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THE DYNAMICS OF THE CLUSTER OF GALAXIES A2029

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ABSTRACT

Redshifts have been determined for 31 additional galaxies in the rich cluster A2029. The velocity dispersion, based on 47 members, is found to be $\Delta V = 1430$ km s^{-1}. The result implies a high $M/L_V \sim 500$. Correlations of X-ray luminosity and temperature with velocity dispersion in rich clusters are strengthened by the high ΔV.

Many of the galaxies which appear projected against the cD envelope have large velocities relative to the cD, indicating that they are not being cannibalized. This is consistent with the expectation that few victims could be seen at any one time, as a result of the short time scale for their consumption.

The cluster, which is highly flattened, shows no signs of large-scale rotation. Models are constructed and statistically tested which show that the flat distribution is not likely to be supported by rotation, but rather reflects an anisotropic velocity field. Cannibalism by the cD of galaxies in the anisotropic field might account for the flattening of the cD envelope and its alignment to the cluster.

Subject headings: galaxies: clusters of — galaxies: redshifts — galaxies: structure

I. INTRODUCTION

A2029 has figured prominently in several studies of clusters of galaxies (Dressler 1976, 1978*a*, *b*, 1979; Faber and Dressler, 1976; Hintzen and Scott 1979) because of its great richness, unusual luminosity function, high X-ray luminosity, and exceedingly luminous cD galaxy. In addition, the cluster is highly elongated (and aligned with the cD major axis), making this a prime case in which to look for cluster rotation.

This paper reports an additional 29 redshifts of cluster members, which brings the total number to 47. With a better knowledge of the cluster's dynamics, it is possible to reevaluate some of the previous work and examine the evidence for cluster rotation.

II. THE DATA

Thirty-one new redshifts in A2029 were determined from spectra taken with the Palomar Hale 5 m Digital spectrograph on 1979 June 19–21 and with the Las Campanas 2.5 m du Pont Reticon spectrograph on 1979 March 27–28 and 1980 February 15–16. The SIT and Reticon data were reduced as described in Dressler (1979) and Dressler (1980), respectively. Several galaxies overlapping the Faber and Dressler (1977) sample of 18 were repeated during each of the new observing runs. Redshifts were determined by finding the centroids of the absorption lines of Ca II H and K, the G band, and occasionally Mg *b* and Na D. This procedure, done by eye using graphs of the spectra, was found, through repeated observations, to be accurate to better than 100 km s^{-1} with Reticon data and 150 km s^{-1} with SIT data. SIT and Reticon spectra were also obtained of several K0 III stars, which indicated that zero-point errors are less than ~ 50 km s^{-1}. Six galaxies (see Table 1) were observed at least twice with different instruments. Comparison of these spectra suggested a systematic shift of $+100$ km s^{-1} for the Faber and Dressler velocities and -100 km s^{-1} for the Reticon velocities, relative to the velocities determined with the 5 m SIT. Since these offsets are not excessive compared to the expected random and systematic errors, no attempt has been made to adjust the zero points of the velocity scales, and simple averages have been taken in the cases of multiple measurements. The adopted *cz* velocities and their sources are listed in Table 1.

Figure 1 (Plate 1) is a finding chart of the cluster identifying the 49 galaxies in Table 1. The plate used is a 103a-O emulsion baked for 4 hr in forming gas and exposed for 1 hr with a Wratten 2C filter. The seeing on the plate is $\sim 1''$. Counts of galaxies to ~ 1 mag above the plate limit were made using this plate, and the resulting galaxy density in 5×5 mm bins (1 mm = 10''.94) is shown in Figure 2.

$H_0 = 50$ has been assumed throughout this paper in the determination of distance scales.

III. THE VELOCITY DISPERSION

Figure 3 is a histogram of the (cz) velocities of the 47 member galaxies of Table 1, collected into bins of 500 km s^{-1}. The ambiguity in the velocity dispersion reported by Faber and Dressler (1977) is clearly resolved by the new data. The line-of-sight velocity dispersion determined from the *cz* value of the 47 members is $\Delta V_0 = 1540$ km s^{-1}. The 1 σ confidence interval, determined by the χ^2 test, is 1390–1740 km s^{-1}. In order to determine the velocity dispersion in the rest frame of A2029, these values must be divided by $\sim (1 + z)$, which yields $\Delta V = 1430$ $(+185, -140)$ km s^{-1}.

The new systemic velocity of A2029 is $c\bar{z} = 23{,}000 \pm 225$ km s^{-1}. The cD galaxy, whose velocity is $23{,}290 \pm 50$ km s^{-1}, is thus found, within the errors, to

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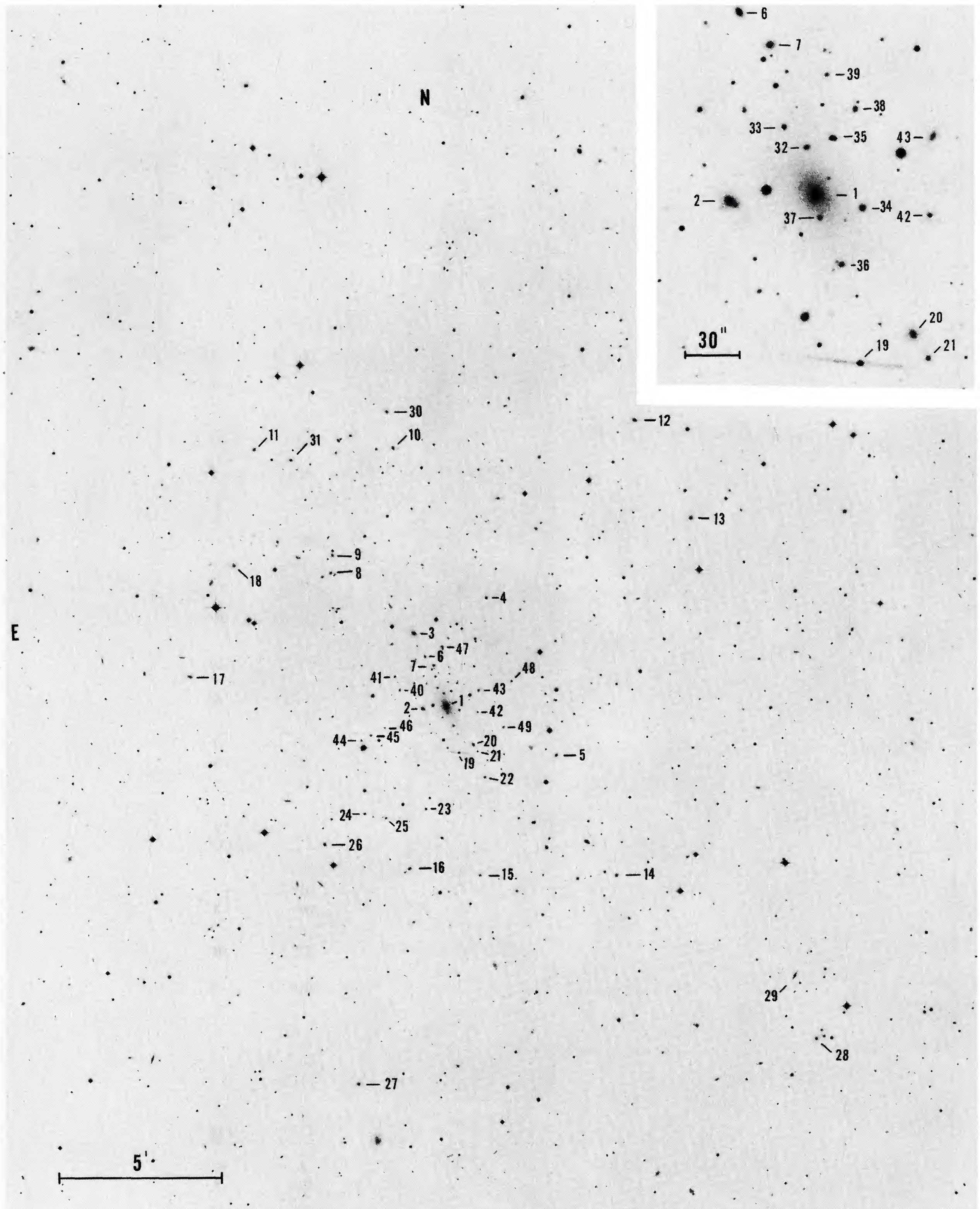

FIG. 1.—Direct 103a-O plate taken with the du Pont 2.5 m telescope of A2029, identifying the galaxies for which radial velocities have been obtained.

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TABLE 1

A2029 VELOCITIES

Number	cz	References
1	23290	1, 2, 3
2	26670	1, 2, 3
3	23600	1, 3
4	22300	1
5	22010	1
6	22280	1, 2
7	23250	1, 2
8	24000	1
9	23060	1
10	26640	1
11	21990	1
12	22240	1
13	22410	1
14	24520	1
15	22520	1
16	24290	1
17	20000	1
18	22370	1
19	6630[a]	3
20	21720	3
21	24170	3
22	20730	3
23	22070	3
24	24510	3
25	25260	3
26	20550	3
27	25800	3
28	22920	3
29	23700:	3
30	24330	3
31	23560:	3
32	23880	2
33	23070	2
34	21480	2
35	? [b]	2
36	21390	2
37	21810	2
38	24060	2
39	24630:	2
40	19960	2
41	22100	2
42	21100	2
43	22250	2
44	23890	2
45	22330	2, 3
46	22740	2
47	24760	3
48	22920	3
49	22200	3

[a] Foreground.

[b] Probable cluster member, but heavily contaminated by a foreground star.

REFERENCES.—(1) Faber and Dressler 1977. (2) Hale 5 m. (3) du Pont 2.5 m.

lie at the dynamical center of the cluster. This is to be expected since its mass is at least 10 times greater than the other cluster members.

The velocity dispersion for the 18 galaxies within 100″ of the cD ($\bar{r} \sim 50''$) is $\Delta V = 1540\,(+325, -230)$, while for the remaining 29 members ($\bar{r} \sim 380''$, or about 2 core radii), $\Delta V = 1395\ (+230, -185)$. This 10% drop in the velocity dispersion is consistent with that found by Rood *et al.* (1972) for the Coma cluster and would be expected if the cluster is well described by an isotropic King model. However, the uncertainties in the two values presented here are too large to consider this a confirmation of such a model.

The velocity dispersion of the seven galaxies projected within the cD envelope ($r < 50''$) is no lower than that of the remaining members. Thus it seems unlikely that most of these galaxies are the remnant cores of more massive galaxies which are being cannibalized by the cD, as suggested by Dressler (1978*b*). The residence of so many galaxies in the cD envelope was itself a difficulty for the dynamical friction model, since each would be devoured in less than $\sim 10^9$ yr. Thus the new data appear to remove this problem, as they imply that although one or two of these close companions may be victims, the majority are either projections or are moving too rapidly to suffer the frictional effects of the cD envelope.

The velocity dispersion has figured prominently in three other areas of study.

1. The mass/light ratio of the cluster is now calculated to be $M/L_V \sim 450$–550 (see Dressler 1978*b*). This implies one of the largest "mass discrepancies" of any cluster. This value would be moderated by any additional luminosity in the faint extension of the cD envelope, but this is unlikely to reduce M/L by more than 50%.

2. Dressler's (1979) model of the cD in A2029 assumed a velocity dispersion of $\Delta V \sim 1000$ km s^{-1} for the cluster and a core radius of 300 kpc. If the core radius is left unchanged, the higher velocity dispersion of ~ 1400 km s^{-1} would imply a factor of 2 increase in the central mass density of the dark component. This would cause the velocity dispersion in the cD envelope to rise more rapidly than is observed. However, the model has considerable latitude in this area since the core radius of the cluster could easily be as high as ~ 450 kpc (see Dressler 1978*b*), which would leave the central mass density of the cluster and, thus, the rise in ΔV in the cD envelope unchanged.

Of perhaps greater concern is the choice of $\Delta V = 500$ km s^{-1} for component 2—the luminous material stripped from other galaxies—which illuminates the cD envelope. It is unclear whether it is reasonable to expect galaxies moving with a $\Delta V \sim 1400$ km s^{-1} to slow down, presumably through two-body relaxation and dynamical friction, to ~ 500 km s^{-1}. If not, one might be suspicious that Dressler's measurements are lower limits to the velocity dispersion in the cD envelope, since there could be additional power in broad wings of the absorption lines to which the measurement procedure is rather insensitive.

3. A2029 is one of the most copious emitters of X-rays and thus is pivotal in the determination of possible correlations of X-ray luminosity and temperature with velocity dispersion (Mushotsky *et al.* 1978; McHardy 1978). Hintzen and Scott (1979) have shown that a value of $\Delta V \sim 1500$ for A2029 strengthens the positive correlations of X-ray luminosity and temperature with cluster velocity dispersion. On the other hand, the high velocity dispersion in A2029 exemplifies the large scatter, far

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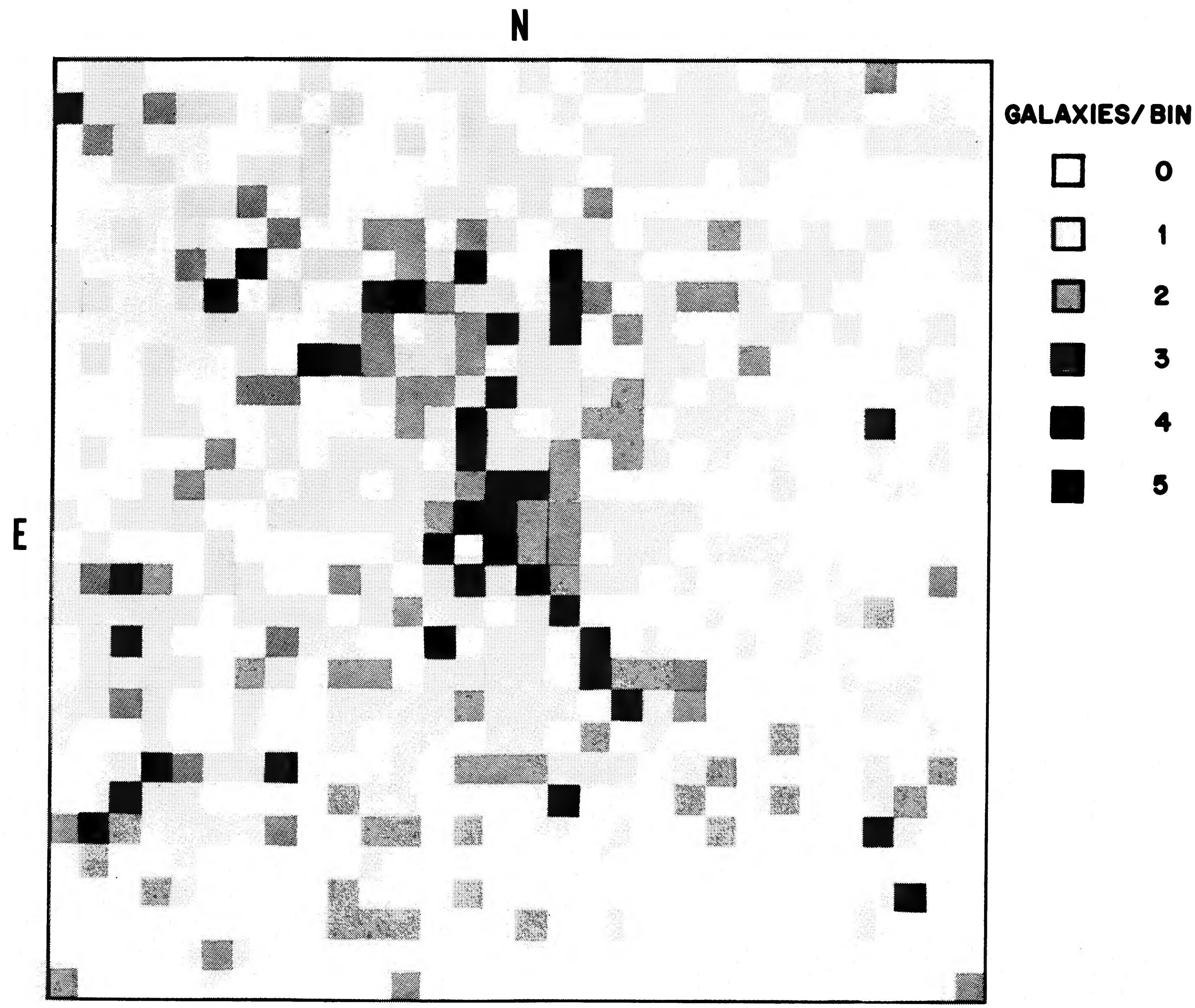

FIG. 2.—Number counts of galaxies $m_V \lesssim 19.0$ on the du Pont plate in 5×5 mm bins (1 mm = 10″.94). The cD galaxy lies in the darkest central square. A NE to SW axis can be seen in the distribution at a position angle of approximately 30°.

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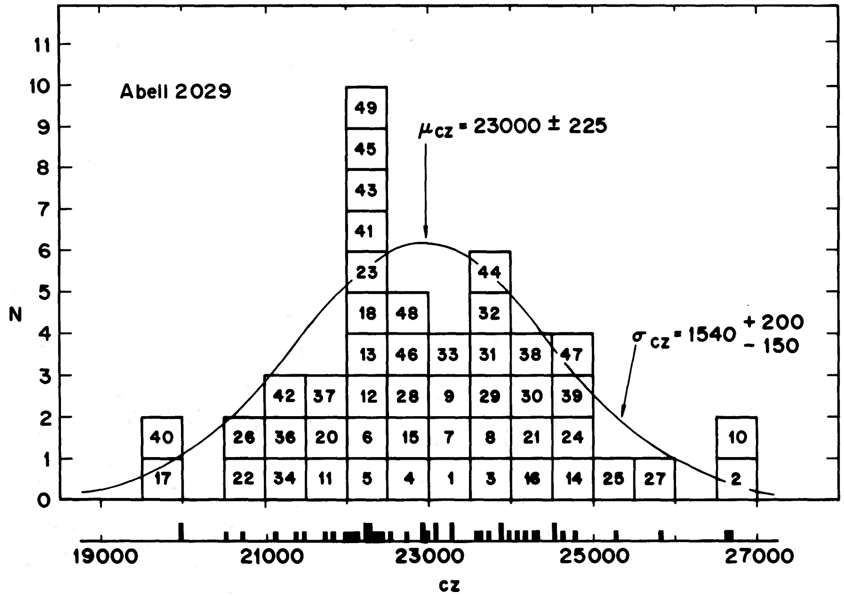

FIG. 3.—The cz velocity histogram of the 47 member galaxies in bins of 500 km s^{-1}. The solid curve is a Gaussian curve with mean and dispersion determined by χ^2 minimization.

greater than observational errors, from any mean relation. For example, A2029 and A754 have nearly the same X-ray luminosity, but their velocity dispersions are 1430 (+185, −140) km s^{-1} and 785 (+75, −85) km s^{-1} (Shectman and Dressler 1980), respectively. The rather poor correlation between X-ray and dynamical properties of clusters (e.g., Faber and Dressler 1976; Jones and Foreman 1978; McHardy 1978) suggests that early models of the X-ray emission mechanism (e.g., Solinger and Tucker 1972) were oversimplified. Such factors as the ratio of the mass of the X-ray emitting gas to total cluster mass (Silk 1976) or a number of different temperature components (Mitchell and Mushotsky 1980) may vary significantly from cluster to cluster and thus account for the large scatter in the observables.

IV. CLUSTER ROTATION

A visual inspection of the photographs of A2029 (Fig. 1) and the number counts (Fig. 2) shows that the galaxies in the cluster lie in a highly flattened distribution with a major axis approximately coincident with that of the cD galaxy. In order to test the statistical significance of the cluster's asymmetry, a procedure applied by Schipper and King (1978) to the Coma cluster was employed. Galaxies cataloged by Dressler (1976) with $m_F < 17.5$ within 2 Mpc of the cluster center were binned in 30° sectors. A χ^2 test confirmed there is less than a 1% chance that the observed distribution is a statistical fluctuation from a circularly symmetric one. A result of equal significance was obtained by repeating this procedure with galaxies within one core radius ($r \lesssim 200''$) and with $m_v \lesssim 19.0$ counted on the Las Campanas plate.

Choosing instead an elliptical boundary and assuming the isodensity contours to be concentric ellipses resulted in reasonable fits to the sector counts for values of the eccentricity $0.6 < e < 0.9$. The best-fitting model $e = 0.8$ is shown in Figure 4. The largest discrepancy, a significant excess in the +30° sector, seems to be due to the subcondensation of galaxies to the NE of the cD.

Inspection of the radial velocities as a function of their perpendicular distance from the minor axis (Fig. 5) shows no indication that this very flattened system is supported

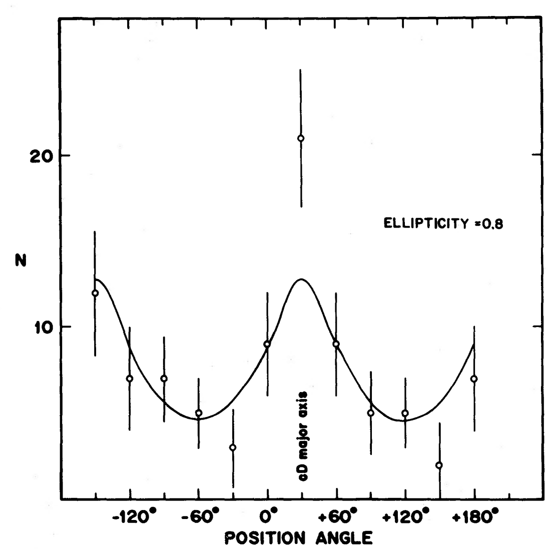

FIG. 4.—The number counts of galaxies in 30° sectors within an elliptical boundary with a semimajor axis of ~2 Mpc and $e = 0.8$, compared to a model which assumes elliptical isodensity contours. Note the alignment to the major axis of the cD.

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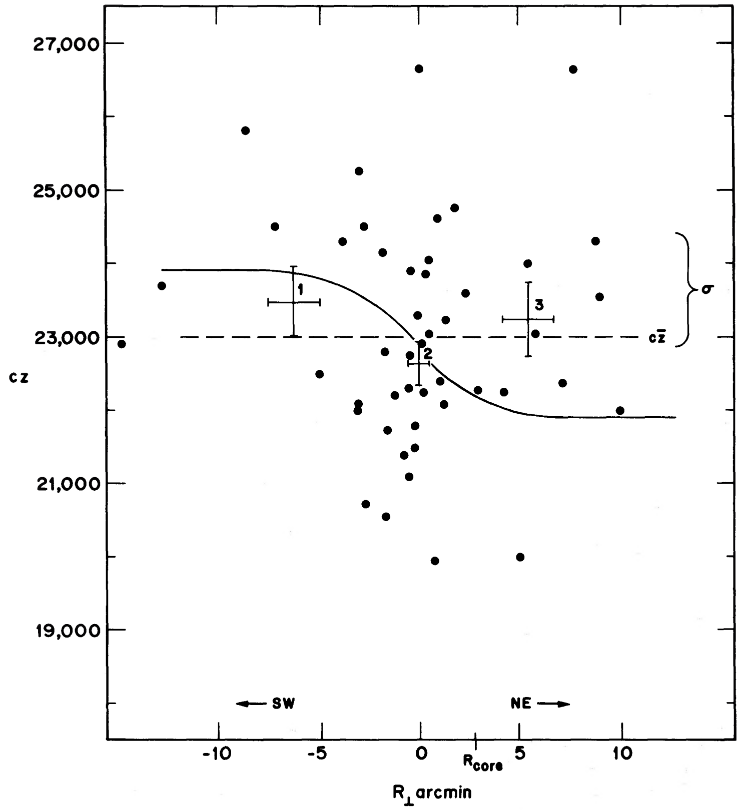

FIG. 5.—The radial velocities as a function of $R_\perp$, the perpendicular distance from the minor axis ($\theta = 120°$). The means and standard deviations of the means are shown for (1) $R_\perp < -2'$, (2) $|R_\perp| \leq 2'$, (3) $R_\perp > 2'$. The solid curve is the form of the assumed rotation curve, which has been tested and rejected as a poor fit to the data.

by large-scale rotation, which would require a rotational velocity comparable to the velocity dispersion (see, e.g., Schechter and Gunn 1979). It is possible to test the contrary hypothesis by assuming a rotation curve and testing the fit of such a curve to the data. The rotation curve used here, schematically represented in Figure 5, rises linearly in the cluster core where galaxy density is approximately constant, but then levels off ($V \rightarrow \text{constant} \equiv V_{\text{rot}}$) since the isothermal sphere model, which fits the $r < 2$ Mpc distribution fairly well, implies that $\int_0^R M(r) \propto R$. The following conclusions result when this model is compared to the data. (1) Models with $V_{\text{rot}} < 1000$ km s^{-1} and $V_{\text{rot}}/\Delta V > 0.6$ are excluded by a χ^2 test with greater than 99% certainty. (2) Models with $V_{\text{rot}} > 1200$ km s^{-1} are excluded by a Fisher sign test (see Hollander and Wolfe 1973), i.e., most of the velocities are too high on one side, too low on the other, at the 98% confidence level. The only model that cannot be ruled out has $V_{\text{rot}} \approx 1000$ km s^{-1} and $\Delta V \approx 1400$ km s^{-1}, which is rejected by both of the aforementioned tests at the 90% confidence level. Thus, although oblate models supported by rotation are completely ruled out ($V_{\text{rot}} \gtrsim \Delta V$ is required in oblate models), a prolate model with $V_{\text{rot}}/\Delta V \sim 0.7$ is permitted at the 10% level by these two independent tests. The prolate model additionally requires that the cluster has, on the average, an eccentricity $e \lesssim 0.6$, so that its present, more-flattened appearance is also a statistical fluctuation.

In summary, a prolate model supported by rotation is a poor fit to the data, but not completely ruled out. In view of several studies which show that elliptical galaxies are not supported by rotation (Bertola and Capaccioli 1975; Illingworth 1977; Schechter and Gunn 1979) and Schipper and King's (1978) similar conclusion concerning the flattening of the Coma cluster, it seems reasonable to conclude that A2029 is another such example. The flattening may reflect a long-standing velocity anisotropy frozen into the system at the time of galaxy formation (e.g., Binney and Silk 1979) or might be the result of a more recent merger of two clusters. The alignment of the cD galaxy to the galaxy distribution seems to favor the first suggestion since the cannibalism of galaxies in a flattened system by the cD would likely result in a flattened and aligned cD envelope.

V. CONCLUSIONS

A2029 is rich cluster dominated by a cD galaxy which, judging by its well-developed core and smooth galaxy distribution profile, is well advanced dynamically. The radial velocities of 47 members confirm A2029 to be a

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single cluster with little apparent substructure, and although the galaxy distribution is highly flattened, there is no evidence that the structure is supported by rotation. An alternative explanation of frozen-in anisotropy is consistent with other studies and may provide, through cD cannibalism, a natural explanation of the alignment of the cD envelope with the galaxy distribution.

The higher-than-average velocity dispersion of A2029, $\Delta V = 1430$, implies a high $M/L \sim 500$ and tends to strengthen published correlations of X-ray luminosity and temperature with velocity dispersion. Since the galaxies seen projected against the cD envelope also show this high velocity dispersion, it seems unlikely that more than one or two of their galaxies are presently the victims of cD cannibalism, which is consistent with the short time scale associated with their expected destruction.

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