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THE DYNAMICS AND STRUCTURE OF THE cD GALAXY IN ABELL 2029

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ABSTRACT

Spectra of the envelope of the cD galaxy in A2029 out to over 100 kpc have been obtained with the Hale 5 m and the SIT digital spectrograph. A Fourier cross-correlation program was used to measure the position, strength, and width of the H and K lines of Ca II and the G band. From these data it is concluded that the galaxy is not supported by rotation and that the line strength and implied metal abundance are relatively constant throughout the envelope.

The primary result is that the velocity dispersion is *increasing* as a function of radius in the galaxy, in contradiction with the prediction of constant $\mathfrak{M}/L$ models. A rough dimensional argument suggests that $\mathfrak{M}/L_V$ has risen from its nuclear value of ~ 12 to $\sim 67\ \mathfrak{M}_\odot/L_\odot$ at $R \approx 100$ kpc.

We present a detailed three-component isotropic King model which accounts for the luminosity profile of the cD galaxy and the increasing velocity dispersion, and provides the mass necessary to bind the cluster. The three components are interpreted as (1) a normal elliptical galaxy ($\mathfrak{M}/L_V \approx 10$) which has acquired (2) a halo of luminous material ($\mathfrak{M}/L_V \approx 35$) through the accretion of other cluster members, positioned in the middle of (3) a dark ($\mathfrak{M}/L_V > 500$) cluster-filling and cluster-binding superstructure. This superstructure may be composed of material which at one time belonged to individual cluster galaxies.

The necessity of determining whether cD galaxies are uniquely associated with the dynamical centers of rich clusters is discussed in connection with the model.

Subject headings: galaxies: clusters of — galaxies: internal motions — galaxies: structure

I. INTRODUCTION

The giant cD galaxies which are often found in rich clusters of galaxies (Matthews, Morgan, and Schmidt 1964) are the largest and most luminous stellar aggregations. Despite the considerable attention paid to understanding their nature, it is still unclear whether they are merely extreme examples of normal elliptical galaxies or, alternatively, the result of either a special creation process or evolutionary growth.

Dressler and Oemler in observational studies of the luminosity functions and cluster profiles of cD clusters (Dressler 1978*a*, *b*) and the luminosity profiles of cD galaxies (Oemler 1976) have both argued that cD galaxies represent a special class of objects and not just an extension of the luminosity and structure of normal ellipticals. Several authors (e.g., Richstone 1976; Ostriker and Tremaine 1976; White 1976) have attempted to model the evolution of cD's, starting with a luminous but normal elliptical and adding a halo of material stripped from other cluster galaxies.

This study was motivated by the hope that a description of the dynamics of a cD galaxy, that is, the internal motions of the luminous stellar component, would help settle the question of cD origin. The recent interest in the dynamics of all types of galaxies (e.g., Roberts and Rots 1973; Rubin 1978; Faber and Jackson 1976; Sargent *et al.* 1977) provides a large data base with which to compare the dynamical structure of cD galaxies.

The paper is divided into three parts. Section II deals with the selection of the cD studied. Section III discusses how the data were obtained as well as the analysis technique and results, including tests of the method, error analysis, and internal consistency. Section IV contains a discussion of the results, including a model for the cD, and the implications for the problems of missing mass and dark halos.

II. SELECTION OF THE cD

The rich cluster of galaxies Abell 2029 contains an outstanding example of the cD phenomenon. The luminosity of this giant galaxy $M_V \approx -24.5$, out to a surface brightness of 23.5 mag arcsec^{-2}, qualifies it as one of the most luminous galaxies known, and its extended envelope can easily be traced out to several hundred kiloparsecs.

A2029 has been studied extensively by the author (Dressler 1978*a*, *b*), and thus the luminosity function, structure, and velocity dispersion are available. The cluster is comparable to or richer than the Coma cluster and has a redshift of $z = 0.0778 \pm 0.0003$. The cluster luminosity function is unusually steep at the bright end and deficient in bright galaxies. Furthermore, the cluster appears to have a "core within a core" structure, i.e., a central density spike at the center of a more extended isothermal core. Both of these peculiarities may be the result of the growth of

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the cD by the accretion of cluster galaxies; hence this is an ideal cD for the study of that hypothesis. Additional evidence that the cD has been built from accreted galaxies will be reviewed in § IV.

The velocity dispersion is not well known at present because of the presence of three galaxies of ambiguous membership (Faber and Dressler 1977). Additional redshifts will be needed to obtain a good estimate of σ.

III. DATA AND ANALYSIS

a) The Data

The spectra used for this project were obtained with the Gunn-Oke digital spectrograph on the Hale 5 m telescope at Palomar Observatory. This instrument employs a two-dimensional SIT target (Westphal and Kristian 1976) which provides $\sim$40 spectra of 512 points each. This corresponds to a sky coverage perpendicular to the dispersion of about 1′ with the long slits.

The instrument was used with the 1200 line mm^{-1} grating in first order, which provided a spectral coverage of 3700–5300 Å at $\sim$3 Å per pixel. Most of the data in this study were taken through a 4″ wide slit which degraded the resolution from its nominal 5–6 Å to about 9 Å FWHM. By positioning the nucleus of the cD near one end of the slit (Fig. 1*b*), the spectra of the galaxy were obtained from 7″ NE of the nucleus to 46″ SW, corresponding to a spatial extent of 16 kpc NE to 106 kpc SW assuming $H_0 = 50$ km s^{-1} Mpc^{-1}.

The SIT is not a continuous readout device. Rather, exposures are made for a specified time, and then the accumulated charge on the target is read out and recorded. Therefore, alternate 1800 s exposures were made of the galaxy and nearby sky, with equal time spent on each. On the nights of 1978 May 6–7 and 7–8, approximately 6 hours was spent each night on the galaxy/sky. An additional 0.6 hours with the better resolution of the 2″ slit was kindly provided by Steve Shectman in 1977 July.

The spectra were reduced from the two-dimensional SIT frames using a program written by the author for Ratheon 704 computer. This program enables the user to work in an interactive mode, performing the routine arithmetic manipulations necessary to reduce the two-dimensional frames to calibrated spectral scans. This includes dividing by the flat fields, removing S distortions, and determining wavelength scales. An additional program written by J. Rose allows the determination of absolute fluxes by calibrating to stars with known fluxes. Sample scans of the May 6–7 data are shown in Figure 2 for five regions in the galaxy.

b) Analysis

i) The Program

A Fourier cross-correlation program written by Rose was used to determine the velocity V, velocity dispersion σ, and line strength γ for each spectrum. This program is similar to those used by Illingworth (1973), Simkin (1974), and P. L. Schechter as described in Sargent *et al.* (1977) in which discrete Fourier transforms of objects and templates are compared.

Two differences in the treatment by Rose are worthy of note:

1. The important problem of properly subtracting the continuum shape of the galaxy has been solved by selecting intervals in the spectrum which contain no strong features and then fitting a smooth curve generated by a cubic splines interpolation to these points. This is then subtracted from the original spectrum, effectively removing the power of low frequencies due to trends in the data.

2. The most important decision to be made in constructing a cross-correlation program is the choice of the χ^2 quantity to be minimized, that is, how the object, template, and model are to be weighted and compared. Any quantity involving *ratios* of the Fourier transforms such as $\tilde{G}/\tilde{S}$ (galaxy/star) has the inherent deficiency of weighting certain points too heavily when $\tilde{S}_k \to 0$. That is, even if $\tilde{G}$ and $\tilde{S}$ have normally distributed errors, their quotient will not. Therefore, we have chosen to minimize the quantity

$$\chi^2 \equiv \sum_{k_L}^{k_H} |\tilde{S}_k \tilde{B}_k - \tilde{G}_k|^2 \frac{1}{\langle \tilde{S} \rangle_k} ,$$

where $\tilde{S}_k$, $\tilde{G}_k$, and $\tilde{B}_k$ are the Fourier transforms at frequency k of the template star, galaxy, and model (broadening function, see eq. [2] of Sargent *et al.*), respectively. The transform $\langle \tilde{S} \rangle_k$ is formed by fitting a smooth curve to $\tilde{S}_k$. This weighting eliminates the problem described above and mimics the form of a classical χ^2 determination. We have chosen $\langle \tilde{S} \rangle_k$ rather than $\langle \tilde{G} \rangle_k$ because experimentation indicated that this form came closest to weighting the residuals equally, simply a heuristic way of deriving a quantity which behaves like a formal χ^2. We find that with good signal-to-noise (S/N) data, the determination of V, σ, and γ is insensitive to gross changes in the weighting scheme. However, some improvement in the treatment of poorer data was noted using the form of χ^2 defined above.

ii) Input Parameters and Tests

1. *Choice of the spectral region*. The region containing the H and K lines of Ca II was chosen over the red spectral region used by Faber, Burstein, and Dressler (1977) because of (1) the unfortunate coincidence of night-sky emission λ5577 with Mg b; (2) the large equivalent width of H and K compared to the Na D lines and Mg triplet; and (3) the higher quantum efficiency of the SIT photocathode at 4000–4500 Å as compared to 6000–6500 Å.

Because of the low surface brightness of the envelope of the cD, it was decided to use an unusually wide 4″ slit which degraded the instrumental resolution from 6 Å to about 9 Å. Only H, K, and the G band were intrinsically broad enough to be resolved with this wide slit—the other features had essentially the instrumental profile. In order to verify that the velocity

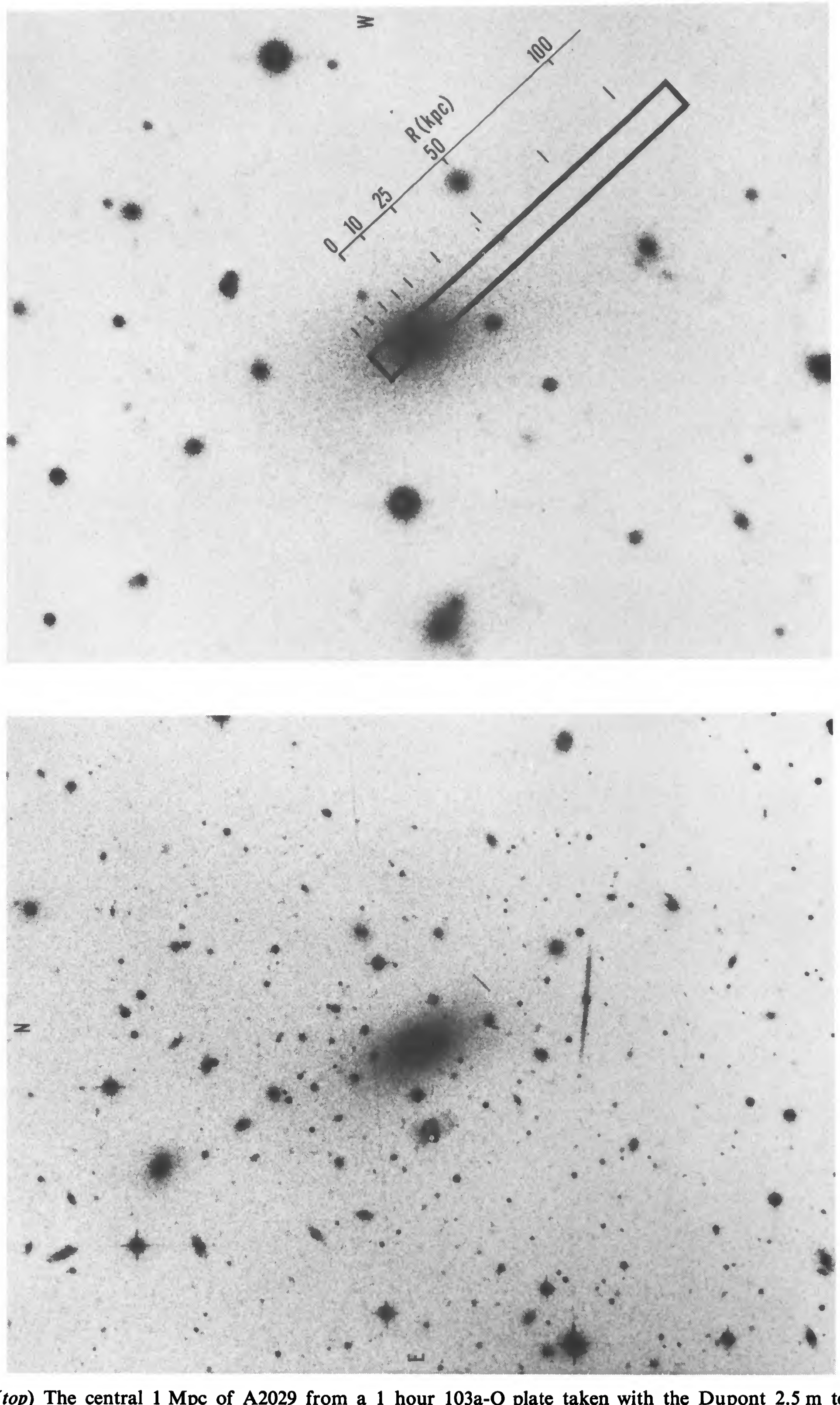

FIG. 1.—(*a*) (*top*) The central 1 Mpc of A2029 from a 1 hour 103a-O plate taken with the Dupont 2.5 m telescope at Las Campanas Observatory. (The very flat galaxy south of the cD has a much lower redshift than the cluster.) The limit of the spectral data shown, as indicated in Fig. 1*b*, is marked by the black line. Scale 1."8 mm^{-1}. (*b*) (*bottom*) The central 300 kpc of A2029 showing (in lower contrast than Fig. 1*a*) the cD galaxy and the position of the 4" slit used in 1978 May. The spectra along the slit were grouped into the eight regions indicated. Scale 0."53 mm^{-1}. The slit is approximately 1′ in length.

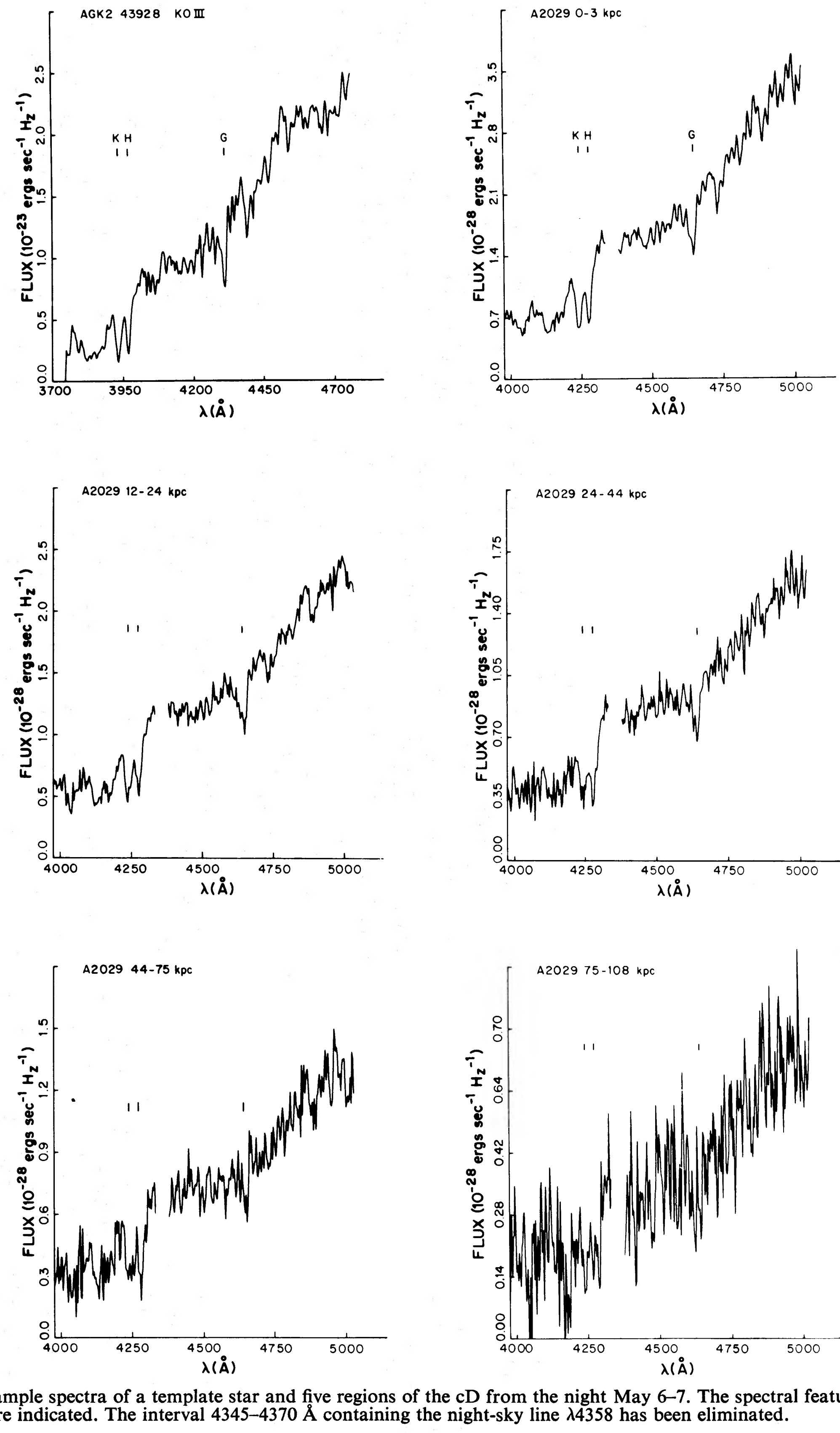

FIG. 2.—Sample spectra of a template star and five regions of the cD from the night May 6–7. The spectral features H, K, and the G band are indicated. The interval 4345–4370 Å containing the night-sky line λ4358 has been eliminated.

dispersion could be measured with H, K, and the G band, we artificially degraded *both* the star (template) and object spectra by convolution with a Gaussian and repeated the Fourier analysis. Not until the resolution was degraded to about 16 Å did the errors in σ become large. Thus the slit width used here was well below the maximum permissible. As a further check, the data obtained by Steve Shectman with the 2″ slit were analyzed and show good agreement with the 4″ data (Fig. 5).

2. *Preparation of the data.* The interval 3875–4415 Å in the rest frame, corresponding to 180 points at 3 Å point^{-1}, was chosen for the analysis. The continuum was flattened as described above, and 10% of each end was masked with a cosine bell function (see Brault and White 1971). The low- and high-frequency cutoffs k_L and k_H (see eq. [1]) were chosen as 5 and 80 cycles per 540 Å. The determination of V, σ, and γ was found to be insensitive to variations in these parameters, as noted in Sargent *et al.*

The program also allowed the masking of spectral regions. The interval 4345–4370 Å was eliminated to avoid contamination by inexact subtraction of Hg night-sky λ4358, which was saturated on some object exposures.

The SIT data contain a periodic fluctuation in sensitivity with a wavelength of approximately 6 pixels, apparently caused by "shadow" of the vidicon mesh, a grid in close proximity to the target (Gunn 1978). The fluctuations are imperfectly removed by the flat fields, probably owing to "beam bending" in the readout (see below). The remnant sensitivity variation of about 1–2% produces a noticeable spike in the Fourier domain, which we have masked as a precaution. (The problem is virtually eliminated if four or more adjacent spectra are added together.)

As the charge on the target is read out, the charge distribution itself deflects the beam and thus introduces positional inaccuracies that vary with exposure. This so-called beam bending results in a maximum positional uncertainty of ~0.5 pixels, which complicates the determination of accurate radial velocities and limits the ability of the flat fields to remove all fluctuations and irregularities. Fortunately, the movement of the beam is affected by a large area of the charge distribution, and not by local fluctuations in intensity, so that adjacent spectra are very consistent and line profiles are unaffected.

3. *Further tests of the method.*

i) The velocity dispersions, line strengths, and systematic velocities were determined separately for regions around H and K and the G band. Good agreement was found for the two regions. However, it became apparent that the random errors of the H and K interval were smaller, as might have been expected from the greater strength of H and K. In the following analysis a region containing both features was employed exclusively.

ii) Results of the program were insensitive to the choice of standard star used as a template. The final results quoted are an average of those obtained for three stars of G8 III to K0 III spectral type.

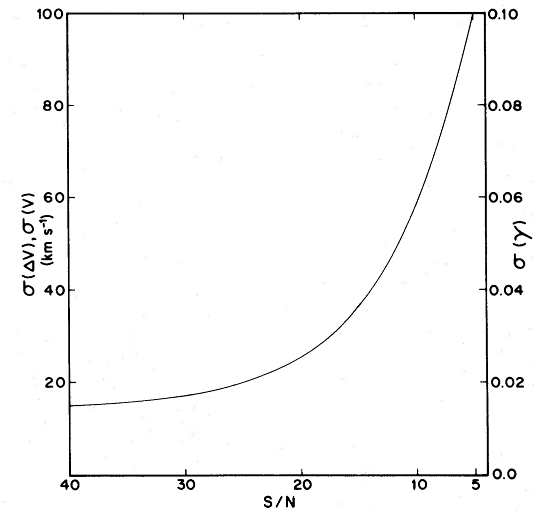

FIG. 3.—Estimation of the errors in V, γ, and σ (indicated as ΔV) as a function of S/N (see text).

iii) Two tests of the effect of decreasing S/N were made. In one a good-quality spectrum was degraded to S/N ratios of 20, 15, 10, 7.5, 5 by the addition of white noise. By repeating this procedure 20–30 times, the uncertainties in V, γ, and σ were estimated (Fig. 3). These error estimates have been used in the data presented below. Even though the noise in the instrument is not white, these error estimates seem to be reasonable from inspection of the scatter in the data. No systematic dependence of V, γ, or σ on S/N was found.

Additionally, data from the nucleus were divided (both spatially and temporally) into several lower S/N spectra, and the results were compared to the sum of the data. No systematic trends were found, and all the results agreed within expected errors.

c) Results

i) *Systematic Velocity*

The radial velocities for the May 6–7 data are shown in Figure 4*b*. We have compensated for the beam bending by measuring the shifts of the night-sky lines λ4046 and λ4358. There is no evidence of rotation within 30 kpc, but the data indicate a rotational velocity of 100–200 km s^{-1} in the outermost regions. We consider this result tentative and necessary of further verification.

As seen in Figure 1, the slit was orientated approximately along the major axis of this very flattened galaxy. Even if the aforementioned rotational velocity is real, it is obvious by comparison with the velocity dispersion that this galaxy is not supported primarily by rotation, consistent with the results of other studies of elliptical galaxies (Bertola and Capaccioli 1975; Illingworth 1977; Gunn and Schechter 1978).

ii) *Line Strength*

The line strength parameter γ is a measure of the strengths of the spectral features relative to the

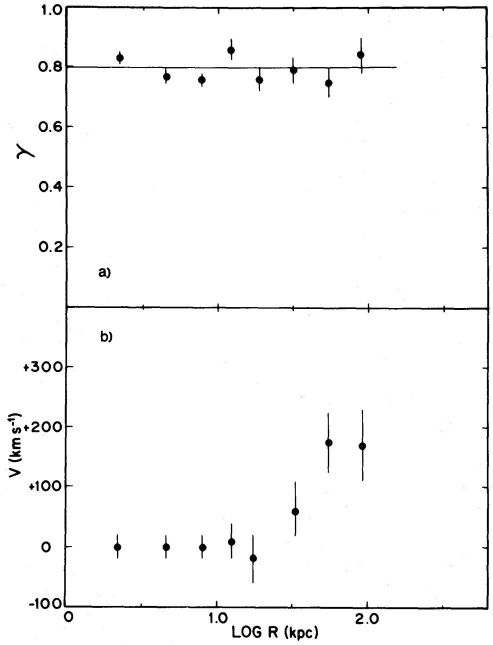

FIG. 4.—(*a*) The run of γ, the line strength parameter, as a function of radius. The adopted value of 0.8 is indicated. (*b*) The systemic velocity as determined from the May 6–7 data. An allowance has been made for beam bending of -50 km s^{-1} in the outermost regions.

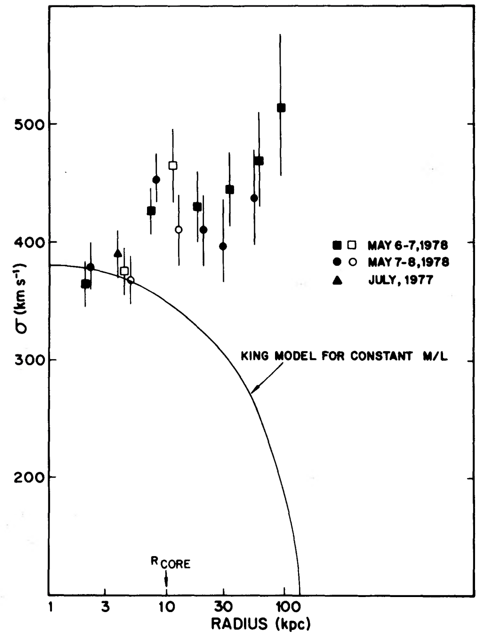

FIG. 5.—The run of the velocity dispersion as a function of radius for the 1978 May data. Also indicated is the nuclear value determined from the 1977 July data provided by Shectman. Open symbols are points to the NE; closed symbols are points to the SW. Errors bars were calculated from the data in Fig. 3. The solid curve is the run of σ for a constant $\mathfrak{M}/L$ King model with $R_{\text{COR}} = 10$ kpc.

continuum. Figure 4*a* demonstrates that there is no noticeable gradient in this parameter as a function of radius. The dependence of this parameter on metal abundance has not yet been calibrated, but it is safe to say that an order-of-magnitude variation in the metal abundance is ruled out. Visual comparison of the strengths of the spectral features (Fig. 2) confirms that the outer regions of the galaxy are not metal poor.

Color gradients can also be used to estimate variations in metal abundance (Strom *et al.* 1977; Sandage and Visvanathan 1978). Photographic photometry by the author with the Lick Crossley telescope indicates a gradient of less than 0.1 mag in $B - V$ over the region of interest. The colors in the rest frame are, of course, several hundred angstroms bluer, with centroids of approximately 4100 and 5100 Å. SIT direct photometry by Hoessel (1978) also indicates the absence of a gradient at the 3–4% level in the color $G - R$ ($\sim$4600–6000 Å in the rest frame). $U - B$ (rest frame) colors were also calculated from the spectra used in this analysis. Although the colors of the inner 20 kpc could not be used because of differential atmospheric refraction, the region from 20–100 kpc indicated a color gradient of about 0.2 mag in the sense of decreasing color index with increasing radius. Additional $U - V$ photometry is required to verify whether this gradient is real or an artifact of the data, but it seems likely that the color gradient in this galaxy is, in any case, small. Strom *et al.* (1977) and Sandage and Visvanathan (1978) estimate a metallicity variation of about 3–4 for a $U - V$ gradient of a few tenths. We therefore conclude that there is no contradiction between the limited color information and the absence of a gradient in γ.

The white-noise tests described above indicated a noticeable correlation of σ and γ in the sense that an overestimation of the line strength will result in an overestimation of σ and vice versa. It was found in the tests that constraining γ in the analysis of very noisy data considerably reduced the scatter in σ. Therefore, using the data of Figure 4*a* as a guide, we have set $\gamma = 0.8$ for the entire run of the data.

iii) *Velocity Dispersion*

The quantity of primary interest in this investigation is the velocity dispersion σ. Figure 5 presents the results of the 1978 May 6–7 and 7–8 data and one additional measurement from the Shectman 1977 July data. Although there is substantial agreement, the scatter of the May 6–7 data is somewhat smaller than that of the May 7–8 data. This is probably due to the presence of very light cirrus clouds on May 7–8, which caused variations in the sky brightness of a few percent. For this reason the final point centered at $\sim$90 kpc, where the galaxy has a surface brightness of only about 10% of the sky, was not determined with the May 7–8 data. The night of May 6–7 was photometric.

Good agreement is found, in addition, between the points NE and SW of the nucleus, and between the 2″ slit measurement and the remaining 4″ data.

The reality of the "bump" at 10 kpc is questionable. It should be mentioned that to the SW there is a companion galaxy which may be contaminating this area (see Fig. 1).

IV. DISCUSSION

a) Mass-to-Light Ratios

The primary result of this investigation is that *the velocity dispersion is not decreasing with radius as would be expected for a galaxy with a constant $\mathfrak{M}/L$.* Figure 5 clearly shows a marked contradiction of the data with a constant $\mathfrak{M}/L$ King (1966) model. (This model assumes a value of $R_{\rm COR} = 10$ kpc for the cD galaxy [see Fig. 6*a*]. This very large core radius [an order of magnitude larger than that of M87] will be discussed below.)

The dependence of $\mathfrak{M}/L$ on radius and velocity dispersion can be estimated using the equation of hydrostatic equilibrium. Substituting

$$P = \rho(r)\sigma^2(r)\,, \tag{1}$$

we have

$$-\frac{d}{dr}\rho(r)\sigma^2(r) = \frac{G\mathfrak{M}_R\rho(r)}{r^2}\,, \tag{2}$$

where $\mathfrak{M}_R$ is the mass interior to radius R. Assuming

$$\rho \propto r^n \tag{3}$$

implies

$$\mathfrak{M}_R \propto r^{3+n}\,, \tag{4}$$

$$\sigma^2 \propto r^{2+n}\,, \tag{5}$$

$$\mathfrak{M}_R \propto (\sigma^2)^{(3+n)/(2+n)} \quad (n \neq -2)\,. \tag{6}$$

To obtain the luminosity, we assume

$$I(r) \propto r^p\,, \tag{7}$$

where $I(r)$ is the observed (projected) intensity, which implies

$$L(r) \propto r^{p-1} \tag{8}$$

and

$$L_R \propto r^{p+2}\,, \tag{9}$$

where $L(r)$ is the luminosity at radius r and L_R is the luminosity interior to R. Combining expressions (4) and (9), we obtain

$$\mathfrak{M}/L \propto r^{1+n-p}\,. \tag{10}$$

From the luminosity profile (Fig. 6*a*)

$$p \approx -1.5\,, \qquad r > R_{\rm COR}\,.$$

Approximating σ (10 kpc) ≈ 400 km s^{-1} and σ (100 kpc) ≈ 525 km s^{-1}, equation (5) implies $n \approx -1.75$. Therefore,

$$\mathfrak{M}/L \propto r^{0.75}\,. \tag{11}$$

An estimate of the central $\mathfrak{M}/L$ has been calculated with equations (2) and (3) of Rood *et al.* (1972), which determine the central luminosity and mass density for a King model. Using Hoessel's (1978) photoelectric measurement of $m_V \approx 15.3$ within a 14.″5 diameter aperture, and allowing 0.2 mag for K-dimming and galactic absorption,

$$(3) \Rightarrow \lambda_0 \approx 0.02\, L_\odot\, \text{pc}^{-3}\,.$$

With $\sigma(0) = 375$ km s^{-1} and $R_{\rm COR} = 10$ kpc

$$(2) \Rightarrow \rho_0 \approx 0.24\, \mathfrak{M}_\odot\, \text{pc}^{-3}\,,$$

and thus

$$\frac{\rho_0}{\lambda_0} \approx 12\, \mathfrak{M}_\odot/L_\odot\,.$$

Assuming that the $\mathfrak{M}/L$ at 10 kpc is approximately equal to this central value, equation (11) implies

$$f(100\text{ kpc}) \equiv \mathfrak{M}/L_V \approx 67\, \mathfrak{M}_\odot/L_\odot\,.$$

This is the *global f* for all material projected inside R, which, of course, implies that *f at* 100 kpc should be somewhat higher. This calculation is too crude, however, to justify the determination of the differential $f(R)$. A physically more realistic model will be presented below.

b) Interpretation

It has been suggested by White (1976) and Ostriker and Tremaine (1976) that cD galaxies are built by the tidal stripping of neighbor galaxies as they undergo dynamical friction in the extensive cD envelope. Another related but slightly different interpretation by Richstone (1976) suggests that a luminous but normal elliptical galaxy is merely sitting in a sea of material stripped from cluster galaxies by tidal encounters. This would result in a distribution of stripped material similar to the cluster profile.

The velocity dispersion of the cD in both these schemes should be representative of the high-velocity dispersion ($\sigma \approx 1000$) of the cluster members. The results of this study confirm an *increase in velocity dispersion, which is a necessary* (*but not sufficient*) *condition in the proof of the stripped debris hypotheses.*

The fact that the stars are bound to the system with this high-velocity dispersion implies, as shown above, that the $\mathfrak{M}/L$ is increasing significantly. To understand the implication of this result, it is necessary to review briefly the "missing mass" problem which has puzzled astronomers for over 40 years. (A more complete discussion can be found in Bahcall 1977.)

Pioneering work by Zwicky (1933) and Smith (1936) uncovered the paradox that while the dynamics of clusters of galaxies imply $\mathfrak{M}/L_V \approx 200$, the $\mathfrak{M}/L$ values of individual galaxies as determined by rotation curves or velocity dispersions are an order of magnitude less. Where, then, is the remaining 90%+ of the cluster mass?

Through the years various attempts to treat the dynamics more carefully (e.g., Rood *et al.* 1972; Oemler 1974; Chincarini and Rood 1976, 1977) have resulted in small changes in the cluster $\mathfrak{M}/L$ and thus offer no resolution of the problem. Likewise, the suggestion that the missing mass is present in

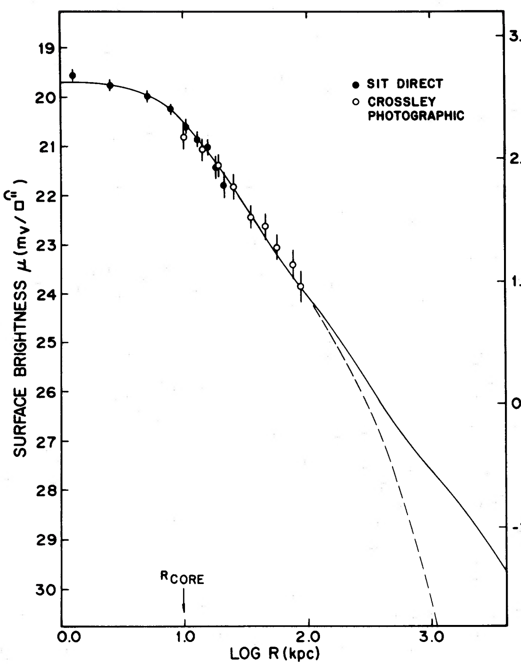

FIG. 6*a*

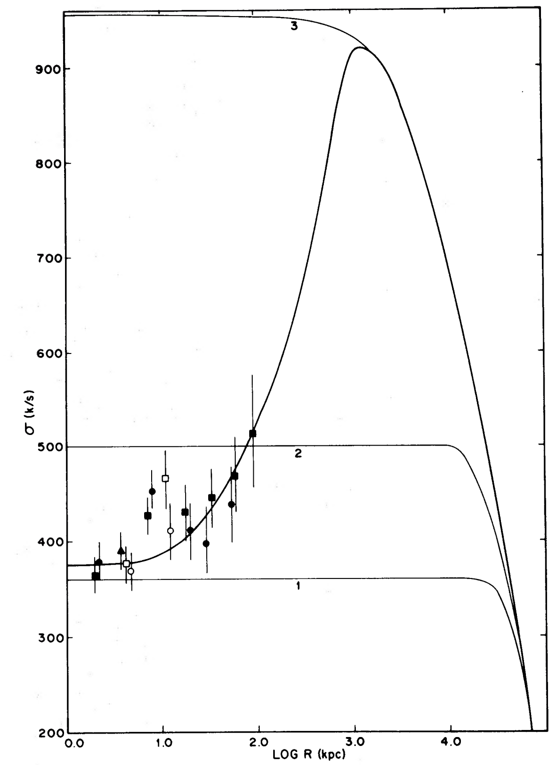

FIG. 6*b*

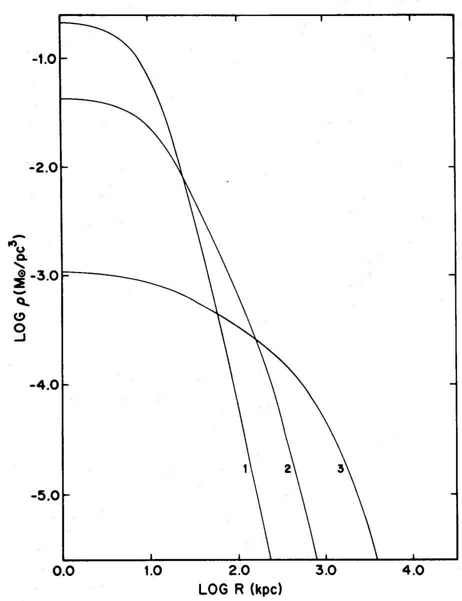

FIG. 6*c*

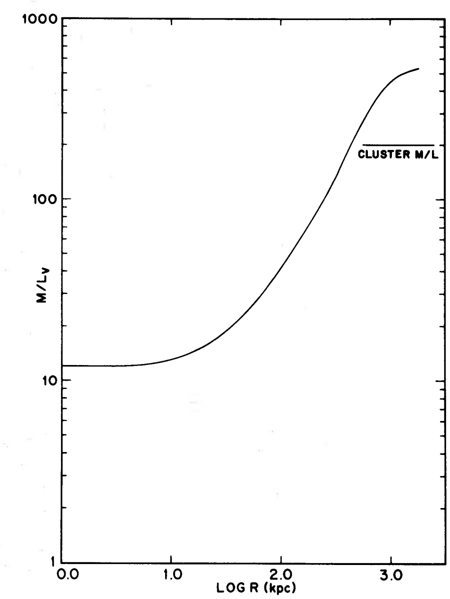

FIG. 6*d*

FIG. 6.—The three-component, nonrotating, isotropic King model from a program written by Gunn. (*a*) The luminosity profile compared to data from a Palomar 1.5 m SIT direct frame and photographic photometry done by the author with the Lick Observatory Crossley telescope. The dashed curve indicates the luminosity profile for a much darker component 3, $\mathfrak{M}/L = 10^4$. (*b*) The velocity dispersion of the three components and the luminosity-weighted average (*dark curve*). The data of Fig. 5 are reproduced. (*c*) The run of the space density of the three components. (*d*) The run of $\mathfrak{M}/L$ in the model as a function of the physical (not projected) radius. The cluster value of 200 is indicated.

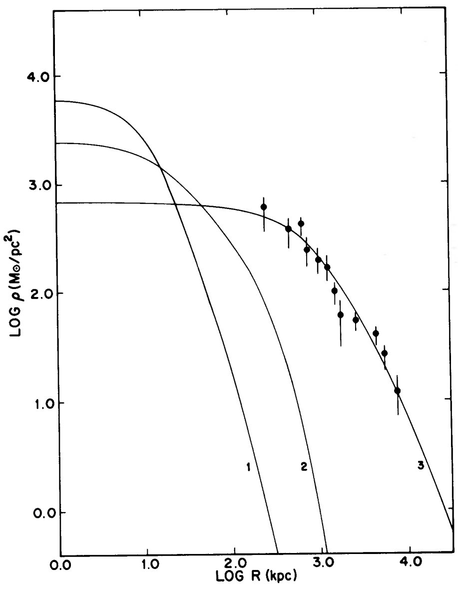

FIG. 6*e*.—The projected density profile of the three components. The cluster-filling component 3 is compared to the cluster's galaxy density profile (Dressler 1978*b*).

intracluster gas has fallen by the wayside as new observational techniques have placed tight constraints on the amount of gas present. Indeed, the major gas component appears to be that of an ionized X-ray emitting gas ($T \approx 10^8$ K), which can account for only about 10% of the required virial mass (Lea *et al.* 1973).

Finally, one is left with the suggestion that surrounding the luminous material normally identified as a galaxy, there exists a much higher $\mathfrak{M}/L$ component. Ostriker and Peebles (1973) originally suggested this idea, which has subsequently been developed by many others. A recent discussion by Gunn (1977) demonstrates that the formation of such a component follows naturally in a simple model of protogalaxy collapse and later infall of outlying material. The makeup of the extended halo is not determined by the model (e.g., stars, black holes, massive neutrinos), but Gunn points out that low-mass, high $\mathfrak{M}/L$ stars might form in the immediate postdecoupling epoch.

Observational evidence intended to confirm the existence of this dark material has been suggestive but not compelling. The dynamics of the local group has been offered as evidence (e.g., Gunn 1974), but the dynamical history and present motions are still in doubt (Yahil, Tammann, and Sandage 1977). Analysis of binary systems and small groups has been controversial and resulted in a wide range of $\mathfrak{M}/L$ values (e.g., Page 1966; Turner 1976; Turner and Gott 1977; Rose 1977; Yahil 1977). Selection biases, membership, and sufficiently accurate radial velocities are among the formidable problems faced in these studies. Perhaps the best evidence for the existence of a massive dark component has come from the optical (e.g., Rubin 1978) and H I (e.g., Roberts and Rots 1973; Krumm and Salpeter 1977) rotation curves of spiral galaxies. These studies indicate that the rotation curves "flatten out," implying rising $\mathfrak{M}/L$ at distances of 20–30 kpc from the nucleus. This is not sufficiently far out, however, to result in more than a factor of 2 or 3 rise in the *global* $\mathfrak{M}/L$ and may only reflect a change in the makeup of the disk. We are as yet unable to trace the dynamics of these galaxies to sufficient distances to confirm the existence of the postulated halos.

Here, however, is where the present investigation bears on the missing mass problem. The fate of the alleged high $\mathfrak{M}/L$ halos is quite different in clusters than in the field, for although field galaxies would be able to hold on to their extensions, galaxies in dense clusters would almost certainly be stripped. These stripped halos would then become the common property of the cluster (Richstone 1976). This is consistent with White's (1977) contention that, were the missing mass associated with individual cluster galaxies, then a much greater amount of equipartition of energy than is observed would have taken place.

We now turn our attention to the issue of whether such a pervasive, high $\mathfrak{M}/L$ component can explain the existence of cD galaxies and the increase in velocity dispersion with radius found in this study.

c) *The Model*

James Gunn generously provided the author with a computer program he has written for generating multicomponent, isotropic King models. The model, described in detail by Gunn and Griffin (1979), assumes truncated Maxwellian velocity distributions (King 1966) for each component and uses the combined potential to solve for the individual density distributions. The basic idea was to see if a low $\mathfrak{M}/L$ "normal elliptical" with a low σ (cold) coexisting with a high $\mathfrak{M}/L$ "hot" component could explain the rise in σ as a function of radius.

i) *Input Parameters and Constraints*

We assume first that there are two components. One is a normal elliptical of M87–like luminosity and size. For this component we have $\sigma_{r=0} = 375$ km s^{-1}, a central $\mathfrak{M}/L = 12$, and an unusually large core radius of 10 kpc (photometry discussed below). The second component is a high $\mathfrak{M}/L$ structure which follows the cluster profile. This implies $R_{\rm COR} \approx 300$ kpc and $R_{\rm eff}$ (total radius) ≈ 10 Mpc (Dressler 1978*b*).

Assuming $\mathfrak{M}/L = 10$ for the luminous galaxies and using the author's estimate of $\mathfrak{M}/L$ for the cluster of about 200 (Dressler 1978*b*), we conclude that there is about 20 times as much mass in the dark component as in the visible galaxies. This fact, combined with the projected central surface brightness of the luminous galaxies of $\sim 3 \times 10^{12} L_\odot$ Mpc^{-2} and a core radius of 300 kpc, implies a central density of the dark component of $10^{-3}\,\mathfrak{M}_\odot$ pc^{-3}. This is a factor of 250 down from the central density of the luminous central galaxy, $\rho_c \approx 0.2\,\mathfrak{M}_\odot$ pc^{-3} but implies a difference of only one order of magnitude in their projected densities.

Observations suggest that less than 40% of the cluster light is in a diffuse cluster-filling component (Oemler 1973; Melnick, White, and Hoessel 1977). This provides the final constraint, that $\mathfrak{M}/L_V$ of the dark component must be greater than 500.

ii) *Results*

The above constraints produced the rather unexpected result that although a simple two-component model could easily be fashioned which fits the velocity dispersion data, the luminosity profile could not be fitted if the dark component had $\mathfrak{M}/L > 500$.

To help clarify this, we refer the reader to Figure 5 of Oemler (1976). The cD galaxies have the flattest profiles of all elliptical galaxies, having $I \sim r^{-1.5}$ over great distances. In comparison, M87, typical of giant ellipticals, has an intensity falloff $I \sim r^{-2}$. Of course, this is a tautology—it is the existence of the shallow falloff that earns a galaxy the cD label. The point is, however, that there is not enough of the dark, high-velocity component in the $\sim$100 kpc region to add significantly to the light. Thus the profile should be at least as steep as the normal elliptical. It might even be steeper because of the "pulling in" of the luminous galaxy by the extra mass of the dark component. Even if one could argue that interaction with the dark component has caused a puffing up of the normal galaxy, the fact would remain that within several hundred kiloparsecs a cD galaxy is many times brighter than an M87–type elliptical, and this extra luminosity cannot be supplied by a constant $\mathfrak{M}/L > 500$ component which fills the cluster. In Richstone's (1976) model there is no possibility of a $\mathfrak{M}/L$ gradient since the material stripped would be thoroughly mixed. We argue, then, that Richstone's interpretation of the cD as a normal elliptical floating in a sea of stripped galactic halos is incomplete—additional luminous material must be supplied to form the luminous cD envelope.

The logical move, therefore, is to build a three-component model, the added component having an intermediate $\mathfrak{M}/L$ and, since it is more extended than a normal elliptical and less extended than the cluster, an intermediate velocity dispersion. Ostriker and Tremaine's (1976) suggestion that other massive galaxies in the cluster would be slowed down and torn apart by dynamical friction as they traverse the cluster core provides exactly the material required: low $\mathfrak{M}/L$ and intermediate velocity dispersion. We must now impose one additional constraint, that this component have a total luminosity of not more than a few giant galaxies.

The three-component model described in Table 1 and illustrated in Figure 6 satisfies all of the aforementioned constraints. The luminosity profile agrees well with the author's photographic and SIT direct photometry (Fig. 6*a*) and is an excellent match with the other cD profiles presented by Oemler. A. G. de Bruyn kindly provided the SIT frame, taken in good seeing with the Palomar (1.5 m) direct SIT, which confirmed the exceptionally large core radius mentioned earlier. The photometry from this device is certainly as good as the 10% accuracy required for this determination. Figure 6*a* also illustrates the effect of a much darker ($\mathfrak{M}/L_V = 10^4$) component 3.

Figure 6*b* shows good agreement with the velocity dispersion data. Using the density profiles plotted in Figure 6*c*, we have calculated the run of $\mathfrak{M}/L_V$ with radius (Fig. 6*d*). At 100 kpc the $\mathfrak{M}/L_V$ has risen to $\sim$40, but, in fact, the velocity dispersion at a *projected* distance of 100 kpc is really measuring $\mathfrak{M}/L$ at an even greater distance. Furthermore, even though most of the mass and light within 100 kpc is provided by components 1 and 2, it cannot be argued that measuring the velocity dispersion out to this distance is a confirmation of them alone. Component 2 could not even be bound with its needed density and a reasonable total mass without the presence of the cluster-binding dark component 3. Viewing the model as a total picture, then, we see that the velocity dispersion measurements over this relatively small distance are a surprisingly good indication of the model's applicability on a much larger scale.

Finally, Figure 6*e* demonstrates that the projected density distribution of component 3 is in good agreement with the cluster galaxy counts done by the author (Dressler 1978*b*), indicating that a model can be built in which this component is distributed in the same way as the cluster galaxies.

We note that these observations and the interpretation are consistent with the findings of the study by Faber, Burstein, and Dressler (1977), in which a velocity dispersion was measured (with considerable uncertainty) at 43 kpc in the cD of A401.

In summary, a model can be fashioned which

TABLE 1

MULTICOMPONENT KING MODEL

	$\mathfrak{M}/L_V$	σ (central)	ρ (central) ($\mathfrak{M}_\odot$ pc^{-3})	L_V (total) ($10^{12} L_\odot$)	$\mathfrak{M}$ (total) ($10^{13} \mathfrak{M}_\odot$)	Identification
Component:						
1........................	11	375	2.5×10^{-1}	0.33	0.36	"Normal" elliptical
2........................	35	500	4.2×10^{-2}	1.16	3.87	Accreted luminous galaxies
3........................	525	955	1.2×10^{-3}	16.5	825	Stripped dark halos
Luminous galaxies...........	10	$\sim$1000	6.70×10^{-5}*	43.7*	43.7	...

* Dressler 1978*b*.

accounts for all of the observables, including the luminosity profile of the cD galaxy and its dynamical structure as well as the high velocity dispersion of the cluster and the apparent "mass discrepancy." Thus the assumption of the existence of dark halos which are stripped from their parent galaxies in a rich cluster leads to a successful interpretation of the existing data.

d) *Additional Evidence of the Dynamical Friction Process*

The author (Dressler 1978*a*, *b*) has studied the cluster A2029 in some detail and has noted some evidence, summarized below, for the growth of the luminous cD galaxy at the expense of other bright cluster members.

1. The luminosity function of this extremely rich cluster is practically devoid of bright galaxies other than the cD. These would be the likely victims of the cD cannibalism (Ostriker and Tremaine 1976).

2. There is a strong density enhancement of galaxies (over and above what is expected for the isothermal core) which is due largely to the presence of many small galaxies in the cD envelope. Their apparently high surface brightnesses for their luminosities suggest that they may be the nuclear remains of more-massive galaxies which have been accreted.

3. Those bright galaxies which are found in the cluster appear to be no more, or even less, concentrated toward the cluster center than the fainter galaxies, this despite the expectation that such a dynamically evolved cluster would have undergone some 2-body relaxation with the opposite result. This could be evidence that most of the massive galaxies *did* relax into the center and were chewed up by the cD, leaving only their suburban counterparts whose low-eccentricity orbits kept them far from the cluster core.

4. The cD envelope is highly flattened and aligned with the flattened galaxy distribution of the core. We can now be certain that this flattening is not primarily due to a net angular momentum. Therefore, it seems reasonable to suggest that the cD envelope assumes the distribution of galaxies that it cannibalizes. ("Man ist was man isst"!)

5. Finally, Ostriker and Hausman (1977) predict a growth in the core radius of the cD galaxy which agrees well with the abnormally large values found in this and other cD's (Oemler 1976), which are at least an order of magnitude larger than normal ellipticals.

This indirect evidence gives some support to the idea that dynamical friction is instrumental in the production of the cD envelope. Deposition of this low $\mathfrak{M}/L$ stellar material could well account for the additional luminosity needed in the model to reproduce the luminosity profile.

e) *Future Work*

In addition to the need for more and better data for this and other cD galaxies, we can point to a specific observational test which can clarify the major ambiguity of the interpretation presented here. That is, although the observations indicate an increasing $\mathfrak{M}/L$ in the neighborhood of the cD, we cannot be certain that this trend continues into the cluster and that the same material which binds the cluster is responsible for the dynamics of the cD envelope. That is, a local high $\mathfrak{M}/L$ structure whose velocity dispersion is not as high as the cluster's could probably explain these observations.

There is, however, a direct test of this alternative. If, on one hand, the dark material is associated with the cluster as a whole, then cD galaxies should be uniquely associated with the dynamical centers of clusters. If, on the other, they have self-contained high $\mathfrak{M}/L$ components which are bound only to them, then they could exist outside of a cluster center. This question is still in doubt, basically because of the inability to define a clear set of criteria as to when a galaxy is to be called a cD. We suggest, however, that the case of NGC 4839, an extensive, luminous Coma cluster galaxy far from the cluster core yet cited by Oemler (1976) as a possible cD, could provide a critical test. If it can be shown that the velocity dispersion in this galaxy increases with radius as in A2029, then it must be that the high $\mathfrak{M}/L$ structure is associated with the galaxy itself and not the cluster as a whole. Conversely, if $\sigma(R)$ goes down with increasing radius, then it seems likely that the existence of cD galaxies may well be tied to overall cluster dynamics and structure, and an alternative explanation (such as a giant disk of material like an S0 galaxy) will be needed for cases like NGC 4839.

V. CONCLUSION

Spectra at the envelope of the cD galaxy in A2029 out to over 100 kpc have been analyzed using a Fourier cross-correlation technique. The measured velocity dispersion apparently increases with radius, implying that the mass-to-light ratio of this structure is increasing rapidly.

A three-component King model composed of a "normal elliptical" galaxy, a high $\mathfrak{M}/L$ cluster-filling and cluster-binding superstructure, and a component of intermediate $\mathfrak{M}/L$ and σ which supplies the light of the "extended halo," can account for all that is presently known about the cluster and cD. The high $\mathfrak{M}/L$ component is tentatively identified with stripped dark halos of cluster galaxies, and the intermediate $\mathfrak{M}/L$ material is attributed to the dynamical friction process which disrupts massive, luminous galaxies as they encounter the cD envelope.

Additional observations of this and other cD galaxies should be able to settle the question of cD origin, particularly if they decide the question of whether cD galaxies are uniquely associated with the dynamical centers of rich clusters.

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