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SPECTROSCOPY OF GALAXIES IN DISTANT CLUSTERS. II. THE POPULATION OF THE 3C 295 CLUSTER

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ABSTRACT

We present 20 new spectra of objects in the field of the cluster of galaxies 3C 295 obtained with a new multislit technique. Together with our previous data for this cluster, we now have good-quality spectra of 26 objects in the field. Redshifts have been determined for all but three of these objects.

We find that the field is heavily contaminated by a foreground cluster of galaxies. Less than half of the blue galaxies cataloged by Butcher and Oemler and studied by us are actually cluster members. Therefore, in a strict sense, the *Butcher-Oemler* effect (an excessively large percentage of blue galaxies when compared to similar present-epoch clusters) is *not confirmed in 3C 295*. That is, the *color distribution* in the cluster is *not unusual* when compared with nearby clusters of similar morphological type. On the other hand, the six blue objects that *are* members of 3C 295 are all very unusual for present-day clusters, including three galaxies with *active nuclei* and three galaxies which have evidence for *large bursts of star formation.*

Our sample now includes at least five objects in this field that have spectra typical of Seyfert galaxies, one in the foreground at $z = 0.30$, three in the 3C 295 cluster, including a broad-lined Seyfert 1, and one in the background at $z = 0.57$. These data support our previous speculation that these galaxies with active nuclei may be much more prevalent at high redshift, which, in turn, suggests a strong evolution of active galactic nuclei in the last 5×10^9 years.

We also find three galaxies only moderately bluer than elliptical galaxies ($B - V_0 \approx 0.74$) whose spectra are dominated by strong Balmer absorption lines. This color is typical of Sb spirals in the present epoch (and these are the normal constituents at this color of present-day clusters), but the integrated spectrum of an Sb spiral is completely imcompatible with the spectra of the three objects in 3C 295. Rather, these spectra are consistent with an old population mixed with an equal blue luminosity of A stars, which indicates a large burst of star formation 10^9 years before the light left the galaxy. Luminous galaxies with such bursts of star formation are not unprecedented in present-epoch clusters, but they are rare, so the data again suggest that a strong evolution of this type of activity may have occurred over the last 5×10^9 years.

We have yet to find a galaxy in this cluster whose spectrum is typical of a spiral. Either there are few spirals in the population or the activity previously described is taking place in otherwise normal spirals and is masking the normal spectra.

Subject headings: galaxies: clusters of — galaxies: nuclei — galaxies: redshifts — galaxies: stellar content — stars: formation

I. INTRODUCTION

In a previous paper (Dressler and Gunn 1982, hereafter Paper I), we presented low-resolution spectroscopy of 17 galaxies in the two clusters in which Butcher and Oemler (1978, hereafter BO) originally reported a large fractional population of blue objects. We showed that the four red galaxies we observed in each cluster were very similar to present-epoch ellipticals but that the nine blue galaxies were not typical of present-day spiral galaxies, as BO suggested. Specifically, we were able to obtain redshifts of five of these blue objects, and found that two of these in the 3C 295 field are foreground galaxies at $z = 0.30$ and $z = 0.13$, and that one in 3C 295 and two in Cl0024+1654 are cluster members. Surprisingly, two of these three have spectra typical of the active galactic nuclei (hereafter AGN) of Seyfert 2 galaxies, despite the fact that these objects are very rare in clusters today. We tentatively concluded that if these occurrences are representative, this indicates a strong evolution of Seyfert galaxies like that found for quasars.

The spectra of four very blue objects in the 3C 295 field showed no recognizable features; nevertheless, we were able to rule out the possibility that they are normal spiral galaxies in the cluster by comparing their [O II] emission and B − V colors to a fairly tight relation of these quantities for a sample of nearby cluster spirals. This left two of the central questions unanswered: Is there an excess of blue galaxies in these fields that are, in fact, cluster members; and if they are not spirals, what kind of galaxies are they, i.e., why are they blue?

In this paper we present 20 additional spectra in the 3C 295 field that were obtained using a multiaperture technique. Combined with our previous data for this field, we now have good spectra of 26 objects and redshifts for 23 of these. From these data we conclude that over half of the blue galaxies cataloged by BO in this cluster are foreground or background objects; thus the color distribution in this cluster is not markedly different from nearby clusters of similar morphological type. On the other hand, the spectra of these blue objects that are cluster members are not the spectra of the normal spirals that make up the blue distribution of nearby clusters. Rather, the spectra are indicative of galaxies that are rare in present-day clusters—viz., those with active galactic nuclei and those which have had large bursts of star formation. Thus, if these data are representative, they indicate a strong evolution for these types of systems over the last 5×10^9 years.

The remaining sections of the paper are organized as follows. In § II we discuss the acquisition of the data using a multislit technique and the PFUEI Spectrograph/Camera. In § III we give an inventory of the population of the 3C 295 field by combining the data from this study with those of Paper I. In §§ IV and V we discuss the implications of our data for galaxy evolution.

II. DATA ACQUISITION AND REDUCTION

The new spectra of galaxies in the 3C 295 field presented in this paper were obtained on 1982 April 23, 24, and 25 with the PFUEI (see Paper I) at the prime focus of the 5 m Hale telescope on Palomar Mountain. The configuration used was like that for the Cl0024+1654 data of Paper I, a 400-line transmission grating and a 800 × 800 Texas Instruments CCD with a readout noise of ~7 electrons per pixel.

Previously we used a 2″ × 150″ slit positioned to cross two or three objects. For this and subsequent runs, we have developed a multislit capability similar to that used with the Cryogenic Camera at KPNO. Our technique involves making a photographic mask which is opaque except for 5–10 slits 2″ wide that are staggered to correspond to the positions of objects in the field. The masks were produced by laying a sheet of frosted acetate over an isophotal map of the cluster covering 30 square arcminutes made from a PFUEI direct frame. Images of the slits were marked by opaque tape, and the three masks thus produced were reduced onto Kodalith Ortho Type 3 film at the Mount Wilson and Las Campanas Observatories Photolab to the proper scale of 11″.90 mm^{-1} of the 5 m prime focus with the Wynn corrector. A metal insert was fabricated to hold the masks at the PFUEI focal plane.

Observing procedures were straightforward, with a majority of the setup time going to achieving the proper position angle of the slit assembly which, because of various errors accumulated along the way, were rotated approximately 1°–2°. Since the slits generally cover a rectangular area of 1′ × 4′ (we are restricted to a 1′ wide swath by the optics of the PFUEI), it is essential to set the position to better than 1/2 degree. This was accomplished by taking a picture of the field and a separate picture of the slits in the PFUEI direct mode, then measuring the pixel positions of the objects and the centers of the slits on opposite ends of the masks and rotating the instrument mounting base accordingly. Finally, a star was found in the offset guider, and the telescope and/or instrument was moved in order to translate the group of objects into their slits. The entire procedure takes between 30 minutes to an hour; therefore we chose to take only one field per night to minimize dead time, and to expose for approximately 3–5 hours in two or three exposures. The observations also included a flux standard on each night which was trailed at a rate of 4″ s^{-1} across one of the slits. The particulars of the exposures are given in Table 1.

Reduction of these data was in most respects the same as had been done previously for long-slit data as described in Paper I. The reduction routines used were those written by Boroson for the Astronomy VAX-780 at Caltech. We encountered no significant difficulties in sky subtraction in spite of the fact that the slit images, since they are copies of tape, are imprecise and have variations in width (~5%), straightness, and tilt. Sky subtraction was only marginally worse than for the more accurate metal slit used previously.

Since the flat fields were taken through the multislit assembly, the critical removal of pixel-to-pixel variations and interference fringes was no different than for a single

TABLE 1

NEW 3C 295 DATA

BO No.	Date Observed	Exposure Time (s)
6	1982 Apr 23	2 × 8000
15	1982 Apr 23	2 × 8000
19	1982 Apr 23	2 × 8000
29	1982 Apr 23	2 × 8000
40	1982 Apr 23	2 × 8000
50	1982 Apr 23	2 × 8000
60	1982 Apr 23	2 × 8000
71	1982 Apr 23	2 × 8000
75	1982 Apr 23	2 × 8000
86	1982 Apr 23	2 × 8000
12	1982 Apr 24	3 × 6000
48	1982 Apr 24	3 × 6000
61	1982 Apr 24	3 × 6000
80	1982 Apr 24	3 × 6000
81	1982 Apr 24	3 × 6000
1	1982 Apr 25	1 × 9000
14	1982 Apr 25	1 × 9000
19	1982 Apr 25	1 × 9000
26	1982 Apr 25	1 × 9000
33	1982 Apr 25	1 × 9000
45	1982 Apr 25	1 × 9000
48	1982 Apr 25	1 × 9000

slit. Helium-neon comparison arcs were also taken through the multislits. Each spectrum, of course, has a different function of wavelength with pixel number because of the staggering of the slits. In order to make certain that the important blue end of the spectrum was always covered, the grating was set blueward of where it was for the Cl0024+1654 data. This meant that some of the spectra did not reach beyond 8500 Å. Todd Boroson, who played a vital role in the data reduction, made one necessary modification to the way the reduction program produces absolute fluxes by means of a standard star. Previously the procedure was to use the standard star exposure to determine and thus correct the combined effects of instrumental sensitivity with wavelength and vignetting. Since we did not take a standard star exposure in each of the slits, this technique was inapplicable. Instead, we used the flat field to correct for the vignetting (we divided each spectrum by its flat field scaled down to numbers of order 1) and then determined the absolute calibration by repeating the procedure on the standard star. This gave the spectral sensitivity of the instrument as a function of wavelength (rather than as a function of pixel number, as had been done previously) which was then applied to each spectrum. The method seems to have been generally successful, but repeat observations of numbers 19 and 48 indicate an uncertainty in the $B-V$ rest frame colors of order 0.10 mag. We do not know if this error in the color is a result of the multislit technique or simply the uncertainty in colors that arises from doing spectrophotometry through slits.

III. THE POPULATION OF THE 3C 295 FIELD

Combined with the 3C 295 data from Paper I, we now have signal-to-noise ratios (S/N) $\gtrsim 10$ spectra for 26 objects in the 3C 295 field which are identified in Figure 1. In all but three cases, this is sufficient to allow an unambiguous determination of the redshift. A simple inventory of these redshifts, detailed in Table 2, reveals the following. Of the six objects that BO determined to be red ($V-r \sim 1.50$ corresponding to $B-V \sim 0.95$ in the rest frame at $z=0.46$) that we have studied, numbers 1, 41, 45, 46, 49, and 61 are all cluster members with spectra typical of elliptical galaxies. Of the 20 remaining "blue" objects ($V-r \lesssim 1.3$), six are in the 3C 295 cluster, six are foreground galaxies, one is a foreground star, two are background galaxies, and three are as yet unidentified.

The foreground contamination is significant, as was suggested by Mathieu and Spinrad (1981). Six galaxies, numbers 15, 40, 50, 71, 75, and G2, belong to a foreground cluster at $z=0.28$–0.30 (although the redshift of number 50 is different enough that it may be unassociated with this group). Because of the K-correction, red galaxies in this cluster appear moderately blue if assumed to be at the redshift of 3C 295, and blue galaxies are mistaken to be extremely blue members of 3C 295. Conversely, this foreground cluster

TABLE 2

DATA FOR GALAXIES IN THE FIELD OF 3C 295

No.	BO m_R	BO $V-R$	z	Comments
1	20.54	1.33	0.474	Red cluster member; E-like
6	19.62	0.69	0.472	Very blue cluster member; Seyfert 1
7	21.47	0.31	0.131	Foreground; high-excitation emission
12	21.55	0.69	...	Continuum break ~5200 Å
14	19.54	1.13	0.000	Foreground star
15	20.69	0.58	0.274	Foreground spiral; metal absorption
19	21.18	1.12	0.471	Blue cluster member; strong Balmer absorption
26	19.98	1.19	0.450	Blue cluster member; strong Balmer absorption
29	20.90	1.11	0.572	Background; very blue; high excitation emission
33	20.81	1.19	0.470	Blue cluster member; moderate Balmer absorption
40	21.63	0.63	0.282	Foreground spiral (?); emission
41	18.16	1.52	0.461	Red cluster member; 3C 295 radio galaxy
45	20.93	1.54	0.459	Red cluster member; E-like
46	20.15	1.75	0.451	Red cluster member; E-like
48	20.24	1.06	0.451	Blue cluster member; metal absorption; [O III]; AGN?
49	19.96	1.58	0.449	Red cluster member; E-like
50	21.59	0.78	0.260	Foreground; high-excitation emission
52	20.17	0.79	0.467	Blue cluster member; high-excitation emission;
60	21.83	0.96	0.634	Seyfert 2?
61	19.73	1.36	0.449	Background; very blue; high-excitation emission?
71	20.65	0.63	0.284	Red cluster member; E-like
75	21.80	0.57	0.285	Foreground spiral (?); low-excitation emission
80	21.86	0.76	...	Foreground spiral (?); weak emission
81	21.83	0.14	...	Continuum break ~5200 Å
86	21.10	0.75	0.331	Flat spectrum; featureless
G2	not in BO		0.285	Foreground spiral; low-excitation emission
				Foreground; moderate Balmer absorption

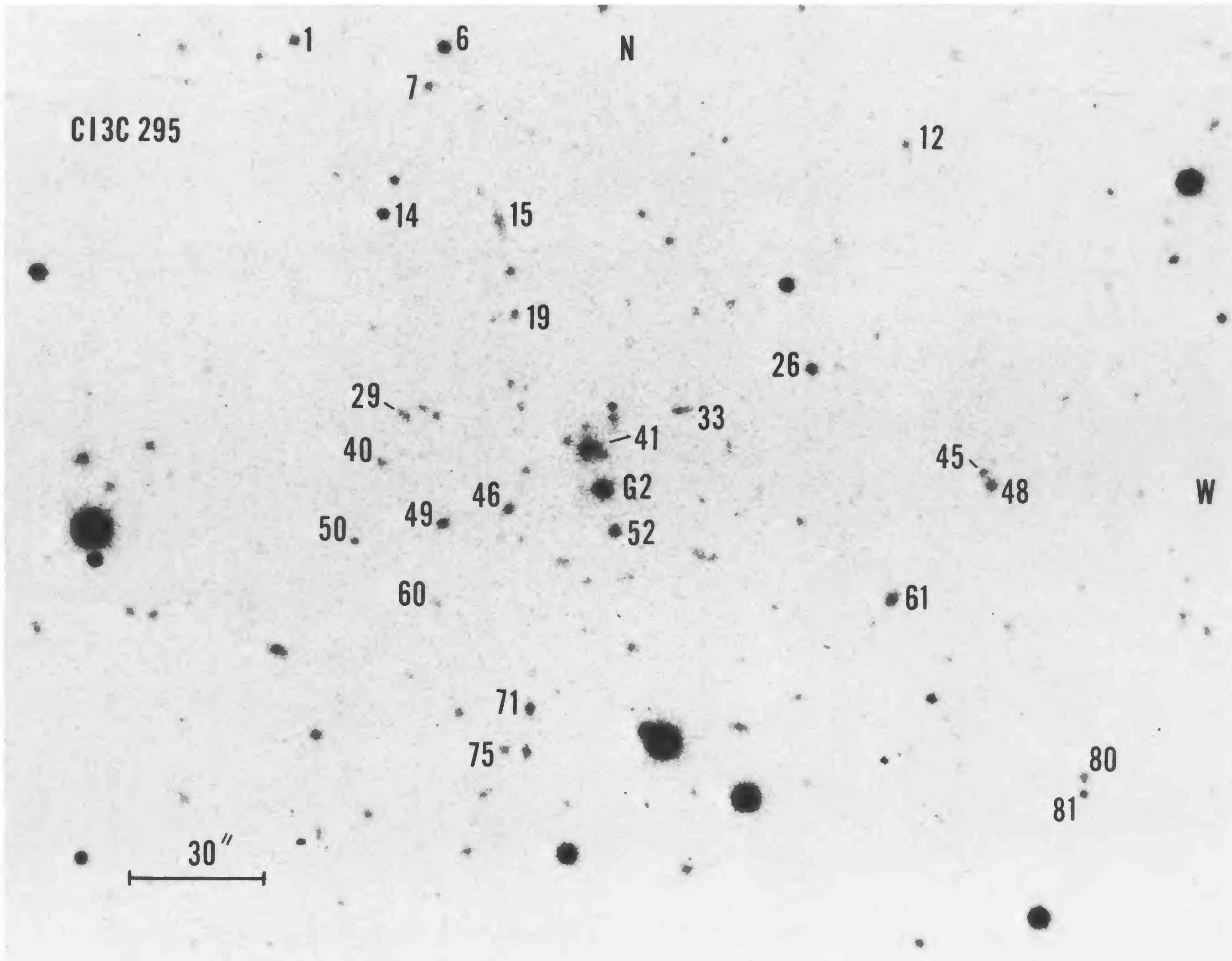

FIG. 1.—The field of 3C 295 from a limiting IIIa-J 4 m Mayall plate taken by H. Spinrad. All objects for which good spectra have been obtained (except for No. 86, off lower left center) are marked by their BO numbers.

should not be able to contaminate the red population of 3C 295, and this is borne out observationally. There are also two other foreground galaxies, number 86 at $z = 0.331$ and number 7 at $z = 0.13$, and a star misclassified as a galaxy (BO number 14). Most of the foreground galaxies have emission-line spectra typical of spiral galaxies ([O II] > Hβ > [O III]), but number 50 has the high-excitation spectrum of an AGN such as a Seyfert 2. BO number 40 is intermediate with a spectrum of either an unusually active spiral or an AGN. Examples of the spectra of these foreground objects are shown in Figure 2.

The field contains two background galaxies, number 29 at $z = 0.57$ and number 60 at $z = 0.63$, which are shown in Figure 3. The spectrum of number 29 is that of a high-excitation AGN like a Seyfert 2. This may also be the case for number 60, which has [O II] and [O III] emission but in which the [O III] and Hβ lines fall in a region of intense night-sky emission so it is difficult to be certain of the excitation in this object.

Three of the spectra show no obvious features, and thus no redshift was determined. This includes two objects, numbers 80 and 81, previously studied (Paper I) with the same lack of success. Though we have better spectra than before, and the continuum shape and colors agree well with those previously determined, we still see neither absorption nor emission lines. By the test we used in Paper I of comparing the [O II] strength and $(B-V)_0$ color to those of nearby spiral galaxies, we can say with certainty that these objects are not normal spirals at $z = 0.46$. We point out that this test was successful in predicting that numbers 71 and 75 were not cluster spirals; they turn out to be foreground galaxies, which seems likely for numbers 80 and 81 as well. These spectra are shown in Figure 4. BO number 12 is sufficiently faint that we lack sufficient counts in the spectra to be able to determine its redshift. Failing to discern features in this spectrum is probably due to the poor S/N ratio. This is not the case in numbers 80 or 81 where we expect, based on the similar S/N ratio of other spectra, to see lines.

In summary, only six of the blue objects, numbers 6, 19, 26, 33, 48, and 52, are bona fide cluster members with redshifts $z = 0.45$–0.47. (The coordinates of these six objects are given in Table 3.) Eleven out of the 20 of the blue objects we studied from the BO sample are

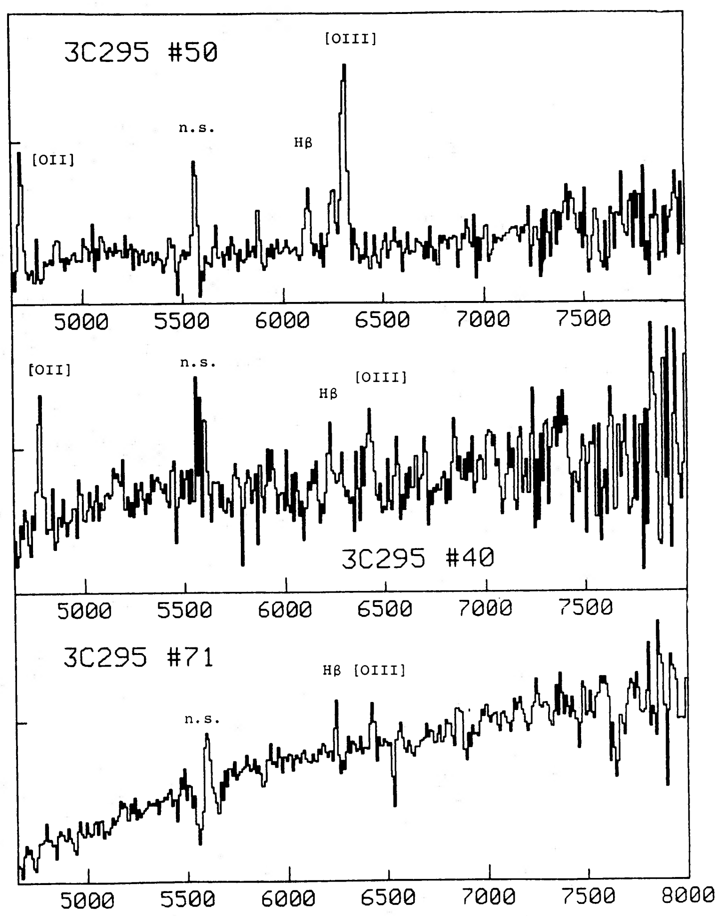

FIG. 2.—Spectra of three of the foreground cluster members. BO No. 50 has a high-excitation spectra like that of an AGN or H II galaxy. Nos. 40 and 71 have lower excitation spectra. No. 71 has a spectrum typical of spirals (see Fig. 6). KEY: n.s. = night sky artifact.

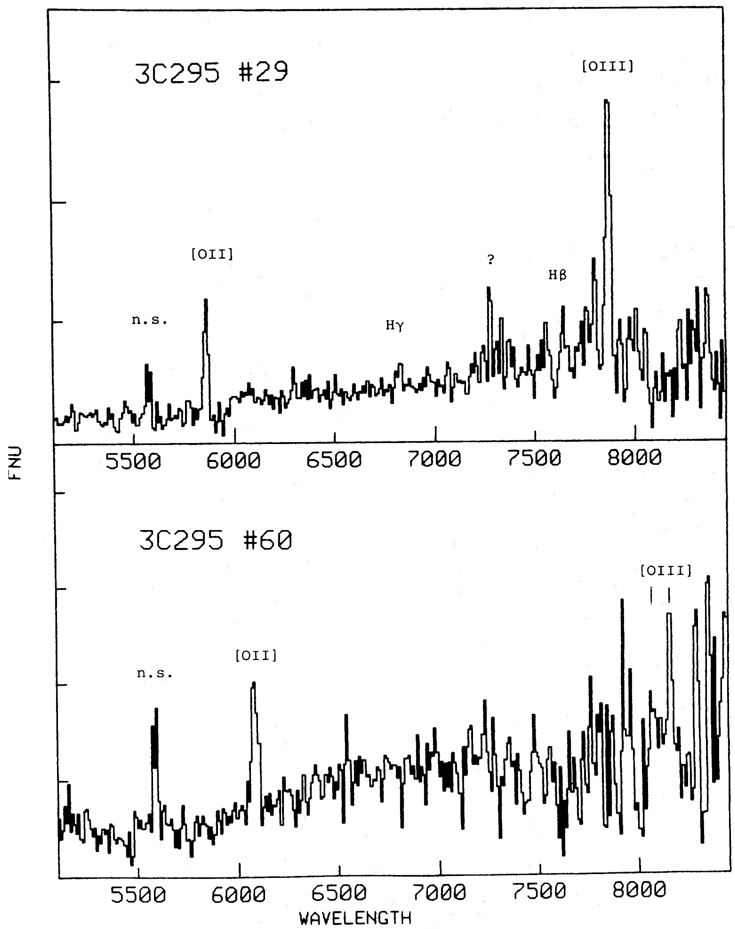

FIG. 3.—Spectra of two background galaxies in the 3C 295 field. Both are extremely blue. No. 29 has a high-excitation spectra like an AGN or H II galaxy. The excitation of No. 60 is uncertain. KEY: n.s. = night sky artifact.

not members of the cluster, and three others are uncertain members at best. According to Table 3 of BO, about 40% of the objects in the 3C 295 field are bluer than $V-r = 1.30$. Since we now know that most of these blue objects are not in the cluster (and all of the red objects studied to this point *are* in the cluster), this means that the true population of blue galaxies is only ~20% of the cluster population. This is not particularly unusual for nearby clusters of similar type, so one can say that, for the cluster 3C 295 at least, there is no Butcher-Oemler effect in the original sense, i.e., no excess of blue galaxies when compared to present-epoch clusters.

TABLE 3

POSITIONS OF THE "ACTIVE" GALAXIES IN 3C 295

No.	ΔR.A. (s)	ΔDecl.(″)[a]	R.A.[b]	Decl.[b]
41 (CD).....	0.00	0.0	$14^h09^m33^s.3$	+52°26′12″
6............	+2.95	+82.0	14 09 36.3	+52 27 34
19............	+1.52	+27.2	14 09 34.8	+52 26 39
26............	−4.94	+14.8	14 09 28.4	+52 26 27
33............	−2.02	+7.3	14 09 31.3	+52 26 19
48............	−8.76	−9.2	14 09 24.5	+52 26 12
52............	−0.53	−16.7	14 09 32.8	+52 25 55

[a] Offsets from 3C 295; good to of order ±1″.
[b] R.A. and decl. based on Minkowski's 1960 optical position.

Thus, based on photometric information alone, and if there had been no significant contamination of the 3C 295 field by noncluster members, one might have concluded that the population of this cluster was not very different from nearby clusters. The color distribution is typical of a normal range of Hubble types with a small percentage of blue galaxies, probably Sb–Sc spirals. In the next sections we show how mistaken this conclusion would have been and how the additional information contained in low-resolution spectroscopy has led us to conclude that this small percentage of blue objects is anything but ordinary.

IV. EMISSION-LINE GALAXIES

There are many high-excitation (O III/H$\beta \gtrsim 3$) spectra in our sample, including three of the six blue cluster members, at least one of the two background galaxies, and two of the foreground objects. We have attempted to classify these objects on the scheme of Baldwin,

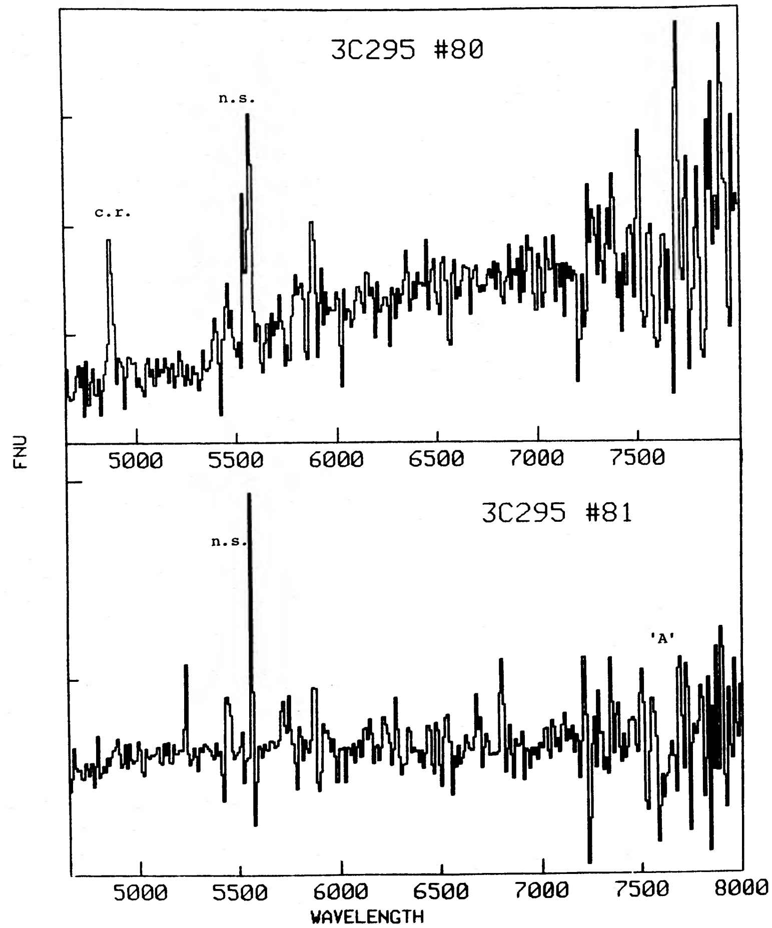

FIG. 4.—Spectra of two as yet unidentified objects in the 3C 295 field. No. 80 appears to have a break at 5200–5300 Å. No. 81 is featureless. KEY: n.s. = night sky; c.r. = cosmic ray; A = atmospheric A band.

Phillips, and Terlevich (1981, hereafter BPT), though the quality of the spectra of these very faint objects makes the task a little difficult. In none of the spectra is [O III] λ4363 or [O II] λ6300 seen, and the resolution is such that the [N II] lines cannot be separated from Hα; thus the only tool we have is the 5007/4861, 3727/5007 index.

The three cluster members fortuitously turn out to be the easiest objects to classify. There is, first, no doubt whatever as to the nature of number 6, since even at our low resolution the hydrogen lines are very broad, with a velocity FWHM of 4000 km s^{-1}. It is a classical Seyfert 1, and in fact is the only X-ray source detected in a long *Einstein* exposure on the field aside from 3C 295 itself (Henry *et al.* 1983). (The nondetection of X-ray flux from the other blue cluster members is, however, consistent with the L_x/L_{opt} of 3C 295 number 6, since the others are optically fainter than number 6.) The hydrogen lines are not seen at all in numbers 48 and 52, and the limits on 5007/Hβ place the objects in the power-law photoionization region in the BPT diagram. They are otherwise like Seyfert 2's, and that is almost certainly what they are. It is to be noted that number 48 has a continuous spectrum which, redward of about 3500 Å in the rest frame, is completely typical of an elliptical galaxy, and so must be a quite early-type system. The continua in numbers 52 and 6 are probably power laws.

Of the two background objects, number 29 is almost certainly a Seyfert 2. It appears to be double with a separation of ~2″, but our spectrum comes from the combined system. Object 60 also has an interesting spectrum. The [O II] lines are stronger than the [O III], but it is not clear that one sees the hydrogen lines at all; certainly 5007/4861 is 2 or greater. Thus the galaxy falls in the "shock-heated" region in the BPT diagram. The object is quite clearly extended and has low surface brightness. Unfortunately it is sufficiently faint that obtaining a much better spectrum will be difficult with present equipment.

Three of the four foreground objects fall in the "normal H II region" area in the BPT diagram. Galaxy 71 is doubtless a normal spiral, while the fainter and bluer galaxy 40 has a spectrum like Magellanic irregulars but is more luminous. Galaxy 50 has a rather higher-excitation spectrum and may be a Seyfert 2. Galaxy 7, at $z = 0.13$, has visible hydrogen lines in a quite good spectrum (Paper I). Its redshift is sufficiently small that we do not see λ3727, but the 5007/4861 ratio (~ 4) alone places it in the Seyfert region in the BPT diagram.

The Seyfert population of the cluster in our sample comprises half the blue galaxies we have found to be cluster members, or, if one is allowed to do statistics on three objects, about *10%* of the cluster membership. This is to be compared with Coma, say, where of more than 200 galaxies with spectra, there are none, and the Dressler survey in Abell clusters, where of ~ 1200 spectra there are ~ 10. Perseus, for example, has NGC 1275 (and the 3C 295 cluster has 3C 295), but it is the brightest galaxy and a strong radio source; the cluster has no other Seyferts. The temptation to conclude that the Seyfert phenomenon is very much more prevalent in this cluster than in clusters at the present epoch is strong, as is the temptation to make general statements when one considers that, of two blue objects in the cluster 0024+16 we have looked at (Paper I), one of them is a Seyfert 2. We will show in the next section that the other three blue cluster members are as strange, and so the study of what has turned out to be a quite ordinary fraction of blue cluster members has proven very rewarding.

V. GALAXIES WITH BURSTS OF STAR FORMATION?

a) Observations and Models

Balmer absorption lines are the most conspicuous features in the spectra of three of the six blue cluster members, numbers 19, 26, and 33, despite the fact that they are only moderately blue, $B-V \sim 0.7$ (see Fig. 5). Because of the similarity of the three spectra and the poor S/N ratio of each individually, we have summed them together after rebinning to rest wavelengths. This spectrum, hereafter referred to as spectrum S, is shown in Figure 6. Except for small differences in our color measurements ($\Delta B-V \sim 0.1$) which may or may not be real[1] (see § II), the spectrum of each of these three galaxies is consistent with spectrum S. We will assume, therefore, in the following discussion that spectrum S is representative of each galaxy, though some differences will undoubtedly be found when better data are available.

Spectrum S has Balmer absorption lines with an average hydrogen line strength $\text{H} \equiv \overline{\text{H}\beta + \text{H}\gamma + \text{H}\delta} =$ 7–8 Å and a $B-V \approx 0.74$. An F5 V star has about the right Balmer line strength but a bluer color of $B-V \approx 0.45$. A $B-V$ color of 0.74 is typical of late G dwarfs, but these have Balmer absorption lines of only a few angstroms equivalent width. A combination of *two* stellar populations, on the other hand, consisting of early A dwarfs and K0 giants *is* able to reproduce not only the color and Balmer line strength of spectrum S, but the continuum shape as well. We make this comparison in Figure 6 where we show Reticon spectrum of K giants, in this case a typical elliptical galaxy, and a spectrum which is the sum of A1 V and A5 V stars. Adding these together with equal flux at 4400Å produces the composite spectrum shown in Figure 6 just below spectrum S (*top right panel*). These two are in excellent agreement over the entire range of our data from 3400 to 5400 Å including the continuum shape and the depths of the features. The only disagreement is in the line profiles, and this is simply due to the lower spectral resolution of the PFUEI data.

Any stellar system in which there has been significant star formation in the last 10^9 years will contain A dwarfs and K giants. Our first comparison, therefore, should be with present-epoch spirals, since they are the most common type of galaxy with continuing star formation. In Figure 6 we show composite spectra of spirals spanning the color range $\langle B-V \rangle = 0.54$–0.84 from the data of Paper I. It is clear that none of these match spectrum S. The spirals with the proper $B-V$ color have H = 2–3 Å; and even the bluest spirals, whose spectra are consistent with constant star formation rates (SFR) (Searle, Sargent, and Bagnuolo 1973, hereafter SSB), fall short in hydrogen line strength. The interpretation is straightforward. There are too few B, A, and F stars in these galaxies at the present time compared to the accumulated "old" giant population to give H = 7–8 Å as in spectrum S. Furthermore, the spirals also have ongoing star formation, as evidenced by the higher UV flux and [O II] emission seen in Figure 6, which is absent in spectrum S. Present-day spirals, therefore, are an unacceptable model for our 3C 295 data.

A better match to the color and Balmer line strength of spectrum S is found in the data of Searle and Smith (1983) for clusters in the Magellanic Clouds. Their type V clusters, thought to be coeval generations of stars 2–3 × 10^9 years old, have sufficiently strong Balmer lines and colors which are a bit bluer than spectrum S, $B-V \sim 0.6$–0.7. Most of the light comes from the turnoff A–F stars (due to their large numbers) and K giants (due to their high luminosities), so it is not surprising that this is close to our original A star plus elliptical model of Figure 6. Thus, spectrum S could be interpreted as a coeval burst of star formation some 2–3 × 10^9 years old added to a negligible older generation of K giants. A more reasonable model is the addition of a coeval population of about 1 × 10^9 year age, which has an earlier turnoff with stronger Balmer lines, to an older population of K giants, i.e., the pre-existing galaxy.

To quantify these comparisons, we have followed the procedure used by SSB, who built evolving galaxy models assuming exponentially declining rates of star formation. For our models we used predictions of luminosity, color, and Balmer line strengths for aging, coeval populations produced by Manduca (1983). Manduca's models are built with synthetic stellar spectra, updated Yale evolutionary tracks, and Salpeter luminosity functions, and they successfully reproduce the Searle and Smith cluster data.

By including separate bulge and disk populations and calculating the strengths of the Balmer lines, our models have a somewhat broader predictive ability than those of

[1] The BO $(V-r)$ colors of numbers 19, 26, and 33 are 1.12, 1.19, and 1.19, respectively, which are identical within their errors.

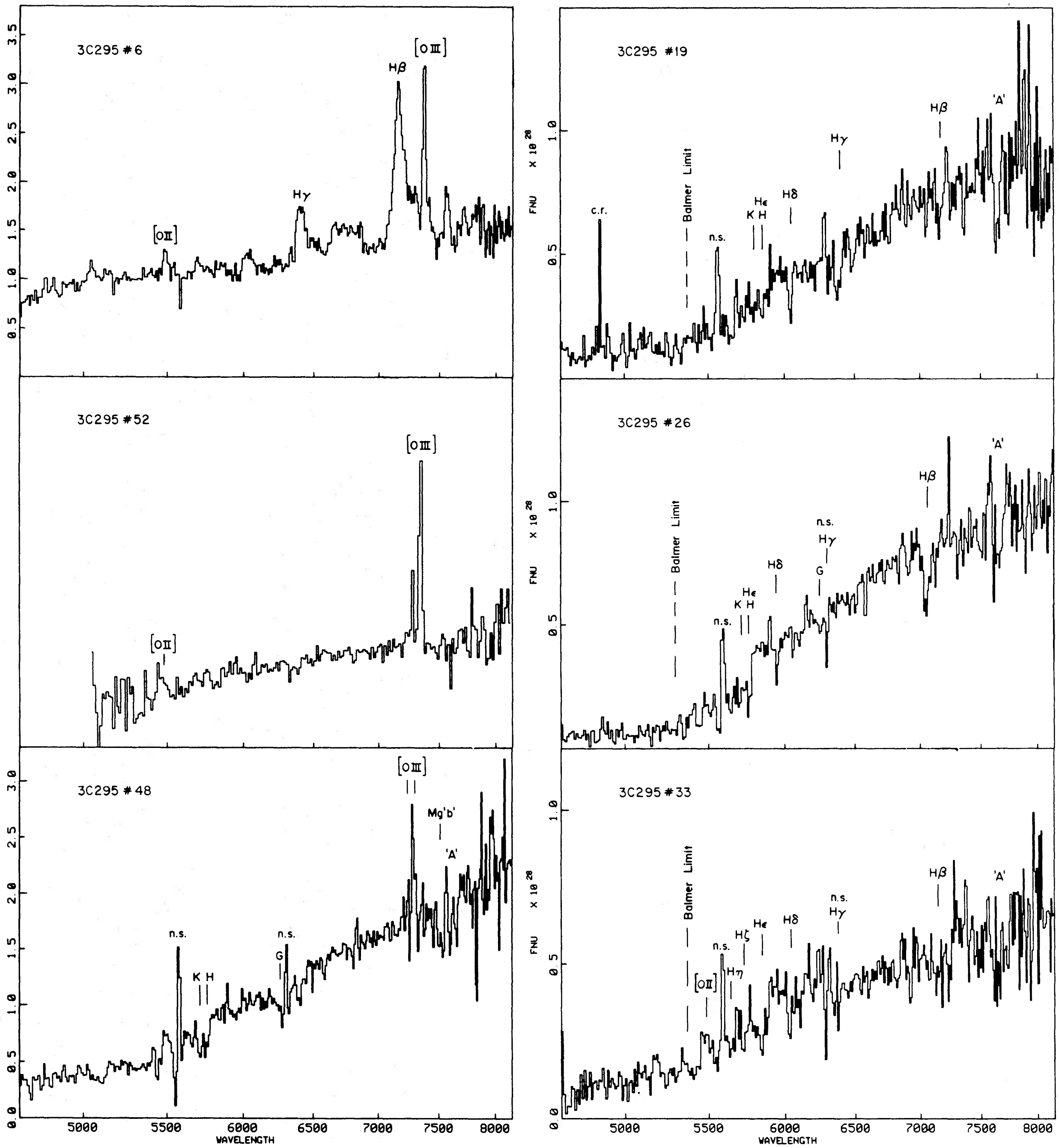

FIG. 5.—The spectra of the six blue galaxies that are confirmed to be members of the 3C 295 cluster. Three (Nos. 6, 48, and 52) high-excitation emission spectra typical of AGNs. No. 6 is a Seyfert 1. No. 52 is possibly a Seyfert 2. Nos. 19, 26, and 33 are only moderately blue ($B-V \approx 0.74$) but show unusually strong Balmer absorption lines. Key to notations as in Fig. 4.

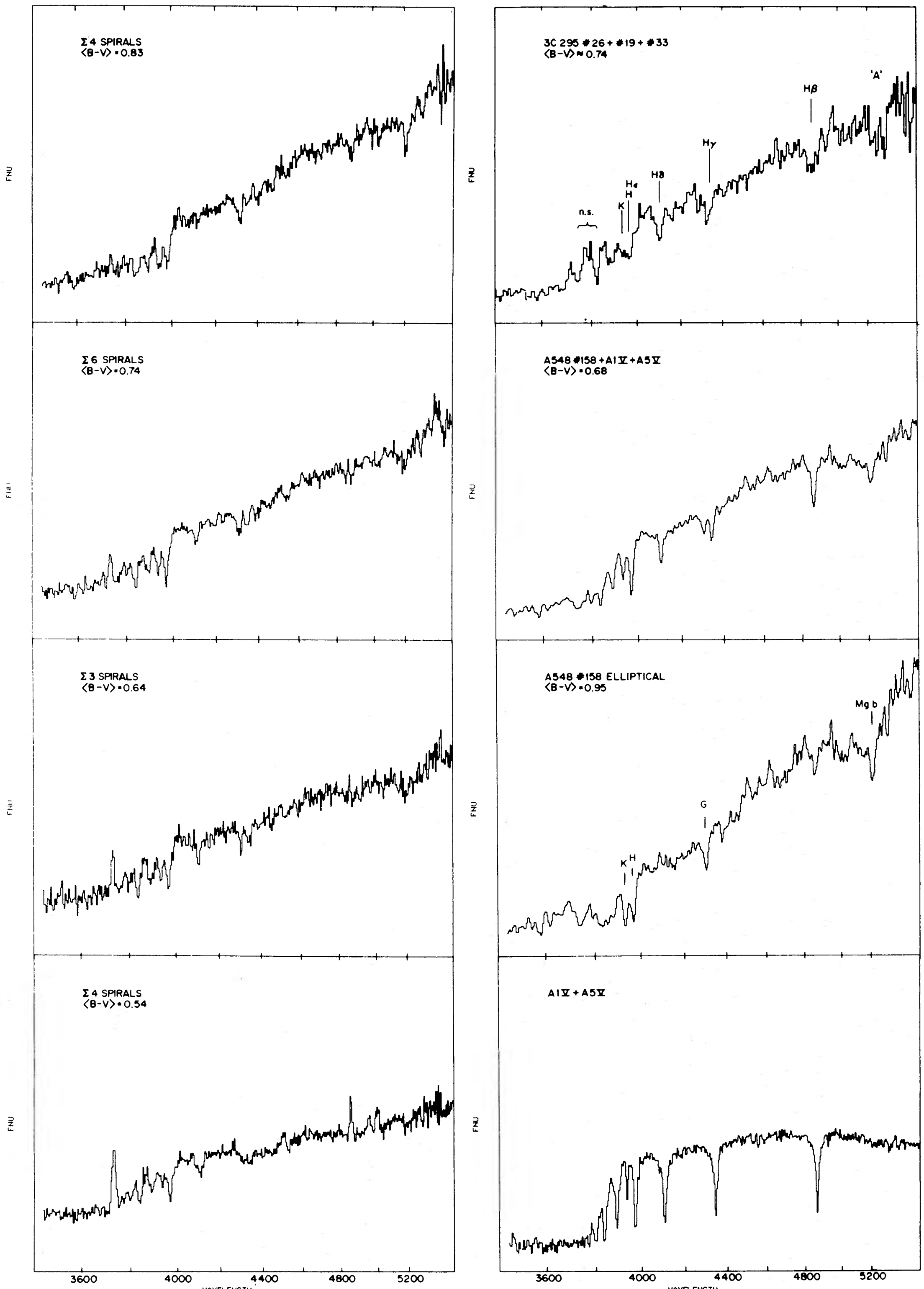

FIG. 6.—A comparison of the summed spectra of Nos. 19, 26, and 33, called spectrum S in the text (*upper right*), with (*a*) spirals of different colors (*left panel*) and (*b*) the sum of an old population and A stars (directly below spectrum S). The Balmer lines are always too weak in the composite spiral spectra to match spectrum S, particularly at the proper color of $B-V = 0.74$. The A star + elliptical spectrum *is* a good match to spectrum S, both in continuum shape (color) and line strengths. This type of spectrum is characteristic of an old population in which a large burst of star formation has recently (within 1–2 × 10^9 years) occurred.

SSB. We follow the evolution of a galaxy by allowing stars to form at 1×10^9 year intervals according to exponentially declining star formation rates with e-folding times $\tau_{\rm disk}$ and $\tau_{\rm bulge}$. After specifying the disk/bulge luminosity ratio of the latest model, usually taken to be 16 billion years old, we follow the evolution back in time and compute H, $B-V$, and the contribution to the total luminosity from different age populations. At each 10^9 year interval we also add a population of O and B stars (not included in Manduca's models) in an amount L_B(O, B stars)/L_B(A stars) = 4, determined from inspection of the luminosity function in the solar neighborhood (Miller and Scalo 1979). This gives two models at each age, one with continuing star formation and one truncated 10^9 years before observation.

Our models of late-type galaxies (disk/bulge > 3, $\tau_{\rm bulge} = 10^9$ years) with continuing star formation confirm SSB's conclusion that the colors of these galaxies can be well matched by varying only $\tau_{\rm disk}$. The reddest spirals in Figure 6 correspond to models with $\tau_{\rm disk} =$ 3–5 $\times 10^9$ years and the bluest to $\tau_{\rm disk} = \infty$ (constant SFR). The strengths of the Balmer lines also agree with the data to $\pm 10\%$. As in SSB, no normal spiral requires a rising SFR. If we look at models of spirals as they appeared 5×10^9 years ago, approximately the age of the 3C 295 galaxies, we find, as before, that those with continuing star formation and $B-V \sim 0.7$ have weak Balmer lines, H $\sim$ 3 Å. The model with declining SFR that comes closest to spectrum S is that of a late-type spiral at an age of 11×10^9 years and a constant SFR that stopped star formation 1×10^9 years before the observation. This model has a B−V = 0.73 and H = 5.4 Å. If our determination of H = 7–8 Å in spectrum S is correct, this model, too, is unacceptable.

This leads us to consider models with SFRs *greater* than the past average, as SSB did to explain the very blue ($B-V < 0.4$) Markarian and Zwicky dwarf galaxies. A good fit with spectrum S is obtained with a burst of star formation 1×10^9 years before observation added to an older population that formed 10–11 $\times 10^9$ years earlier. This model has $B-V = 0.70$ and H = 7.0. If the burst produces only high-mass ($M > 1\ M_\odot$) stars, then only $\sim 2\%$ of the mass of the galaxy needs to be converted to stars; but if the lower main sequence is populated, this fraction rises to $\sim 20\%$! Similarly good fits could be obtained from truncating star formation in spirals with rising SFRs or by delaying disk formation by $\sim \frac{1}{2}$ Hubble time, but observations of present-epoch spirals seem to rule out these models.

Thus we are led to a characteristic model consistent with spectrum S in which a preexisting galaxy converts up to $\sim 20\%$ of its mass into stars in a burst lasting less than 5×10^8 years. Such a galaxy might be of *any morphological type*, and the results of even such a vigorous episode of star formation would be difficult to detect in its ancestor 5×10^9 years later, since the burst by this time would only account for less than 30% of the blue light and its present spectrum would be only slightly different from that of a much older population of giants.

b) Examples of Starbursts in Present-Day Galaxies

The detection of three luminous cluster galaxies at high redshift that underwent extraordinary episodes of star formation does not, of course, establish this phenomenon as a common occurrence 5×10^9 years ago. Nevertheless, in an attempt to understand the nature of at least these three systems and, perhaps, younger galaxies in general, it is helpful to look around our local neighborhood for examples of such activity. We will find that though there are likely to be present-day analogs, relevant observations are scarce and the behavior of even these nearby objects is not well understood.

Primary candidates are the Markarian (Huchra 1977) and Zwicky dwarf galaxies. The bluest of these ($B-V < 0.4$, $U-B < -0.4$) were shown by SSB to be consistent with bursts of star formation in which the SFR has risen well above the past average. Many of these are still in the process of forming stars, but it is after this activity diminishes that we expect them to have spectra like our 3C 295 examples.

Most of these galaxies with starbursts are relatively low luminosity ($-13 < M_B < -20$) systems that are intrinsically fainter than the 3C 295 objects which have $M_B \sim -20$ to -21. However, it may be that their behavior is entirely analogous and that our observations show that such starbursts took place in more massive galaxies in the past. The S0 galaxy NGC 5102 is one of the more luminous examples ($M_B \approx -18.7$) which is reasonably well studied. Pritchet (1979) found that it has blue colors of $B-V \sim 0.7$ over a substantial fraction of its disk and bulge, and a spectrum $\sim$1 kpc from the center taken by Dressler shows strong Balmer lines like in spectrum S. Signs of continuing star formation are seen in the outer regions, and the system still contains a large H I component; nevertheless, the episode of star formation that took place several billion years ago was apparently a large increase over the past average SFR and has now abated. The reason for this outburst is unknown, but NGC 5102 is a member of a group which possibly includes another peculiar system, NGC 5128.

Very luminous ($-20 > M_B > -23$) galaxies of this type may be represented in the sample of Balick, Faber, and Gallagher (1976), who find early type galaxies with abnormally blue colors and high H I contents. Sparke, Kormendy, and Spinrad (1981) have also found two very blue S0 galaxies whose *nuclear* spectra match the old population plus A stars model. Unfortunately, no integrated spectra covering *large spatial areas* are available for these systems with which we can compare our 3C 295 data. The class of galaxies classified in the revised Hubble-Sandage system as Irr II are also possible analogs. M82 is judged to have an extraordinary number of massive stars (Rieke and Lebofsky 1979) but is quite red in color, probably due to internal reddening by dust. It is reported to have an "A-type spectrum," but this term is loosely applied to any system having significant Balmer absorption lines, so again we cannot compare the continuum shape or line strengths of M82 with our 3C 295 data. Similarly the regions surrounding the nuclear activity in NGC 1275 (Rubin *et al.* 1977) and NGC 1068 are described as having A-type spectra, but we again lack the relevant spectra covering large spatial areas. These last examples are particularly interesting because we have found several AGNs in the 3C 295 cluster. This suggests a possible evolutionary link among all six blue cluster members we have observed by associating nuclear activity with star formation. For example, both activities might result from unusually high accretion of surrounding gas (Sarazin and O'Connell 1983; Fabian, Nulsen, and Canizares 1982 and references therein), or a Seyfert outburst might generate a shock wave capable of initiating abnormally high levels of star formation over a radius of several kiloparsecs.

These examples give us some confidence that the type of activity we see in 3C 295, numbers 19, 26, and 33, may well be present in some galaxies at the present epoch. However, these present-day examples are not well understood, and it seems unlikely that any one explanation will cover them all. Some bursts of star formation are undoubtedly triggered by encounters with other galaxies, while others like NGC 1275 may be the result of gas accretion. Indeed, some systems like NGC 5102 or M82 seem to have launched into activity with little outside influence. Perhaps the only thing we *can* conclude is that *these types of systems make up only a small fraction of the population of blue field and cluster galaxies today*, so that if our 3C 295 data are representative, they suggest a *large increase in the occurrence of bursts of star formation in luminous galaxies* in the relatively recent past.

Without a comprehensive model of these present-day systems, there is little value in speculating about the exact nature of the 3C 295 examples, particularly until we have enough data to determine if this is a general phenomenon in other clusters and the field at high redshift. It is, however, of some use to note that the interpretations that will inevitably follow should be tested against certain constraints. If the onset of the episode of star formation in 3C 295 is to be triggered by acretion or pressure from the dense, hot intergalactic medium in this cluster (Perrenod and Henry 1981), then there should be examples of the same types of galaxies in nearby clusters at the same stage of dynamical evolution. That is, these types of models offer no obvious dependence on redshift that may be implied by our data. Further, the *products* of these models should not be galaxies that are rare in present-day clusters, since our sparse statistics in 3C 295 imply that this activity is relatively common. For example, the spiral stripping model could be attractively refashioned by suggesting that Sc galaxies falling into the dense intergalactic medium are shocked or squeezed into turning their remaining 20% gas into stars. This would produce a class of small-bulge S0 galaxies, however, that are not common in today's clusters (Dressler 1980). Larger bulge spirals, even 5×10^9 years ago, would be unlikely to have such a high fraction of gas, but these could be candidates if only massive stars were produced in the burst. Again, however, present-day examples should be abundant, and they do not seem to be.

A better start can be made when we know if these galaxies with bursts of star formation are typical of only a small fraction of clusters with certain global characteristics such as a dense intergalactic medium or a recent collapse. This might establish conditions or time scales for the phenomenon. On the other hand, if it is found that this is a very general activity found in a wide range of environments at high redshift, this may imply that some internal mechanism and clocking is at work. With this information we may be in a position to turn the problem around and explain the nearby examples of galaxies that have undergone bursts of star formation.

VI. SUMMARY

With spectra of 20 blue and six red galaxies in the BO field of 3C 295, we now have enough data to evaluate the claimed excess of blue cluster galaxies. We find that most of the blue objects are not cluster members, but are foreground and background galaxies. Instead of a population of about 40% blue galaxies, the correct value seems to be of order 20%. This is not unusually high for present-epoch clusters, so, in a strict sense, the BO effect is not verified in this first distant cluster to be investigated spectroscopically.

On the other hand, a 20% population of blue galaxies in similar present-epoch clusters is typically made up of normal spiral galaxies, and this is not the case in the cluster containing 3C 295. All six of the blue cluster members we have found in the 3C 295 field have the spectra of active galaxies: three have active nuclei (Seyfert 1 and Seyfert 2 types), and the other three show large bursts of star formation. The occurrence of so many of these active galaxies suggest a tenfold increase in these types compared to the population of present-day clusters, indicating, for example, that Seyfert galaxies may undergo a strong evolution like that of quasars. This tentative conclusion is supported by several high-excitation spectra of foreground and background galaxies in the 3C 295 field, and one Seyfert 2 we have found in Cl0024 + 1654 (Paper I). Confirmation of these trends requires the spectroscopic study of other distant cluster of galaxies.

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