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$B - V$ COLOR PROFILES OF THE LUMINOUS ELLIPTICAL GALAXIES NGC 4472 AND NGC 5846 AND THE cD GALAXY NGC 6166

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ABSTRACT

$B - V$ color profiles to low surface brightness are presented for the normal giant elliptical galaxies NGC 4472 and NGC 5846 and the cD galaxy NGC 6166. Compared to the ellipticals, the cD shows a larger gradient and a somewhat bluer outermost envelope. This behavior would seem most consistent with models for cD formation in which the extended halo is either captured tidal debris torn from the outer regions of cluster members during high-velocity encounters or the remains of lower-luminosity galaxies. Although the present small sample and the limited accuracy of measurement do not warrant firm conclusions, color profiles of cD galaxies seem a promising attack on the problem of cD origin.

Subject headings: galaxies: individual — galaxies: photometry — galaxies: structure

I. INTRODUCTION

The giant spheroidal systems known as cD galaxies are distinguished from normal elliptical galaxies by their immense envelopes of low surface brightness (Morgan, Kayser, and White 1975; Oemler 1976). cD's are the most luminous members of many rich clusters of galaxies (e.g., R. A. White 1978). Several studies have shown that cD galaxies occur preferentially in clusters when the space density of galaxies is highest (Oemler 1974; Dressler 1978*a*, *b*; van den Bergh and deRoux 1978). This tendency, plus the fact that cD galaxies are often located near the cluster core, has led many authors to speculate that cD galaxies were formed as a result of interactions between cluster members.

According to one line of reasoning, cD's were produced through the outright merger of the most massive cluster members, which are imagined to have spiraled to the center as a result of dynamical friction (e.g., Ostriker and Tremaine 1975; Gunn and Tinsley 1976; Sastry and Alladin 1977; Hausman and Ostriker 1978). N-body simulations of clusters (White 1976) strongly confirm that dynamical friction should act efficiently to drag the most massive cluster members into the core within just a few cluster crossing times, after which point mergers appear to be an inevitable consequence. This scenario could account in a natural way for the peculiar luminosity functions of cD clusters (Dressler 1978*a*), which apart from the cD itself are systematically deficient in bright galaxies. The multiple cores present in many cD's (e.g., Jenner 1975) would then represent the latest stages in the merger of two or more galaxies.

Alternatively, it has been suggested that high-velocity encounters between cluster members will lead to tidal stripping of outer envelopes throughout the cluster (Gallagher and Ostriker 1972; Richstone 1976). This tidal debris might then be captured by a central, massive galaxy, leading to the formation of an extended envelope of low surface brightness.

Finally, of course, it is possible that cD's were not produced through interaction at all but simply represent normal statistical fluctuations in the luminosity function for ordinary elliptical galaxies. A number of authors have analyzed the absolute-magnitude distribution of cD galaxies with a view to testing this hypothesis, but no unanimous consensus has as yet emerged (Geller and Peebles 1976; Sandage 1976; Tremaine and Richstone 1977; Dressler 1978*b*; Schechter and Peebles 1976; Godwin and Peach 1979).

These three hypotheses for the origin of cD galaxies apparently predict rather different color gradients within the low-surface-brightness envelopes. For example, S. D. White (1978) finds from N-body simulations that radial mixing of stars during mergers is significant. If cD's formed as a result of mergers of massive cluster members, we might therefore expect them to display flatter color gradients in the envelopes than normal giant ellipticals. On the other hand, tidal debris would be stripped from the outer regions of galaxies less massive than the central object. Because of the well-known relationship between color and absolute magnitude for elliptical galaxies (Sandage 1972; Faber 1973), we expect this material to be systematically bluer than the nuclear region of the

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accreting massive galaxy, particularly so if the envelopes of the tidally truncated galaxies have color gradients of their own. Thus the tidal stripping picture might suggest color gradients in cD's that are stronger than those of normal ellipticals. Finally, if cD's are simply normal ellipticals of high luminosity, their envelope color gradients ought not to differ significantly from those of other giant elliptical galaxies.

Very little is known at present about color gradients in the outer envelopes of normal ellipticals or cD's. Faber, Burstein, and Dressler (1977) obtained a spectrum at a radius of 43 kpc in the cD located in the Abell 401 cluster. The line strength was low relative to the nucleus, implying that the halo is significantly bluer than the inner regions. However, no measurements of normal giant ellipticals at comparably low surface brightness were available for comparison.

Here we report results from an exploratory attempt to determine the broad-band color profiles of E and cD galaxies at very low surface brightness. We compare $B - V$ colors for the cD NGC 6166 in Abell 2199 with those of the normal luminous ellipticals NGC 4472 and NGC 5846. Our results suggest that measurements such as these are a promising line of attack of cD formation but that data of high quality on many more galaxies must be obtained before a clear conclusion emerges.

II. OBSERVATIONS

A variety of problems confront efforts to obtain photometric measurements at a surface brightness level below that of the night sky, including confusion by faint stars or galaxies, scattered light in the telescope, detector stability, and spatial and temporal variations in the airglow. Many of these difficulties may be minimized by making rapid differential measurements between the object and a sky reference position chosen to be empty on the Palomar sky survey prints. Such measurements can be accomplished using a single-channel, pulse-counting photometer in conjunction with a chopping secondary mirror (Gallagher and Hudson 1976*a*, *b*). The field of view of the photometer is then switched at a rate of 1–10 Hz between the object and a sky position symmetrically located about the telescope's optical axis. Scattered light and light loss are both small since the optical system is quite simple.

We derive an expression for the time t_s to reach a signal-to-noise ratio S/N based on errors from photon statistics alone. Let R_s be the observed mean sky count rate in s^{-1} ($R_s \gg$ dark rate) with a given aperture-filter-telescope-photometer combination. Suppose that we measure part of the galaxy with surface brightness GR_s. Then

$$\mathrm{S/N} = G\left(\frac{R_s t}{2 + G}\right)^{1/2}, \qquad (1)$$

where t is the integration time. The time to reach a specific S/N is

$$t_s = \frac{(2 + G)(\mathrm{S/N})^2}{G^2 R_s}. \qquad (2)$$

Thus $t_s \propto G^{-2}$ for $G \ll 1$. Since equation (1) gives a good description of our best data (see below), the assumption that errors are due to photon statistics appears to be valid for beam-switched photometry (also see Davidson 1977). Equation (2) indicates that most of the time is spend on the point of lowest surface brightness. For this reason we chose not to employ the FASTSCAN technique used by Strom and Strom (1978*a*) for our program.

The first set of observations was obtained with the UCSD–University of Minnesota 1.5 m telescope on Mount Lemmon during the week of 1976 May 22–29. An EMI 9558QA S-20 photomultiplier tube was used with pulse-counting electronics and all-glass *BVR* filters. Because of an electronics problem with the least significant bits in the data acquisition package, the accuracy of these data was somewhat reduced. The chopping secondary on the UCSD–UM 1.5 m allows throws of up to 7′, and sky reference positions were typically 3′–6′ from the galaxy positions. In other respects, the observing procedure was identical to that described by Gallagher and Hudson (1976*b*).

A second series of measurements was made on 1978 May 4 with the Kitt Peak National Observatory 1.3 m telescope. The Kinman Mark 2 computer-controlled photometer on the 1.3 m allowed B and V measurements to be interwoven over short time intervals, and a longer throw of $\sim 15'$ for the chopping secondary was available. Reference positions were thus typically 8′–10′ from the galaxies. An Oke-modified S-20 ITT FW 120 phototube was used. As a test of this system's performance, blank sky was observed and no signal was found to a 1 σ level of $\mu_V \approx 28.5$. We also checked the possibility that galaxy observations at large radii might be contaminated by scattered light from the bright central regions by determining the instrumental response as a function of radius for a bright star. These measurements, made on a night of mediocre quality, and a more extensive set of observations taken under better conditions by T. D. Kinman (private communication) indicate that scattered light was not an important factor in our data.

For both sets of data, instrumental magnitudes were transformed to the *BV* system using standards chosen from Landolt (1973). The Mount Lemmon $V - R$ colors were placed on the Johnson system using preliminary standards supplied by W. E. Kunkel (private communication). Results are presented along with other relevant data in Table 1, where errors are derived from comparison of multiple observations. Colors are often more accurate than total magnitudes, being less affected by changes in centering between different observations. We also note that μ_v is less certain than V because of possible errors in determining the effective areas of diaphragms.

The agreement between the Mount Lemmon and KPNO data is excellent. In comparison to the $B - V$ colors of Sandage (1973) and de Vaucouleurs and de Vaucouleurs (1972), our values for NGC 6166 and NGC 5846 appear to be bluer by a few hundredths of a magnitude. However, when compared with Tifft's

TABLE 1

OBSERVATIONS OF $B - V$ COLORS IN ELLIPTICAL GALAXIES

OBJECT	TYPE	TEL	AP	POS	V	B−V	V−R	μ_V	E(B−V)	E(V−R)	K_{B-V}	K_{V-R}	$(B-V)_o$	$(V-R)_o$	X	r_{eq}	R_{eq}	D	M_V
NGC 4472	E2	1.5 m	28.″3	nucleus	11.00 ±.02	1.059 ±.013	0.865 ±.009	17.99	0.00	0.00	.009	.003	1.05	0.86	---	---		22 Mpc	−23.4
		1.3 m	58.6	nucleus	10.07 ±.01	0.998 ±.008	---	18.65					0.99	---	---	---			
		1.5 m	28.3	1	12.08 ±.02	0.957 ±.025	0.863 ±.019	19.07					0.95	0.86	30″	27″	2.9 kpc		
		1.5 m	28.3	2	13.71 ±.03	0.960 ±.025	0.816 ±.019	20.70					0.95	0.81	60	54	5.7		
		1.5 m	28.3	3	14.85 ±.04	1.029 ±.034	0.816 ±.029	21.88					1.02	0.81	96	86	9.2		
		1.3 m	58.6	4	15.96 ±.02	0.96 ±.06	---	24.54					0.95	---	438	394	42		
NGC 5846	E0	1.5 m	28.3	nucleus	12.06 ±.02	1.050 ±.024	0.911 ±.019	19.05	0.03	0.04	.02	.006	1.00	0.87	---	---	---	36	−22.6
		1.5 m	28.3	1	14.25 ±.02	1.052 ±.027	---	21.24					1.00	---	38	38	6.6		
		1.5 m	46.1	2	14.36 ±.02	1.067 ±.028	---	22.41					1.02	---	76	76	13.3		
NGC 6166	cD	1.5 m	9.3	nucleus	15.41 ±.03	1.101 ±.032	---	20.0	0.00	0.00	.09	.03	1.01	---	---	---	---	181 $\lesssim$	−24.3
		1.5 m	28.3	nucleus	13.50 ±.01	1.064 ±.007	0.881 ±.005	20.49					0.97	0.85	---	8	7		
		1.3 m	35.6	nucleus	13.27 ±.03	1.035 ±.02	---	20.76					0.95	---	---	16	14		
		1.5 m	28.3	1	14.99 ±.02	1.035 ±.02	0.820 ±.021	21.98					0.95	0.79	25	18	16		
		1.5 m	28.3	2	15.42 ±.03	1.056 ±.036	0.818 ±.023	22.41					0.97	0.79	35	25	22		
		1.3 m	35.6	3	15.00 ±.01	1.003 ±.010	---	22.50					0.91	---	34	25	22		
		1.5 m	28.3	4	16.47 ±.03	0.996 ±.035	---	23.46					0.91	---	59	32	22		
		1.3 m	35.6	5	17.36 ±.02	1.001 ±.046	---	24.86					0.91	---	117	90	79		

(1969) photometry of NGC 4472 and NGC 5846 transformed to the $B - V$ system using a calibration supplied by Burstein (unpublished data), our colors are about 0.02 mag too red. Corrections for galactic extinction were made following the suggestions of Burstein and Heiles (1978, and unpublished data), and K-corrections are from de Vaucouleurs, de Vaucouleurs, and Corwin (1976, hereafter RC2) or from Sandage (1973). Other aspects of Table 1 are discussed in § III.

III. RESULTS

NGC 4472.—Probably the most luminous member of the Virgo cluster (Visvanathan and Sandage 1977), NGC 4472 typifies a giant elliptical galaxy. In Table 1, X gives the projected galactocentric position of the observations which were taken on the major axis and r_{eq} is the equivalent radius of the observations using an ellipticity of 0.2 from the type E2 given in the RC2. All dimensions are based on a distance of 22 Mpc for the Virgo cluster (Sandage and Tammann 1976) ($H_0 = 50$ km s^{-1} Mpc^{-1}). Absolute magnitudes are based on B_T and $(B - V)_T$ in the RC2 plus our corrections for redshift and galactic extinction.

$B - V$ is plotted as a function of μ_v in Figure 1 and versus equivalent radius in Figure 2. NGC 4472 shows no detectable gradient in $B - V$ outside of the central region, which is redder than the rest of the galaxy. This type of color variation with radius is normal in elliptical galaxies (Tifft 1969) and usually is ascribed to a change in metallicity with radius (Faber 1977; Sandage and Visvanathan 1978*a*).[3]

[3] Tifft has found that at very small radii, NGC 4472 becomes bluer and thus is a member of his Ep class. However, exterior to the nuclear region, the color gradient appears normal.

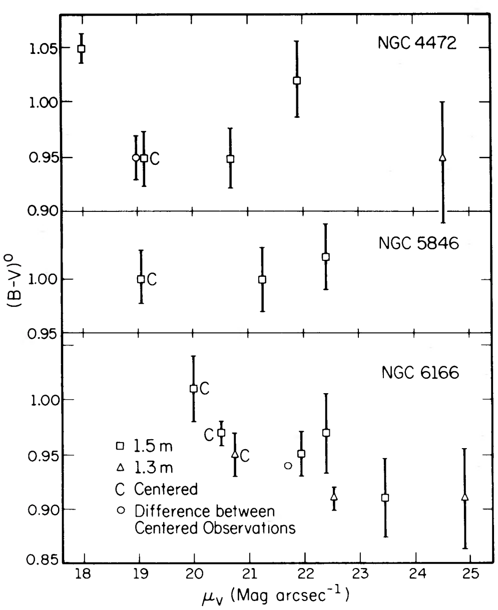

FIG. 1.—$(B - V)^0$ colors of program galaxies as a function of visual surface brightness. Error bars are $\pm 1\ \sigma$ from statistics of multiple observations.

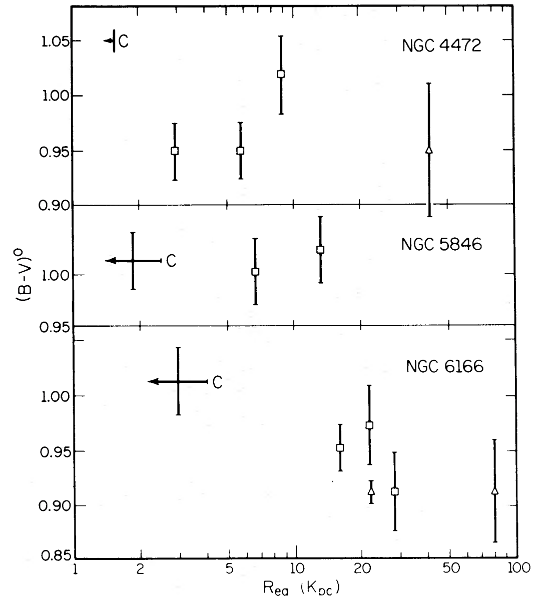

FIG. 2.—The same data as shown in Fig. 1 plotted as a function of equivalent radius. Symbols are also the same as in Fig. 1. See text for the methods used to find effective radii; large-aperture centered points are not plotted since it is difficult to assign appropriate effective radii.

Strom and Strom (1978*a*, *b*, *c*) have also found that color gradients are relatively uncommon in the outer envelopes of cluster elliptical galaxies. The asymptotic color $(B - V)^0$ is 0.95, compared to $(B - V)_T{}^0 = 0.94$ from the RC2. From Table 1 we estimate that $(B - R)_T{}^0 = 1.76$ for the envelope. The color distribution in NGC 4472 can be taken to be representative of the most common type of luminous elliptical.

NGC 5846.—This E0 is the dominant member of the NGC 5846 group (de Vaucouleurs 1975). Unlike NGC 4472, NGC 5846 does not show a central reddening in color, and thus is probably an example of the Tifft (1969) Eb class, some members of which are characterized by a nearly neutral central color gradient. Although the observations do not extend to as low a surface brightness as in NGC 4472, there is no indication for any radial change in $B - V$, and thus we have $(B - V)^0 = 1.00$ [as compared with $(B - V)_T{}^0 = 0.95$ using RC2 data] while $(B - R)^0 = 1.87$. To within the accuracy of the observations and color corrections, NGC 5846 is certainly not bluer and is probably slightly redder than NGC 4472, even though NGC 4472 is 0.7 mag more luminous. It is well known that the color–absolute-magnitude relationship for ellipticals shows a significant amount of scatter (e.g., Sandage and Visvanathan 1978*a*, *b*); the slightly redder color of NGC 5846 is therefore not a peculiarity but merely an example of the cosmic noise in the color–absolute-magnitude correlation.

NGC 6166.—An archetypal cD galaxy (Morgan and Lesh 1964), NGC 6166 dominates the A2199 cluster, for which we take $D = 181$ Mpc on the basis of the velocities given by Tifft (1974). The nuclear structure is complex; four components were identified by

Minkowski (1961). Three are relatively compact and could be interpreted as remnants of galaxies captured by NGC 6166, while the fourth seems to be the extended, low-surface-brightness core of the main body. All the components lie within a region of about 15″, or 13 kpc, and are therefore included in the 28″.4 and 35″.6 diaphragms. Observations at $X \lesssim 15''$ might therefore be complicated by the multiple nuclear structure, and the possibility exists that the red colors are associated with the compact components. This, however, seems unlikely, as Faber has obtained an absorption line strength measurement with the Wampler-Robinson IDS on the Lick 3 m telescope for the diffuse component alone and finds strong lines which are characteristic of a metal-rich stellar population. The brightest compact component, NGC 6166 A, is definitely more metal poor than the diffuse core of NGC 6166 and has line strengths which are weaker than NGC 3379, suggesting that it is not the remains of a formerly luminous elliptical.

The absolute magnitude of $M_V = -24.3$ in the table is a lower limit. Oemler (1976) finds $M_V = -24.9$, while Carter (1977) suggests that the total light from NGC 6166 has not converged at a brightness level of $\mu_V \approx 28$. Since our apertures are of significant size in NGC 6166, we have determined r_{eq} from the observed surface brightness using Oemler's plot of μ_V versus r_{eq} given in his Figure 5.

The color data shown in Figures 1 and 2 suggest that NGC 6166 has a red center with $(B - V)^0 = 1.01$ and $(B - R)^0 = 1.86$ and that the color declines smoothly to the envelope, where $(B - V)^0 = 0.91$ and (with less accuracy) $(B - R)^0 \approx 1.70$. While the central regions have normal colors for a giant elliptical, the outer regions are apparently slightly too blue in both the $(B - V)^0$ and $(B - R)^0$ colors. The difference in $(B - V)^0$ amounts to 0.03–0.07 mag, with considerable uncertainty, however.

IV. DISCUSSION

The observations present a complicated picture, particularly in view of the fact that the two normal ellipticals differ from one another, NGC 4472 showing a core gradient while NGC 5846 does not. The data do suggest, however, that the overall gradient in NGC 6166 is larger than in the normal ellipticals, and further that the outermost envelope in NGC 6166 is bluer than the envelopes of the two normal objects. As an additional comparison, $(B - V)^0$ colors for a number of other members of A2199 are collected in Table 2. These data indicate that for typical luminous members of the cluster, $\langle (B - V)^0 \rangle = 0.96 \pm 0.02$, similar to NGC 4472 and NGC 5846 but again somewhat redder than the envelope colors of the cD.

Taken at face value, these findings seem most consistent with a model in which a massive galaxy has grown at the expense of smaller, bluer galaxies. This could occur by the tidal stripping process, according to which the extended halo of the cD would consist of shorn off outer regions of many small galaxies. The merger process between massive equals as proposed by Ostriker and his collaborators would predict a color gradient which would be at most the order of magnitude of the average color gradient of the galaxies captured to produce the cD. Although the size and frequency of color gradients in members of clusters of galaxies are still not well determined (see Strom and Strom 1978*a*, *b*, *c*), preliminary evidence would suggest that the gradients are too small to produce the color variations in NGC 6166. It therefore is not clear whether mergers between massive galaxies could have been responsible for the creation of this cD. In view of the small number of objects in the present sample and the limited accuracy of our measurements, these suggestions concerning the origins of cD galaxies are exceedingly tentative. However, our result is in qualitative agreement with the Stroms' finding that large color gradients occur preferentially in luminous cluster galaxies with extended, low-surface-brightness halos (Strom and Strom 1978*a*, *b*, *c*).

On the basis of *N*-body simulations, S. D. White (1978) has also argued against mergers as the origin of cD galaxies. His merger products have cores more centrally condensed and of higher surface brightness after coalescence, in contrast to the cores of cD's,

TABLE 2

$B - V$ COLORS OF A2199 CLUSTER MEMBERS

Galaxy	Type	Ap. Diam. (arcsec)	Source[a]	V	$B - V$	$(B - V)_0$	M_V[b]
NGC 6166	cD	35.3	SS	13.33	1.09	1.00	$\lesssim -24.3$
		35.6	1.3 m	13.27	1.04 ± 0.02	0.95	
NGC 6158	E	28.3	1.5 m	14.61	0.96 ± 0.03	0.87	−23.0
		35.3	SS	14.00	1.04	0.95	
SS 9	S0	17.7	SS	15.61	1.05	0.96	−20.9
SS 17	E	28.3	1.5 m	14.92	1.07 ± 0.03	0.98	−21.6
SS 25[c]	E	28.3	1.5 m	15.35	1.15 ± 0.04	1.06	−20.8
SS 26	E	18	1.5 m	15.47	1.01 ± 0.03	0.92	−22.1
		28.3	1.5 m	14.92	1.02 ± 0.04	0.93	
		35.3	SS	14.76	0.95	0.86	
SS 68	E	17.7	SS	15.18	1.04	0.95	−21.5

[a] SS = Strom and Strom 1978*c* observations with the KPNO 1.3 m telescope.

[b] All M_V, except NGC 6166, from Strom and Strom 1978*c*.

[c] Identification is uncertain.

which are diffuse and have abnormally low surface brightness (Oemler 1976).

Although these new data are suggestive, it is not our purpose in this paper to draw firm conclusions regarding the formation of cD galaxies, which may in the end prove to involve more than one mechanism. We simply note that accurate color profiles of the sort presented here for a significant number of ellipticals and cD's could provide a useful additional clue to the origin of cD galaxies.

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