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BLUE DISK GALAXIES IN THE COMA CLUSTER: ANALOGS TO $z = 0.5$ CLUSTER MEMBERS?

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ABSTRACT

Long-slit spectroscopy of blue disk galaxies that are located in the central portion of the Coma Cluster reveals the presence of Balmer absorption lines with equivalent widths comparable to those observed for some blue galaxies in the 3C 295 cluster. These anomalously strong Balmer absorption lines indicate the presence of a large population of main sequence A–F stars that has presumably arisen from a relatively recent star formation event. Unlike the case in 3C 295, however, the blue Coma disks also have strong Balmer emission lines indicating that this star formation event has not yet subsided. Combining the inferred star formation rates with the very low H I contents of the Coma spirals yields gas depletion time scales that are quite short in comparison with normal late-type spirals. This implies that the present-day star formation rate is significantly higher than the average past rate, a conclusion that was also reached by Dressler and Gunn for galaxies in the 3C 295 cluster. From these data, we argue that accelerated star formation rates may accompany gas removal processes that have been excited via the interaction of the galaxies with the intracluster medium. Alternatively, vigorous galaxy-galaxy interactions in distant clusters could enhance the star formation rate and/or foster the development of a high degree of nuclear activity. Whatever process is the cause, a rapid increase in the star formation rate effects a significant increase in blue surface brightness, thereby enhancing the probability of detection of blue galaxies at high redshift.

Subject headings: galaxies: clustering — galaxies: formation — galaxies: stellar content

I. INTRODUCTION

The idea that substantial evolution of cluster spirals has occurred between $z = 0.5$ (5–7 Gyr lookback time) and the present epoch stems directly from measurements by Butcher and Oemler (1978, 1984) that indicate a notable excess of blue galaxies in the cores of distant, concentrated clusters of galaxies compared with similar clusters at low redshift ($z < 0.1$). The startling evolutionary rate of cluster galaxies implied by these observations challenges our understanding of the phenomena in question and a consistent picture has not been forthcoming (Dressler 1984). For instance, the spectroscopic study of the 3C 295 cluster conducted by Dressler and Gunn (1982, 1983) indicated that many of the blue galaxies detected by Butcher and Oemler (1978) were foreground galaxies. Moreover, the true blue population in this cluster is made up of Seyfert and "poststarburst" galaxies, that is, no normal spirals were detected. In costrast, the study of CL 0024+1654 by Dressler, Gunn, and Schneider 1985) found a large population of blue members that exhibit spectra characteristic of normal spiral galaxies. This dramatic difference between the spectroscopic properties of blue galaxies in the 3C 295 cluster compared with CL 0024+1654 clearly argues that the evolution of cluster galaxies with redshift is not a uniform process. Indeed, another cluster in this redshift range, CL 0016+16, apparently contains few, if any, blue cluster members (Koo 1981).

Extensive observations of low-redshift galaxy clusters have also done little to unravel the evolutionary history of cluster spirals. Bothun, Schommer, and Sullivan (1982) demonstrate that many low-z galaxy clusters contain disk galaxies that are no more advanced in their evolution than similar field spirals. Moreover, Kennicutt (1983) and Kennicutt, Bothun, and Schommer (1984) have argued that the disks of all spirals galaxies evolve with a nearly constant star formation rate (SFR) regardless of their environment. On that basis, we would expect to observe only modest and smooth amounts of evolution with redshift (lookback time) for spirals. Discontinuities in this smooth evolutionary history might signify some abrupt, violent event (e.g., a large burst of star formation) in the otherwise quiet evolution of disk galaxies.

If the Butcher-Oemler effect is biased by the higher probability of detecting a special event in the evolution of cluster galaxies (an event that serves to increase the average blue surface brightness of some cluster members), then our view of this evolution may be significantly biased. In order to better understand the kinds of blue galaxies that are discovered at $z \approx 0.5$, it is necessary to find low-z analogs. Dressler and Gunn (1983, henceforth DG) commented that no appropriate low-z analog has yet been detected, consistent with the results of Bothun, Schommer, and Sullivan (1982) who find that most clusters contain many examples of blue disk galaxies that are not exceptional in their overall properties. However, the Coma Cluster does harbor a unique collection of very H I poor, yet very blue disk galaxies which have rather high SFRs (see Bothun, Schommer, and Sullivan 1984; Kennicutt, Bothun, and Schommer 1984). This is perhaps even more significant because Coma is regarded as a dynamically well-evolved

[1] Observations were made at Palomar Observatory as part of a collaborative agreement between CIW and CIT.

cluster, one to which the properties of rich clusters at $z \approx 0.5$ are often compared (see Dressler 1984).

In this paper, we present long-slit spectroscopic observations of seven very blue disk galaxies that are located in the Coma Cluster. In § II we describe the properties of the sample selected for spectroscopic observation. In § III we compare the Balmer line strengths of these Coma disks with those of the blue galaxies in 3C 295 and emphasize that in Coma, we may be witnessing the same phenomenon that occurred several billion years ago in the 3C 295 cluster. In § IV we offer a qualitative model of how enhanced star formation, caused by some interaction of the galaxy with the cluster environment, may be responsible for the prevalence of blue cluster galaxies at high redshift.

II. OBSERVATIONS AND CHOICE OF SAMPLE

a) Sample Characteristics

Our primary goal in this investigation is to obtain a low-z sample which approximates the environment and characteristics of blue galaxies in distant clusters. The Coma Cluster is the densest cluster within $z = 0.04$. In the Coma Cluster, approximately 50% of the spiral galaxies within $R = 1°$ have $(B-V)_T{}^0 < 0.6$ and most of these are quite H I poor (Bothun, Schommer, and Sullivan 1984). Might these blue galaxies be similar to the blue galaxies that populate more distant clusters? In order to address this question, we have obtained long slit spectra of disk galaxies that are located within 0°.7 from the center of Coma and which have $(B-V)_T{}^0 < 0.55$ and $(V-R)_T{}^0 < 0.7$.

Table 1 lists the properties of this sample. The galaxies themselves are displayed in Figure 1 (Plate 1). For comparison, the bottom left panel of Figure 1 displays N4911, a very red, H I–deficient spiral in the center of Coma. With respect to N4911, most of the blue galaxies have some degree of morphological peculiarity, most notably, rather chaotic spiral structure. The bulk of the observational parameters can be found in the catalog of Bothun *et al.* (1985). In Table 1, column (1) contains the galaxy's conventional name and column (2) contains its designation in Dressler (1980). Columns (3)–(6) are the $(B-V)$, $(U-B)$, $(V-R)$, and $(B-H)_{-0.5}$ colors corrected for reddening and redshift. Column (7) contains the Hα equivalent width from Kennicutt, Bothun, and Schommer (1984). Columns (8)–(9) contain the H I mass or upper limit from the recent data of Giovanelli and Haynes (1985) and the absolute blue magnitude. To derive these quantities, we assume a distance modulus to Coma of $(m-M) = 34.2$ ($H_0 = 100$ km s^{-1} Mpc^{-1}). Finally, column (10) lists the galaxy's recessional velocity.

The range of $(B-V)_T{}^0$ and $(V-R)_T{}^0$ colors for this sample is similar to the range observed for the blue galaxies that inhabit the 3C 295 cluster and CL 0024+1654. However, only N4848 has an absolute magnitude ($M_B = -20.5$ for $H_0 = 100$) which is similar to the galaxies studied in these more distant clusters. Furthermore, as stressed by Dressler and Gunn (1982), blue galaxies in these distant clusters seem to possess anomalously high surface brightness with respect to normal spirals, although no quantitative estimates of this difference are available.

In the case of the Coma sample, limited surface brightness data are available from CCD observations with the 0.9 m telescope at Kitt Peak. Figure 2 shows the blue surface brightness profile of three of the galaxies in the present sample, namely N4848, Z160086, and Z160106. These profiles were obtained through reduction of the CCD frames utilizing the GASP surface photometry package, originally written by M. Cawson and modified by one of us (G. B.). Details of this reduction procedure can be found in Cornell *et al.* (1985). As can be seen, these galaxies are well represented by an exponential disk, although Z160106 has some excess light emanating from a very bright nucleus and N4848 has a rather distorted profile in the inner regions. For N4848 the scale length of the exponential disk is 3.7 ± 0.3 kpc while in the case of the two Zwicky galaxies the scale lengths are 1.8 ± 0.2 kpc. While these are small scale lengths, the galaxies are nevertheless fairly luminous because of rather high disk central surface brightnesses. After correction for reddening and redshift, we find central blue surface brightnesses $B_c(0) = 19.9$, 20.4, and 19.7 for N4848, Z160086, and Z160106 respectively.

b) Data Acquisition

The galaxies listed in Table 1 were observed with the Palomar 5 m telescope on 1984 May 7 using the 2D-FRUTTI detector on the double spectrograph. The data covered the spectral range 3400–5000 Å. The objects were observed through long slits 2″ or 4″ wide, resulting in a spectral resolution of 3–5 Å FWHM. Exposure times ranged from 600 to 1000 s. The objects were reobserved for 200–300 s the following night with a redder spectral range that included [O III] in order to determine if any of the objects had high-excitation spectra ([O III]/Hβ > 1). The fact that all seven have low-excitation spectra is clear evidence that the emission lines seen are not produced in active nuclei but rather in normal H II regions. Figure 3 displays the spectra of the seven blue disks in Coma. For reference, the bottom panel of Figure 3 shows a spectrum of a luminous elliptical in Coma that was taken with the same instrumental setup. Note that beyond

TABLE 1

PROPERTIES OF BLUE DISK GALAXIES IN THE COMA CLUSTER

Galaxy (1)	Dressler Number (2)	$(B-V)_T{}^0$ (3)	$(U-B)_T{}^0$ (4)	$(V-R)_T{}^0$ (5)	$(B-H)_{-0.5}$ (6)	EW(Hα) (7)	log $M_{\rm H}$ (8)	M_B (9)	Velocity (10)
IC 4040	D169	0.43	−0.20	0.62	3.1	35	<8.90	−19.2	7650
N4848..........	D220	0.50	−0.19	0.68	2.9	23	8.91	−20.6	7250
N4858..........	D195	0.37	−0.18	0.63	...	...	<8.50	−18.8	9450
Z160073	D54	0.39	−0.05	0.54	2.5	24	8.60	−19.1	5350
Z160086	D51	0.26	−0.27	0.48	2.1	58	<8.95	−18.9	7500
Z160098	D246	0.55	−0.06	0.61	3.0	...	8.81	−19.2	8900
Z160106	D47	0.50	0.01	0.67	2.7	20	<8.82	−19.4	7200

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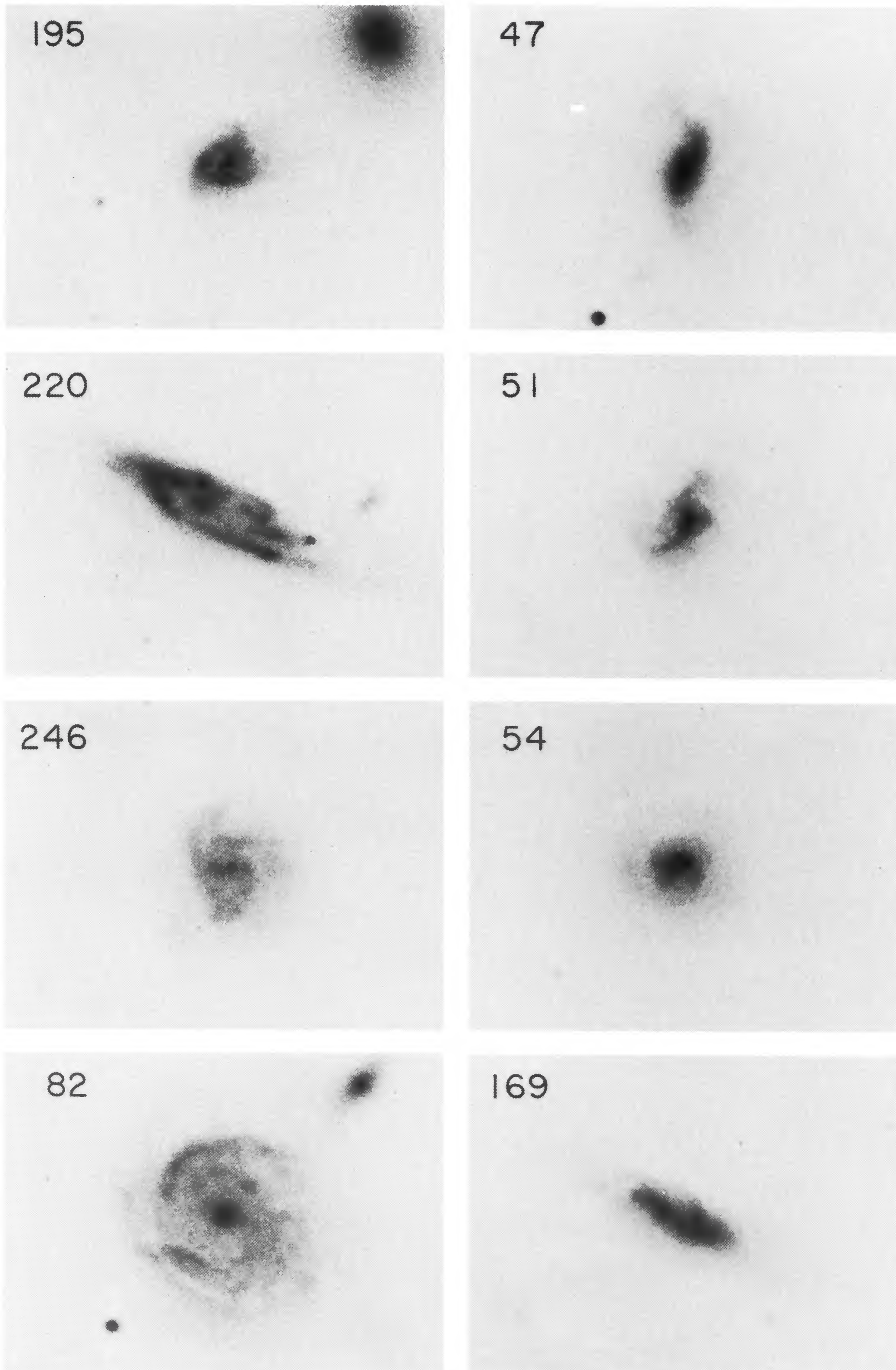

FIG. 1.—Enlargements of the blue Coma disk galaxies from the original duPont plate. Note the disturbed morphology of all of these galaxies. The galaxy at the bottom left of Fig. 1 is NGC 4911, a very red and H I–poor spiral in the Coma Cluster. In contrast to the bluer members, this galaxy has rather regular morphology.

BOTHUN AND DRESSLER (*see* page 58)

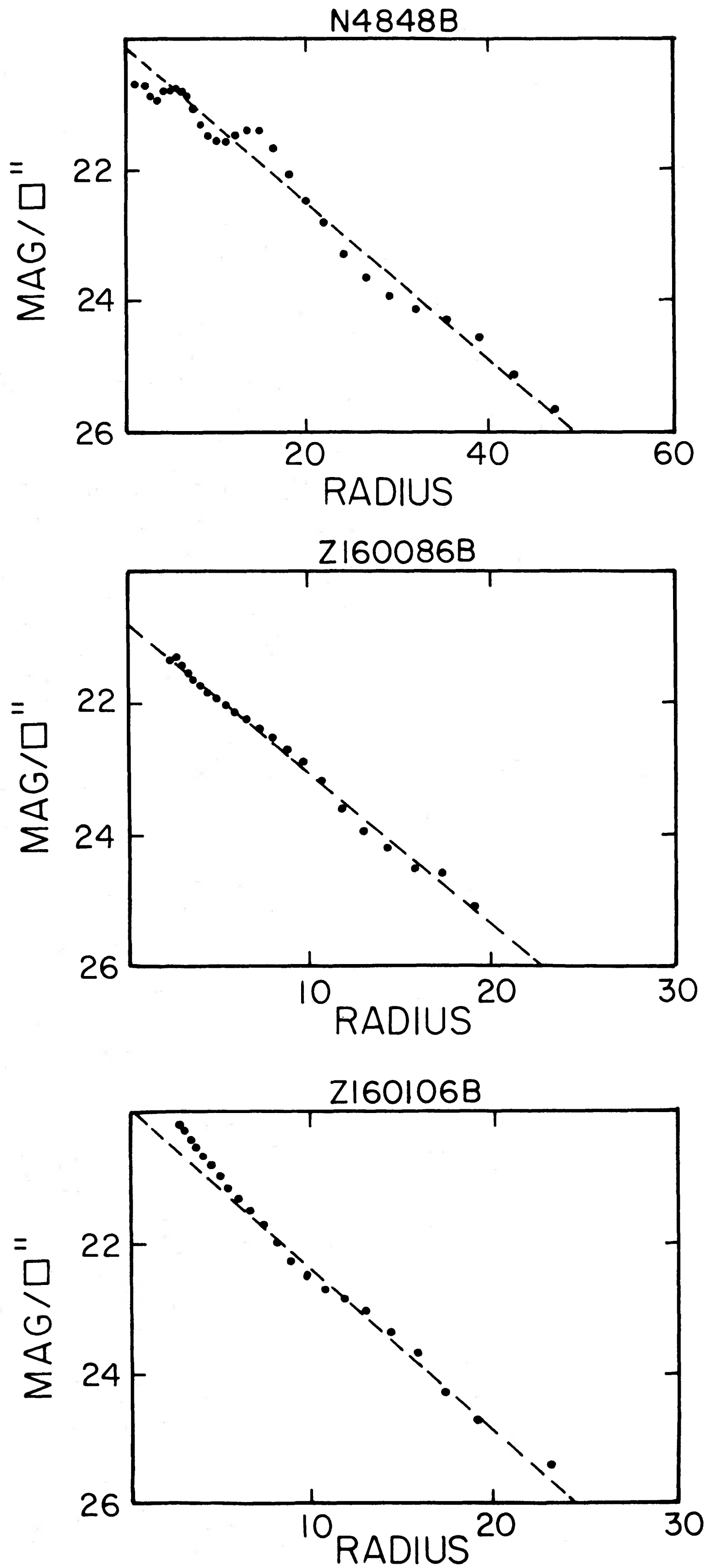

FIG. 2.—Blue surface brightness profiles of N4848, Z160086, and Z160106. The x-axis is in units of arc seconds. The dashed line is a least-squares fit to the data from which the extrapolated central surface brightnesses and disk scale lengths have been derived.

~4600 Å the flux scale is uncertain due to the presence of a dichroic filter in the beam.

III. COMPARISON WITH THE 3C 295 CLUSTER

One immediate and important difference between the sample of blue galaxies in the 3C 295 cluster and the Coma sample is the larger percentage of active galactic nuclei (AGNs) in the former. In fact, Coma contains only one Seyfert galaxy, NGC 4922b (Huchra, Wyatt, and Davis 1982). DG have already commented on the apparently large increase in the surface density of Seyferts at modest redshifts ($0.3 < z < 0.5$). Whether this is the result of the cluster environment or is simply a manifestation of the tendency for galaxies in general to be more active at higher redshift (e.g., Windhorst 1985) awaits a detailed comparison of the percentage of AGNs inside and outside of clusters in this redshift range. For more nearby samples ($z < 0.2$), there does appear to be a strong preference for AGNs to reside in regions of above average local density or to occur in interacting systems (Heckman *et al.* 1984; Kennicutt and Keel 1984; Dahari 1984; Keel *et al.* 1985).

Strong Balmer absorption lines are the most noteworthy feature of the spectra of the non–AGN blue galaxies in the 3C 295 cluster (see DG). From inspection of Figure 3 it is obvious that our sample of blue disks in the Coma cluster also has conspicuous Balmer absorption lines (see in particular D51). Unfortunately, there are two obstacles that prevent the direct comparison of line strength: (1) The blue disk galaxies in Coma exhibit strong Balmer emission lines which fills in Hβ, Hγ, and Hδ. The higher order Balmer absorption lines are relatively unaffected by this emission. (2) At the redshift of 3C 293, Hζ, Hη, and Hθ lie close to the strong night sky emission at $\lambda\lambda$5577 and cannot be reliably measured. Thus, to compare the line strengths of Coma galaxies to those in the 3C 295 cluster, we are forced to consider differing sets of Balmer lines. Table 2 lists the various equivalent widths of the Balmer lines as well as the Ca II K line for the disks in Coma. For comparison, DG obtain a mean equivalent width of 7–8 Å for Hβ, Hγ, and Hδ.

According to DG, strong Balmer absorption lines arise from a substantial population of main sequence A–F stars. What is unusual about the galaxies in the 3C 295 cluster is the strength of these lines relative to the integrated continuum $B-V$ color of the underlying galaxy. In particular, the mean $B-V$ color is 0.74, which indicates the presence of a substantial population of old stars, although a large amount of internal reddening [e.g., $E(B-V) > 0.3$] cannot be (completely) ruled out. The composite stellar population that best approximates the measurements is one in which a very large burst of star formation,

TABLE 2

EQUIVALENT WIDTHS

Galaxy[a]	Ca II K	Hδ	Hη	Hθ	Hζ
IC 4040	4	4	4	10	6
N4858..........	1.5	...	...	5.5	4
Z160073	1.5	3	4	4.5	7
Z160086	2.5	7	3	9	5
Z160098	4	4.5	7	13	6
Z160106	2	4	8	12	8

[a] Nominal uncertainty in EW is 20%.

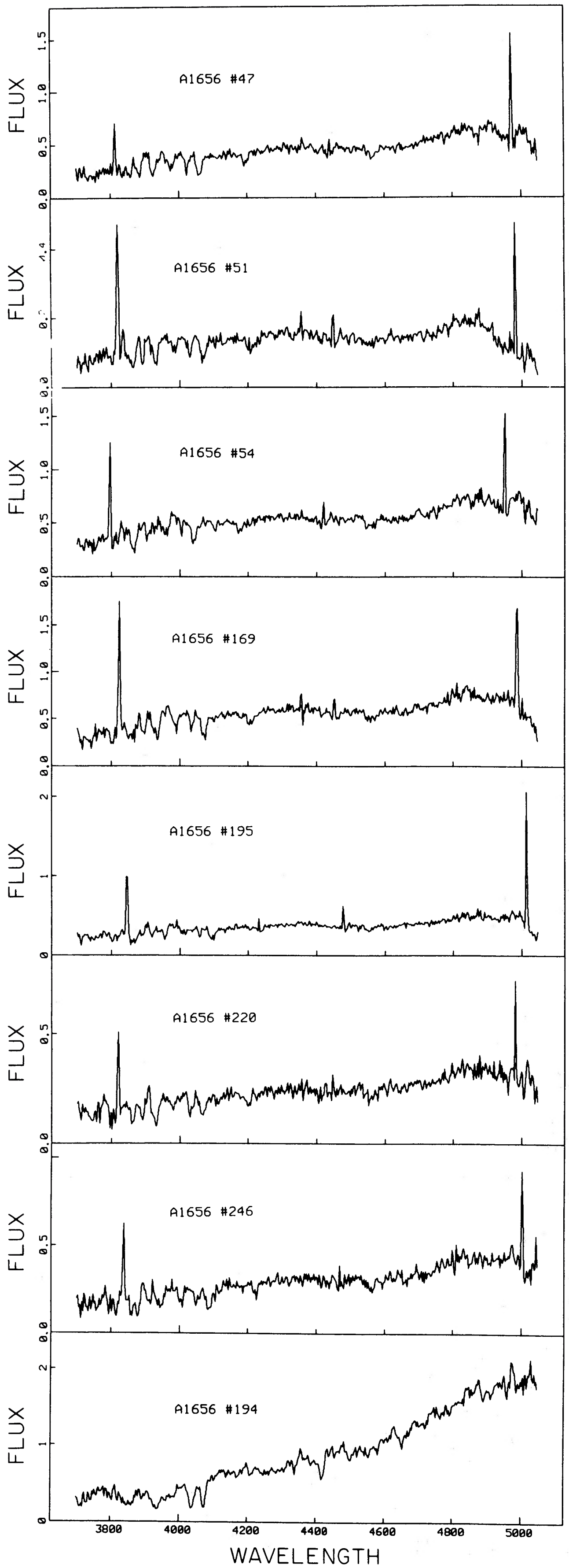

FIG. 3.—Spectra of the blue disks in the Coma Cluster. Note that both Balmer emission and absorption lines are present. The bottom panel is the spectrum of a luminous elliptical taken with the same instrumental system. The flux scale is in arbitrary units.

superposed upon this substantial population of old K and M giants (which has $B-V = 1.0$), has decayed to an age of ~ 1 Gyr. For a Salpeter IMF, the observations require that 10%–20% of the total galaxy mass has participated in this star formation event. Such a burst causes an initial increase of about 4 mag in the blue, but this burst luminosity rapidly fades. However, even at 1 Gyr, the central blue surface brightness of the galaxy is about 1.5 mag higher than it would have been without this extraordinary star formation event.

An important feature of this odd combination of strong Balmer absorption lines and relatively red integrated colors is that only a very narrow range of population synthesis models are compatible with the data (see DG). For time $\tau < 1$ Gyr after the burst, the continuum colors are much too blue to match the data, while for time $\tau > 1.5$ Gyr, the luminous A stars have vanished from the main sequence and the remaining F stars are insufficient to account for the observed Balmer line strengths. For instance, Balmer line equivalent widths of 7–10 Å are typically observed for intermediate age clusters in the LMC as well as M33 (Searle and Smith 1984; Cohen, Searle, and Persson 1984; Schommer *et al.* 1985). However, these clusters generally have $0.3 < B-V < 0.6$. Therefore, the "poststarburst" galaxies in 3C 295 must have a dominant old stellar population, presumably distributed in a bulge, in order to explain the observed combination of strong Balmer absorption lines yet somewhat red $B-V$ color. Possibly these galaxies are even ellipticals.

For the Coma Cluster, the mean $(B-V)_T{}^0$ color of our sample disks is 0.43 ± 0.04, which is significantly bluer than in the case of the 3C 295 galaxies (unless they are heavily reddened). Furthermore, the Coma disks exhibit Balmer and [O II] emission which signify the presence of ongoing star formation involving O and B stars. This color difference between the 3C 295 galaxies and the Coma disks most likely arises from the combination of current star formation and the low bulge-to-disk ratios (B/D) in the latter sample (see Dressler 1980). Although the Coma spirals have low B/D, there is still a significant contribution to the light from an underlying old disk population as evidenced by their observed $(B-H)$ colors as well as the relatively strong Ca II H and K lines.

Using the calibration of the SFR implied by Hα luminosity derived by Kennicutt (1983), in conjunction with the observed fluxes tabulated in Kennicutt, Bothun, and Schommer (1984), we derive SFRs for the blue Coma disks that range from 1 to 4 solar masses per year (for $H_0 = 100$ km s^{-1} Mpc^{-1}). These rates are fairly large compared to normal late-type spirals of similar luminosity. As a consequence, the central blue surface brightness of at least three of the blue Coma disk galaxies (N4848, Z160086, and Z160106) are 1.0–1.5 mag brighter (see Fig. 2) than the canonical central disk surface brightness of Freeman (1970) (see also Boroson 1981). Were these central surface brightnesses to fade to normal values, it is doubtful that either of the two small galaxies would be bright enough to be included in the Zwicky catalog.

As stressed by Bothun, and Sullivan (1984), these blue disks in Coma are conspicuous in possessing a very low H I content. Those data and more recent observations of Giovanelli and Haynes (1985), combined with the SFRs calculated above, imply gas depletion timescales in the range 0.5–2.0 Gyr. These time scales are remarkably short in comparison to other late-type spirals (see Kennicutt 1983) which suggests that, like the 3C 295 galaxies, these disks in Coma are also undergoing a special event in their evolution.

IV. A GLOBAL ENVIRONMENTAL EVENT?

a) Ram-Pressure Induced Star Formation

The connection between the blue galaxies in the 3C 295 cluster and those in the Coma cluster is twofold: (1) both sets of galaxies have similar Balmer absorption line strengths (in fact, because 20%–30% of the continuum light at 4000 Å is coming from O and B stars, the equivalent width of the Balmer lines will increase after these stars have died); (2) the remarkably short gas depletion time scales of the blue disks in Coma imply a present SFR that is significantly higher than the past average, a conclusion reached earlier by DG for the poststarburst galaxies in the 3C 295 cluster.

It follows that the production of blue galaxies in both Coma and the 3C 295 cluster requires a mechanism which accelerates the SFR, thus increasing the blue surface brightness. Since the 3C 295 cluster and Coma provide the extreme in galaxian environments, i.e., high density, it is tempting to connect this process of accelerated star formation with some environmental interaction which affects many galaxies at once. We propose that this mechanism is connected with ram-pressure sweeping and arises when very gas-rich galaxies that inhabit the periphery of the cluster fall into the core and encounter the intracluster medium (ICM) for the first time.

Henry *et al.* (1979) show that the number density of the ICM in the 3C 295 cluster is relatively high and similar to that observed by Serlimitsos *et al.* (1977) for the Coma cluster. Hence, ram pressure is a force to be reckoned with in both clusters. In fact, Henry *et al.* (1979) originally argued that the population of blue galaxies observed by Butcher and Oemler (1978) is unlikely to be a collection of rapidly evolving spirals, since gas-bearing spirals would not survive in such a hostile environment. The observations of DG seem to confirm this conjecture.

In the simplest form of ram-pressure sweeping (see Gunn and Gott 1972), the ram-pressure force depends upon ICM density and the square of the relative velocity ($V_{\rm rel}$) of the disk with respect to the ISM. Since the velocity dispersion of rich clusters is 700–1000 km s^{-1}, it follows from Gunn and Gott (1972) that most, if not all, disks moving through a rich (i.e., $n_e > 10^{-3}$ cm^{-3}) ICM would be stripped of their cold disk gas. Yet in no cluster has a good relation between gas content (or H I deficiency) and $V_{\rm rel}$ been observed (Bothun 1981; Giovanelli and Haynes 1985). Recently, however, Dressler (1985) has used the Giovanelli and Haynes sample to show that projection effects may be the major reason such a relation was not found. When information on spatial distribution is included in the analysis, there is substantial evidence that the gas-poor spirals are moving at high $V_{\rm rel}$ on near-radial orbits that carry them into the cluster core.

The most thorough investigations of the effects of ram pressure by virial motion through a hot medium are those of Lea and DeYoung (1976) and Kent (1980). In particular, Kent (1980) refines the original Gunn and Gott (1972) treatment by considering the ISM as a two-component, medium—cold, dense molecular clouds interspersed in a warm H I sea. In this case, the less dense portion of the ISM responds to low values of ram pressure whereas only very high values are capable of sweeping out the dense clouds. Kent's (1980) model requires a ram-pressure force of $P_{\rm ram} = 1\text{–}5 \times 10^{-10}$ dyn cm^{-2} to completely strip a galaxy. Using the formalism of Gunn and Gott (1972) and the ICM medium parameters of Coma (Serlimitsos *et al.* 1977), Kent shows that only galaxies with $V_{rel} > 3000$ km s^{-1} will experience this force. However, to sweep out the less dense H I component in the outer regions requires only $P_{ram} = 10^{-11}$ dyn cm^{-2}, which is achieved at $r < 3$ core radii for $V_{rel} = 500$ km s^{-1}. Most of the blue Coma disks have a relative velocity which is sufficient for them to have lost significant amounts of H I via ram-pressure sweeping. However, it is important to consider what the effects of ram pressure are on the cloud medium, assuming that dense molecular clouds are part of the ISM of all disk galaxies.

For guidance, we turn to calculations of Jura (1976) who derives a relation involving the minimum mass required for cloud collapse as a function of external pressure. For an external pressure of 10^{-11} dyn cm^{-2}, this minimum mass is 20–30 solar masses, which is 10–100 times less than the minimum collapse mass induced by the passage of galactic density waves or supernova shocks (Jura 1976; Shu *et al.* 1972). Therefore, we suggest that in clusters with high ICM densities, ram-pressure induced star formation is a real possibility.

In practice, the situation is likely to be very complicated and extremely difficult to model. First, the orientation of the disk with respect to the ICM seems crucial. Ram pressure exerted in a direction perpendicular to the disk is more effective in removing material than that directed parallel to the disk. In the latter case, we might expect star formation to be even more efficient as the ISM piles together under the influence of this external shock. Second, if ram pressure is very effective in removing the warm, intercloud medium, replacing it with a hot, but thin ICM, then the cold clouds may rapidly evaporate. At present, the theory of thermal evaporation (e.g., Balbus and Mckee 1982) does not adequately describe the effects on cold, dense clouds of direct contact with a hot ICM. Finally, Kent (1980) shows that if a hydrodynamical code is used to model the interaction, a bow shock forms at the interface of the galaxy with the ICM which facilitates the flow of material around the disk (instead of through the disk). This may actually inhibit the excitation of cloud collapse.

b) Galaxy-Galaxy Interactions

The evidence that starburst activity is a direct consequence of galaxy-galaxy interactions is ambiguous. On the one hand, Lonsdale, Persson, and Matthews (1984) demonstrate that violently interacting/merging galaxies often have very high SFRs, as judged by the IRAS data. Similarly, Keel *et al.* (1985), Kennicutt and Keel (1984), and Wasilewski (1983) find that a large percentage of interacting galaxies have nuclear emission lines that are reminiscent of nuclear starburst activity. Despite these positive results, a detailed study by Bushouse (1985) (see also Bushouse and Gallagher 1984) reveals a large variation in the response of the SFR to galaxy-galaxy interactions. Interestingly, Bushouse (1985) does claim that large populations of A–F stars are present in some interacting systems. In addition, a small study of the efficacy of galaxy-galaxy interactions as a means of gas removal for cluster galaxies was done by Bothun and Schommer (1982) who found that, once again, some interacting systems show signs of enhanced star formation while others do not. This result is consistent with the earlier study of Larson and Tinsley (1978).

In a related vein, the notion that galaxy-galaxy interactions are responsible for the onset of activity in galactic nuclei has now become quite fashionable (Bothun *et al.* 1982; Hutchings 1983; de Robertis 1984; Heckman *et al.* 1984), although the evidence that supports it is mostly circumstantial. In particular, although the hosts of QSOs tend to be located in groups of galaxies (Yee and Green 1984; Dahari 1984; Smith *et al.* 1985), and QSO fuzz often has peculiar morphology (Hutchings *et al.* 1984), there is little direct evidence, aside from Bothun *et al.* (1982), that vigorous interactions between hosts and companions are actually occurring. For instance, the spectroscopic observations of Heckman *et al.* (1984) lack the velocity resolution to distinguish companions belonging to the same group as the host from those that are actually interacting.

The key to whether interactions are important in the initiation of star formation and/or nuclear activity rests on the nature of the encounter. Specifically, tidal encounters between galaxies are most effective at disturbing the stellar and gas distributions when the encounter is slow, that is, when the encounter velocity is similar to the rotation velocity or the internal velocity dispersion of galaxies (Toomre 1972). As discussed by Bothun *et al.* (1982), the likely spawning grounds for nuclear activity is the group environment where the velocity dispersion is generally 200–300 km s^{-1}. Similar arguments can be made regarding the degree to which star formation can be excited via interactions (Keel *et al.* 1985). A clear prediction from this reasoning is that AGNs/starburst galaxies should not occur in the cores of rich clusters where the velocity dispersion is generally 700–1000 km s^{-1}. This is consistent with the data of Dressler, Thompson, and Shectman (1985) who find that the frequency of emission-line galaxies in low-redshift ($z < 0.1$) clusters is a factor of 5 less than in the field.

However, if clusters form through the amalgamation of smaller subunits, each with internal velocity dispersions of 200–300 km s^{-1}, one might expect to find a significant population of AGN and starburst galaxies, excited by interactions, populating the periphery of clusters in formation (i.e., clusters at high redshift). Thus, in the case of 3C 295, the blue galaxies (both the AGNs and the starbursts) may be the result of interactions that are occurring in these subunits. On the other hand, because 3C 295 is already a luminous X-ray source, it is likely that this substructure has been erased. For instance, Kent and Gunn (1982) find no evidence for substructure in the Coma Cluster, a similarly luminous X-ray cluster. Furthermore, since the blue disks in Coma are clearly not interacting with other galaxies at present, the interaction model fails to explain their starburst activity.

c) A Qualitative Model

While it is difficult to defend rigorously the concept of ram-pressure induced star formation, we believe that the data are at least qualitatively consistent with this picture. This idea was expressed earlier by DG who speculated that Sc galaxies falling into a dense ICM would experience a sudden increase in their SFR. DG give little credibility to this process, however, due to the lack of small B/D S0's in clusters—the likely descendents of the infalling Sc's. Yet Coma does, in fact, possess a noticeable population of such small B/D S0's (see Bothun, Schommer, and Sullivan 1984).

Furthermore, Kent (1980) speculates that the densest molecular clouds experience a drag force which causes them to collect in the center of the galaxy, perhaps facilitating the formation of an active nucleus or nuclear star burst. Indeed, Kent (1980) claims that the nuclear spectra of three of the galaxies in our sample (IC 4040, Z160106, and Z160073) support his speculation. Our data, in conjunction with that of Kennicutt, Bothun, and Schommer (1984), argues strongly that this starburst is not strictly confined to the nucleus, but instead pervades most of the disk, thus elevating the average surface brightness. If this increase in the gas consumption rate via star formation is accompanied by the general removal of the outer H I, the galaxy will quickly lose or deplete the bulk of its atomic and molecular gas.

Therefore, in order to explain the strong Balmer lines that are observed in the Coma disks and the galaxies in the 3C 295 cluster, we suggest a model in which accelerated SFRs are the consequence of the infall of gas-rich galaxies into a dense ICM. We note that the velocity dispersion $\sigma = 1535$ km s^{-1} of the Coma examples (calculated assuming a mean cluster velocity $V_0 = 6890$ km s^{-1}) is much higher than value $\sigma \approx 1000$ km s^{-1} for the entire cluster. This, and the high relative velocities of the 3C 295 examples ($\Delta V \sim 2000$ km s^{-1}), supports our interpretation that ram pressure is involved. The striking similarity of the individual spectra of both the 3C 295 starburst galaxies and the blue Coma disks leads us to conclude that in each cluster the bursts were triggered more or less simultaneously (i.e., $\tau \lesssim 3 \times 10^8$ yr) by this global process.

For this proposed mechanism to be effective, a cluster must have a dense ICM and very gas-rich galaxies (i.e., fractional gas contents $\gtrsim$10%–20% by mass, assuming a normal IMF) must infall in a time that is long compared to the timescale of formation for the ICM. Specifically, if cluster formation occurs on a time scale which is long relative to the formation of galaxies, there may be few, if any, very gas-rich galaxies left to interact with the ICM when it eventually forms, judging from the fact that few luminous spirals at the present epoch have fractional gas contents greater than 10%. Moreover, because the time scale of cluster formation is directly related to cluster density, the resulting ICM is also likely to be of low density, thereby further reducing the chances that ram pressure induced star formation can occur. On the other hand, if cluster formation is very rapid, most of the gas might be swept from its galaxies during the process of cluster virialization (thus forming a hot, dense ICM). Therefore, there may only be a narrow range of initial conditions of cluster formation that are conducive for the process of ram-pressure induced star formation to eventually occur.

If and when this process does occur, it should significantly increase the blue surface brightness of some cluster members, thus greatly facilitating their detection. The "spirals" seen in CL 0024+1654 by Dressler, Gunn, and Schneider (1985) and the poststarburst galaxies observed by DG probably benefit from this effect, and it seems clear that the smaller blue disk galaxies in Coma would not have been cataloged by Zwicky *et al.* (1961–1966) without it.

d) *Observational Tests*

In principle, the ideas presented in this section can be tested by additional observations of both cluster and field galaxies in the redshift range $0.3 < z < 1.0$. In order to choose between ram-pressure induced star formation and galaxy-galaxy interactions as the mechanism responsible for the production of blue galaxies in distant clusters, it will be helpful to construct simple dynamical models of these clusters (e.g., Beers, Geller, and Huchra 1982; Bothun *et al.* 1983) in order to properly assess their dynamical state, i.e., the degree of subclustering present. This requires the acquisition of many more redshifts than are presently available and thus may require 10 m class telescopes, but already there is some indication from their respective velocity distributions that the degree of subclustering is much more pronounced in CL 0024+1654 than in the 3C 295 cluster (see Dressler, Gunn, and Schneider 1985).

If galaxy-galaxy interactions are more important than the effects of ram-pressure, we might expect both AGNs and starburst galaxies to be present only in environments which have a small velocity dispersion. Note that we might never expect AGNs to populate cluster cores (with the exception of the hosts of luminous radio sources that may be powered by cooling flows) since, according to the models of Kent (1980), ram-pressure forces are insufficient to disrupt the ISM in the centers of most galaxies and the velocity dispersion in cluster cores is too high for interactions to be effective in altering the stellar and gaseous distributions within galaxies.

Observations with the Hubble Space Telescope (HST) should also help resolve this issue. Blue galaxies in distant clusters can be directly examined for morphological peculiarities and/or the presence of nearby companions, and the increased spatial resolution provided by HST will make it possible to perform fairly accurate surface photometry of galaxies out to $z \approx 1$. This should allow determination of SFRs as a function of B/D and redshift which will greatly aid in determining the time scale over which S0 galaxies exhaust their gas through astration. These observations are crucial in properly interpreting the Butcher-Oemler effect as one that is caused by the environment as opposed to a universal trend of more active star formation in large B/D systems in the past.

Thus, in contrast to the present epoch situation where cores of X-ray luminous clusters are devoid of normal star forming galaxies, we arrive at the curious situation that if ram-pressure induced star formation is important in high-redshift clusters, then large B/D galaxies with the largest SFRs should preferentially be found in or near the virialized portions of luminous X-ray clusters! As the cluster redshift decreases, we would expect to find this process occurring in galaxies of progressively smaller B/D. In Coma, for example, ram-pressure induced star formation at the present epoch is only possible for galaxies of small B/D, since, by now, field galaxies with large B/D have become gas-poor through normal astration (see Bothun 1982). We implicitly assume that galaxies of small B/D never form in the virialized cores of clusters but arrive there later via infall. This assumption can also be tested by ST.

V. SUMMARY

The principal observational result of this paper is that blue disk galaxies located in the central region of the Coma Cluster have Balmer line absorption strengths that are comparable to what Dressler and Gunn (1983) have observed for three galaxies in the 3C 295 cluster. The important differences between the two populations of blue galaxies is that (1) there is a high frequency of AGNs among the 3C 295 population, and (2) in Coma, the episode of enhanced star formation has not yet subsided as Balmer emission lines are prevalent. Although we cannot uniquely specify the physical reasons for the presence of blue galaxies in high-redshift clusters, we have argued that the 3C 295 data and the Coma data are at least qualitatively consistent with a picture of ram-pressure induced star formation.

For this process to be effective, a population of gas-rich galaxies must fall into a dense ICM. In the case of 3C 295, this population may well contain galaxies with large B/D, whereas at the present epoch in Coma, the only remaining gas-rich galaxies are those with small B/D. As these galaxies infall, they are violently stripped and undergo a period of enhanced star formation. Their remnants probably augment the S0/elliptical population that dominates the cores of clusters.

We emphasize that if this process is generally important in the past, then the parent population must be weighted toward large B/D systems in order to properly account for the observed B/D distribution of nearby galaxies ($z < 0.1$) as a function of local density (Dressler 1980). This suggests that large bulge systems are either more susceptible to the process or that they are preferentially on radial orbits that carry them into the densest part of the ICM (Dressler 1985). If no such biasing mechanism can be identified, then the lack of small B/D galaxies in dense environments probably argues against the formation of most cluster S0's in this manner. HST images of distant cluster galaxies will provide the crucial data by showing how strongly the B/D distribution evolves with redshift.

Alternatively, the excess population of starburst galaxies and AGNs at higher redshift may be a signature of the increasing prevalence of galaxy-galaxy interactions (or mergers?) with redshift. Evaluation of these two alternatives requires the acquisition of more radial velocities as well as surface brightness profiles of both cluster and field galaxies at $z \approx 0.5$. Our tentative conclusion in this investigation is that these blue galaxies are the result of some special process that enhanced their star formation rate and increased their surface brightness by 1–2 mag, thus facilitating their discovery. If this picture is correct, these blue cluster galaxies may not be representative of the common evolutionary history followed by the majority of galaxies in clusters.

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