Color Evolution from $z=0$ to $z=1$

Karl D. Rakos

Inst. for Astronomy, Univ. of Vienna

James M. Schombert

Infrared Processing and Analysis Center
Jet Propulsion Laboratory
California Institute of Technology

ABSTRACT

Rest frame Strömgren photometry (3500Å, 4100Å, 4750Å and 5500Å) is presented for 509 galaxies in 17 rich clusters between $z = 0$ and $z = 1$ as a test of color evolution. Our observations confirm a strong, rest frame, Butcher-Oemler effect where the fraction of blue galaxies increases from 20% at $z = 0.4$ to 80% at $z = 0.9$. We also find that a majority of these blue cluster galaxies are composed of normal disk or post-starbursts systems based on color criteria. When comparing our colors to the morphological results from HST imaging, we propose that the blue cluster galaxies are a population of late-type, LSB objects who fade and are then destroyed by the cluster tidal field. After isolating the red objects from Butcher-Oemler objects, we have compared the mean color of these old, non-star forming objects with SED models in the literature as a test for passive galaxy evolution in ellipticals. We find good agreement with single burst models which predict a mean epoch of galaxy formation at $z = 5$. Tracing the red envelope for ellipticals places the earliest epoch of galaxy formation at $z = 10$.

Subject headings: galaxies: photometry - galaxies: evolution
1. INTRODUCTION

Observational astronomy has one major advantage over any other physical science, the phenomenon of lookback time. The combination of enormous distances plus the finite speed of light permits the study of the behavior of objects in our distant past and, with respect to extragalactic astronomy, this allows direct observation into the evolutionary history of galaxies, as opposed to just deducing the past based on their contents at the current epoch. This furnishes data for the investigation of the evolution of stellar populations, star formation history and the conditions of galaxy formation, all relatively new fields as our telescope collecting power has increased in recent years. Unfortunately, the study of distant galaxies is inhibited by several difficulties primary being that their great distances imply small sizes and faint apparent luminosities. In addition, large distance also means the redshifting of regions of interest (e.g. the near-blue) into the technically and observationally troublesome near-IR.

The study of color evolution of galaxies has divided into three parts in recent years. Foremost are optical and near-IR studies of extremely high redshift galaxies, mostly radio selected systems, to probe the conditions immediately after the time of galaxy formation (Eisenhardt and Chokshi 1990, McCarthy, Perrson and West 1992). The main purpose of these studies has been to search for protogalaxies, but they also place tight constraints on the the star formation history of galaxies. Second are color selected galaxy surveys in broadband colors or the 4000Å break which have been used to test spectrophotometric model predictions out to redshifts of two (Hamilton 1985, Eisenhart and Lebofsksy 1987). Lastly are the numerous photometric studies on the fraction of blue galaxies in clusters (Butcher and Oemler 1984, Dressler, Gunn and Schneider 1985) relating to the rapid changes in cluster populations at only modest redshifts (0.2 to 0.5).

This study is a photometric analysis of galaxy cluster populations out to a redshift of one (10 Gyrs ago, \( H_o = 50 \text{ km sec}^{-1} \text{ Mpc}^{-1} \), \( q_o = 0 \)). We attempt a compromise between a full spectral analysis of distant clusters, versus simple, K-corrected broadband colors, by using narrow band blue filters “redshifted” to the cluster redshift \( (\lambda_{\text{obs}} = \lambda_o(1+z)) \). This use of narrow band-passes, rather than direct spectroscopy, produces some loss in spectral resolution but gains in increased S/N per object and coverage of the entire cluster per exposure. We present new photometry for 8 clusters from \( z = 0.6 \) to \( z = 1 \) (the limit of ground based, optical photometry). When combined with our previous results from our zero, low \( (z = 0.2) \) and intermediate \( (z = 0.4) \) redshift samples (Fiala, Rakos and Stockton 1986, Rakos, Fiala and Schombert 1988, Rakos, Schombert and Kreidl 1991, Schombert et al. 1993), we can use the results to address four galaxy evolution questions: 1) the change in the fraction of red to blue galaxies with redshift (Butcher-Oemler effect), 2) the nature of blue cluster galaxies, 3) the mean colors of ellipticals as a function of redshift (color evolution) and 4) the redshift of galaxy formation.

2. OBSERVATIONS

These observations were taken with the KPNO 4m PFCCD using Strömgren \( uvby \) filters centered at 3500Å, 4100Å, 4750Å and 5500Å (hereafter referred to as \( uz, vz, bz \) and \( yz \)) in the rest frame of the clusters studied. The sample of high redshift clusters was taken from the lists of Gunn, Hoessel and Oke (1986) which provided redshifts, coordinates and finding charts. Each of these filters are approximately 200Å wide (see Figure 1) and were specially designed so that they are “redshifted” to the cluster wavelength in order to maintain a rest frame color system. The KPNO data was taken over three runs in Oct 1990, Jun 1991 and May 1992. The PFCCD setup with the TE1K chip, a 1024 by 1024 CCD with a 70% QE at 8000Å and 0.48 arcsecs per pixel was used on
all runs. A total of over 15 filters ranging from a wavelength of 5500 to 9900 Å were used. Flattening was performed by dithering the exposures of 600 secs and making sky flats. Most of the data was taken during bright time, but OH emission dominated the sky counts rather than scattered moonlight. Calibration used spectrophotometric standards from Massey et al. (1988) combined with tabulated filter transmission curves. Colors and magnitudes were measured using FOCAS and are based on metric apertures set at 32 kpc for cosmological parameters of $H_0 = 50$ km sec$^{-1}$ Mpc$^{-1}$ and $q_0 = 0$. Our typical errors were 0.05 in $u_z - y_z$ and 0.06 in $b_z - y_z$ for $AB(5500)=18$ galaxies at the bright end of the high redshift sample and 0.13 and 0.18 for the faint end of $AB(5500)=21$. A greyscale image of our most distant cluster, CL1622.5+2352, at a redshift of 0.927 is shown in Figure 2.

Since our filters are specific to the redshift of the cluster, we can use the spectral shape of galaxies around the 4000 Å break to discriminate between stars, foreground and background objects. Stars and foreground galaxies will be sampled by the redshifted filters along the red portions of their spectra producing artificially blue $u_z - y_z$ and $v_z - y_z$ colors. Background galaxies will have their $v_z$ fluxes in the near-UV producing flat spectrum $u_z - v_z$ colors. Discriminating between foreground and background objects is performed using our $m_z$ index described in Paper III. But, we note that our observations are pointed at distant rich clusters and any foreground contamination will be minimal due to the small angular size of the cluster and any background contamination is restricted by the S/N depth of the frames. In addition, one can see from inspection of Figure 1 that our filter system avoids all the major emission lines, such as [OII] at 3727 Å or Hβ at 4861 Å, associated with either star formation or active galactic nuclei (AGN) phenomenon, thus preventing the exclusion of unusual galaxy types due to emission lines.

Histograms of $b_z - y_z$ for all the clusters are found in Figure 3. Data for clusters with redshifts less than 0.5 were taken from Papers I through III of our series and displayed herein for completeness. Table 1 presents the reduced cluster data, again for our new data and all clusters from Papers I through III. The table formation is as follows: column 1 is the cluster id, column 2 is the redshift of the cluster taken from the literature, column 3 is the number of galaxies in the cluster with available colors in at least three passbands, column 4 and 5 are raw cluster mean colors, column 6 is the $b_z - y_z$ color selection for star forming objects (see §3.3), column 7 and 8 are the mean cluster colors with the color cut applied and columns 9 and 10 are the fraction of blue galaxies in each cluster defined by the indicated color. Cluster errors are 1$\sigma$ errors on the means for each color. Rather than publishing extensive tables of our photometry, we have arranged to make the data available by contacting either author on email (js@ipac.caltech.edu).

3. DISCUSSION

The extragalactic meaning of the Strömgren colors are described in detail in our previous papers. Briefly, the Strömgren colors are crude estimators of recent star formation, mean age and metallicity. The $u_z$ filter is centered in the near-UV and measures the amount of recent high-mass star formation, $v_z$ is centered of the CN-Fe blend at 4170 Å and is sensitive to metallicity effects and $b_z$ plus $y_z$ are centered on regions with no strong spectral features and serve as continuum measures. In previous papers, we have used $u_z - v_z$ as a measure of the 4000 Å break, $v_z - y_z$ as a measure of global metallicity and $b_z - y_z$ as a measure of mean age of the underlying stellar population. However, precise understanding of these colors requires comparison to SED models with various assumptions (e.g. redshift of formation, mean metallicity and IMF) since varying star formation histories inhibit a unique interpretation of the colors. For example, $v_z - y_z$ colors are only sensitive to metallic-
ity only for a homogenous age population. Recent star formation can also strongly influence $vz - yz$ (see Figure 1). To this end, we have convolved our filters with models from Guiderdoni and Rocca-Volmerange (1987) and restrict our interpretation to global properties of the sample and state the model dependence of our results specifically in our discussion and conclusions. In addition, we have focused our analysis on four phenomena, the changing fraction of blue to red galaxies in clusters (Butcher-Oemler effect), the nature of this blue cluster population, the color evolution of red galaxies (assumed to be the progenitor of present-day ellipticals) and estimating the epoch of galaxy formation from the red envelope (O’Connell 1987).

3.1. BUTCHER-OEMLER EFFECT

The Butcher-Oemler effect is the strongest evidence of direct evolution of the stellar populations in galaxies that has been discovered to date. In its simplest form, the Butcher-Oemler effect is the observed increasing ratio of blue galaxies in a cluster as a function of redshift. There has long been an expectation that galaxy colors change with redshift since the gas depletion rates for many galaxy types are less than a Hubble time. Cessation of star formation naturally leads to a reddening of the integrated colors of the galaxy as massive blue stars in the underlying stellar population evolve to the red giant branch. Also, in practical terms, star formation rates are zero today for ellipticals and S0’s, whereas they must have been non-zero at some point in the past to produce the current population. Thus, at some past epoch, their mean integrated colors must have been bluer. However, the Butcher-Oemler result is surprising because of the extremely rapid change in the fraction of blue galaxies from nearly zero at the current epoch to approximately 20% at only modest redshifts of 0.4, approximately 4 Gyrs ago (Butcher and Oemler 1984). In contrast, even evolutionary models with late galaxy formation epochs predict that color changes were minor below a redshift of 0.5.

Our color data is unique from previous cluster studies in that we can determine the fraction of blue to red galaxies in rest frame colors without any K-corrections or model dependent parameters. Our color indices also remove any background or foreground contamination, a major inhibitor in broadband photometry surveys which require substantial background corrections or spectroscopic redshift confirmation. Our narrow band colors are also more finely tuned to test for star formation versus metallicity effects. In addition, matching to the cluster redshift eliminates contamination from emission lines.

The original broadband definition of the fraction of blue to red galaxies, $f_B$, given by Butcher and Oemler (1984) is the fraction of galaxies 0.2 mags bluer than the mean color of the E/S0 sequence after K-corrections to the total number of galaxies in the cluster. As discussed in Paper III, a sample of nearby spirals and irregulars is used to determine a value of $bz - yz$ and $vz - yz$ in our filter system that separates star-forming from quiescent galaxies. From this previous analysis, we have defined the fraction of blue galaxies, $f_B$, as the ratio of the number of galaxies bluer than $bz - yz=0.20$ or $vz - yz=0.40$ to the total number of galaxies. Since the mean $bz - yz$ color of a present-day elliptical is 0.37 (Schombert et al. 1993) and $bz - yz$ maps into $B - V$ in a linear fashion with a slope of 1.33 (Matsushima 1969), then a cut at $bz - yz=0.20$ is effectively the same as Butcher and Oemler’s 0.2 mag selection. To match limiting absolute magnitudes from cluster to cluster, we have only used galaxies with $yz$ mags greater than the magnitude of the 3rd ranked galaxy plus three (similar to Abell’s definition of cluster richness). Since the lower redshift clusters were imaged on 1 to 2 meter class telescopes, and the clusters above $z = 0.6$ on the KPNO 4m, we found the completeness of the data in terms of absolute luminosity was effectively balanced by S/N. Both $bz - yz$ and $vz - yz$
are used to calculate \( f_B \) and are listed in Table 1. Our cluster data is shown in Figure 4 along with the original Butcher and Oemler (1984) data and a dotted line as our interpretation of the trend discussed below. Errors are \( \sqrt{N} \) the number of members in each cluster. The value of \( f_B \) from either \( b_z - y_z \) or \( v_z - y_z \) color produces basically the same distribution with redshift, as seen in Figure 4, even though \( v_z - y_z \) is sensitive to metallicity effects and \( b_z - y_z \) specifically tests continuum colors. This would support our claim that foreground galaxies have not significantly contaminated our sample since foreground galaxies would produce bluer \( v_z - y_z \) colors relative to \( b_z - y_z \) and background galaxies produce very red \( v_z - y_z \) colors and flat spectrum \( u_z - v_z \) colors. In either scenario, our color selection index, \( m_{zB} \), would remove these objects from the sample as demonstrated in Papers I through III.

Our measurements of \( f_B \) can be tested by comparison to previous studies. For example, our sample has two clusters in common with the Butcher and Oemler (1984), A370 and CL0024.5+1653, with their values of \( f_B \) of 0.21 and 0.16 respectively. Our values are 0.18±0.10 and 0.17±0.10, in good agreement. In addition, one cluster (CL0939.7+4713) in our sample was observed by HST and published in a morphological/color study of high redshift clusters (Dressler et al. 1994). Our color criteria of \( b_z - y_z < 0.20 \) corresponds to \( g - r < 0.02 \) in rest frame colors. Applying a K-correction of 1.19 for a redshift of 0.04 (Schneider, Gunn and Hoessel 1983) gives a \( g - r < 1.21 \) cutoff for blue galaxies. For galaxies with morphological classification brighter than \( g=22.0 \) (100 galaxies), the Dressler et al. data produces a value of \( f_B \) of 0.34, which is well within the errors of our value of 0.28±0.10. The morphological information of the blue cluster galaxies is also insightful. Of the 100 galaxies, 42 are described as early-type (E,L,S in their system) and 58 are classed as spiral or merger (A,B,C,D,M). Of the blue galaxies \( (g - r < 1.21) \), only 3 are early-type and 33 are late-type. Of the red galaxies, 39 are early-type and 25 are late-type. Thus, it appears that the blue cluster population contains few early-type galaxies (as expected), but the red population contains a mixture of ellipticals, S0’s and spirals (see discussion below).

Beyond a redshift of 0.2, the data in Figure 4 shows that \( f_B \) increases steadily to a value of 0.80 by a redshift of 0.9. This change in cluster populations is dramatic, not only in terms of the rapid pace of galaxy evolution as first discovered by Butcher and Oemler, but also in the extent of the blue galaxy population dominates the entire cluster population at high redshifts. The largest value of \( f_B \) from either Butcher and Oemler (1984) or Dressler, Gunn and Schneider (1985) was 0.36 at redshifts of 0.4. The dashed line in Figure 4 represents Butcher and Oemler’s interpretation of the trend with redshift from their sample of \( z < 0.4 \) clusters. A second line is drawn displaying our interpretation from the high redshift sample. Our data suggests a slightly more rapid Butcher-Oemler effect than the lower redshift studies. In fact, many of our low redshift clusters have higher \( f_B \) values than Butcher and Oemler’s clusters at the same redshifts. The present-day mixture of spirals in rich clusters is 20% Sa’s, 16% Sb’s and 4% Sc+Irr’s (Whitmore, Gilmore and Jones 1993). The mean \( B-V \) color of these types are 0.94, 0.87 and 0.69 respectively (Oemler 1991). The 0.20 mag cutoff for the calculation of \( f_B \) signifies that only galaxies with colors bluer than \( B - V = 0.79 \) are selected. Thus, only Sc’s and Irr’s are counted in present-day clusters which agrees with Butcher and Oemler’s value of 0.04 for low redshift clusters. However, our narrow band filters are less sensitive to reddening effects \( (E(b_z - y_z) = 0.22 \) versus \( E(B - V) = 0.32 \) and a 0.10 mag difference in internal reddening is sufficient to include Sa and Sb type galaxies into our measurements of \( f_B \). This would explain why are values of \( f_B \) for \( z = 0.2 \) clusters are, on average, higher than the mean value from Butcher and Oemler clusters at
the same redshift.

The relationship outlined in Figure 4 is not smooth nor clearly linear. Two clusters (A227 and A2317) display high fractions of blue galaxies at only $z = 0.2$ ($f_B = 0.51$ and 0.65). One cluster at $z = 0.66$ (CL0128.8+0628) has a low value for its redshift of $f_B = 0.25$. The Butcher-Oemler effect in previous studies has shown similar behavior in that the observed pattern is more a deficiency of clusters dominated by red galaxies at high redshift, rather than an overabundance of blue dominated clusters or a correlated trend with redshift. In other words, at low redshift one can find clusters with both high and low values of $f_B$, but at higher redshifts we only find clusters with high $f_B$ values. One possible explanation for the scatter at low redshifts is that various cluster types (irregular to compact) are being selected, whereas at higher redshifts only the richest, densest clusters are detected and cataloged. For example, Allington-Smith et al. (1991) finds that the value of $f_B$ varies with cluster luminosity from a value of 0.30 for high luminosity clusters to 0.05 for low luminosity clusters. This would introduce a bias in that clusters detected at high redshift are found to be of much higher richness (i.e. cluster mass) than surveys of nearby clusters (the Scott effect). This might select clusters with stronger gas gradients at high $z$ relating to higher gas stripping rates or cluster galaxies with later infall times relating to a longer lasting blue population. This could be interpreted that the mechanism behind the Butcher-Oemler effect works best in dense clusters, or the Butcher-Oemler effect takes time to evolve and the richest clusters are the oldest (Mamon 1986).

### 3.2. THE NATURE OF BLUE CLUSTER GALAXIES

The origin of the blue galaxies that result in the Butcher-Oemler effect has had two possible interpretations in the literature. The original papers by Butcher and Oemler propose that the blue cluster galaxies are unusual due to ongoing star formation. However, a different interpretation was proposed by Dressler and Gunn (1983) based on spectroscopic observations of Butcher-Oemler clusters. They found that some of the Butcher-Oemler galaxies did indeed have strong emission lines indicative of a protracted period of star formation, but there also exists an unusual number of objects with post-starburst signatures, such as strong Balmer absorption features (E+A galaxies), and with AGN features. For example, the 3C 295 cluster displayed a tenfold increase in the number of galaxies with high excitation emission lines compared to present-day clusters (Dressler and Gunn 1983). Thus, the mystery lies both in the rapid timescale of the blue population’s evolution, as related to the spectroscopic evidence of starbursts, and the identification of the ancestors of the blue population in present-day clusters.

The blue cluster population is selected based on $bz - yz$ continuum colors, although the same population is identified from $uz - yz$ colors. However, the 4000Å break colors, $uz - vz$, are more relevant to testing the style and existence of star formation. Figure 5 displays the histograms of $uz - vz$ and $uz - yz$ color for the sample of clusters with redshifts less than 0.6 and greater than 0.6. There is no significant change in the $uz - vz$ colors between the high and low redshifts unlike the sharp change in mean $vz - yz$ or $bz - yz$ colors from Figure 3. The bottom panels of Figure 5 display the high redshift sample divided into red and blue galaxies based on the $bz - yz < 0.2$ criteria. Although the blue galaxies have a slightly bluer median $uz - vz$ color than the red galaxies, the difference is not what would be predicted from changes in $bz - yz$ or $vz - yz$ (Schombert et al. 1993). The same galaxies are easily distinguished in $uz - yz$. In other words, the blue cluster galaxies at high redshift have redder $uz - vz$ colors than would be expected from their continuum colors and higher $uz$ fluxes compared to the red galaxies. Redder $uz - vz$ color signals a strong 4000Å break which, in turn, is also an indication
of a hot star component due to recent star formation. This can be seen by considering a typical old population spectrum in the 4000 to 5000Å region shown in Figure 1. Any hot, young star component will increase the near-UV flux as seen in the $uz-yz$ histograms, but will also sharply increase the flux on the red side of the 4000Å break (i.e. compare the 1.5 Gyr model to the 17 Gyr model in Figure 1), resulting in redder $uz-vz$ colors compared to a normal elliptical SED. We rule out emission lines or AGN activity as a source of blue colors since our filters are specifically chosen to avoid all the significant emission features in the near-blue (O[II], H$\beta$, O[III], etc.). If the blue galaxy population was due primarily to emission features, then they would not be distinguished in our narrow band colors as unusual. Therefore, we interpret the trend in $uz-vz$ colors with redshift as evidence that the blue galaxies primarily have a young to intermediate age, post-starburst component dominating their colors rather than a strong, ongoing star formation episode.

The blue cluster population is a sample of galaxies with recent star formation, so there are three global possibilities for their evolution since the same population is absent in present-day clusters. First, they have either evolved into some known red cluster galaxy type, such as cluster ellipticals and S0’s. Second, they have faded from view and are simply not cataloged in our surveys of cluster populations (i.e. are of low surface brightness galaxies, LSB). Or, third, they are destroyed as identifiable units.

Considering the last option first, it is difficult to imagine a scenario where over 80% of a cluster population ($f_B$ values at $z = 0.9$), or about 1/2 the total cluster luminosity, is destroyed with no remaining evidence. There are strong tidal forces to play in rich clusters; however, interactions with other cluster members or a central cD galaxy occur at high velocities which is a condition that is not accommodating to tidal disruption (short interaction times) as much as tidal stripping (Merritt 1985, Malumuth and Richstone 1984). Even assuming some mechanism that only disrupts blue galaxies while ignoring red ones (perhaps the blue galaxies are low density structures that formed late), then the newly freed stellar population are still bound to the cluster potential. These stars would produce a luminous halo centered on the cluster core and, although giant halos have been detected around cD galaxies (Oemler 1976, Schombert 1988) and they have total luminosities which rival the brightest cluster members luminosity and not the total cluster luminosity necessary to explain the missing blue cluster population.

The second option is that blue cluster galaxies have faded from view. As the upper main sequence of a stellar population is depopulated after a burst of star formation, the red giant branch grows and the integrated colors redden. In addition, as high mass stars evolve into low luminosity white dwarfs, the luminosity per square parsec declines and the mean surface brightness of the galaxy decreases. For a disk population with a standard IMF, there is a change in one blue mag arcsec$^{-2}$ for every 0.23 mags change in $B-V$ color and, over a period of 5 Gyrs, a galaxy can drop 4 to 5 mags from its peak blue luminosity (Arimoto and Yoshii 1987). The peak luminosity of the blue cluster galaxies must be of order $M_B = -19$ to $-20$ for the blue population to be detected in the cluster surveys thus far. This amount of luminosity is only obtained from a starburst involving $4 \times 10^9 M_\odot$ of material. However, this is a strong burst of star formation where a significant fraction of the mass of the galaxy is turned into stars and, after such an episode, the total number of stars has not decreased so its final surface brightness would remain high. To see this consider a normal sized disk galaxy with an exponential scale length, $\alpha$, of 2 kpc with total blue mags of $-20$. Its initial central surface brightness ($\mu_o \propto M_B + 5 \log \alpha$) is 20.0 $B$ mag arcsec$^{-2}$ which would fade to 24.0 $B$ mag arcsec$^{-1}$ in 5 Gyrs, still quite visible in present-day cluster surveys. In order for fading
to be plausible, consider a larger galaxy with an \( \alpha = 10 \text{ kpc} \) and the same absolute magnitude. It would have an initial central surface brightness of 22.5 \( B \text{ mag arcsec}^{-2} \) which would fade to 26.5 \( B \text{ mag arcsec}^{-2} \). If we assume there were no high surface brightness bulge components (e.g., galaxy type Sc or later), then such a galaxy would be invisible on the Palomar Sky Survey prints and missing from any galaxy catalog.

This proposed LSB population would also explain the high fraction of AGN activity in high redshift clusters (Dressler and Gunn 1983). In a study of nearby, giant LSB galaxies, Knezek and Schombert (1994) found that 60% have low luminosity AGN activity. The weak emission is assumed to be due to the low surface density of gas in the cores of these systems, making a deficiency in fuel for the central engine. If the same event which triggers star formation in the blue cluster population also increases the core gas density, then the hidden AGN would increase in luminosity and the higher AGN fraction observed by Dressler and Gunn would be realized.

Unfortunately, there is presently no observational support for a hidden LSB population in present-day clusters. Photographically enhanced surveys of the Virgo cluster (Binggeli, Sandage and Tammann 1985, Impey, Bothun and Malin 1988) have achieved a depth of \( \mu_{\text{lim}} \approx 27 \text{ B mag arcsec}^{-2} \) and have not detected a population of large, LSB disk galaxies. Field surveys for LSB galaxies (Schombert et al. 1992) have found numerous examples of LSB counterparts to normal disk galaxies (scale length \( \alpha \) of 2 to 4 kpc) and large (\( \alpha > 10 \text{ kpc} \)) Malin galaxies, but none in a cluster environment (see Bothun et al. 1993).

Analysis of the structure of LSB galaxies demonstrates that their low luminosity densities reflect low surface mass densities and, thus, their is an expectation that such systems would not survive in a cluster environment (McGaugh 1992).

The remaining possibility for the fate of the blue cluster population is that they have evolved into some other kind of galaxy type. This galaxy type would also have to be red so as to reconcile the current distribution of galaxy colors in clusters to those in the past. Although there are highly reddened, dust-rich Sa’s in clusters, the dominate red galaxy types are ellipticals and S0’s. Ellipticals are poor candidates for the blue cluster population since they are composed of a single burst population of at least 12 Gyrs old with no evidence of recent star formation (Wyse 1985) plus have the correct morphological fraction from low to high redshift. In the previous sections, we have shown that a large fraction of the cluster members have star forming colors by \( z = 0.9 \). Since 40% of present-day cluster galaxies are S0’s and 40% are spirals, the change from 20% at \( z = 0.2 \) to 80% at \( z = 0.9 \) is suggestive that the increasing number of blue galaxies in clusters are star-forming S0’s and early-type spirals. The decline in blue galaxies to the present epoch would then represent the gradual halt in star formation due to gas depletion. The later passive evolution of the stellar population from a young, blue one to an old, red one would result in a quiescent S0. The rapid reddening of blue cluster galaxies is also not unexpected in the context of spectrophotometric models. For example, Ellis (1988) showed that a 10% burst (i.e. a strong burst) on top of an old population can evolve in less than one Gyr to a galaxies whose colors are indistinguishable from a 16 Gyr population and blue galaxies at \( z = 0.5 \) have sufficient time to evolve into the red galaxies. A plausible scenario is one where large bulge S0’s have a burst or past episode of star formation in their disks. For redshifts from 0.4 to 0.9, the brightness of the disk dominates and the integrated color of the galaxy is blue. As the disk fades, the bulges dominates and the galaxies quickly becomes red. This hypothesis is supported by the near-IR colors of S0 disks which indicate that they have had their last episode of star formation 4 Gyrs ago or redshifts of 0.3 (Bothun and Gregg 1990).

It is tempting, then, to envision an evolutionary progression where spirals are converted...
to S0’s and various mechanisms have been proposed over the past decades using ram pressure stripping or other gas depletion methods (Spitzer and Baade 1951, Gunn and Gott 1972, Larson, Tinsley and Caldwell 1980). However, the single greatest barrier to relating S0’s to spirals has been that the distribution of bulge to disk ratios (B/D) for S0’s is extremely different from that of spirals (Dressler 1980). The Hubble sequence is also a sequence of increasing B/D from Sc to S0, where B/D is defined either by isophotal size or relative luminosity. If the Butcher-Oemler effect is a progression of spirals exhausting their gas supply with star formation to become red S0’s, then the progenitors must be large B/D, early-type spirals. Whitmore, Gilmore and Jones (1993) propose that the B/D ratio is also an indicator of formation time, with larger B/D galaxies forming first. Then, the succession from S0 to Sc is a chain of formation epochs where the older galaxies (i.e. future S0’s) run out of gas first. Thus, the cluster Sa’s of today are the S0’s of tomorrow and the separation of B/D between Hubble types is maintained, not by converting late-type spirals into S0’s, but by merely adding early-type, large B/D galaxies to the S0 class in a steady fashion. This slowly shifts the distribution of B/D for S0’s as a function of redshift, but maintains their high mean B/D value as compared to star-forming, gas-rich spirals in the cluster. If this conversion process is responsible for the Butcher-Oemler effect, then the blue galaxies in clusters at high redshift should be large B/D spirals where their blue component is a bright, star-forming disk.

Further insight to this scenario can be found if we return to the HST results on CL0939.7+4713 at $z = 0.40$ (Dressler et al. 1994) and examine the morphological types of the blue galaxies. Of the 100 galaxies brighter than $r = 22$ with morphological classification, 20 are ellipticals, 22 are S0’s (type S or L) and 58 are late-type galaxies (Sa’s through Sd’s plus seven interacting/merger systems). In contemporary clusters, the mean morphological mixture is 20% E’s, 40% S0’s and 40% spirals and irregulars (Oemler 1991) so already we can see that there is a deficiency of S0’s and an overabundance of spirals in CL0939.7+4713. The breakdown for spirals and irregulars in present-day clusters are 20%, 16% and 4% for Hubble types Sa, Sb and Sc+Irr (Whitmore, Gilmore and Jones 1993). However, in CL0939.7+4713, the fractions are 12%, 23% and 23%. There is a deficiency of S0’s and Sa’s and an overabundance of Sb’s and Sc+Irr’s. Using Dressler et al. color values for the blue galaxies ($g - r < 1.21$), only three were classed as E or S0 from the HST images, the remaining 33 are late-type systems Sa through Irr. Of the red galaxies, 39 were E/S0 and 25 were disk systems. There were no galaxies classed later than Sc in the red sample and the spiral sequence itself also shows a division from blue to red with only 3 blue Sa versus 9 red Sa’s, 11 blue Sb’s versus 12 red Sb’s and 7 blue Sc’s versus 4 red Sc’s. This distribution has all the signatures of a gas depletion scenario since the ratio of HI mass to luminosity ($M_{HI}/L_B$) is also a decreasing function with galaxy type such that early-type spirals have lower current star formation rates and, therefore, redder optical colors. However, the data from Dressler et al. do not find large numbers of Sa’s evolving into a population of S0’s but, instead, an overabundance of late-type spirals whose B/D’s are incompatible with conversion to S0’s. Although there are proposals to build large B/D galaxies from late-type galaxies with recent star formation (see Pfenniger et al. 1994) the stellar populations of present-day bulges do not support this hypothesis. In addition, the luminosity of Butcher-Oemler galaxies is not much brighter than normal cluster spirals and any fading to an S0 would produce a luminosity function for present-day cluster S0’s that is fainter than field S0’s, which is not found. All this would argue against a scenario where blue galaxies are transformed into present-day S0’s; however, a B/D study of the HST images would
further resolve this problem.

Our interpretation that the blue narrow band colors are due to disk systems with normal star formation rates or post-starburst galaxies, rather than an ongoing starburst event, is also confirmed by HST imaging. Dressler (1993) reports that the brightest blue cluster galaxies are interacting or merger systems; however, a majority are normal disk systems in appearance. In addition, the morphology of red objects at high redshift is homogenous (Couch et al. 1993) such that they can not be highly reddened starbursts systems, put represent smooth, old population objects. The colors of the late-type galaxies are also bluer than their present-day counterparts. After taking the Dressler et al. $g - r$ colors, applying a mean $K$-correction of 1.19 (variation by type was less than 0.05) and converting to $B - V$, we obtain means colors for Sa, Sb and Sc+Irr to be 0.70, 0.60 and 0.19. Oemler (1991) reports that cluster values for Sa, Sb and Sc are 0.94, 0.87 and 0.69 respectively. The field values, also from Oemler (1991), are 0.77, 0.69 and 0.52. So even at a redshift of 0.4, the late-type galaxies have higher star formation rates then cluster spirals today, more in-line with field spirals colors. The Sc+Irr colors are too blue even for field spirals, but are similar to the colors of LSB disk galaxies (McGaugh 1992). Color evolution is not confined to just the Butcher-Oemler galaxies, but all galaxy types in the cluster.

Interestingly enough, when combining the above information from ground-based photometry and HST imaging, none of the three evolutionary scenarios for the blue cluster population are without significant drawbacks or contradictions. The fading and destruction scenarios fail to match current observational limits for LSB galaxies in clusters or large luminous halos. However, if the HST results for CL0939.7+4713 are indicative of all high redshift clusters, then neither is it plausible for a large fraction of the blue cluster galaxies to evolve into S0’s since the progenitors are mostly small B/D late-type spirals. On the other hand, some fading must occur since the colors of the spirals in CL0939.7+4713 are much bluer than present-day cluster spirals and, when this episode of star formation ends, their mean surface brightnesses must decrease. If we eliminate the late-type spirals in this manner than the ratio of E/S0/Sa is roughly similar to present-day clusters implying that S0’s had completed their star formation by redshift of CL0939.7+4713 ($z = 0.4$) in agreement with the disk ages from Bothun and Gregg (1990). The fraction of ellipticals is slightly higher as compared to present-day values (37% versus 20%); however, bright ellipticals in rich clusters are merger products (Schombert 1988) and, therefore, their numbers will be decreased as dynamical friction produces numerous mergers among bright ellipticals in the cluster core.

An alternative to the above scenarios is to assume that shortly after the bright, star-forming period of its life, the blue cluster galaxies are destroyed while the stellar remnants evolve and dim, a hybrid of the destruction and fading scenarios for the evolution of the blue cluster population. If the blue galaxies have their origin as an infalling population of LSB disk galaxies, who are undergoing an enhanced phase of pressure-induced star formation (Evrard 1990), then shortly after their blue phase they will encounter the cluster core and be tidally disrupted, spreading the fading stellar population into the cluster potential. Since the population is undergoing a burst of star formation, it has an enhanced surface brightness to increase their detection at higher redshifts. In addition, the surface mass density is still as low as their present-day field counterparts making them more susceptible to tidal effects than normal disk systems. This hypothesis has the advantage of preferentially destroying these low surface density blue galaxies so as to explain why no giant LSB systems are seen in present-day clusters and also fading the remnant stellar population that would make up the large cluster halos. There is some observa-
tional support for this hybrid scenario since HST images of high redshift blue galaxies indicates that many have a LSB appearance (Couch et al. 1993) and LSB galaxies have also been offered up as candidates for the faint blue field population that plagues galaxy counts studies (Mc-Gaugh 1994). The major drawback to this scenario that the combined effects of ram pressure induced star formation, enhanced AGN activity from increased fuel supply, fading then tidal destruction is a somewhat contrived scenario and too highly fine tuned to produce large numbers of red clusters galaxies at the present epoch.

3.3. COLOR EVOLUTION IN ELLIPTICALS

Ellipticals are the best subjects for testing color evolution since they are relatively free of dust, nebular emission and non-thermal sources. They also represent the simplest test cases since all indications are that they are composed of a single burst system, i.e. a galaxy where all the stars formed at a single epoch of star formation near the time of formation and where subsequent supernovae removed the remaining gas by galactic winds. The color history of single burst objects becomes an exercise of composite stellar evolution. The variables in evolutionary models of this type are the form of the stellar mass function (IMF), metallicity distribution and history, redshift of galaxy formation and cosmological parameters such as $H_0$ and $\Omega_0$ (see Buzzoni 1989).

An analysis of color evolution in ellipticals first requires a separation of star-forming, AGN and other active galaxies from the “passive” ellipticals. Our filter system uses multiple colors to distinguish blue from red galaxies and, therefore, a separate analysis can be done on the red objects as individuals. At low redshifts, cluster populations are dominated by red objects which are a mixture of ellipticals (20%) and So’s (40%) (Oemler 1991). At higher redshifts, the Butcher-Oemler effect begins to strongly influence the cluster population such that a over 80% of the cluster population is involved in some current (weak to strong) star formation. However, analysis of the stellar populations in present-day ellipticals indicates that their epoch of star formation was at least 4 Gyrs before $z = 0.9$ and that the duration of star formation was less than one Gyr to explain the metallicity dispersion (Rose 1985, Wyse 1985). Thus, this remaining 20% of red galaxies at $z = 0.9$ must be the progenitors of the current epoch cluster ellipticals.

In our earlier papers we separated the ellipticals from other cluster members with a multiple color criteria (primarily $bz - yz > 0.2$, $mz > -0.2$). This criteria, based on the colors of present-day ellipticals and spirals, is conservative and our analysis was relativity insensitive to our selection process since only 20% or less of a cluster population was excluded up to redshifts of 0.4. However, beyond a redshift of 0.4, the number of blue galaxies increases rapidly introducing contamination problems from galaxies within the cluster itself. Also, by redshifts of 0.7, the mean color of an elliptical, as predicted by SED models, approaches our blue limit for galaxy formation redshifts between 5 and 10. The end result is that our selection of the red population will be model dependent beyond $z = 0.6$.

There are three avenues for analyzing the red population given the expected changes in mean color from the standard models. The first is to continue to apply our previous color selection based on present epoch galaxies. These produce the values shown as open symbols in Figure 6 and, even applying this crude selection, the mean color of red objects, i.e. ellipticals, changes by 0.2 mags bluer from a redshift of 0.5 to 0.9 whereas the changes below $z = 0.5$ were very small. This is the first evidence in our filter system that there is significant color evolution in ellipticals. A second method is to use the predictions of the spectroevolutionary models to estimate a new color correction for each redshift. In this case we have use the UV-cold models of
Guiderdoni and Rocca-Volmerange (1987, hereafter GRV) for a redshift of formation of 5 (the best fit to the $z < 0.4$ uncorrected clusters). Our original color criteria was 0.17 blueward of the mean elliptical color at the present epoch and we use the models to maintain this 0.17 mags difference at each redshift. The cutoff $b_z - y_z$ values are listed in Table 1, column 5 and the new mean colors using these cutoff values are found in columns 6 and 7 and plotted as solid symbols in Figure 6. The third method was to use a constant percentage of the cluster population by color. Guided by the morphological mixture in present-day cluster, we choose 20% of the reddest objects for each cluster beyond $z = 0.6$. This selection produced a distribution of mean colors identical to the model cuts above and, therefore, are not shown in Figure 6.

The mean colors of the red population from model cuts are shown in Figure 6 as the solid symbols (error bars are errors on the mean value for each cluster) along with the GRV models ($H_o = 50$, $\Omega_o = 0$ and a Miller-Scalo IMF for a single 1 Gyr star burst at $z_g = 5$ and 10). Independent of the model tracks, there is a clear trend for increasing red colors to a redshift of 0.4 with a sharp bluerward change from 0.6 to 0.9. There is little difference between the various methods of calculating the mean cluster color out to redshifts of 0.7. There is also fairly good agreement with the GRV models in both $b_z - y_z$ and $v_z - y_z$ including the prediction of a red bump at $z = 0.4$ (see Paper II). This small peak is due to a increased contribution from AGB stars 4 Gyrs ago and is not predicted by other models which do not include late stages of stellar evolution. This provides an example of how color observations can be used to test specific parameters in SED models, such as stellar tracks or global metallicity. On the other hand, a faster decrease in color is seen at high redshifts then predicted by the models. Interpreting the data strictly within the context of these models indicates a redshift of elliptical formation in clusters cores as between 4 and 5. However, we note that from redshifts of 0.6 to 0.9 there still exist truly red ($b - y > 0.35$) objects in all clusters and, assuming that these are not dust shrouded starbursts, this implies that cluster ellipticals did not all have the same epoch of formation (see §3.4).

The $b_z - y_z$ colors track the UV-cold models quite well for a formation redshift between 4 and 5. The $v_z - y_z$ colors are also in good agreement with these same models and formation redshifts. However, for individual cluster values of $b_z - y_z$, the $v_z - y_z$ colors are slightly bluer than model predictions by 0.05 to 0.10 mags between $z=0.4$ and $z=0.9$, although in agreement from $z=0$ to 0.4. There are two possible sources for this discrepancy between the continuum colors and the metallicity colors. One is that there is an increasing contribution from low metallicity stars are a function of redshift that is not accounted for in the SED models. Since the models are only for solar metallicity stars, a distribution of metallicities (similar to the bulge to halo distribution in our Galaxy) was not considered. The metallicity effects of line blanketing and the mean temperature of the giant branch as well as unusual stellar types from low metallicity populations such as blue horizontal branch stars are more than sufficient to cause this discrepancy and future SED codes that contain a full chemical evolution treatment can address these observations. The second possibility is that there is contamination from the blue galaxy population. The fact that the bluer $v_z - y_z$ colors begins at the same redshift where the blue cluster population begins to dominate is suggestive. In previous papers, we have pointed out that our study only samples the bright end of the luminosity function (down to about 1/2 $L^*$). Normally for a cluster population, the bright end is dominated by ellipticals and S0’s. However, if the blue cluster population is a population of star-forming S0’s, then some post-starburst S0’s may contribute to the mean cluster colors regardless of our selection criteria since the distinction between blue and red galaxies is not discrete. On
the other hand, one expects a population of blue S0’s to fade very quickly since present-day cluster S0’s have large B/D ratios and when undergoing a star formation phase the disk light will dominate, but as the star formation ceases, the large bulge component will quickly replace the disk as the dominate source of integrated color. In either case, we can not ignore the possibly of contamination resulting in slight variations in the different colors with redshift.

3.4. EPOCH OF GALAXY FORMATION

The redshift of galaxy formation is a critical constraint on cosmological models. For example, standard CDM with a biasing factor of \( b = 2.5 \) is unable to reproduce large scale structure in a top-down hierarchy with a galaxy formation redshift greater than 3. Early formation redshifts \( (z \geq 10) \) have been suggested in numerous high redshift studies (Hamilton 1985, Steidel and Hamilton 1993, Hu and Ridgeway 1994). Their results can be summarized that up to redshifts of 3.5 one can still identify red, old population galaxies. Given our current understanding of the photometric evolution of a single burst population, a red galaxy at redshifts greater than three or, 15 Gyrs ago, requires an addition two Gyrs to evolve a dominate red giant branch. This additional evolution requires the epoch of first star formation to be greater than \( z = 5 \).

To explore the earliest epoch of galaxy formation the concept of the “red envelope” was invented (O’Connell 1987). This idea selects out the reddest (i.e. oldest) objects at any particular epoch then traces the red edge in the color distribution of galaxies as a function of redshift. Since objects in this study are selected on a multicolor plane, it is unlikely that our red population is contaminated by highly reddened objects but must represent objects which are red due solely to their stellar population. To estimate the redshift of galaxy formation for ellipticals in clusters, we define the red envelope as the 3\( \sigma \) edge of the red galaxy distribution in color. The data for the mean colors for red galaxies (i.e. ellipticals) in Figure 6 indicates a model dependent formation redshift approximately five. However, the red envelope data, shown in Figure 7 along with GRV SED models of various formation redshifts, indicates a a formation redshift of 10 for the oldest ellipticals in cluster cores. At \( z = 1 \), the typical elliptical has mean color indicative of a F star population (E+F type rather than E+A for post-starburst blue galaxies). Thus, we can rule out formation epochs less than \( z = 4 \) for ellipticals.

This estimate assumes the reddest objects are the oldest objects, but there are several other factors which can effect the red envelope such as systematic errors in the photometry (i.e. bias towards detecting red objects) or metallicity effects (i.e. galaxies with the highest mean \([Fe/H]\) have the reddest integrated colors). Systematic errors in our photometry seem unlikely and work in the opposite direction since sky brightness increased in our reddest filters enhancing the detection of blue galaxies. Metallicity effects are also minor since the color-magnitude relation indicates very small changes in color (less than 0.002 mags in \( b_{z} - y_{z} \), see Schombert et al. 1993) over the range of luminosity sampled herein \( (L > 1/2L^*) \). However, we note that the \( vz - yz \) colors are slightly bluer than the \( b_{z} - y_{z} \) colors compared to model tracks and indicate a redshift of formation of 8. Since a metallicity distribution of stars within the galaxy was not specifically included in the models (see Arimoto and Yoshii 1987), then the interpretation of red envelope is more accurate using \( b_{z} - y_{z} \) colors. In addition, since the red envelope indicates a redshift of formation of 10, yet the mean colors produce a value of 5, we interpret this to imply that cluster ellipticals are not coeval.

In the same fashion as the red envelope, we can define a blue envelope to estimate the formation epoch of the blue cluster population. Rather then defining a lower 3\( \sigma \) envelope, we simply calculate the mean color of the blue population as
shown in Figure 7. The track from these colors indicate a formation redshift between two and three. If the blue population is composed of LSB galaxies, then this would correct identify this first epoch of star formation, even though the galaxy itself may have formed as a quiescent gas cloud at higher redshifts. This scenario is consistent with the spatial distribution of LSB galaxies (Mo et al. 1994) and quiescent gas clouds (Lacy et al. 1993). If the blue population is composed of large B/D proto-S0’s, then this track would not indicate the formation redshift, since the spheroidal components have similar ages to ellipticals, but rather the last epoch of disk star formation at $z = 0.4$, a redshift consistent with S0 disk age estimates (Bothun and Gregg 1990).

4. SUMMARY

Although our understanding of color evolution and the formation of galaxies has focused on searches for distant protogalaxies, there is still a great deal that can be learned from photometry of lower redshift clusters from $z = 0$ to $z = 1$. This study has taken several small steps with information extracted from simple photometry using narrow band filters that sample specific portions of the spectrum relevant to star formation, metallicity and other evolutionary factors. We adjust the center wavelength of the filters to match the rest frame of the cluster, thus avoiding any model dependent K-corrections or strong emission lines. We summarize our primary results as the following:

1. We find a continuation of the Butcher-Oemler effect, the fraction of blue to red galaxies in a cluster, from values of $f_B = 0.20$ at redshifts of 0.4 to $f_B = 0.80$ at redshifts of 0.9. This trend is much stronger than found by early studies and suggests that all cluster galaxies with disks (S0’s and spirals) are involved in star formation 9 to 10 Gyr’s ago.

2. The colors of the Butcher-Oemler galaxies, the blue cluster population, is similar to that of an ongoing and post-starburst population. Redder $u_z - v_z$ colors (a strong 4000Å break) indicates a young stellar population similar to the E+A galaxies found spectroscopically by Dressler and Gunn (1985). The formation epoch of this population is between a redshift of 2 and 3 based on a blue envelope analysis.

3. Our color information, when combined with morphological HST studies in the literature, leads us to conclude that the evolution of the blue cluster population is such that they can not be converted to red galaxy types (i.e. ellipticals and S0’s) on the short timescales from $z = 0.5$ to the present. We propose that the Butcher-Oemler effect is due to a population of low surface density galaxies which are blue due to pressure induced star formation that occurs upon infall to the cluster environment. This population is later preferentially destroyed by the cluster tidal field over red galaxy types and the stellar remnants fade below detectable limits.

4. The mean colors of ellipticals displays a trend of redder colors until a redshift of 0.4 then a blueward drop out to the edge of the sample at $z = 0.9$. We find good agreement with the UV-cold SED models of Guiderdoni and Rocca-Volmerangre (1987) including a red bump at $z = 0.4$ due to an AGB star contribution and a smooth transition to blue optical colors by a redshift of 0.9. Our metallicity color, $v_z - y_z$, is slightly bluer than model predictions beyond a redshift of 0.6, probably due to a metal-poor component to
the underlying stellar population and indicates the need for a full chemical evolutionary treatment in the models (see Arimoto and Yoshii 1987).

5. Assuming the cosmological constants needed to match globular cluster ages, we find the mean epoch of galaxy formation to be \( z = 5 \). However, tracing the red envelope in the cluster data finds the oldest (i.e. reddest) galaxies to have formation redshifts of approximately 10. This is a major challenge to structure formation theories.

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Fig. 1.— The modified Strömgren filter system used herein is shown along with the SED models for an old, metal-rich galaxy (17 Gyr) and a young post-starburst SED (1.5 Gyrs, from Guiderdoni and Rocca-Volmerange 1987). Note that although the near-UV flux increases by any measure of $uz - yz$, $vz - yz$ or $bz - yz$, the 4000Å break colors, $uz - vz$, become redder with a younger population.

Fig. 2.— A greyscale image of our most distant cluster, CL1622.6+2352, taken with the KPNO PFCCD system for 3000 secs in our $yz$ filter. The field of view is 3.2 arcmin with north at the top and east to the left. The cluster is the small concentration of faint objects in the center of the frame. (This figure is not included in this preprint version)

Fig. 3.— Histograms of the continuum color, $bz - yz$ for the 17 clusters in our samples. Data for clusters with redshifts less than 0.6 are from Papers I through III. Note how the median color shifts by 0.7 mags from $z = 0.2$ to 0.9.

Fig. 4.— The Butcher-Oemler effect as seen in rest frame Strömgren colors. Solid diamonds are the new data from this paper, the crosses are from the original Butcher and Oemler (1985) data. We confirm previous studies in that strong evolution is present in the data. The dashed line is the original interpretation of the Butcher-Oemler effect. The dot-dash line is our new estimation based on the higher redshift data. The fraction of blue galaxies ($f_B$) rises sharply from a present-day value of 0.04 to approximately 0.80 at a redshift of 0.9 in roughly a linear fashion. Since the mixture of present-day galaxy types is 20% E’s, 40% S0’s and 40% spirals in rich clus-

This 2-column preprint was prepared with the AAS L\TeX macros v4.0.
ters, this new data indicates that all disk systems are consumed in significant star formation 8 Gyrs ago.

Fig. 5.— Histograms of near-UV color, \( uz - yz \), and the 4000Å break color, \( uz - vz \). The top panels display the summed data for all cluster galaxies with a redshift less than 0.6. The second panels display the summed data for all cluster galaxies with redshifts greater than 0.6. The bottom sets of panels display the distribution of colors for red and blue galaxies (selected by \( bz - yz \) colors) from only the high redshift clusters. The near-UV color changes little between the high and low redshift samples, although the blue and red galaxies are clearly distinguished by UV flux, assumingly from increased massive star contribution in the blue galaxies. The blue and red galaxies are identical in \( uz - vz \), i.e. the blue galaxies are too red for their continuum colors. This signals an enhanced 4000Å break component from a young stellar population.

Fig. 6.— Color as a function of redshift for the red population in each cluster (mean values, error bars are errors on the mean). These objects are the progenitors of the present-day cluster ellipticals. Open symbols are raw colors using a constant \( bz - yz < 0.2 \) cutoff. Solid symbols are mean colors from model determined cutoffs listed in Table 1. Similar trends are seen in both our metallicity color \((v - y)\) and continuum color \((b - y)\). Evolution in both filters is roughly redward till \( z = 0.5 \) then a sharp blueward trend to \( z = 1 \). Model tracks are from Guiderdoni and Rocca-Volmerange (1987) for the cosmology and star formation parameters listed. Good agreement exists between the model and observations, although the metallicity color is slightly bluer than model predictions matched to \( bz - yz \) color indicating a low metallicity population unaccounted for by the models.

Fig. 7.— Red and Blue envelopes to determine the earliest epoch of galaxy formation and the star formation epoch of the blue cluster galaxies. The reddest galaxies are selected from 3σ from the cluster mean colors to form the red envelope. Model fits suggest the earliest redshift of elliptical formation is at least 10. The median colors of the blue cluster population are used to define the blue envelope. The blue envelope indicates the epoch of star formation for the Butcher-Oemler effect is between a redshift of 2 and 3.
Figure 3
Figure 3 (cont.)
Figure 3 (cont.)
$H_0=50, \Omega_0=0$

IMF = Miller–Scalo

- $z_{gb}=5$
- $z_{gb}=10$

Figure 6
$H_0 = 50, \Omega_0 = 0$

IMF = Miller-Scalo

○ - Blue Envelope

● - Red Envelope

Figure 7