SYSTEMATICS OF THE 4000 ANGSTROM BREAK IN THE SPECTRA OF GALAXIES

ALAN DRESSLER AND STEPHEN A. SHECTMAN
Mount Wilson and Las Campanas Observatories, Carnegie Institution of Washington, 813 Santa Barbara Street, Pasadena, California 91101-1292
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ABSTRACT

We have measured the strength of the 4000 Å break from moderate-resolution spectra of 950 galaxies in the fields of 12 rich clusters. We find only a weak dependence of the 4000 Å break amplitude on either the total or bulge luminosity of the galaxy. Since the $U-V$ colors of spheroidal systems appear to correlate with absolute magnitude, a correlation attributed to line blanketing, our result indicates that the 4000 Å break amplitude is insensitive to changes in metal abundance, at least over the range characteristic of galactic bulges. On the other hand, we show that the break *is* a sensitive probe of star formation, by correlating the break amplitude with emission and absorption features indicative of recent star formation. This sensitivity to star formation but insensitivity to metal abundance makes the 4000 Å break a powerful diagnostic for studying evolution with observations of galaxies at large lookback times.

I. INTRODUCTION

Spinrad (1980,1986) has compared the amplitude of the 4000 Å break in nearby elliptical galaxies with break amplitudes of galaxies at large redshift. He finds a significant change, which he attributes to a rapid evolution of stellar populations over the last ~5 billion years, but his sample is heterogeneous since many of the distant objects are very strong radio sources with a more homogeneous sample of the reddest field galaxies over a broad range of apparent magnitudes. Hamilton (1985) concluded, to the contrary, that the break amplitude has shown little change since $z = 0.5$. Because of the Malmquist effect, however, more distant galaxies in Hamilton's sample are, on average, likely to be considerably brighter than those at low redshift. Therefore, a demonstration of the insensitivity of the break amplitude to absolute magnitude was an essential part of Hamilton's study. Using spectrophotometry of ~70 galaxies from Heckman, Balick, and Crane (1980), he showed that the dependence on absolute magnitude for this sample is indeed weak.

Hamilton's result is a bit puzzling, since his own Fig. 10 shows a fairly strong correlation of the break amplitude with $U-B$ color, which, as shown in Sandage and Visvanathan (1978), *does* correlate with absolute magnitude. A possible resolution of this apparent contradiction might be that distances to the galaxies in the Heckman, Balick, and Crane sample, most of which are relatively nearby field galaxies, are sufficiently inaccurate so as to add a considerable noise to the correlation of break amplitude (distance independent) to absolute magnitude (distance dependent). If this were true, the distance-independent $U-B$ color would correlate better, as observed. Support for this interpretation can be found in Larson, Tinsley, and Caldwell (1980, see Fig. 2), in which Sandage and Visvanathan's (1978) $U-V$ colors for E and S0 galaxies are plotted versus absolute magnitude, separately for cluster and field populations. The stronger correlation for cluster galaxies suggests that distance uncertainties may be a problem (although these data might instead be indicative of a genuine difference in star-formation histories for field and cluster galaxies).

Because the 4000 Å break is a potentially important tool in the study of galaxy evolution with lookback time, we sought to re-examine this question of luminosity dependence with a much larger data set consisting mostly of cluster galaxies whose distances are well known. With spectra of over 800 galaxies, we are able to study the correlation of the 4000 Å break amplitude with both total and bulge luminosity, with morphological type, and with spectral features indicative of recent star formation. In Sec. II we describe the data used for this study and measurement procedures, and in Sec. III we present the derived correlations and a brief discussion of the results and the implications for use of the 4000 Å break in the study of galaxy evolution with lookback time.

II. DATA

a) Selection and Observation

Spectra of 1268 galaxies in the fields of 14 rich clusters were taken by us during 11 observing runs from 1978 to 1982 with the Reticon spectrograph on the 2.5 m duPont telescope at Las Campanas Observatory. The primary aim was to measure radial velocities for a study of cluster dynamics, but these spectra have also been used to determine the frequency of emission-line galaxies in clusters (Dressler, Thompson, and Shectman 1985) as well as the present work.

Selection of the objects was, with a few exceptions, done by the following rules. All objects were taken from Dressler's (1980) calalog. Those galaxies with $mb \geqslant 6$ in Dressler's system, corresponding to a bulge magnitude $V \leqslant 16.5$, were automatically included in the redshift survey. In a few clusters this was extended to $mb \geqslant 5$ ($V \leqslant 15$), and even some $mb = 4$ objects were included. All galaxies with $V \leqslant 15$ were also automatically included, which added spiral galaxies with little or no spheroid to the sample.

Nearly all of the spectra were taken through $2'' \times 4''$ apertures with a 600 line/mm grating that gave a spectral resolution of ~5 Å FWHM and a total wavelength coverage of approximately 3500–7000 Å. Typical spectra have several tens of photons per angstrom at 5000 Å, or a $S/N \approx 10$–15 per resolution element.

b) Reduction and Measurement

The resulting one-dimensional spectra of (sky) and (object + sky) were processed with a reduction program written by S. Mochnacki and later with the SD package on a Digital PDP 11/34 at MWLCO. Spectral scans of tungsten lamps were used to correct for small scale variations in the sensitivity of the chain of image tubes and the Reticon detector. Wavelength calibration was accomplished with helium and argon source lamps. Spectra of hot subdwarf stars for flux calibration were taken on only a few runs; therefore the data were not normally reduced to relative fluxes.

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Radial velocities were measured by cross correlation with templates of K giant spectra over the wavelength region 3700–5400 Å, which includes the prominent absorption features H and K (Ca II), the G band, and the Mg 'b' triplet. For a few percent of the spectra, radial velocities were determined by visual measurements of the wavelengths of emission features [O II], Hβ, and [O III]. Heliocentric corrections were applied. Repeat measurements of 42 galaxies indicated an rms accuracy of $\sim$45 km s^{-1} per spectrum.

The sample galaxies were sorted by cluster membership using the velocity intervals given in Table I. On this basis, 826 galaxies in the sample are cluster members and 124 superposed field galaxies. (As listed in Table I, the A1736 field actually contains two clusters, but the difference in redshift is small enough to be considered one cluster for the purpose at hand.) The 12 clusters have an average redshift $z = 0.044$ with an rms dispersion $\Delta z = 0.007$. This spread in distance is equivalent to a dispersion of 0.32 mag in distance modulus. Compared to the range of 4 mag for total magnitudes and 7 mag for bulge magnitudes, this is sufficiently small that it has been ignored in combining the data for different clusters.

A computer program was written to measure the equivalent widths of the spectral features [O II], K, H + Hϵ, Hδ, G, Hγ, Hβ, [O III], and the Mg 'b' triplet. The bands defining these indices, given in Table II, are typically 20 Å wide for the feature and 20–70 Å wide for each of the two continuum intervals. Because these features are defined locally, the fact that the spectra were not reduced to relative fluxes is unimportant. This is not the case with the wider break index D(4000), which has been defined following Bruzual (1983) as the ratio of the average flux density F_ν in the bands 4050–4250 Å and 3750–3950 Å. Because of this wider 500 Å spread, D(4000) is not strictly local but is actually a narrow-band color. Therefore, it is necessary to have at least a crude conversion to relative fluxes and to correct for atmospheric extinction. A more narrowly defined index would have relaxed these requirements but would have been less accurate due to a smaller number of photons and also would have been difficult to compare with previous work. Figure 1 shows examples of typical spectra with break amplitudes of 2.14 and 1.41.

Three of the observing runs had exposures of at least one flux-standard star on four or more nights. With these data we verified that the instrumental response function remained sufficiently stable as long as the operating parameters (voltages, alignment, etc.) remained unchanged. Fortunately, seven of the observing runs that met this condition contained 74% of our total sample. In order to recover the raw counts for each night, we next had to undo the division by the tungsten-lamp spectrum (since no attempt had been made to repeat this procedure from night to night in a rigorously controlled way). This was accomplished by reducing six spectra from each night without dividing by the tungsten spectrum, and comparing the D(4000) index for the divided and undivided spectra. This resulted in a multiplicative correction factor that was applied to all scans for that night. The uncertainty in these correction factors is $\lesssim 1\%$. We also corrected for atmospheric extinction when the airmass exceeded 1.4; however, this correction was never more than a few percent.

Two methods were used to combine the seven data sets. For a few of the runs, standard stars were available to provide a relative flux calibration. These runs were used to establish the zero point of the entire data set; therefore the derived D(4000) values should correspond to the ratio of F_ν fluxes as defined above. For those runs without a flux calibration, the median value of D(4000) was determined and then a multiplicative correction, typically 10%–20%, was applied to bring each set into agreement with those having the flux calibration. We estimate that the individual runs were combined to an rms accuracy of $\lesssim 5\%$, and that the zero point of the D(4000) index is of that order. The entire process seems to have been successful, judging from the plots of bulge luminosity vs D(4000) (Fig. 2) for each individual

TABLE I. Clusters in the sample.

Cluster	z	Velocity interval (km/s)	N (cluster)	N (field)
Abell 548	0.040	10 000–15 000	89	1
Abell 754	0.054	14 000–19 000	82	7
Abell 1631	0.053	12 000–16 000	71	2
Abell 1644	0.049	11 000–18 000	91	11
Abell 1736	0.048	9000–11 500	60	7
	0.035	11 500–16 000	33	
Abell 1983	0.046	12 000–15 000	49	15
Abell 2151	0.036	9000–13 000	39	3
DC 0003-50	0.035	9500–11 500	34	21
DC 0428-53	0.041	10 000–15 000	84	14
DC 0559-40	0.049	11 000–17 000	78	7
DC 0608-33	0.035	10 500–12 500	23	21
DC 2048-52	0.046	11 000–16 000	93	15

TABLE II. Wavelengths for spectral indices.

	Continuum	Feature	Continuum
[O II]	3653–3718	3718–3738	3738–3803
K	3895–3915	3924–3944	4000–4020
H + Hϵ	3895–3915	3958–3978	4000–4020
Hδ	4055–4080	4091–4111	4120–4145
G	4230–4270	4280–4320	4360–4400
Hγ	4230–4270	4330–4350	4360–4400
Hβ	4786–4851	4851–4871	4871–4939
[O III]	4874–4939	4997–5017	5017–5082
D(4000)	3750–3950		4050–5250

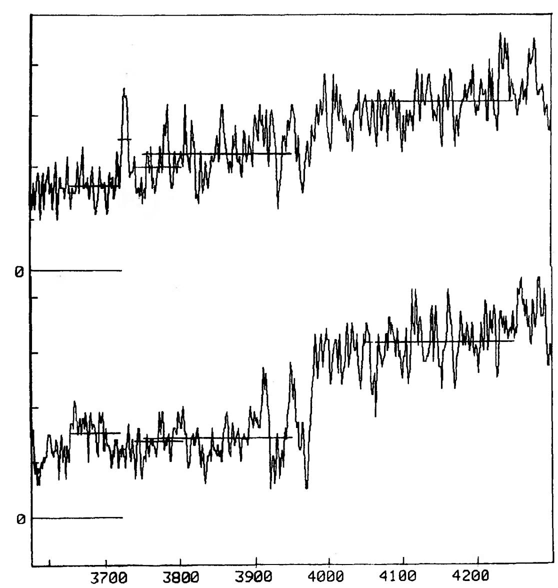

FIG. 1. Typical spectra from the sample. For the upper spectrum the 4000 Å break index D(4000) is 1.41, defined by the ratio of the two long horizontal lines. The bands defining the strong [O II] emission are also marked. The lower spectrum has a larger break index, D(4000) = 2.19.

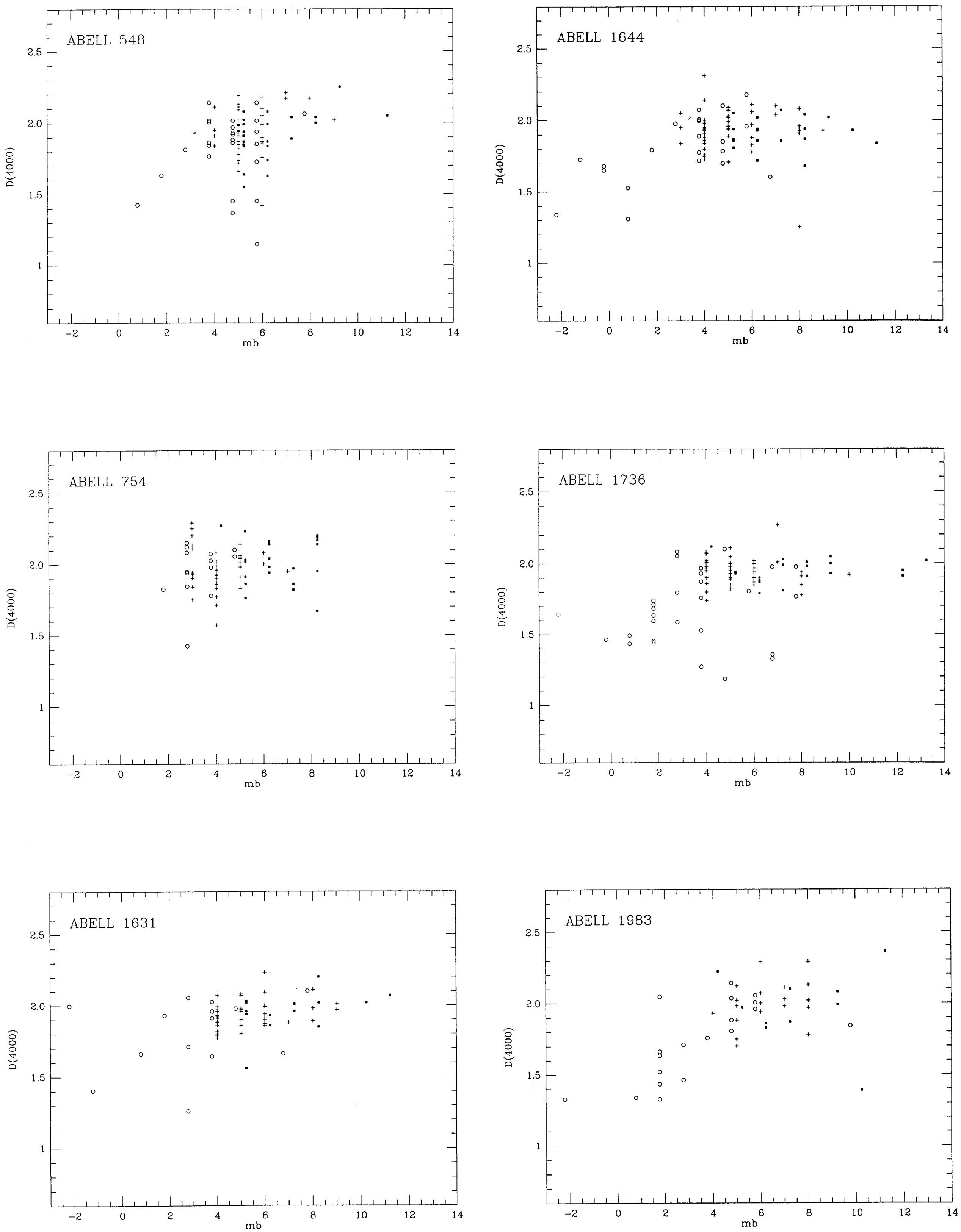

FIG. 2. $D(4000)$ plotted versus bulge magnitude for each cluster. For Dressler's (1980) *mb* scale, $\Delta mb = 2$ corresponds to a change of roughly one magnitude. The brightest galaxies in the sample (right) have $mb \sim 12$, or bulge magnitudes $m_v \sim 12.0$. The different symbols show different morphological types—dark squares: ellipticals; plus signs: S0's; light circles: spirals. These have been slightly offset for clarity.

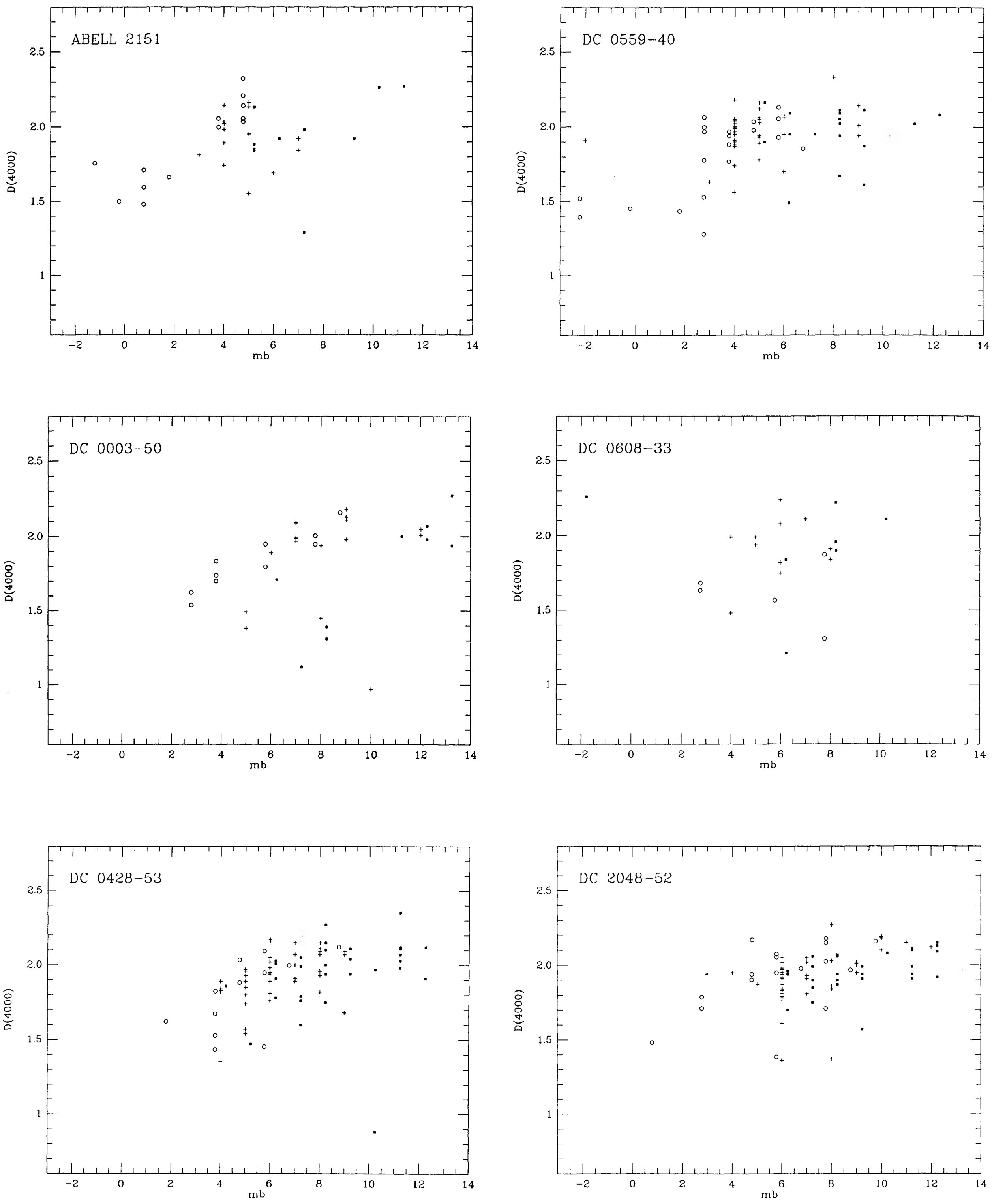

FIG. 2. (continued)

cluster. Although some clusters were observed on only one run, while others were observed on several runs, these plots all show the same general relationship and an upper envelope of $D(4000) \sim 2.3$. What differences are seen are clearly a result of different mixes of morphological type, as demonstrated by the use of different symbols in the plots for elliptical, S0, and spiral galaxies. (The symbols have been offset slightly for clarity.) The implications of these data are discussed below.

III. RESULTS AND INTERPRETATION

We start by investigating the correlation of $D(4000)$ with total galaxy magnitude. In Fig. 3(a) we show the data for the cluster sample divided into subsamples of ellipticals, S0's, and spirals. The first thing to note is that the points fill a triangular region in which the maximum break amplitude of $D(4000) \sim 2.3$ is independent of total luminosity. The points spread to lower values of $D(4000)$, particularly for the fainter spirals, but the median values of $D(4000)$, given in Table III, only change by $\sim 10\%$. The same diagram for the field galaxies (Fig. 3(b)) shows a large scatter (even the brightest galaxies have a large spread in $D(4000)$), and again there is little trend.

Except for a minority of late-type spirals, our data are mostly representative of spheroidal stellar populations like ellipticals and the bulges of disk galaxies. Since the star-formation history of the spheroidal components is likely to be relatively uncoupled from the rest of the galaxy, a plot of $D(4000)$ vs bulge magnitude rather than total magnitude should be a more sensitive test of trends in $D(4000)$ with luminosity. The individual plots of Fig. 2 have been combined to form a cluster sample, shown in Fig. 4(a). A field sample is also shown in Fig. 4(b), but it should be remembered that the distance moduli of these objects have a much greater spread, so that the combining of apparent magnitudes is not really justified, Even if the diagram were made using absolute magnitudes, strong selection effects would be present in the field sample that are not in the cluster sample.

Figure 4(a) contains two interesting results. The first concerns the very weak trend in $D(4000)$ as a function of luminosity. There is a well-defined upper envelope of $D(4000) \sim 2.3$ and even the median values, given in Table IV, change very little for the elliptical and S0 galaxies from $mb = 3$ to $mb = 13$ ($\Delta m_v = 5$ mag). The second result is that the bulges of spirals have, on average, much lower values of $D(4000)$. In fact, with the exception of some of the larger bulges that seem to mimic the ellipticals and S0's, their distribution looks very different.

What does the weak dependence of $D(4000)$ on bulge luminosity tell us about the sensitivity of the index to metal abundance? Our data cover a range of spheroidal luminosity of $-19 > M_B > -24$ and the typical radius sampled is about 2 kpc. The faint limit is comparable to the luminosity of the bulge of our galaxy. Studies of the metal abundance in

TABLE III. Break amplitude dependence on total magnitude.

V	All N $D(4000)$	E N $D(4000)$	S0 N $D(4000)$	Sp N $D(4000)$
12	3 2.08	2 2.14	0	1 2.09
13	40 2.07	23.1.11	9 2.11	8 1.84
14	134 1.96	40 2.00	51 1.96	41 1.80
15	367 1.93	71 1.98	169 1.95	124 1.75
16	282 1.93	77 1.90	172 1.94	30 1.92

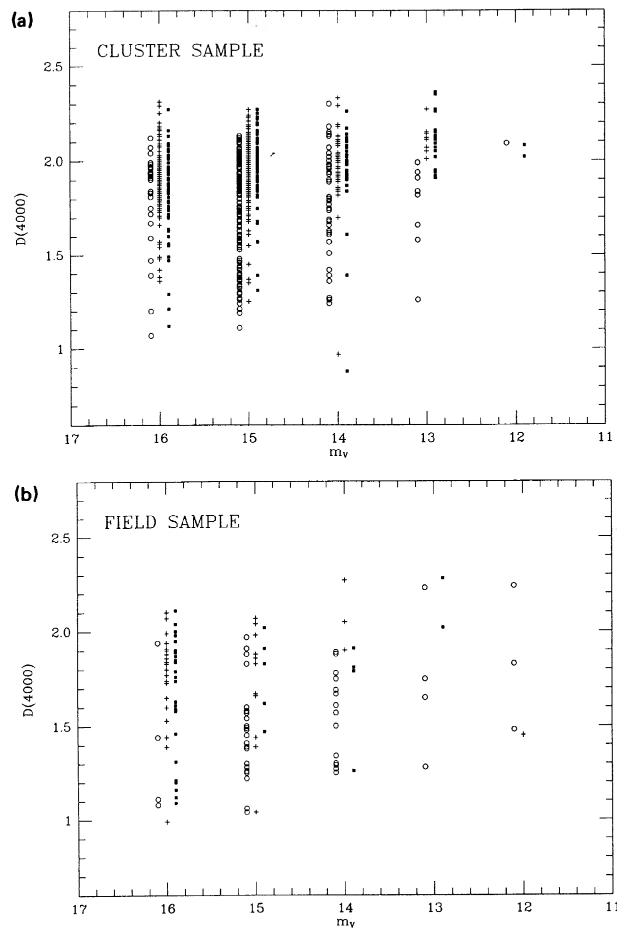

FIG. 3. (a) Total apparent V magnitude vs $D(4000)$ for all 826 cluster galaxies. The distance modulus of the sample is approximately $(m - M) \sim 38$. Separation by morphological type is done as in Fig. 2. The figure shows an upper envelope of the $D(4000)$ index independent of absolute luminosity, but a spread to lower values for fainter galaxies, particularly spirals. (b) Same as (a) for the 124 field galaxies.

the Galactic spheroid (see Rich 1986 and references therein) show an order-of-magnitude spread in metal abundance, but an average value of solar is certainly appropriate. From population-synthesis models it appears that the most luminous ellipticals, like M87, have average abundances of several times solar. Thus our sample spans a range in metal abundance of 2–3, over which we see an approximately 10% change in $D(4000)$. Over the same range, the Sandage and Visvanathan (1978) data show a $U - V$ color gradient of 0.5 mag for cluster ellipticals but considerably less for cluster S0's and group members of all types. On average, then, the change in $U - V$ seems to be a 30%–40% effect, much larger than we find for $D(4000)$. This is at least partly explained by the wider baseline, since the V band is basically unblanketed (see Wildey *et al.* 1961) while both sides are subject to substantial blanketing in the case of the $D(4000)$ index. This accounts for about half of the difference in sensitivity to metal abundance for the two indices, but does not seem to account for it all. Similarly, there seems to be no upper envelope of the $U - V$ colors the way there is for the $D(4000)$ index. Thus it remains somewhat of a mystery why the $U - V$ color has a stronger and qualitatively different de-

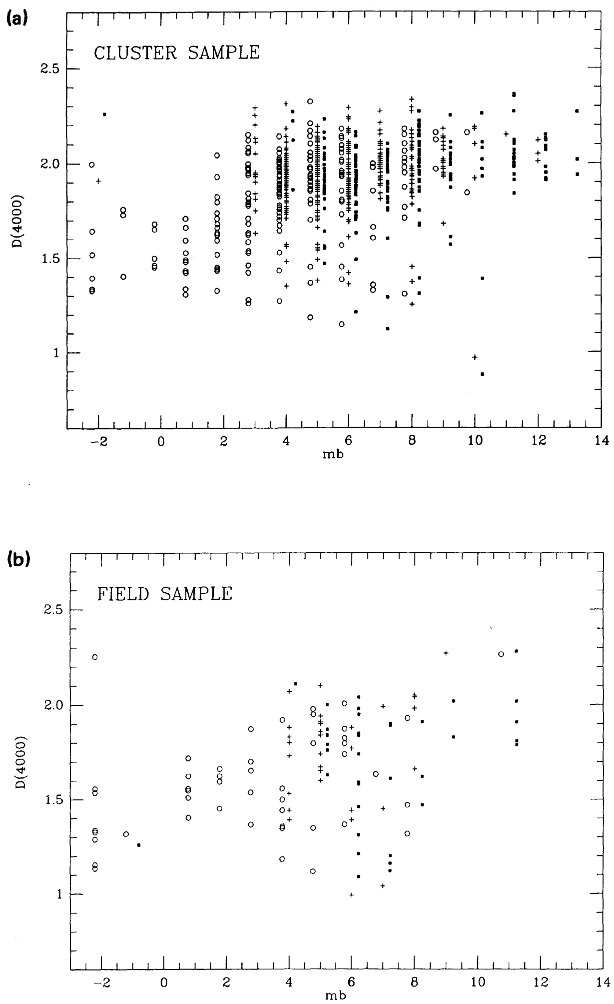

FIG. 4. (a) Same as Fig. 2 for all of the clusters combined. The $D(4000)$ index shows no strong trend with bulge luminosity over two orders of magnitude, except for a scattering at low values in the bulges of many spirals. As shown in Fig. 5(a), these lower values of $D(4000)$ can be attributed to recent star formation or a nonthermal continuum. The upper envelope and weak trend in $D(4000)$ for both ellipticals and S0 bulges indicates that $D(4000)$ is only a weak function of metal abundance over the range found in such systems. (b) Same as (a) for the 124 field galaxies.

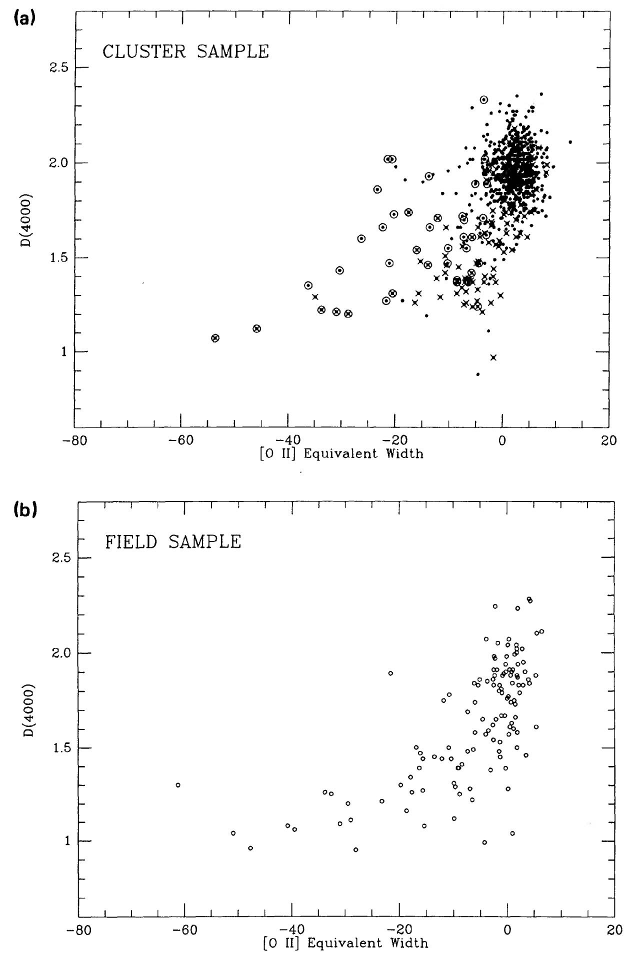

FIG. 5. (a) $D(4000)$ vs [O II] equivalent width in angstroms. Cases of small $D(4000)$ are usually associated with strong emission indicative of ongoing star formation or dilution of the break amplitude by a nonthermal continuum. Other cases of small $D(4000)$ with little or no emission are apparently galaxies in which the star-formation rate was recently high (as indicated by the ×'s, where H + Hε > K) but has suddenly declined. The light circles mark cases of high-excitation emission, many of which are active nuclei. (b) Same as (a) for the 124 field galaxies.

TABLE IV. Break amplitude dependence on bulge magnitude.

mb	*V*	All *N D*(4000)	E *N D*(4000)	S0 *N D*(4000)	Sp *N D*(4000)
13	12.5	3 2.02	3 2.02	0	0
12	13.0	15 2.07	12 2.08	3 2.05	0
11	13.5	19 2.07	18 2.06	1 2.15	0
10	14.0	16 2.05	9 2.03	5 2.10	2 1.96
9	14.5	40 2.01	19 1.99	18 2.01	3 2.09
8	15.0	91 1.96	42 2.00	37 1.94	12 1.95
7	15.5	64 1.96	28 1.93	28 2.02	8 1.71
6	16.0	153 1.93	41 1.92	86 1.94	26 1.91
5	16.5	173 1.94	36 1.92	104 1.95	33 1.94
4	17.0	151 1.91	4 2.17	102 1.92	44 1.85
3	17.5	46 2.08	0	16 1.95	30 1.75
2	18.0	20 1.76	0	0	20 1.58

pendence on luminosity than the $D(4000)$ index. It would be useful to have a much larger set of color data over apertures similar to those used here to validate this difference. High-dispersion spectra of K giants with a range of metal abundance might also be helpful in inferring the amount of blanketing expected.

The fact that unusually low values of $D(4000)$ are generally found for spiral bulges suggests that star formation is responsible, since ellipticals and S0 bulges rarely show signs of recent star formation. This suspicion is readily verified by Fig. 5, which plots $D(4000)$ vs [O II] equivalent width. The general trend is quite clear in that galaxies with strong [O II] emission, commonly associated with ongoing star formation or an active nuclear region, have low values of $D(4000)$. This is not surprising, since a contribution from hotter stars or a nonthermal continuum will necessarily lower $D(4000)$.

However, there are galaxies with little or no emission that also have low values of $D(4000)$, seen below the main cluster of points in Fig. 5(a). These are galaxies in which star formation has occurred recently but is not ongoing. This is demonstrated by the fact that in these cases the equivalent width of H + Hϵ is greater than the equivalent width of K (marked by X's in Fig. 5(a)), whereas in the main body of the data (upper right) the opposite is true. A stronger contribution by Hϵ indicates greater numbers of hotter A and F stars in the galaxy, the remnants of earlier, now defunct, star formation. These are mild cases of the post-starburst phenomenon discussed by Dressler and Gunn (1983). Thus these low values of $D(4000)$ without strong emission are explained by the presence of hotter stars from recent star formation.

Of those galaxies with strong emission, most have strong Balmer absorption as well. These are undoubtedly cases of active star formation. However, there are also a few cases with strong [O II] emission which is likely instead to be due to an active nucleus where a strong central source ionizes the gas. A signature of such AGN activity is a high-excitation emission spectrum where, for example, [O III] > Hβ. These points are circled in Fig. 5(a). Many of these were, in fact, identified as Seyfert 1 and 2 galaxies by Dressler, Thompson, and Shectman (1985). It is particularly interesting to note the subset of these for which there is strong [O II] yet a large $D(4000)$. These are probably cases in which the emission comes from a nonthermal source that is sufficiently obscured by dust that the nonstellar continuum is too weak to diminish the break amplitude.

In summary, we have found that the dependence of the 4000 Å break amplitude on luminosity is very weak, as Hamilton suggested. There is a strong dependence on morphological type, but on further investigation this seems entirely due to a correlation of the break amplitude with recent star formation. Exceptions to this general trend are easily understood as cases where star formation has rapidly declined or where nuclear activity is responsible for emission lines in the spectra. The insensitivity to luminosity and well-understood dependence on star formation are very encouraging for use of the $D(4000)$ index in studies of distant galaxies at large lookback times. Since the main aim in this type of work is to look for effects due to an evolving stellar population, and a principal complication is selection bias by luminosity, this index is ideally suited for the task. The data presented here provide a firm statistical base for the sample at zero redshift. Measurements of $D(4000)$ for galaxies in clusters with $z > 0.5$ (Dressler 1987) should be decisive in demonstrating the evolution of stellar populations in the Big Bang model.

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