4*a* (constant SFR bursts and the stripped model) and 4*b* (delayed SFR bursts and the stripped model). Error bars in both plots show DG's estimated uncertainties for the observed $\langle H \rangle$ and $B-V$ of E+A spectra. The first 1 Gyr of evolution for the stripped model prior to stripping is contained within the tight clump of points near ($B-V$, $\langle H \rangle$) = (0.43, 5.4 Å), attesting to the insensitivity of the model to the exact time that stripping occurred. Evolution after stripping is extremely rapid toward higher $\langle H \rangle$ and redder $B-V$. Note that there is no region where the stripped model can be clearly distinguished from all possible burst models. Even at the last point shown at 3.5 Gyr after the burst or stripping event, all models have relatively similar values of $B-V$ and $\langle H \rangle$. For $B-V \leq 0.75$, the stripped model is closely tracked by a constant SFR burst having 6%–7% of the mass of the parent galaxy. This similarity results from the fact that both the constant SFR and stripped models use a truncated

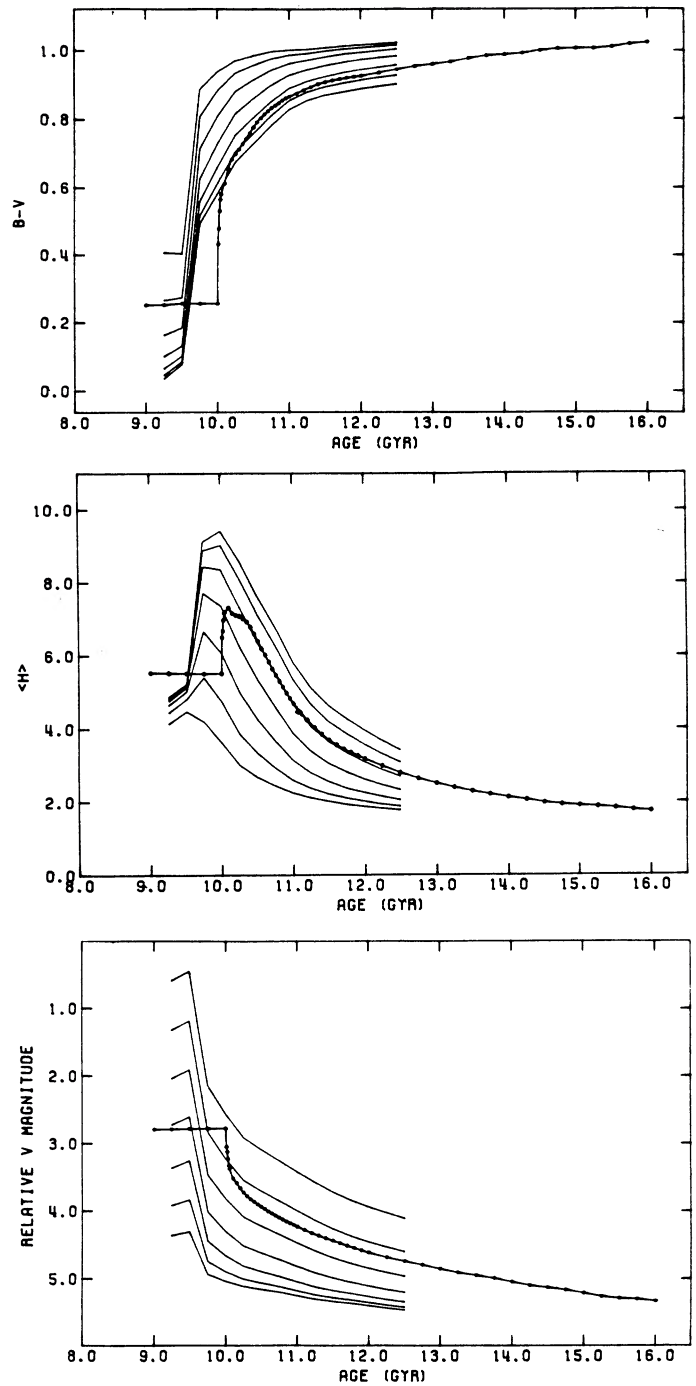

FIG. 2.—Evolution of the stripped model (*curve with dots*) and a family of poststarburst models based upon constant SFR bursts (*curves without dots*). The upper curve for burst models corresponds to a burst consuming 64% of the mass of the parent galaxy. Each successively lower curve corresponds to a reduction by a factor of 2 in the relative burst mass (the lowest curve shown is for a 1% burst).

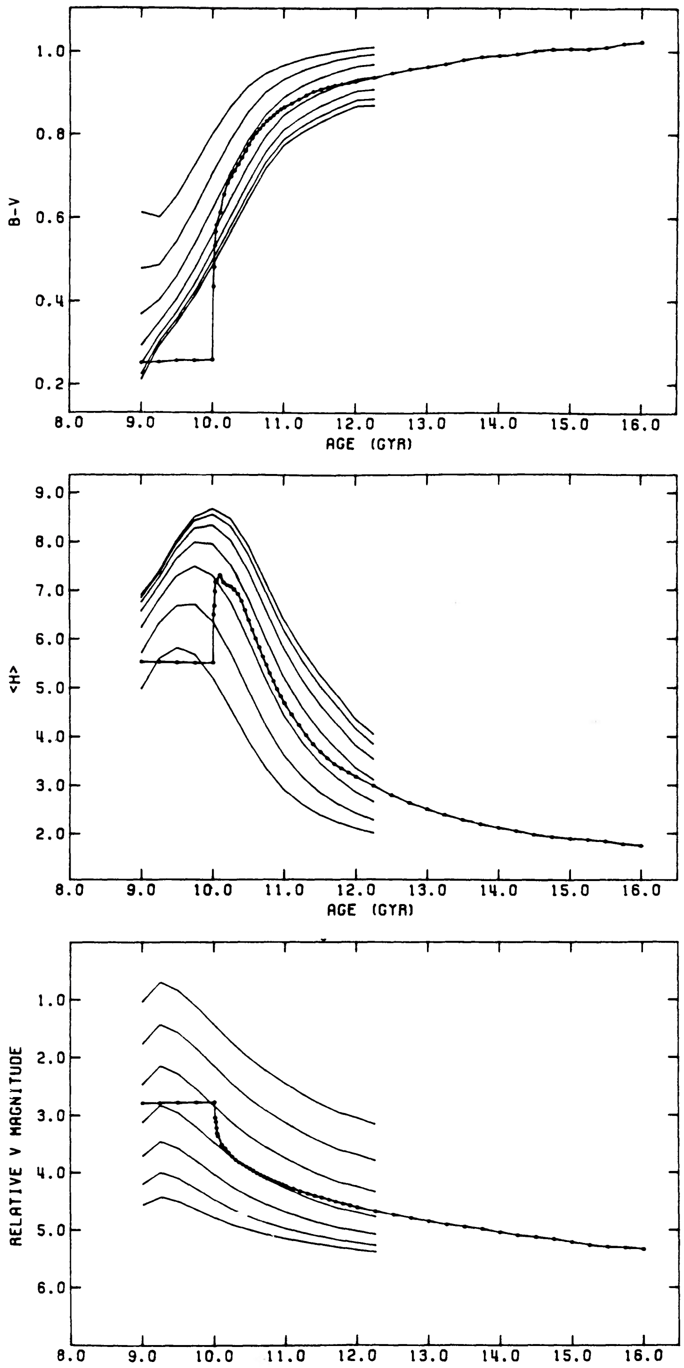

FIG. 3.—Evolution of the stripped model (*curve with dots*) and a family of poststarburst models based upon delayed SFR bursts (*curves without dots*). The various curves are as for Fig. 2.

constant SFR and assume a Miller-Scalo IMF—their difference lies principally in the length of time that old stars accumulated before the termination of star formation. DG's constant burst model required a relative burst mass of $\sim 20\%$ to match the E+A spectra, but our model achieves similar $\langle H \rangle$ with a smaller burst of only 7%–8% of the luminous mass of the parent galaxy. The delayed burst models attain the observed $\langle H \rangle$ with only 3%–4% of the mass of the underlying galaxy. From these comparisons it is clear that the E+A spectra observed by DG having $B-V \approx 0.74$ and $\langle H \rangle \approx 7$–8 Å are well described by a burst model within the observational uncertainties. In addition, our stripped model peaks in Balmer strength at $\langle H \rangle = 7.3$ Å and sustains $\langle H \rangle \approx 7.2$ Å for $\sim \frac{1}{4}$ Gyr, before dropping to $\langle H \rangle = 5.4$ Å about 0.6 Gyr after stripping. DG rejected their stripped model as an explanation for the 7–8 Å Balmer strength of E+A galaxies in 3C 295 because it showed $\langle H \rangle = 5.5$ Å when they sampled it 1 Gyr after stripping. The surge in $\langle H \rangle$ shown by our model is caused by the relatively rapid termination of star formation coupled with the successive disappearance of O and B stars. We have neglected Balmer filling by H II region emission in our stripped model, so the predicted $\langle H \rangle = 5.4$ Å before stripping is, in general, unrealistic. However, more than $\sim 3 \times 10^7$ yr after stripping, no O–B2 stars are present in this model to ionize the gas, so our poststripped model has the appropriate mean Balmer strength. Hence all models—including the stripped model—have some range of parameters within which they are consistent with the observations. For all models, the poststripped or postburst $B-V$ and $\langle H \rangle$ return almost to the values of the parent galaxy within a few billion years after the event. Since we have examined the most extreme models, any such galaxy

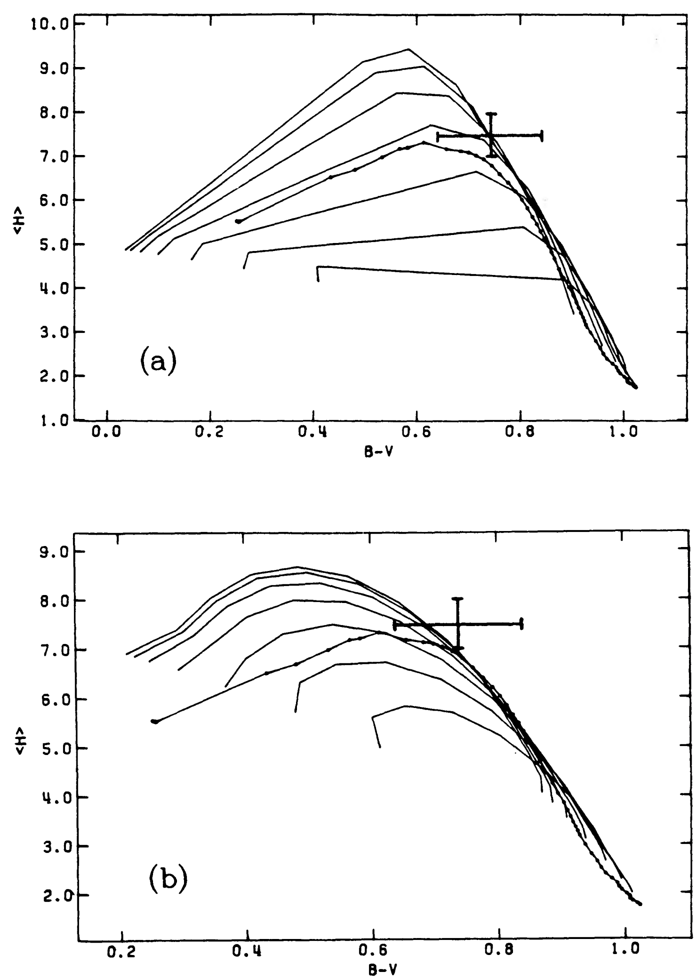

FIG. 4.—Evolution of mean Balmer absorption strength $\langle H \rangle$ vs. $B-V$ for (*a*) constant SFR bursts and the stripped model, and (*b*) delayed SFR bursts and the stripped model. The various curves are as for Fig. 2. The error bars indicate the estimated uncertainty in the observed $\langle H \rangle$ and $B-V$ of E+A spectra (from Dressler and Gunn 1983).

will be virtually indistinguishable in $B-V$ and $\langle H \rangle$ from other normal galaxies within only 2–3 Gyr after stripping or a starburst.

Neither these models nor those of DG included an allowance for internal reddening (color excess). If galaxies experiencing a large starburst or being stripped have some internal absorption, then the models shown in Figure 4 should be shifted redward by some value of color excess $E(B-V)$. The observed parameter space can then be matched by a broader range of models which are otherwise too blue. For example, the stripped model falls within the observational window provided that $0 < E(B-V) < 0.2$. Of course, a stripped galaxy might have a very small color excess—much of the dust may also be stripped along with the gas. If this is the case, then one would expect little reddening in the poststripped model. However, as we noted above, even with a color excess of zero, this model passes within the blue end of the observed parameter space. No luminous galaxies as blue as our prestripped model are observed at low redshift, but adding a prestripped color excess $E(B-V) < 0.2$ produces models having $0.25 < B-V < 0.45$. Such values of $B-V$ are not unusual for nearby galaxies (de Vaucouleurs, de Vaucouleurs, and Corwin 1976; Longo and de Vaucouleurs 1983, 1985). Depending upon the amount of reddening in a stripped or starbursting galaxy, the models spend $\frac{1}{4}$–$\frac{3}{4}$ Gyr in the observational parameter space shown in Figure 4. On average, the stripped model spends only about half as long in this region as do the starbursting models. The probability of observing a stripped or starbursting galaxy is of course related to these relative times, but the values are not so different that they can be used to favor or reject one of the models.

Observations of Coma Cluster galaxies by BD and of Butcher-Oemler blue galaxies in three clusters at $z \approx 0.2$ by LH find galaxies which show Balmer absorption strength similar to those in the 3C 295 cluster. It is curious that galaxies having Balmer lines of 7–8 Å equivalent width are those reported in all studies. Why are galaxies having slightly lower $\langle H \rangle$ not reported? It is unclear whether this is a selection bias in that Balmer lines only become noticeable to observers when they achieve strengths near $\langle H \rangle = 7$ Å, or that this is a signature of the mechanism that gives rise to such spectra. If the latter case is correct, then the plateau at $\langle H \rangle \approx 7.2$ Å shown by our stripped model over a wide range of $B-V$ argues in its favor, because the E+A characteristics can be produced by stripped galaxies having a range of internal reddening. Conversely, a delayed burst is attractive in that any burst consuming 3%–64% or more of the parent galaxy's gas mass lies at some time within the $\langle H \rangle$–$B-V$ space of the E+A galaxies. Interestingly, only a narrow range of constant burst masses fit this same space. Hence we find no compelling reason to reject the stripped model in favor of a postburst model to explain the E+A spectra observed in 3C 295; There appears not to be a unique explanation for the E+A galaxies observed in high-redshift clusters.

We conclude the following:

1. Using $B-V$ and $\langle H \rangle$ as indicators of the stellar population does not lead to clear discrimination between the stripped model and either of the burst models that we have considered.

2. Dressler and Gunn's observations of E+A galaxies which showed moderately red spectra and strong Balmer absorption lines are equally well matched by a model for a rapidly stripped late-type galaxy and by models for a burst of star formation occurring in an early-type galaxy.

3. It is not certain whether the E+A spectra observed in 3C 295 and other dense clusters provide evidence for starburst activity and necessitate a reformulation of the ram pressure theory, or whether they affirm stripping in the cores of dense clusters. We cannot exclude the possibility that both starbursts and stripped galaxies have been observed.

IV. SPECTRAL INDICES FOR POSTBURST AND STRIPPED MODELS

In § III a grid of models for two poststarburst cases and a model for a stripped late-type galaxy were compared in $\langle H \rangle$ and $B-V$. Since these two indices were unable to distinguish between the different models, we have explored a number of other spectral indices which might prove useful in this regard. Considering that these models will be compared with the spectra of faint galaxies, we have limited this effort to those absorption and continuum indices that can be measured reliably in low S/N spectra obtained at typical ~ 10 Å resolution. Another problem arises in comparing model spectra having a *fixed* spectral resolution with the spectra of galaxies in clusters at different redshifts: with a given instrumental setup, the resolution will be higher in the higher redshift data. For application to faint galaxies over a range of redshift, we seek to minimize these problems through suitable choice of indices and by careful placement of their bandpasses.

a) Definitions of the Spectral Indices

In previous studies of galaxy spectra, Faber *et al.* (1985), Pickles (1985), and Rose (1985) defined and measured a variety of absorption indices which give useful information about the constituents of a stellar population. Unfortunately, the continuum and feature bandpasses used by these authors are too narrow for use in spectra of low S/N and ~ 10 Å resolution. Hence we have defined yet another set of bandpasses in order to minimize such problems. For all indices, bandpasses for the local continua were chosen with the maximum possible spectral coverage to yield good continuum fits in actual galaxy spectra. The feature bandpasses are wide enough to accommodate typical ~ 300 km s^{-1} velocity dispersions of luminous galaxies (Faber and Jackson 1976; Whitmore, Kirshner, and Schechter 1979; Malumuth and Kirshner 1981, 1985). The index definitions were adopted after inspection of the regions around strong absorption features in model spectra covering a wide range of model parameters. These provisional bandpasses were finalized after inspection of good quality galaxy spectra. The definitions given in Table 1 are appropriate for spectral resolutions of ~ 5–10 Å.

The Hβ index used here was defined specifically to include the contribution of adjacent multiplet 318 of Fe II, which becomes blended with Hβ in 5–10 Å resolution spectra of late-type stars and early-type galaxies (Rabin 1981; Burstein *et al.* 1984). This is not important in spectra dominated by A stars, but it becomes significant in integrated spectra dominated by old or late-type stars. Although our particular index does not measure the strength of Hβ alone, we decided that it was more reliable to measure the entire blended profile than attempt to deblend it. Our values should not be compared with those of Burstein *et al.* or Faber *et al.* (1985) who used higher resolution spectra and defined a narrower feature bandpass to avoid this problem.

The Hδ line is very weak and exceedingly difficult to separate from metallic features in spectra of moderate resolution, even at high S/N. We therefore have not attempted to isolate the true Hδ strength. Our Hδ index is defined such that its lower continuum bandpass includes a small extension

TABLE 1

DEFINITIONS OF SPECTRAL INDICES

Index	Feature Measured	Bandpasses (Å) Feature	Continua	
CN_1	CN λ3840	3780–3900	3770–3785	3900–3915
H+K	Ca II H+K + Hε	3915–4000	3895–3915	4000–4030
Hδ	Hδ	4060–4140	4010–4060	4150–4180
G band	CH	4275–4320	4230–4270	4415–4445
Hβ	Hβ + metal	4825–4895	4795–4825	4895–4915
Mg	MgH + Mg *b*	5080–5230	5050–5080	5230–5250
4000 Å break	...	...	3750–3950	4050–4250
G-break	...	...	4050–4250	4350–4550

of the wing of the Fe I λ4046 line. This broad continuum bandpass results in better precision at the expense of biasing the measured "Balmer strength" toward slightly smaller values in the spectra of old stellar populations. In any case, we measure the indices in exactly the same way in the models and the galaxy spectra, so this contamination should be inconsequential. We have not used this line in the present study because of similar information content to that of Hβ; we include it in Table 1 for situations when Hβ is unusable.

Our H+K index measures the combined strength of the Ca II H and K lines and the Hε line coincident with Ca II H. Since H and K are separated by only 34 Å, it is virtually impossible to accurately deblend them in spectra of typical 10 Å resolution, and we have merged the H-K-Hε complex into a single index as in Pickles (1985).

Late-type stars show a number of discontinuities in spectral gradient, the best known of which is the 4000 Å break. This feature results from the coincidental occurrence of strong absorption from a number of ionized metallic species within a narrow range of wavelength. We measure the 4000 Å break index according to the f_λ definition of Spinrad (Bruzual 1981). Another useful discontinuity appears in the spectra of late-type stars near 4300 Å as a result of CH absorption (the G band), which we call the "G-break". Since these two indices are strongly correlated in composite spectra (Newberry 1987), the utility of the G-break lies in application to data where limited spectral coverage prohibits measurement of the 4000 Å break. Compared with line and band absorption features, these break indices have a higher precision of measurement and a smaller sensitivity to inaccuracies in the flat-field correction applied to low S/N data. However, these indices are sensitive to inaccuracies in the spectral response calibration of the instrument, although to a lesser degree than broad-band colors such as $B-V$.

The true equivalent width of a spectral feature cannot be measured accurately in available galaxy spectra because of the inability to deconvolve the profiles of overlapping features. We have measured a "local equivalent width" by defining adjacent side bands through which to fit a linear pseudocontinuum. For spectra binned at a linear dispersion of $\delta\lambda$ Å channel^{-1}, the local equivalent width W is defined similar to a true equivalent width,

$$W = \delta\lambda \sum_i \left(1 - \frac{f_i}{f_{c,i}}\right), \quad (1)$$

in which the spectrum flux f_i relative to the adopted continuum level $f_{c,i}$ is determined at each of the i channels within the feature bandpass. For comparison with other authors, these indices may be converted into magnitude units using $\Delta m = -2.5 \log (1 - W/\Delta\lambda)$, where $\Delta\lambda$ is the total width of the feature bandpass given in Table 1.

b) Model Comparisons

Figures 5 and 6 show model results for the Hβ index plotted against the 4000 Å break and G-break continuum indices and the CN_1 (λ3840), H+K, G band and Mg *b* absorption indices; the constant burst and stripped models are compared in Figure 5, while the delayed burst and stripped models are compared in Figure 6. We have selected Hβ as the dependent variable because of its extreme sensitivity to the temperature mix of the composite stellar population, and because it is the only Balmer line that can be measured reliably in low-resolution galaxy spectra (see § II*b*[iii]). The indices chosen for the abscissae represent all other strong features in the 3800–7000 Å region of the spectrum which show significant variation with age and parameter differences between the models.

Both the 4000 Å break and G-break indices are dependent upon the continuum shape and hence are compromised by the color excess $E(B-V)$ that is unknown for high-redshift galaxies and not considered in the models. The contribution of color excess was estimated by computing the indices from stellar reference spectra before and after applying Galactic extinction using the Whitford (1958) reddening law with $A_v = 1.0$. The effects are small: $\Delta(\lambda4000) = 0.30E(B-V)$ and $\Delta(\text{G-break}) = 0.38E(B-V)$. Hence for reasonable amounts of color excess $E(B-V)$ in a galaxy, the break indices should be adjusted to higher ("redder") values by only ~0.1 mag or less.

Plots of Hβ against the 4000 Å break, H+K, and G band show the greatest separation in comparisons of the delayed SFR bursts with the stripped models (Fig. 6). In the Hβ–4000 Å break comparison, a nonzero color excess would shift the delayed bursts toward the right and reduce the separation between the break indices of the two models, but the H+K and G band indices are unaffected by reddening. Unfortunately the region where the indices are clearly separated in the Hβ–G band plot pertains only to older bursts having relatively weak ⟨H⟩, and only the Hβ–H+K comparison shows good separation between the models in cases of high ⟨H⟩. The stripped and delayed burst models can be distinguished in these indices for all Hβ < 7.2 Å, but the measurement precision must be very high for unambiguous separation.

The chemical composition of a stellar population is a major uncertainty in evolutionary synthesis models. How robust are the most useful of our model indices to the metal abundance of the stars that dominate the light of the galaxy? Studies of the G band in stellar spectra (Faber *et al.* 1985) indicate no significant

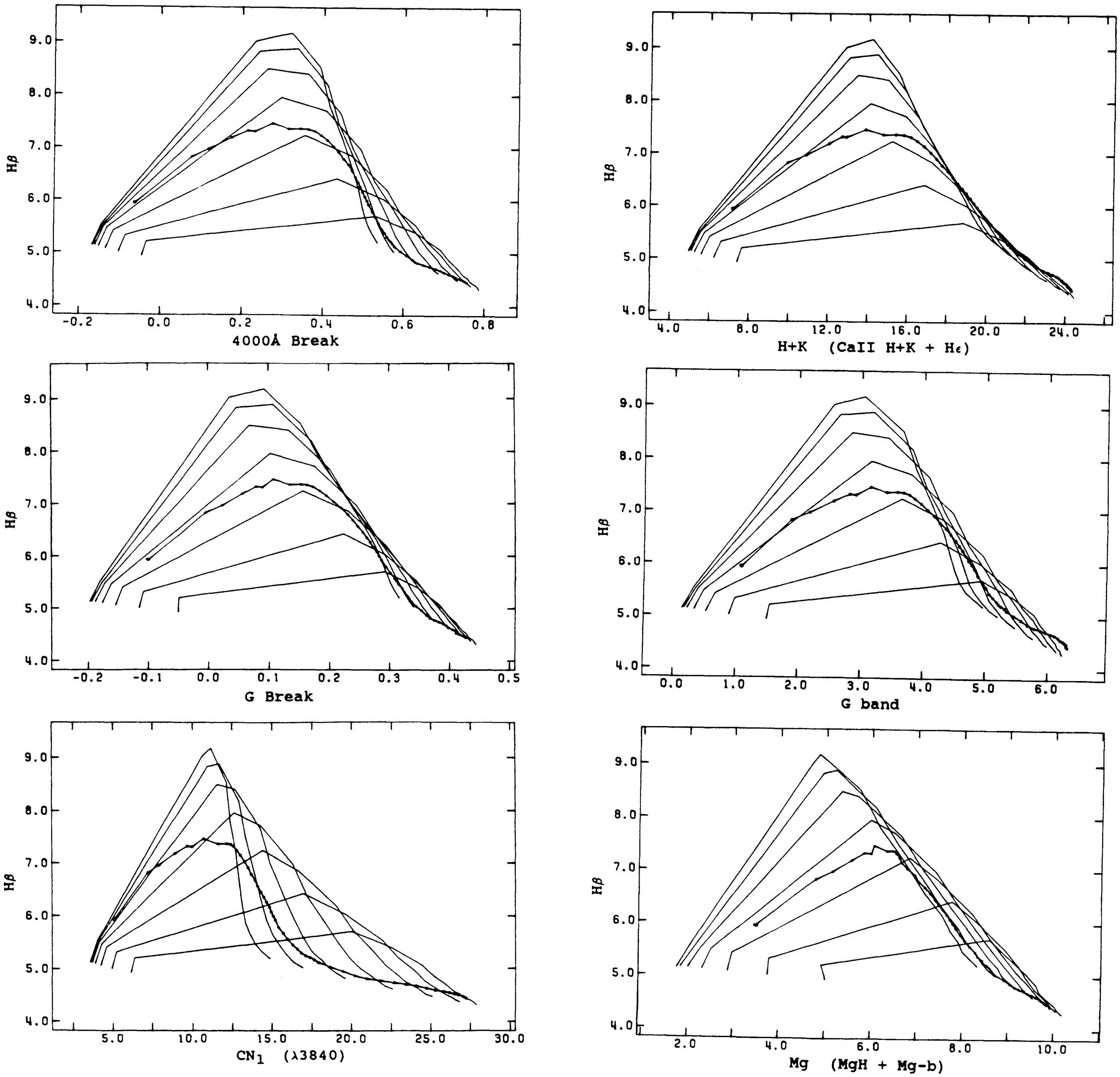

FIG. 5.—Spectral indices for stripped and constant burst models. The various curves are as for Fig. 2.

sensitivity to temperature or abundance for giants having [Fe/H] > −0.5. Therefore, since the models were constructed to accommodate solar or slightly higher abundance and these luminous galaxies are not likely to be metal poor, the G band index should be a good indicator of the stellar populations present in stripped or postburst galaxies. The behavior of the H+K index, which also includes a contribution from the Hε line, is somewhat complicated as a function of spectral type, luminosity class, and metal abundance. Rose (1985) has shown that the strength of H+K in dwarfs is an unambiguous temperature indicator that is insensitive to metal abundance for stars earlier in spectral type than mid-F—its value is constant for cooler dwarfs. Further, Pickles (1985) shows that the strength of his H+K index in giant spectra increases by ∼15%–20% with an abundance increase of Δ[Fe/H] ≈ 0.4. Thus when light from F or earlier dwarfs dominates that from K0 and later giants, the coordinates shown by the burst model are unaffected by a modest difference in metal abundance between the models and the actual galaxy. In the delayed burst model at 3 Gyr age, dwarfs hotter than F5 contribute 63% of the *V* band light from the main sequence whereas K0 and later giants contribute 25% of the total *V* band flux from the population. Horizontal-branch, asymptotic giant branch, and bright giants contribute an additional 27% of the total *V* band light

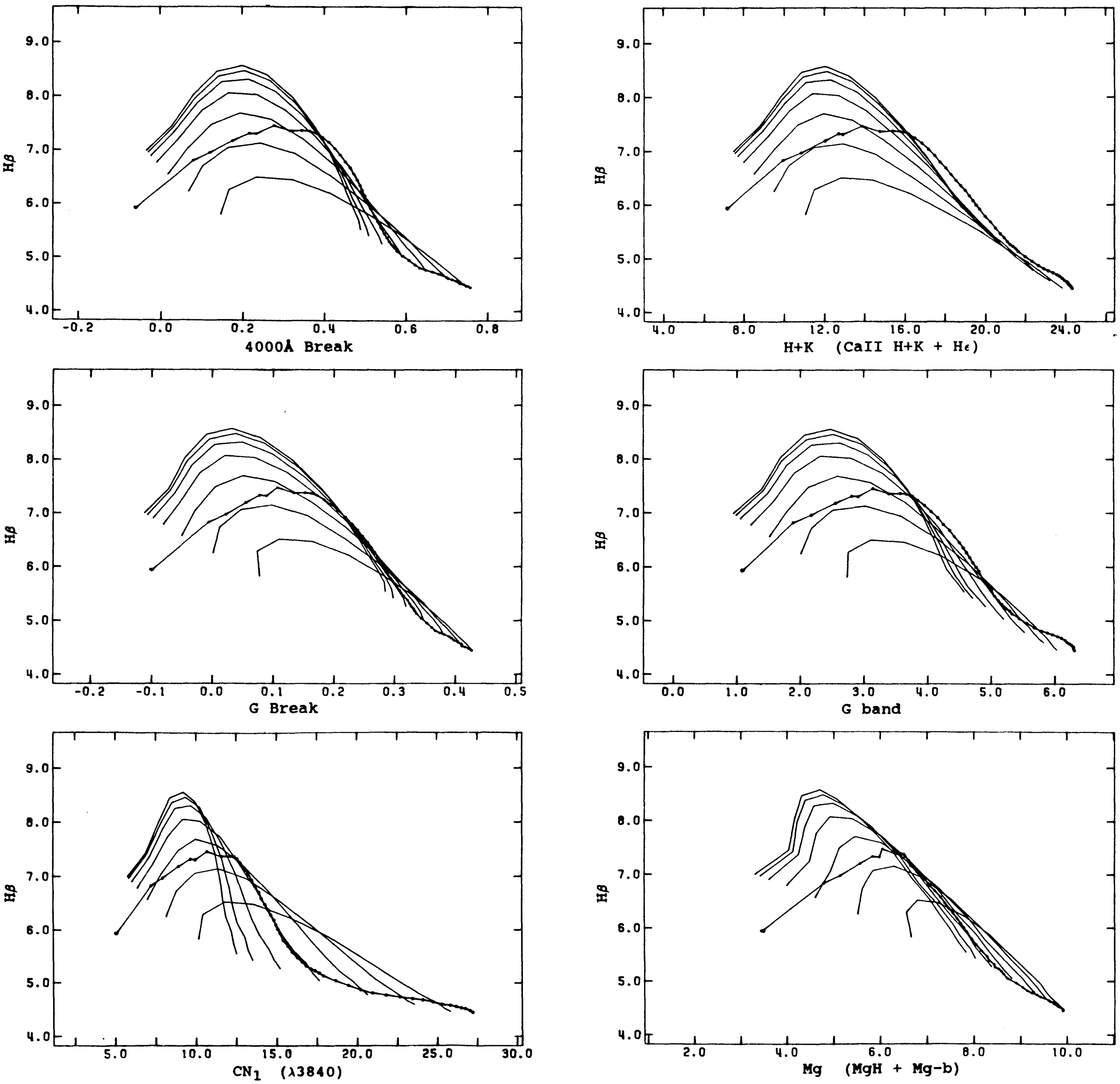

FIG. 6.—Spectral indices for stripped and delayed burst models. The various curves are as for Fig. 2.

at this age. Therefore, with allowance for the different $B-V$ of the dwarfs and giant-like groups of the same spectral class, the models indicate that contributions to the H+K index are approximately equal from stellar groups which have a moderate sensitivity to abundance and from groups which have negligible sensitivity. At younger burst age, the dwarf contribution is relatively high so that the model predictions should be relatively insensitive to abundance differences.

We conclude that galaxies experiencing a starburst of approximately constant SFR are indistinguishable from galaxies in which star formation has halted abruptly. However, starbursting galaxies of the delayed burst type *can* be distinguished—with great difficulty—from stripped late-type galaxies. The distinction exists in comparisons between the Hβ index and the 4000 Å break, H+K, and G band indices. Of these, the H+K index appears to be the most reliable, although the Hβ–H+K and Hβ–G band comparisons can be made using lower S/N data.

V. DISCUSSION

We have shown that the E+A spectra can be modeled by the stripping of an active star-forming galaxy, albeit one which was forming stars at a roughly constant rate prior to stripping. While this model represents an extreme stellar population, it might be the correct description for many of the E+A spectra observed in high-redshift dense clusters. Also, our E+A starburst models pass through the parameter space of the observations and support the starburst picture first proposed by Dressler and Gunn. Recently, Broadhurst, Ellis, and Shanks (1988) have found E + A spectra in the high-redshift field population, although with lower frequency than in dense clusters. An interesting result is that the cluster E + A galaxies rarely show emission lines, but those in the field almost always have them. We recall that DG proposed the starburst origin of cluster E + A galaxies as a result of their own stellar population models, and that they were forced to refashion the ram pressure theory to accommodate starbursting rather than stripping in the dense cluster environment. Bothun and Dressler have noted the difficulty with inducing starbursts through galaxy interactions in a high velocity-dispersion environment: maximum disturbance of galaxies which might lead to large starbursts occurs at relative velocities of the order of only a few hundred km s^{-1} (Toomre and Toomre 1972) while the velocity dispersions of these rich clusters typically exceeds 1000 km s^{-1}. The likelihood of interaction as an initiator of starburst activity is discussed at length in Lonsdale, Persson, and Matthews (1984), Bushouse and Gallagher (1984), and Bushouse (1986). We have shown how difficult it is to distinguish between starbursting and stripped galaxies on the basis of their spectra. Perhaps our stripped late-type galaxy model is the correct explanation for some portion of the E + A galaxies found in rich, dense clusters, while the starbursting picture is correct for field population. The remainder of cluster E + A galaxies could then be initiated by relatively low velocity encounters, possibly within subclusters, or possibly from ram pressure effects at high velocity if DG is correct. In this picture, many of the cluster E + A spectra would be born when gas-rich star forming galaxies fall with velocities greater than ~1000 km s^{-1} from the low density outer regions of a cluster into the dense ICM of its core and are stripped. The prestripped galaxy could be of any morphological type, although a disk system would be favored because stripping could more quickly terminate star formation in systems falling face-on into the cluster core.

To understand the nature of galaxies in high-redshift clusters, the starbursting and stripped galaxies need to be identified correctly. Progress on this question will not require *more* galaxy spectra in more clusters, but *better* quality spectra obtained with the largest current telescopes and the best available detectors. If some of the E + A galaxies observed in the cores of high redshift clusters result from stripping, then a pool of blue galaxies with vigorous star formation should exist in the outer regions of these clusters. Although it is difficult to identify target galaxies far from the center of a distant cluster, this is an important observational test for the stripped model of cluster E + A galaxies.

VI. SUMMARY

We have computed models for the spectral evolution of early-type galaxies that experience a burst of star formation, and for a late-type galaxy which quickly terminates star formation (stripping). We have compared their $B-V$, line and band absorption strengths and continuum break indices, and arrive at the following conclusions:

1. Poststarburst models having burst masses of ~3%–8% of the mass of the underlying galaxy provide an excellent match to mean Balmer strength, $\langle H \rangle$, and $B-V$ of the E + A spectra observed by DG.

2. The $\langle H \rangle$ and $B-V$ of E + A spectra are also reproduced by a model for a stripped late-type galaxy in which star formation ceases within a time of ~0.1 Gyr. A good match persists during a period of slowly changing Balmer strength that lasts ~0.25 Gyr, and the model can accommodate a range of color excess $E(B-V) < 0.2$ in the prestripped galaxy.

3. From both conclusions (1) and (2), we cannot reject stripping in favor of starbursts as a process which could lead to the observed paucity of star-forming galaxies in rich dense clusters near the present epoch.

4. Burst models which do not form O–B2 stars and have a delayed SFR are indistinguishable from the stripped model in many comparisons, but show a small distinction in comparisons between Hβ and the 4000 Å break, H + K, and G band indices. Since the 4000 Å break is affected slightly by the color excess which is unknown for the observed galaxies, the H + K and G band indices appear to be the best discriminators between the models. The distinction is not great in any index and a measurement precision of ~5% is required for conclusive results.

5. Our models suggest that either conventional ram pressure stripping or starburst activity is consistent with the observation of unusual E + A spectra of galaxies observed in the 3C 295 cluster and other Butcher-Oemler clusters. We suggest that many cluster E + A galaxies might be caused by stripping whereas the field E + A spectra at high redshift are attributable only to starbursts.

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