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# SPECTROSCOPY OF GALAXIES IN DISTANT CLUSTERS. III. THE POPULATION OF Cl 0024+1654

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## ABSTRACT

We present the results of a spectroscopic study of 38 objects in the field of the very rich, concentrated cluster Cl 0024+1654 at a redshift of $z = 0.391$. All of the red galaxies and 14 of the 22 blue objects are found to be cluster members. The spectra of the blue cluster members are very similar to those of low-redshift spirals, suggesting that these distant galaxies are also undergoing protracted periods of star formation. These data support Butcher and Oemler's suggestion that this cluster provides evidence for evolution of the blue population of clusters, to the extent that no low-redshift, concentrated cluster is known to have such a large population of blue galaxies.

Three of the blue cluster members have spectra typical of active galactic nuclei, which lends support to the proposal of Dressler and Gunn that such activity was much more common only 4–5 × $10^9$ yr ago. On the other hand, no "starburst" galaxies like those in the 3C 295 cluster have been found.

We describe a technique for finding emission-line galaxies at a known redshift by imaging through a narrow-band filter centered on redshifted [O II] $\lambda3727$ and demonstrate that this procedure detects [O II] emission at a level consistent with our spectroscopic measurements. With this technique, we have found other examples of blue galaxies with [O II] emission, and the strongest of these was confirmed to be an AGN by subsequent spectroscopic measurement. This method is extremely efficient because it covers the entire field at once and will be particularly valuable for work on higher redshift clusters where even multislit spectroscopy is difficult at the present time.

There appear to be a variety of cluster types at $z \approx 0.5$, as evidenced by Cl 0024+1654 with its "spirals," the 3C 295 cluster with its "active" galaxies, and Cl 0016+16 with only red galaxies. We present a model that attempts to explain the available photometry and spectroscopy of these three distant clusters, and the photometry of low-redshift clusters and the field as reported by Butcher and Oemler in 1984. A combination of (1) a preference ab initio for the formation of spheroidally dominated galaxies in dense protoclusters, and (2) a time scale for conversion of gas to stars that is a function of Hubble type would result in clusters ranging from those that collapse early and contain a population of red, dormant galaxies, to those that collapse later and include many spirals still active in star formation at $z \approx 0.5$. Later environmental influences are also likely to have had some effect on the population-density-time relation, but comparison of nearby and distant samples leads to no clear resolution of what that role has been.

*Subject headings:* galaxies: clustering — galaxies: evolution — galaxies: redshifts — galaxies: stellar content

## I. INTRODUCTION

Investigating the properties of high-redshift galaxies is a promising way of choosing among the many paths of galaxy evolution consistent with observations of present-day galaxies. Although there is little or no evidence for evolutionary changes in the reddest galaxies since redshifts $z \approx 1$, it is becoming increasingly clear that the blue galaxies, those with vigorous star formation or active nuclei, may have undergone significant evolution, even since $z \approx 0.5$.

A previous paper (Dressler and Gunn 1983, hereafter Paper II) reported the results of a spectroscopic study of 26 galaxies in the rich and distant cluster containing the luminous radio galaxy 3C 295. The field of the 3C 295 cluster was found to be heavily contaminated by field galaxies, so that only about 40% of the blue galaxies cataloged by Butcher and Oemler (1978, hereafter BOI) are actually members, leading to a blue galaxy fraction for the cluster of about 20%. Whether this is an unusually high proportion of blue galaxies compared to that of a rich, concentrated cluster at low redshift has been a point of considerable debate. In their latest paper, Butcher and Oemler (1984, hereafter BOV) present data for eight such clusters with $z < 0.1$, none of which has a blue galaxy population larger than 5%, this despite the fact that the spiral fraction is often ~20%. If these data are representative of all nearby, concentrated clusters, then it must be concluded that spirals in these clusters differ from a random sample of spirals in the low-density field, because most field spirals are blue under the criteria adopted by Butcher and Oemler (BOV).

In addition to its higher percentage of blue galaxies compared to low-redshift concentrated clusters, the 3C 295 cluster is unusual in the *type* of galaxies that make up its blue population. Of the six blue members found so far, three have spectra which indicate an active galactic nucleus (hereafter AGN), and three show strong Balmer absorption lines but negligible [O II], [O III], or H$\beta$ in emission, suggestive of a strong burst of star formation. In contrast, a present-day blue galaxy is typically a late-type spiral with a spectrum quite different than any of these six. It was suggested in Paper II that this higher frequency of "active galaxies," AGNs and starburst, might be characteristic of a high-redshift cluster, or, alternatively, that this episode of activity was connected with the evolution of the cluster and/or the luminous radio galaxy 3C 295.

In this paper, we present spectroscopic and narrow-band photometric data for the second of the original Butcher-Oemler clusters, Cl 0024+1654. This cluster is richer than the 3C 295 cluster and was reported in BOI to contain an even larger population of blue galaxies. The properties of this cluster deduced from CCD broad-band imaging are discussed in Schneider, Dressler, and Gunn (1985, hereafter SDG). That study includes a new determination of the blue galaxy fraction which confirms the apparently large population of blue galaxies reported in BOI.

Our conclusions, based on the spectra of 38 galaxies in the Cl 0024+1654 field, are quite different from the results for the 3C 295 cluster. The contamination of the blue population by field galaxies is much less, and the large number of blue galaxies that are members have spectra similar to those of nearby spiral galaxies. In addition, although we have found two certain Seyfert 2 and another probable AGN, none of the spectra resemble the starburst galaxies present in the 3C 295 cluster. Therefore although the new data support the case for a significant evolution in the blue population of clusters since $z = 0.5$, the difference in the populations of these two clusters points away from a simple explanation such as the evolution galaxies with cosmological time, independent of such cluster properties as density, environment, or dynamical state.

The remaining sections of this paper are organized as follows. Section II provides a brief description of the cluster and an inventory of the spectra we have obtained. Section III compares the spectra of the blue galaxies to those of nearby spirals, and § IV presents a technique of finding emission-line galaxies at a known redshift by obtaining direct images through a narrow-band filter centered at redshifted [O II]. Some implications of the new Cl 0024+1654 data with respect to the 3C 295 cluster data and BOV are discussed in § V.

## II. THE DATA

In addition to the six spectra in the Cl 0024+1654 field obtained in 1981 November (see Dressler and Gunn 1982, hereafter Paper I), we have acquired 31 additional spectra on 1982 September 18 and 19, 1982 October 14, 15, and 16, and 1983 October 4 and 6, using the PFUEI CCD camera-spectrograph (Gunn and Westphal 1981) at the prime focus of the Hale 5 m telescope. The spectra were taken through six multiaperture masks with slits 2″ wide, produced with software from a previous broad-band CCD frame, and reproduced as described in Paper II. The exposures ranged from 4000–16,000 s in conditions of average seeing, 1″.5–2″.0 FWHM, and often through cirrus clouds. The data were reduced as explained in Paper II, using programs written by Todd Boroson for the VAX 11/750 computer of the Mount Wilson and Las Campanas Observatories in Pasadena. The data cover the spectral range 4500–8500 Å with a resolution that runs from ~25 Å in the center to near 50 Å near the ends. Figure 1 reproduces a section of a 400 s CCD frame of Cl 0024+1654 in the $r$ filter of the Thuan and Gunn (1976) system. The galaxies observed spectroscopically are labeled with the numbering system of SDG, which is used throughout this paper. An additional 6000 s single-slit observation of SDG 223 was made on 1984 November 26 in 4″ seeing, which confirmed the detection of [O II] emission found photometrically, as described below.

Table 1 lists the magnitudes (from SDG) and spectral characteristics of those galaxies with sufficiently good spectra that redshifts could be determined with reasonable confidence. Because of shorter exposures and poorer weather conditions, the sample presented here includes a few spectra of lower quality than the 3C 295 data of Paper II. In particular, four of the field galaxies have uncertain redshifts. It is unlikely, however, that any of these are cluster members since there is at most one spectral feature corresponding to the cluster redshift of $z = 0.38$–$0.40$ in each of these cases. Table 1 includes an estimate of the signal-to-noise ratio (hereafter S/N) *in the continuum* which is given as the quality of the spectrum; however, this does not always imply a one-to-one correspondence with the quality of the redshift because of the variation in line strengths of the different spectral features. The redshifts are given in bins of 300 km s$^{-1}$ in the observed frame, which is comparable to the expected errors.

Table 1 also includes a description of the detected spectral features. The notation "E-type" refers to an early-type spectrum typical of an elliptical or S0 galaxy (see Papers I and II); Balmer lines in absorption and emission lines are indicated. Finally, Table 1 contains values of $C$, the slope of the continuum from 4100–5000 Å, and log $W$, the rest frame equivalent width of the [O II] doublet $\lambda$3727, measured as discussed in § III*b*. Table 2 gives the 1950 positions for the galaxies of Table 1, to an accuracy of approximately $\pm 2''$.

The spectra of the red galaxies 141, 168, and 178 were individually too poor for determination of a redshift, although an E-type spectrum at the cluster redshift was common to all. These spectra were added together to achieve a sufficient S/N, and this average redshift was used in determination of the mean velocity of the cluster, but not its dispersion. Likewise, the spectra of the companion galaxies 128 and 127 were summed to increase the S/N; however, the redshift of these probable foreground galaxies is still uncertain.

## III. ANALYSIS

### *a) Cluster Membership*

Figure 2 is a histogram of the redshifts of 36 galaxies in the Cl 0024+1654 field. Two other objects, 109 and 128 in BOI, were found to be galactic stars. Figure 2 clearly shows that a majority of the objects studied belong to a cluster of galaxies with redshifts $z = 0.38$–$0.40$.

Although the distribution of redshifts in the cluster appears non-Gaussian, this conclusion is not statistically significant with the 26 member galaxies studied to this point. The 14 blue cluster members (defined as $g - r < 1.2$; see SDG) have an average redshift of $z = 0.3936 \pm 0.0015$, higher by 1083 km s$^{-1}$ (in the rest frame) than the mean $z = 0.3886 \pm 0.0015$ of the 15 red members. (Galaxies 141, 168, and 178 were included in the determination of the mean, as noted above.) This difference is marginally significant, and if the populations are treated separately, the rest frame velocity dispersion of the blue galaxies is $\sigma_0 = 1088$ km s$^{-1}$ compared to $\sigma_0 = 1256$ km s$^{-1}$ for 12 red galaxies. Alternatively, the redshifts of both red and blue galaxies are satisfactorily described by a single Gaussian with a

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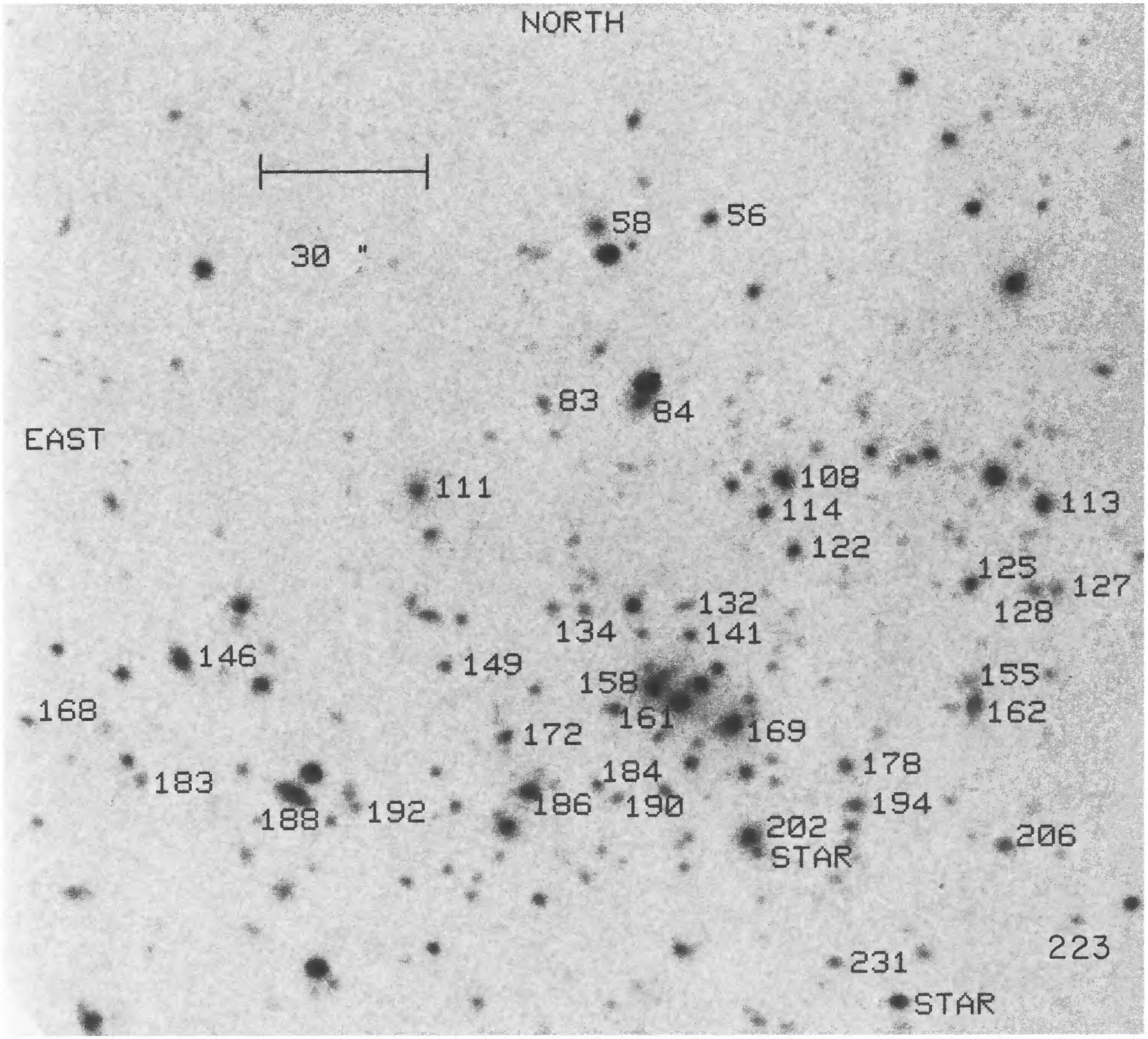


FIG. 1.—Section of a 400 s "r" CCD frame taken with the PFUEI of Cl 0024+1654. The galaxies for which redshifts have been measured from low-resolution spectra also obtained with the PFUEI are indicated. The numbering system is that of Schneider, Dressler, and Gunn (1985).

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TABLE 1

BASIC DATA FOR GALAXIES IN THE Cl 0024+1654 FIELD

| SDG# | BO# | r | g-r | r-i | z | C[1] | log W[2] | OII-g[3] | Q[4] | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| 56 | 2 | 20.45 | 0.52 | 0.24 | 0.386 | 1.60 | 1.20 | -0.15 | G | O II, Hβ |
| 58 | 1 | 19.72 | 0.81 | 0.27 | 0.299: | -- | -- | -0.03 | P | weak Mg, Bal abs |
| 83 | 12 | 20.80 | 0.67 | 0.40 | 0.399 | 1.62 | 1.18 | -0.15 | G | O II, O II:, Hβ: |
| 84 | 15 | 19.36 | 0.96 | 0.26 | 0.386 | 2.03 | -- | -- | F | Weak H,K,G,Bal abs |
| 108 | 29 | 19.43 | 1.47 | 0.50 | 0.385 | 2.91 | -- | +0.05 | E | E-type |
| 111 | 26 | 19.51 | 1.40 | 0.45 | 0.395 | 2.34 | 0.87 | -0.17 | E | E-type |
| 113 | 34 | 19.66 | 0.78 | 0.32 | 0.401 | 1.84 | 0.77 | -0.06 | G | Weak O II, Hβ |
| 114 | 32 | 20.48 | 1.50 | 0.44 | 0.383 | 2.31 | -- | +0.14 | E | E-type |
| 122 | 37 | 20.49 | 1.45 | 0.42 | 0.381 | 2.49 | -- | +0.04 | G | E-type |
| 125 | 48 | 20.22 | 0.40 | 0.01 | 0.399 | 1.38 | 1.89 | -0.64 | E | O II, O III, Hβ , AGN |
| 127 | 50 | 20.37 | 0.31 | 0.41 | 0.215: | -- | -- | -0.08 | G | Bal abs, Hα (5) |
| 128 | 49 | 20.43 | 0.42 | 0.38 | 0.215: | -- | -- | -0.04 | G | Bal abs, Hα (5) |
| 132 | 47 | 21.53 | 1.05 | 0.58 | 0.555 | -- | -- | +0.29 | F | O II, weak Bal abs |
| 134 | 44 | 21.16 | 0.82 | 0.26 | 0.389 | 1.63 | 1.01 | -0.20 | G | O II, Bal abs |
| 141 | 52 | 20.96 | 1.50 | 0.38 | 0.391 | -- | -- | +0.27 | G | E-type (6) |
| 146 | -- | 19.54 | 0.83 | 0.34 | 0.392 | 1.67 | 1.39 | -0.24 | G | O II, O II |
| 149 | 53 | 20.98 | 0.61 | 0.20 | 0.391 | 1.53 | 1.10 | +0.00 | G | O II, O III, Bal abs |
| 155 | 68 | 20.76 | 0.50 | 0.23 | 0.455 | -- | -- | +0.05 | G | O II, O II, AGN |
| 158 | 62 | 18.48 | 1.54 | 0.46 | 0.390 | -- | -- | +0.10 | E | E-type |
| 161 | 65 | 18.37 | 1.60 | 0.46 | 0.390 | -- | -- | +0.03 | G | E-type |
| 162 | 72 | 19.48 | 1.35 | 0.45 | 0.382 | 2.12 | -- | +0.15 | F | E-type |
| 168 | -- | 20.77 | 1.49 | 0.45 | 0.391 | -- | -- | +0.05 | G | E-type (6) |
| 169 | 71 | 18.57 | 1.61 | 0.47 | 0.398 | -- | -- | -0.03 | E | E-type |
| 172 | 70 | 20.39 | 1.11 | 0.44 | 0.390 | 2.61 | -- | -0.07 | F | Weak E-type |
| 178 | 89 | 20.64 | 1.52 | 0.38 | 0.391 | -- | -- | +0.29 | G | E-type (6) |
| 183 | -- | 21.07 | 0.22 | -0.02 | 0.399 | 1.28 | 1.60 | -0.31 | G | O II, O III, Hβ, AGN: |
| 184 | 88 | 21.19 | 1.21 | 0.39 | 0.383 | 2.48 | -- | +0.08 | G | E-type |
| 186 | 87 | 19.20 | 1.43 | 0.50 | 0.390 | 2.32 | -- | -0.06 | F | E-type: |
| 188 | 79 | 18.46 | 0.64 | 0.41 | 0.139 | -- | -- | -0.12 | E | Hα, [S II] em |
| 190 | 92 | 21.10 | 1.26 | 0.67 | 0.386: | 2.56 | 1.02 | +0.02 | F | Weak E-type, O II: |
| 192 | 83 | 20.55 | 1.13 | 0.42 | 0.397 | 2.28 | -- | -- | P | 4000 Å brk, Bal abs |
| 194 | 96 | 20.40 | 0.83 | 0.48 | 0.391 | 1.70 | 0.48 | +0.00 | G | O II, Bal abs |
| 202 | 100 | 19.08 | 1.50 | 0.45 | 0.396: | -- | -- | -0.02 | F | Weak E-type |
| 206 | 113 | 19.66 | 0.78 | 0.32 | 0.161: | -- | -- | -0.05 | F | 4000 Å brk, G, Na D |
| 223 | 123 | 21.43 | 0.23 | -0.44 | 0.394 | 1.17 | 2.10 | -0.93 | G | O II, O III, Hβ, AGN |
| 231 | 124 | 20.99 | 0.22 | 0.02 | 0.397 | 1.25 | 1.58 | -0.20 | E | O II, O III, Hβ |
| --- | 109 | -- | -- | -- | 0.000: | -- | -- | -- | F | Probable K star |
| --- | 128 | -- | -- | -- | 0.000 | -- | -- | -- | E | M star |

NOTES.—(1) $C$: Continuum slope from 4100–5000 Å in the rest frame. (2) Log $W$: log of equivalent width of [O II] in the rest frame. (Null entry denotes an upper limit of 2–3 Å.) (3) O II $- g$: Color formed from $m(5180\ \text{Å}) - g$ as explained in § IV. (4) Q: quality of spectrum: E denotes excellent; G denotes good; F denotes fair; P denotes poor. (5) 127 and 128 spectra combined to obtain redshift. (6) 141, 168, and 178 spectra combined to obtain redshift.

COMMENTS.—Balmer lines in emission (em) unless noted as "Bal abs." O II denotes [O II] doublet $\lambda$3727 Å, O III denotes [O III] $\lambda\lambda$4959, 5007 Å. AGN is active galactic nucleus.

mean redshift $z = 0.3909$ and $\sigma_0 = 1287$ km s$^{-1}$, a velocity dispersion that is not unreasonably high for such a rich cluster. The subclumping in velocity space may prove crucial to understanding the large population of blue galaxies, because the velocity dispersions in these groups could be low enough to favor interactions between galaxies; however, the verification of this substructure must await additional redshifts of member galaxies.

Of the 16 red objects observed, all but one (a foreground M star misclassified as a galaxy in BOI) have the spectra of early-type galaxies at the cluster redshift. This is consistent with the result in Paper II, which found no contamination of the red population of the 3C 295 cluster by field galaxies. Of course, this is expected since foreground galaxies, which are responsible for most of the contamination, cannot be as red as redshifted cluster galaxies, and the coincidence of the proper color and $K$-correction for a background galaxy to match the color of a cluster member is rare.

The blue galaxy population, on the other hand, is always significantly contaminated since both red foreground and blue background galaxies can fall into this broad color bin. There appears to be less contamination, however, in the Cl 0024+1654 field than that found in the 3C 295 field. The 23 blue objects studied include 14 cluster members, five foreground galaxies, two background galaxies, and one star misclassified as a galaxy in BOI. Thus, in contrast to the case of the 3C 295 field, *the majority of blue galaxies in this field are cluster members*, and the ratio of cluster to field galaxies, ~2 for the blue population, is consistent with the expected contamination estimated by BOI and SDG. Thus, the ~25% blue fraction implied by the photometry (see SDG) in the central regions of Cl 0024+1654 is genuine and is not due to the biased selection of a cluster with an abnormally large number of field galaxies along the line of sight. These data therefore substantiate the original contention of BOI that the blue population of Cl 0024+1654 is large.

TABLE 2

Cl 0024+1654 Object Positions

| Galaxy | R.A. (1950.0) | Decl. (1950.0) |
|---|---|---|
| 56 ......... | $00^h23^m56^s.2$ | +16°54′33″ |
| 83 ......... | 00 23 58.3 | +16 54 00 |
| 84 ......... | 00 23 57.1 | +16 54 00 |
| 108 ......... | 00 23 55.3 | +16 53 47 |
| 111 ......... | 00 23 59.9 | +16 53 45 |
| 113 ......... | 00 23 52.1 | +16 53 42 |
| 114 ......... | 00 23 55.6 | +16 53 41 |
| 122 ......... | 00 23 55.2 | +16 53 34 |
| 125 ......... | 00 23 53.0 | +16 53 28 |
| 134 ......... | 00 23 57.8 | +16 53 23 |
| 141 ......... | 00 23 56.5 | +16 53 19 |
| 146 ......... | 00 24 02.9 | +16 53 15 |
| 155 ......... | 00 23 53.0 | +16 53 11 |
| 158 ......... | 00 23 56.9 | +16 53 10 |
| 161 ......... | 00 23 56.6 | +16 53 07 |
| 162 ......... | 00 23 52.9 | +16 53 06 |
| 168 ......... | 00 24 04.8 | +16 53 04 |
| 169 ......... | 00 23 55.9 | +16 53 03 |
| 172 ......... | 00 23 58.8 | +16 53 01 |
| 178 ......... | 00 23 54.5 | +16 52 56 |
| 183 ......... | 00 24 03.4 | +16 52 54 |
| 184 ......... | 00 23 57.7 | +16 52 52 |
| 186 ......... | 00 23 58.5 | +16 52 51 |
| 190 ......... | 00 23 57.4 | +16 52 50 |
| 192 ......... | 00 24 00.7 | +16 52 49 |
| 194 ......... | 00 23 54.4 | +16 52 49 |
| 202 ......... | 00 23 55.7 | +16 52 43 |
| 223 ......... | 00 23 51.7 | +16 52 28 |
| 231 ......... | 00 23 54.7 | +16 52 21 |

### *b) The Spectra of the Blue Cluster Galaxies*

#### i) *Comparison with the Spectra of Nearby Spirals*

The spectra of eight of the blue cluster members are shown in Figure 3 along with the spectrum of a red cluster member and an unnormalized spectrum of the night sky, useful for identifying regions of poor sky subtraction. The spectra are plotted as log wavelength versus flux on the $F_\nu$ scale; however, the spectral shape is only reliable for $\lambda < 7000$ Å. (Due to poor focus on the red end, the sky determination is contaminated by signal from the object.) The wavelength regions with poor sky subtraction and cosmic-ray hits are indicated.

In each of the blue spectra the [O II] doublet $\lambda3727$ is visible in emission at $\lambda \approx 5180$ Å. In some cases [O II] $\lambda\lambda5007$, 4959 and H$\beta$ are also seen, but only in galaxies 125 and 183 are these lines comparable in strength to [O II]. The spectra of 223, not shown, is qualitatively similar to that of 125, with an [O III]/[O II] $\approx 3$ and [O III]/H$\beta \approx 5$. These three cases are "high-excitation" spectra typical of metal-poor H II regions and active galactic nuclei (see Paper II), but the other six shown in Figure 3 have "low-excitation" spectra typical of the star-forming regions of today's luminous spiral galaxies. To test quantitatively this assertion that the spectra of many of the blue galaxies in Cl 0024+1654 resemble those of nearby cluster spirals, we have revived the [O II] versus $B-V$ color correlation of Paper I. For this test, spirals in several nearby clusters with redshifts $z \approx 0.04$ were observed with the Reticon Spectrograph on the du Pont 2.5 m telescope at Cerro Las Campanas through large (12″ × 16″) apertures that include the same 10–20 kpc areas covered in slit spectroscopy of distant galaxies. New data were obtained on 1983 March 16 to supplement the original data of Paper I. Like the PFUEI data, these spectra were reduced to the $F_\nu$ system.

The original test made use of a $B-V$ color determined by adding up the spectral flux in accordance with the shape of the $B$ and $V$ broad-band indices. Unfortunately, the focus at the ends of the PFUEI spectra is often rather poor, and the 2″ slit introduces problems from atmospheric dispersion. The major effect is the poor focus at the red end which results in a mixing of sky and object when the multislit is $\lesssim 15''$ in length, with the result that fluxes beyond 7000 Å (which includes most of the rest frame $V$ band at $z \approx 0.5$) are not reliable. We have, therefore, adopted a new "color" determination, reliable for both the PFUEI and Reticon spectra, which measures the slope of

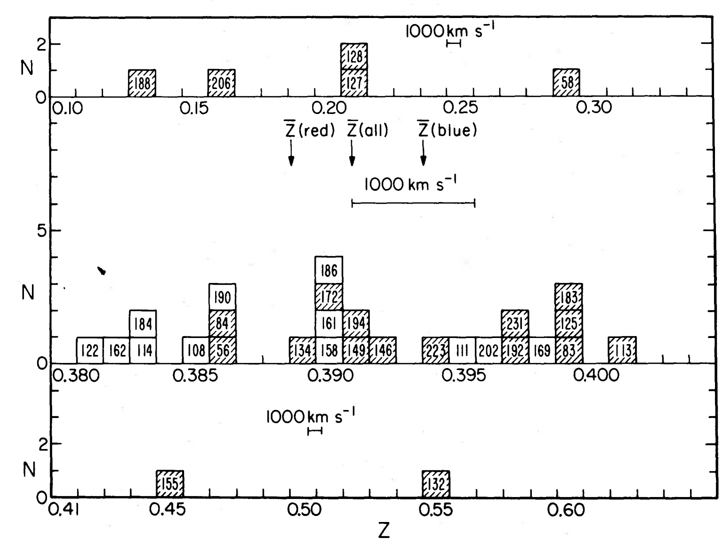


FIG. 2.—The redshift distribution of the galaxies marked in Fig. 1. The seven field galaxies appear to be randomly distributed over a wide redshift range, but the cluster galaxies are confined to $z \approx 0.38$–0.40 (note the different scale of the middle tier). The blue galaxies ($g - r < 1.2$) are shown as shaded boxes; these have a marginally different average redshift compared to the red cluster members of Cl 0024+1654, as shown by the arrows indicating mean redshifts for different samples. There is a suggestion of subclustering in the distribution of redshifts for cluster galaxies, but the present data are also consistent with a single Gaussian distribution with a velocity dispersion of 1310 km s$^{-1}$ in the rest frame.

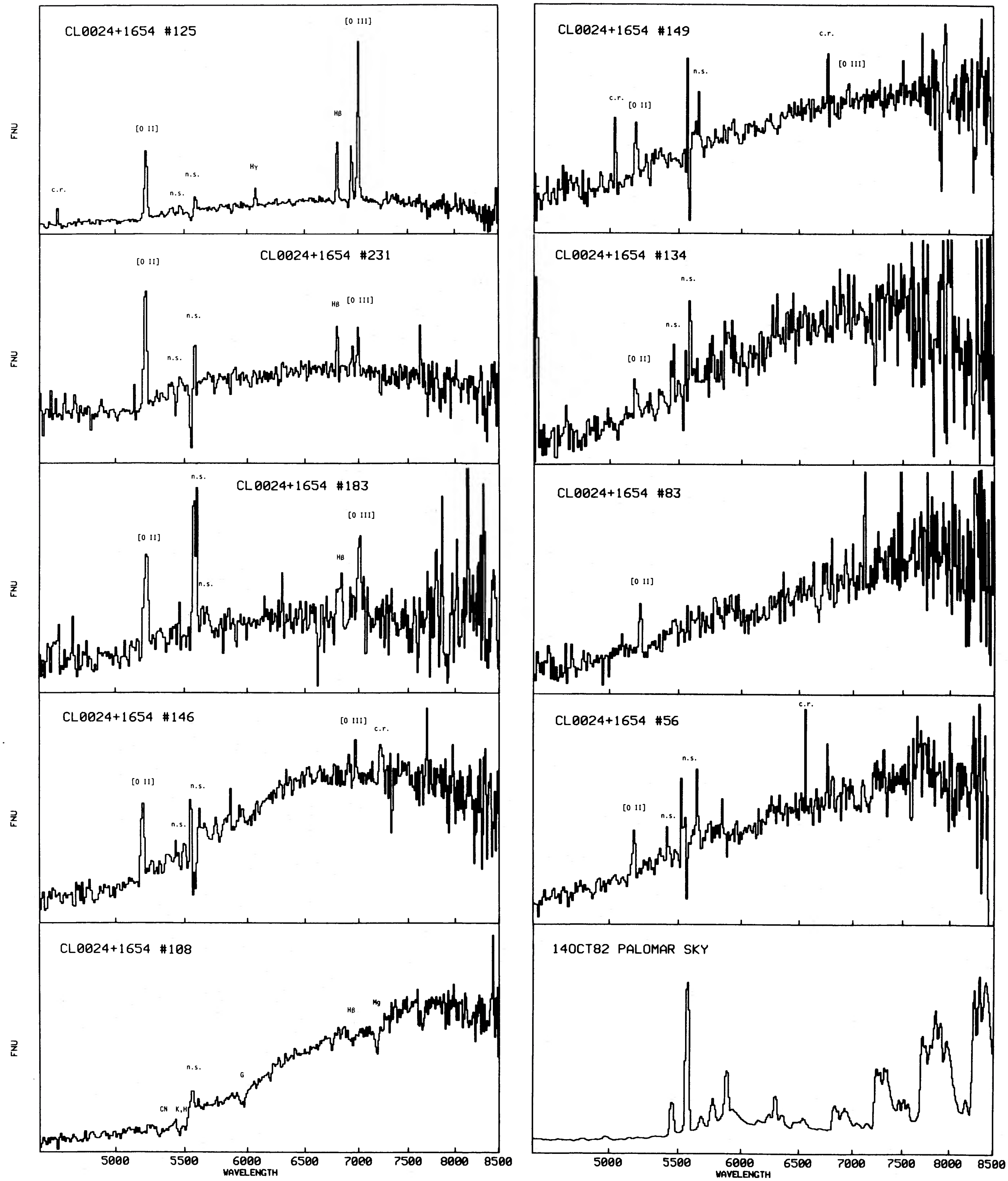


FIG. 3.—The spectra of eight blue members of Cl 0024+1654. Also shown is the night-sky spectrum and the spectrum of a typical red cluster member. The abscissa is a log wavelength scale, and the ordinate is in arbitrary units of flux given as $F_\nu$. Fluxes redward of 7000 Å are unreliable. The [O II] doublet $\lambda$3727 is clearly seen in all of the blue spectra, and [O III] $\lambda\lambda$5007, 4959, and H$\beta$ are sometimes present. The notation "n.s." refers to an artifact of poor subtraction of the night-sky lines; "c.r." indicates a cosmic-ray hit. The spectrum of 125 is typical of Seyfert 2 nuclei, and 183 is also likely to be the spectrum of an active nucleus. The other spectra are consistent with the low-ionization spectra of nearby spiral galaxies.

TABLE 3

[O II] AND CONTINUUM "COLOR" IN NEARBY SPIRALS

| Cluster | Number | Type | $Z$ | E[a] | $C$[b] | Log $W$[c] |
|---|---|---|---|---|---|---|
| A548 .............. | 2 | Sc | 0.041 | C | 1.38 | 1.20 |
| | 73 | Sbc | 0.040 | C | 1.30 | 1.27 |
| | 150 | SBbc | 0.043 | C | 1.95 | 0.43 |
| | 169 | SBb | 0.043 | C | 1.89 | 0.76 |
| | 170 | SBb | 0.042 | C | 1.81 | 0.62 |
| | 190 | Sb | 0.060 | F | 1.43 | 1.08 |
| | 216 | Sb | 0.037 | C | 2.08 | 0.20 |
| | 225 | Sbc | 0.043 | C | 1.94 | <0.20 |
| | 226 | Sbc | 0.039 | C | 1.61 | 0.94 |
| | 307 | Sbc | 0.040 | C | 1.96 | <0.20 |
| A754 .............. | 143 | Sc | 0.018 | F | 1.75 | 1.25 |
| A1139 ............ | 10 | Sc | 0.039 | C | 1.76 | 1.06 |
| A1631 ............ | 5 | S | 0.047 | C | 2.58 | <0.20 |
| | 18 | Sbc | 0.050 | C | 1.93 | 1.09 |
| | 54 | Sb | 0.015 | C | 2.27 | 0.76 |
| | 121 | Sd | 0.011 | C | 1.52 | 1.31 |
| A1644 ............ | 36 | SBc | 0.023 | F | 1.94 | 0.82 |
| | 101 | S | 0.019 | F | 1.65 | 1.33 |
| | 136 | S | 0.044 | C | 1.41 | 1.10 |
| A1736 ............ | 56 | Sbc | 0.036 | C | 2.20 | 0.53 |
| | 166 | SBb | 0.034 | C | 1.80 | 0.46 |
| 0428–53 .......... | 1 | S | 0.004 | F | 1.97 | <0.20 |
| | 62 | Sb | 0.036 | C | 1.94 | 0.52 |
| | 113 | Sc | 0.040 | C | 1.64 | 0.66 |
| 0559–40 .......... | 76 | Sc | 0.048 | C | 1.48 | 0.99 |
| 0608–33 .......... | 46 | SBb | 0.030 | C | 1.72 | 0.75 |
| | 87 | Sbc | 0.030 | C | 1.79 | 0.51 |
| | 119 | Sc | 0.050 | C | 1.58 | 0.86 |
| NGC 157 | | Sc | 0.006 | F | 1.53 | 0.78 |
| NGC 309 | | Sc | 0.019 | F | 1.63 | 0.82 |
| NGC 1087 | | Sc | 0.005 | F | 1.31 | 1.24 |
| NGC 1156 | | Sm | 0.002 | F | 1.31 | 1.49 |

[a] E denotes environment: C denotes member of a cluster; F denotes field galaxy.
[b] $C$: continuum slope from 4100 to 5000Å in the rest frame.
[c] Log $W$: log of equivalent width of [O II] in the rest frame.

the spectral continuum from 4100 to 5000 Å (in the rest frame) using a linear least-squares fit to $F_\nu$ versus wavelength. The value of this slope, $C$, is listed in Table 1 for the PFUEI spectra and Table 3 for the Reticon spectra. Also given in these tables is the equivalent width of [O II], measured for each spectrum by comparing the flux in a 50 Å wide band centered on the doublet with the flux in 40 Å bands at $\pm 50$ Å from the line center. (The wide [O II] band is necessary because of degradation of the focus at the blue end of the PFUEI spectra.) Throughout this paper we will adopt the convention of positive values of the equivalent width for emission lines.

In Figure 4 the equivalent width of [O II] is plotted versus the continuum slope $C$, and, as in Paper I, the relationship is found to be strong for the nearby field and cluster spirals. As discussed in Paper I, this implies a good correlation between the star formation rate "at the present time," i.e., over $\sim 10^{6-7}$ yr, and a longer time average $\sim 10^{8-9}$ yr. The small scatter in the diagram suggests that the star-formation rate in a typical present-epoch spiral does not undergo large variations on time scales of less than $10^8$ yr.

All of the blue members in Cl 0024+1654 and a subset of the red members are also plotted in Figure 4. Some typical error bars for the PFUEI spectra are shown; the errors for the Reticon spectra are a factor of two smaller. Figure 4 clearly shows a relationship between [O II] strength and "color" for the Cl 0024+1654 blue galaxies like that found for the low-redshift spirals. Although this does not prove that the blue galaxies in Cl 0024+1654 are typical spirals (this is a morphological classification that must await higher resolution imaging), the data suggest that the blue colors of these galaxies are due to extended epochs of star formation as in today's spirals. This result is quite different from the conclusion of Paper II that the blue cluster members of the 3C 295 cluster do not have the spectra of typical nearby spirals. Three have the spectra of AGNs, and the other three exhibit stronger Balmer absorption and weaker [O II] emission than is found in low-redshift spirals of their color. In other words, no very blue galaxies were found in the 3C 295 cluster with strong [O II] and weaker H$\beta$ and [O III] emission, as typical of nearby spirals and the blue galaxies of Cl 0024+1654.

Finally, we note from Figure 4 that there is a tendency for the putative spirals of Cl 0024+1654 to have a star formation rate which is higher than average for their color (or, alternatively, a color which is redder than average for their star formation rates) compared to the late-type spirals that make up the low-redshift sample. Although this may only be an artifact of the data or the result of small numbers statistics, it is worth noting that such a shift would be expected for a population of larger bulge, earlier type spirals undergoing more vigorous star formation than is found in such types today.

### ii) *The AGN Frequency*

In Paper II it was suggested that the high fraction of AGN galaxies among the blue population of the 3C 295 cluster might

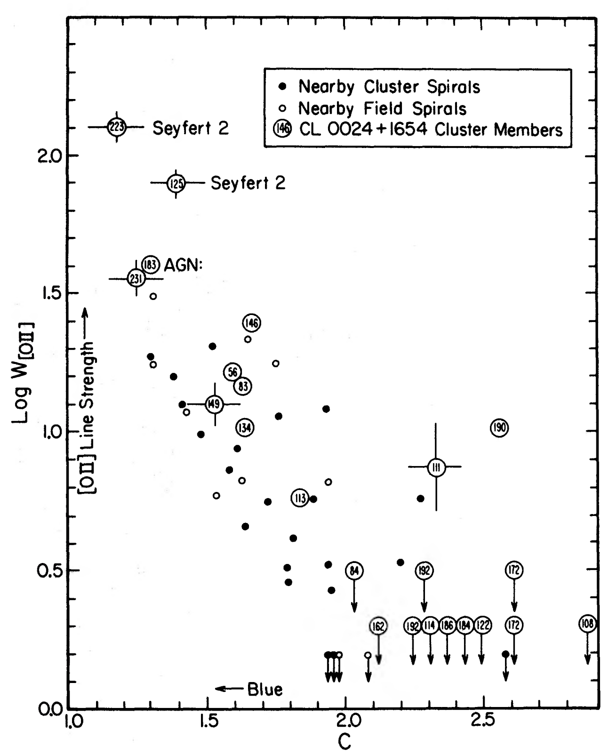


FIG. 4.—The relation between galaxy color and the strength of [O II] emission, introduced in Paper I. Plotted is $C$, the continuum slope determined from the spectra from 4100–5000 Å vs. the log of the equivalent width of [O II] (both determined in the rest frame). The sample includes nearby field and cluster spirals (*small open and closed circles*) and the galaxies in Cl 0024+1654 (*large circles with numbers*). The similarity of the relationship for the nearby and distant samples suggests that the blue cluster members of Cl 0024+1654 are also spirals which experienced extended epochs of star formation. Some typical error bars are shown, as well as upper limits for some of the red galaxies for which [O II] was not detected.

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be evidence for a strong evolution of Seyfert galaxies over the last $5 \times 10^9$ yr. The study of the Cl 0024+1654 supports this speculation, since we have found two certain Seyfert galaxies (125 and 233) and another probable AGN (galaxy 183).

Osterbrock (1984) has noted that the Seyfert fraction is a strong function of absolute magnitude and suggests that the high frequency of AGNs found in the 3C 295 cluster may *not* be different than a nearby sample, since all of the galaxies in the distant sample are very luminous (brighter than $L^*$). Dressler, Thompson, and Shectman (1985) have analyzed the spectra of 1268 galaxies in the fields of 14 rich clusters (Dressler and Shectman 1985) and find that AGNs make up only 1.2% of a nearby cluster sample. The area of the nearby clusters surveyed and the distribution over absolute magnitude of the sample galaxies is similar to the data for the 3C 295 cluster and Cl 0024+1654, and, if anything, the nearby sample is more sensitive in finding AGNs because of higher quality spectra and less dilution from the surrounding galaxy. Dressler *et al.* have adopted the following criteria for classifying spectra as AGN: (1) the rest frame equivalent width $W_{[\mathrm{O\,II}]} > 3$ Å; (2) $W_{\mathrm{H}\beta}$ *or* $W_{[\mathrm{O\,III}]} \approx W_{[\mathrm{O\,II}]}$; and (3) $W_{[\mathrm{O\,III}]} > W_{\mathrm{H}\beta}$. These criteria are not foolproof since a non–AGN may satisfy these conditions; however, no AGN will be excluded by application of these criteria, and experience with low-redshift samples shows that the vast majority of spectra with these characteristics are, in fact, AGNs. Although adding such information as line width would be very desirable, it is not possible at the present time to make the necessary observations at high redshift, so the choice has been made to apply nonoptimal criteria *uniformly* for both nearby and distant samples.

According to the criteria of Dressler *et al.*, galaxies 125, 183, and 223 in Cl 0024+1654, and galaxies 41 (the radio galaxy), 6, 52, and 48 in the 3C 295 cluster are all AGNs. This gives a frequency of over 10% of the galaxies studied. This is greater frequency by an order of magnitude than found in the nearby clusters, but if no more AGNs are found in a deeper search of the 3C 295 and Cl 0024+1654 clusters, the enhancement might be as small as a factor of 3 (i.e., there has been a preference for blue galaxies which may increase the chance of finding an AGN).

It is also interesting to note, as Dressler *et al.* do, that one low-redshift cluster, DC 0428−53, has three AGNs, more than is typical of other low-redshift clusters and as many as have been found in the high-redshift clusters (but not necessarily comparable to the *frequency* of AGNs in high-redshift clusters). Although one or two of these AGNs in DC 0428–53 are so weak that they would have escaped detection in a distant cluster, this result indicates that the high incidence of AGNs could be connected with *individual* cluster evolution in addition to, or instead of, *cosmological* evolution. If such clusters with enhanced activity are rare, they might not have been noticed in nearby samples but could have been preferentially included in distant samples, as in the case of the 3C 295 cluster, to which attention was drawn because of the very luminous radio galaxy.

In summary, the majority of blue galaxies in Cl 0024+1654 have spectra typical of nearby cluster and field spirals, but there are at least two and probably three cases of AGN spectra which adds support to the idea that active nuclei are more common in these distant clusters. We note that Jaffe (1982) has reached a similar conclusion based on an examination of the radio luminosity function in similar, high-redshift clusters.

## IV. FINDING EMISSION-LINE GALAXIES THROUGH NARROW-BAND PHOTOMETRY

There are now more spectra of faint objects in the Cl 0024+1654 field than in any other comparable area in the sky. This is, therefore, an ideal place to test methods of determining cluster membership statistically from photometric rather than spectroscopic data.

Koo (1981) has used four-color photometry to study the population of the distant cluster Cl 0016+16 at $z = 0.54$. From his data he concludes that this rich, concentrated cluster does not have a large population of blue galaxies and therefore demonstrates that the results of BOI are not universal. Figure 5 shows a color-color diagram formed from the $g$, $r$, and $i$ photometry for Cl 0024+1654 (SDG), for 35 galaxies with known redshifts. By denoting cluster members and field galaxies with different symbols. Figure 5 clearly shows a displacement of the field galaxies from the cluster galaxies in the color-color plot. Unfortunately, the field galaxies cannot be unambiguously separated from the cluster sequence as there is considerable overlap. This might be improved with better photometry than is available here, or adding an ultraviolet band as Koo has done, but the principal source of scatter is probably the wide range of galaxy colors at a given redshift, so the method looks unlikely to provide more than a statistical estimate of the ratio of cluster to field galaxies.

More promising is a less general but more sensitive test using a narrow-band magnitude centered on the [O II] doublet. As Figure 4 shows, all of the very blue cluster members in Cl 0024+1654 have fairly strong [O II] ($W_{[\mathrm{O\,II}]} >$ 10 Å). Therefore it is possible to discriminate cluster from field galaxies in clusters of this type by comparing the magnitudes of the blue galaxies in a narrow band centered at redshifted [O II] with a broad-band magnitude at the same wavelength.

On 1983 October 6, CCD frames were obtained of the Cl 0024+1654 field with the PFUEI in its camera mode, using the $g$ filter of Thuan and Gunn (1976) and a filter centered at

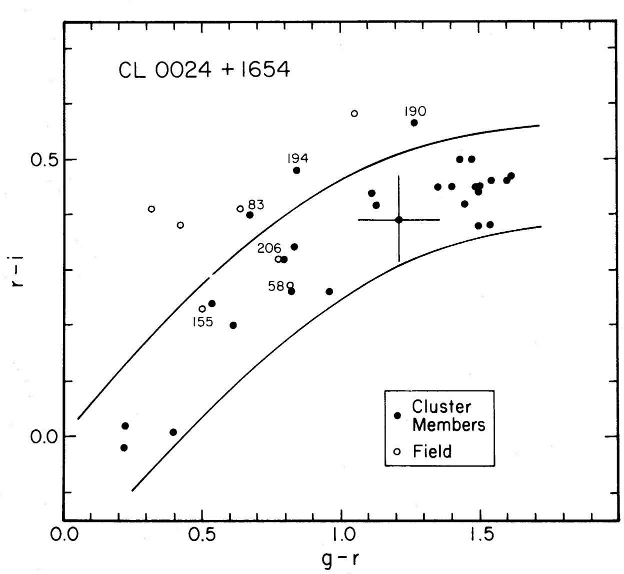


FIG. 5.—A color-color plot of the galaxies for which redshifts have been determined. The diagram shows that although there is a fairly well-defined area occupied by cluster galaxies, this can only be used statistically to eliminate field galaxies, since there is considerable overlap of the two samples.

$\lambda = 5180$ Å with a width of $\sim 100$ Å FWHM. The integration times were 5400 s for the narrow-band filter and 1700 s for the broad-band filter. Conditions were far from ideal as there was moderate cirrus and seeing of 1".8 FWHM. The frames were flattened using standard procedures (see SDG), and $g$ and $m(5180)$ magnitudes were determined from circular apertures with a radius of 2".8. The resulting color $m(5180) - g$ has been arbitrarily normalized to an average value of zero for the brightest cluster galaxies. This color is given as O II $- g$ in Table 1 for the galaxies with redshifts in the Cl 0024+1654 field and will hereafter be referred to as the "[O II] color."

In Figure 6 the equivalent width of [O II] emission from the PFUEI spectrum is plotted versus the [O II] color measured from the direct CCD frames for those galaxies with $g < 21.8$. This diagram shows that, within the errors (dominated by photon statistics for the narrow-band picture), the [O II] imaging has successfully detected all of the galaxies whose spectra show an equivalent width $W > 5$ Å in the rest frame. The dashed line is the predicted relation between the two quantities for a narrow-band filter with an equivalent width of 120 Å. Apparently, an [O II] strength of 20 Å or greater is easily detected with the direct imaging technique. We expect that more favorable observing conditions and a factor of 2 more integration would result in reliable detections down to $W_{[\mathrm{O\,II}]} \approx 10$ Å. Note that all eight of the galaxies for which only upper limits of [O II] emission have been measured from the spectra were null detections in the [O II] color.

Now that the reliability of the [O II] imaging technique has been established, it is interesting to ask, how well would such a technique do in uncovering a population of blue emission-line galaxies at a known redshift? Figure 7 is a plot of the [O II] color versus the broad-band $g - r$ color (from SDG) for all galaxies $g > 21.8$. This is Figure 4, the log $W_{[\mathrm{O\,II}]}$ vs. continuum slope relation, recast with photometric data only. From the results for Figure 4 we predict an increasing negative [O II] color with decreasing (bluer) $g - r$. Considering all the data points of Figure 7, the results are not encouraging, but after separating the cluster members from field galaxies using the redshift determinations, the trend in the cluster galaxies alone is very clear. All six of the blue field galaxies are null detections in [O II] color, as expected, and all of the red galaxies are null detections except galaxy 111, which, from its spectrum, is genuine. Looking at the trend in the diagram, and specifically the distribution of points with $g - r < 1.0$, the diagram confirms that there are emission-line galaxies at the cluster redshift and that the field galaxies or blue cluster galaxies without emission make up a minority of the sample. With hindsight, it appears that such a technique would have yielded the same result as the spectroscopic investigation, for a larger sample of galaxies and with far less expenditure of telescope time.

This approach provides a valuable complement to the low-resolution spectroscopy, but it does not replace it. For example, a photometric analysis of the 3C 295 cluster using this technique alone would have been misleading. Based on the spectroscopy presented in Paper II, it is clear that the galaxies studied so far would have produced a flat [O II] color versus $g - r$ diagram, leading to the probable conclusion that none of the blue galaxies were members. The galaxies with strong

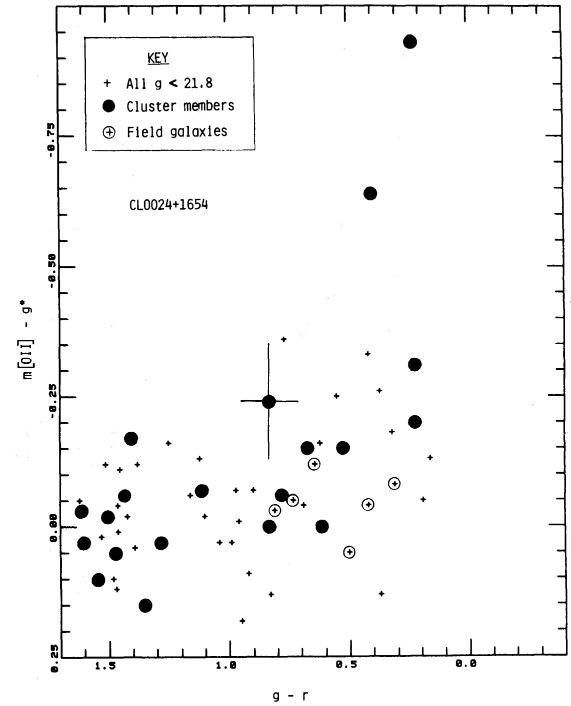


FIG. 7.—The $g - r$ colors of all galaxies brighter than $g = 21.8$ vs. the [O II] color, as defined in § IV. After separating field galaxies (*open circles*) from cluster members (*closed circles*) in those cases where redshifts are known, a trend of stronger [O II] emission with bluer $g - r$ color is seen. This is another version of the relationship shown in Fig. 4 and confirms through photometry what was found spectroscopically: that most of the very blue galaxies in the field have [O II] emission at the cluster redshift.

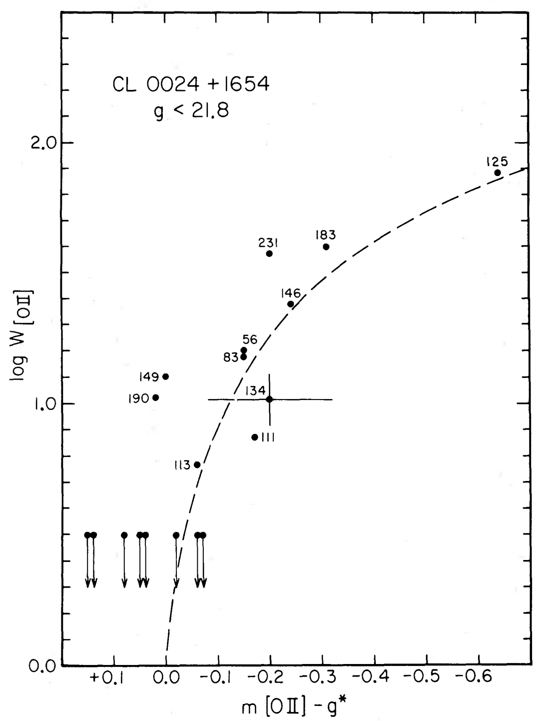


FIG. 6.—A plot of the equivalent width of [O II] emission, measured from *spectra* vs. the [O II] color (see § IV), determined from *CCD direct images* with a narrow-band filter at redshifted [O II] and a surrounding broad-band filter. The dashed line shows the predicted relationship for a narrow-band filter with an equivalent width of 120 Å in the observed frame. $W_{[\mathrm{O\,II}]}$ are given as rest frame values. The scatter of the points from the predicted relationship is consistent with measurement errors, showing that [O II] emission at a known redshift can be measured for an entire field using this technique.

Balmer absorption would not have been noticed, and of the four AGN galaxies, only 3C 295 itself, a red galaxy, would have stood out as an obvious detection (see Fig. 5 of Paper II). Therefore, this procedure is best used as a supplement to spectroscopy, for although a positive correlation in a diagram like Figure 7 is a certain indication of a blue population at the cluster redshift, the 3C 295 case demonstrates that the converse is not necessarily true; a cluster could have a null [O II] versus color test yet still possess a significant blue population.

The real power of this technique is its ability to select objects with strong [O II] emission for spectroscopic follow-up. The AGNs 125 and 183 were easily detected in this relatively short integration, and 232, the galaxy with the largest [O II] equivalent width, was actually found when Figure 7 was first constructed. Spectroscopic follow-up confirmed that this faint, previously undistinguished blue galaxy had a strong Seyfert component. The ability to survey the entire field for AGN candidates is a substantial advantage which will facilitate the study of more distant clusters where spectroscopy is very difficult. This technique promises to be a valuable tool in deciding if AGN evolution has, in fact, been rapid since $z \approx 0.5$. For this purpose, it would be particularly helpful to have similar [O II] images of nearby clusters as well.

## V. INTERPRETATION

Combining the spectroscopic data for Cl 0024+1654 with BOV's result that no nearby concentrated cluster has a blue galaxy fraction larger than 5%, it is clear that the Butcher-Oemler effect has been confirmed to the extent that there are at least two such clusters at moderately high redshift with a blue galaxy fraction larger than 20%. It is not obvious either from our or Butcher and Oemler's work whether the relation of blue fraction versus redshift is a dispersionless one; they maintain in BOV that their data are consistent with a small dispersion. Several results suggest to us that the dispersion is not small. First, there exists at least one cluster, Cl 0016+16 (Koo 1981), which has no significant blue population, at least at the bright end of its luminosity function where there are blue objects in Cl 0024+1654 and 3C 295. Furthermore, the *nature* of the blue objects in Cl 0024+1654 and 3C 295 are very different. Our spectroscopy suggests that 3C 295 has no blue galaxies with ongoing star formation and, without further outbursts, will evolve into a red cluster in about $10^9$ yr, an epoch not very different from that at which Cl 0024+1654 is observed.

Whether there is a real dispersion in the Butcher-Oemler effect is, of course, intimately tied to the question of the *nature* (as opposed to just the *number*) of blue objects in the clusters in which the effect is present. Are the blue objects like blue galaxies today—i.e., late-type, small-bulge spirals, or are they systems which have no analogs among galaxies at the present epoch—for example, large-bulge galaxies with active, star-forming disks?

We know that there is at the present epoch a strong correlation between local galaxy density and Hubble type in the sense that high-density regions are populated preferentially by large-bulge, early-type systems (Dressler 1980). Since the density in a cluster after collapse and virialization is inversely proportional to the square of the collapse time for a system of given mass, this result has the corollary that clusters which collapse early are dominated by large-bulge galaxies. One could therefore make the case that these clusters contain from birth large-bulge systems whose disks were active at these early epochs but which are dormant now. If this is the entire explanation, the blue fraction should not be dispersionless, since there is a large range in cluster collapse times and hence densities and hence early-type fraction. At first glance, the data support this interpretation. Cl 0016+16 has the highest central density of the three clusters; 3C 295, next; and Cl 0024+1654, least. The estimates are 50 for Cl 0016+16 (Koo 1981), 33 for 3C 295 (White, Silk, and Henry 1981), and 27 for Cl 0024+1654 (this paper), all on the scale of and by the prescription of Bahcall (1977) using $H_0 = 50$ and $q_0 = 0$. These numbers are, by nature, uncertain, but the high X-ray luminosity of Cl 0016+16 lends support to the proposition that this cluster has a much higher central density than the others. All three are almost certainly collapsed, virialized objects. These considerations suggest that Cl 0016+16 collapsed much the earliest and would be expected to contain systems which would be already dormant and therefore red at the epoch of observation.

It is common lore that bulge-to-disk ratio is highly correlated with Hubble type, though Sandage (1961) has pointed out a number of glaring exceptions. There is indeed evidence (Meisels and Ostriker 1984) that bulge *luminosity* is a primary determinant of Hubble type. The dominance of massive, tightly bound systems in dense clusters can perhaps be understood in pictures in which galaxies and clusters form from an initial perturbation spectrum with a spectral index near $-1$, as seems to be indicated by the observations (Blumenthal *et al.* 1984; Kaiser 1984). The propensity for mergers (Aarseth and Fall 1980) and variations in tidal torquing with local density (Shaya and Tully 1983; Di Fazio and Vagnetti 1979) might also serve to link the distribution of Hubble type with environment.

Thus a zeroth-order picture emerges which is very simple. Clusters which form very early are dense and are dominated by early-type systems that end their active star-forming phase in a relatively short time. Clusters which form later have intermediate populations that can be seen in their active phases at moderate redshifts, but no clusters which have collapsed by the present epoch are sufficiently tenuous to contain large populations of galaxies that are still blue now. This picture can be tested directly by imaging observations with Space Telescope, which will show, if the model is correct, that the blue galaxies in clusters like Cl 0024+1654 are large bulge systems, the analogs of which are red today.

It is already clear, however, that the real situation must be more complex. The scenario discussed above relies almost entirely on initial conditions to explain the observed effects and ignores the environmental effects on evolution. Studies of the fluxes in Hα (Kennicutt 1983) and H I (e.g., Chamaraux, Balkowski, and Gerard 1980; Giovanelli and Haynes 1985 and references therein) have shown a significant anemia in star formation rate and gas content among some cluster spirals. The conclusion to be drawn from these data is not obvious (see., Bothun, Schommer, and Sullivan 1982, 1983), but it is perhaps safe to say that some sort of environmental influence, either early or late, has altered the evolution of some spirals in relatively dense environments. It would be remarkable indeed if this were not so, since the pressure in the intergalactic gas in the central regions of these clusters is larger than the typical interstellar pressures in systems like the Galaxy, and, if infall is important in sustaining star formation, the supply of gas is probably cut off abruptly at cluster collapse (Larson, Tinsley, and Caldwell 1980). Indeed, if infall is cut off sufficiently early, the disks would not fully form, which might further account for the prevalence of early-type systems in dense clusters (Gunn 1982).

That environment-related effects are at work is also indicated by the presence of the "starburst" galaxies in the 3C 295 cluster. Their spectra can be best explained by the sudden dumping of a large part of the mass of a galaxy into stars with an equally sudden cutoff, as might be occasioned by the passage of a gas-rich system through the shock which separates the collapsed core of the cluster from the cold, still infalling outer regions. Unfortunately, these environmental effects do not, at this point, serve to clarify the picture. They might explain, for example, why some nearby clusters found by BOV have small blue fractions although their *spiral* fractions are several times higher. Alternatively, this apparent decoupling of morphology and color might be no more than a shift toward earlier Hubble-type spirals in these clusters.

It is still difficult to understand how environmental effects would evolve on a cosmic time scale. To the extent that the initial conditions determine population, there is a natural clock, but the environment depends only on the *dynamical* state of the cluster, and it is hard to see why the environment of Cl 0024+1654 0.4 Hubble times ago should be any more hospitable to star-forming galaxies than Virgo is today, nor why if passage through cluster shocks causes starbursts (and perhaps AGNs) there are no bright starburst galaxies and very few Seyfert galaxies seen in today's clusters. The issue of the clock is central to the understanding of the Butcher-Oemler effect, of course. We would like to suggest that the basic picture is as we described above, necessarily modified by complex environmental effects. All that is really necessary for the proposed mechanism to work is that the gas fraction of spiral galaxies be a strongly decreasing function of time, more rapidly in early-type systems than late; the correlation of Hubble type with cluster density takes care of most of the rest. There are no bright starburst galaxies now in clusters because big spirals today have almost no gas. The environment of Cl 0024+1654 at $z = 0.4$ is probably indeed inhospitable to spirals with vigorous star formation but perhaps gas-rich systems are much more difficult to strip than those which have little, as both theoretical (Gisler 1979) and observational (Dressler 1985) studies suggest.

The resolution of the problem almost certainly requires detailed imaging. There are spectroscopic hints already, such as the trend in the color–[O II] relation discussed in this paper, which suggests that the blue galaxies are more bulge dominated than systems of similar star-forming activity today, but the evidence is far from compelling.

## VI. SUMMARY

The rick, concentrated cluster Cl 0024+1654 has a large population of blue galaxies, many of which have spectra like those of low-redshift spiral galaxies. The large number of late-type spirals with robust star formation implied by these spectra is higher than that known for any low-redshift cluster of this type.

Cl 0024+1654 contains at least two AGN galaxies, lending some support to the idea that Seyfert galaxies have undergone significant evolution since $z \approx 0.5$. Imaging a cluster through a narrow-band filter centered at redshifted [O II] has proved a successful way to find candidate AGNs and star-forming spirals over the entire field, providing a significant gain in efficiency.

A model that includes a predisposition for earlier Hubble types in dense clusters can account for many of the available data. Further modification of galaxy evolution through later environmental influence is also likely, but its effect is, at this time, unclear. As pointed out by Gunn (1980), these early and late processes may be intimately connected, as in the case of infall, although other types of later influence, such as interactions between galaxies, may be quite distinct from the formation process. These can be most directly identified by a comparison between field and cluster galaxies at high redshift.

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