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INTERNAL KINEMATICS OF GALAXIES IN CLUSTERS. I. VELOCITY DISPERSIONS FOR ELLIPTICAL GALAXIES IN COMA AND VIRGO

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ABSTRACT

High signal-to-noise ratio spectra have been obtained using the du Pont Reticon spectrograph for 23 elliptical galaxies in the Virgo Cluster and 30 elliptical galaxies in the Coma Cluster. Analysis with a Fourier transform technique has produced velocity dispersions accurate to $\sim 5\%$. Measurements of the metal abundance as indicated by the Mg_2 index accurate to ~ 0.007 mag have also been determined. These data show good correlations of luminosity with both velocity dispersion and Mg_2. In particular, the L-Mg_2 relation is much stronger than that found by Terlevich *et al.* for a sample of field galaxies, and the correlation between the residuals of the L-σ and L-Mg_2 relations (the "delta-delta" diagram) found in that study is weak or absent in the cluster sample presented here. This difference between cluster and field samples is probably not due to distance errors in the field sample, since unreasonably large errors are required. It is more likely that the small sizes of the samples are responsible for the discrepancy, or that there are genuine differences between the field and cluster ellipticals. A more speculative explanation that mass-to-light variations are responsible is also considered.

The L-σ and L-Mg_2 relations are used to estimate the difference in distance moduli of the Virgo and Coma clusters, and thus derive a value of the peculiar Virgocentric velocity of the Local Group of $V_V = 229 \pm 80$ km s^{-1}. This new value is completely independent of other recent determinations, many of which also give a low value of V_V as opposed to the microwave dipole measurement of $V_V = 410 \pm 25$ km s^{-1}. This discrepancy, considered along with the large microwave component in a direction perpendicular to Virgo, suggests that the large motion of the Local Group relative to the 3 K background may be due to the gravitational pull of mass concentrations more distant and more massive than the Local Supercluster.

Subject headings: galaxies: clustering — galaxies: redshifts

I. INTRODUCTION

Studies of the motions of stars in galaxies provide valuable insights into the processes of galaxy formation. It is now believed that elliptical galaxies have a significant anisotropy in their distributions of stellar velocities (Binney 1976; Illingworth 1977). The luminous members of this class owe their oblate, prolate, or triaxial shapes to this anisotropy, while the less luminous ellipticals are oblate systems flattened by rotation (Davies *et al.* 1983). On the other hand, the bulges of disk galaxies, long supposed to be close cousins to the ellipticals because of their similarities in structure and stellar population, appear to be rotationally flattened, with isotropic velocity fields over the entire range of luminosity (Kormendy and Illingworth 1982; Dressler and Sandage 1983). These simple observations are probes of the roles of angular momentum and mergers in the collapse phase of spheroidal stellar systems.

Support for the idea that galaxies are embedded in halos of nonluminous material more extensive and more massive than the luminous material (Ostriker and Peebles 1973) has been found in the rotation curves of spiral galaxies (Rubin, Ford, and Thonnard 1980). At the limit of optical observations the rotational velocity remains nearly constant, implying a steadily increasing ratio of mass to light.

Relations between the luminosities of galaxies and their rotational velocities (in the case of disk systems, e.g., Tully and Fisher 1977) or velocity dispersions (in the case of spheroidal systems, e.g., Faber and Jackson 1976) demonstrate that galaxies in a wide range of present-day environments formed in a uniform way according to rather simple scaling laws. In a more detailed investigation of the Faber-Jackson relation, Terlevich *et al.* (1981, hereafter TDFB) conclude that elliptical galaxies are a *two-parameter* family: in the three-space of luminosity, velocity dispersion, and metal abundance, their data describe a plane with deviations consistent with observational error alone. TDFB also suggest that the "second parameter" might be related to galaxy ellipticity, since the residuals from the L-σ and L-Mg_2 relations correlate with apparent ellipticity in their sample. Establishing the validity of these relations would be a step toward understanding the formation of elliptical galaxies.

Few kinematical data are available for early-type galaxies in rich clusters. The environments of such galaxies are substantially different from the field galaxies that are the subjects of the aforementioned studies, since cluster galaxies reside in areas with a high galaxy density and a pervasive intracluster gas with as much mass as is found in the luminous galaxies themselves. It is also possible that the environment at formation was somewhat different in regions destined to be dense clusters, since these regions are rich in galaxies with luminous spheroidal components, ellipticals and S0's, which are much rarer in the low-density field (Dressler 1980). It is already known that ellipticals in clusters are, to first order, indistinguishable from their field counterparts, but since cluster ellipticals are found in an environment quite different from that of field ellipticals,[1]

[1] The term *field elliptical* in this context refers to those ellipticals found in the low-density field, and includes both members of small groups and those that are relatively isolated.

it is worthwhile to look for any subtle differences in correlations of luminosity, velocity dispersion, metal abundance, ellipticity, or velocity anisotropy.

This paper presents velocity dispersions and measurements of the Mg_2 index for 30 ellipticals in the Coma Cluster and 23 ellipticals in the Virgo Cluster. Similar data for 36 S0 galaxies in the Coma Cluster will be presented in Paper II. In the present work the techniques of data acquisition and analysis are briefly described, and the high internal accuracy of the measurements is demonstrated (§ II). The relationships among galaxy luminosity, velocity dispersion, and Mg_2 are presented and compared with the work of TDFB, particularly in connection with the "second-parameter" question (§ IV).

In addition to the issues of galaxy formation and evolution, these studies of galaxy kinematics may be useful for establishing the extragalactic distance scale and departures from a uniform Hubble flow, as demonstrated using the Tully-Fisher relation by Aaronson *et al.* (1982). In the present work the relations among luminosity, velocity dispersion, and metal abundance for Coma and Virgo ellipticals are compared in order to obtain an independent determination of the peculiar velocity of the Local Group toward the Virgo Cluster. These results are described in § III and are compared with other recent determinations, including that implied by the dipole component of the microwave background.

II. DATA ACQUISITION AND ANALYSIS

The results presented in this paper rest on the determinations of three numbers for each of the galaxies studied. Two of these, the stellar velocity dispersion and metal abundance (as implied by the Mg_2 index) were derived from a uniform set of spectra obtained with the Reticon spectrograph on the 2.5 m du Pont telescope at Cerro Las Campanas. The third quantity is the apparent magnitude of each galaxy, which is drawn from the published literature.

a) Selection of the Objects

The sample of ellipticals in the Coma Cluster consists of 26 out of the 31 ellipticals within 0°25 radius from the center of the cluster (a point midway between NGC 4889 and NGC 4874) as cataloged by Dressler (1980). These range from slightly brighter than 12th visual magnitude to slightly fainter than 16th. This sample was somewhat deficient in very bright ellipticals, so that the circle was expanded to include four other objects with $V \sim 13$. The most removed of these is NGC 4839, 0°73 from the center. Figure 1 is an enlargement of the central region of the Coma Cluster from a du Pont 50 × 50 cm 103a-O plate exposed for 1 hour with a Wratten 2C filter. The Dressler (1980) numbering system for all the objects in this area is included. Table 1 lists the selected Coma ellipticals along with their NGC or IC numbers.

The Virgo sample includes all ellipticals brighter than $B = 14.0$ (or $V = 13.0$) within 6° of the cluster center plus three members of the so-called Southern Extension: NGC 4636, NGC 4697, and NGC 4742. Basic data for these 23 galaxies are also given in Table 1.

b) Velocity Dispersion

i) *General Procedures*

The well-established technique of determining the stellar velocity dispersion in a galaxy relies on comparing the spectra of one or more template stars with the spectra of the galaxy by measuring either the width of the cross-correlation function (Tonry and Davis 1979) or comparing the Fourier transforms of the template and object. In this study a version of the Fourier quotient method pioneered by Simkin (1974) and Schechter (see Sargent *et al.* 1977) was employed, as described in Dressler (1979). However, the velocity dispersions determined in this study have a higher intrinsic accuracy than most published previously, probably a reflection of the higher quality of the data themselves. Since the Reticon spectrograph

TABLE 1

BASIC DATA

NGC or IC No.	Dressler No.	V_{26}	log σ	Mg_2
		Coma Sample		
N4839	31	12.60	2.449	0.298
N4926	49	13.12	2.394	0.318
I3959	69	14.23	2.285	0.305
I3957	70	14.86	2.166	0.282
	87	15.88	1.863	0.224
N4869	105	13.92	2.286	0.326
	107	15.45	1.761	0.231
N4906	118	14.36	2.209	0.302
N4898E	120	15.07	2.113	0.258
N4898W	121	14.07	2.301	0.268
N4876	124	14.53	2.243	0.241
	125	15.60	2.169	0.261
N4874	129	12.27	2.383	0.322
N4872	130	14.36	2.311	0.296
N4867	133	14.50	2.339	0.306
	136	15.52	2.251	0.277
I4051	143	13.46	2.361	0.324
N4889	148	11.85	2.584	0.358
I4011	150	15.31	2.007	0.277
N4886	151	13.98	2.180	0.262
	153	15.28	2.099	0.285
N4864	159	14.26	2.275	0.286
I4045	168	14.11	2.320	0.302
I4021	172	14.87	2.191	0.296
I4012	174	14.82	2.247	0.291
	193	15.37	2.059	0.261
N4860	194	13.49	2.394	0.356
	207	15.04	2.154	0.262
N4881	217	13.67	2.274	0.292
N4841B	240	12.88	2.383	0.321
		Virgo Sample		
N4168	...	11.39	2.242	0.247
N4239	...	12.53	1.716	0.148
N4365	...	9.98	2.412	0.311
N4374	...	9.37	2.480	0.310
N4387	...	12.24	2.059	0.236
N4406	...	9.20	2.355	0.299
N4434	...	12.17	2.009	0.241
N4458	...	12.01	1.949	0.212
N4464	...	12.50	2.079	0.227
N4472	...	8.56	2.474	0.335
N4473	...	10.28	2.268	0.304
N4478	...	11.28	2.170	0.253
N4486	...	8.79	2.528	0.324
N4489	...	12.02	1.778	0.176
N4551	...	11.92	2.021	0.241
N4552	...	9.95	2.391	0.320
N4564	...	11.30	2.185	0.278
N4621	...	9.88	2.338	0.312
N4636	...	9.82	2.303	0.316
N4649	...	8.90	2.514	0.359
N4660	...	10.97	2.262	0.270
N4697	...	9.28	2.276	0.282
N4742	...	11.37	2.027	0.173

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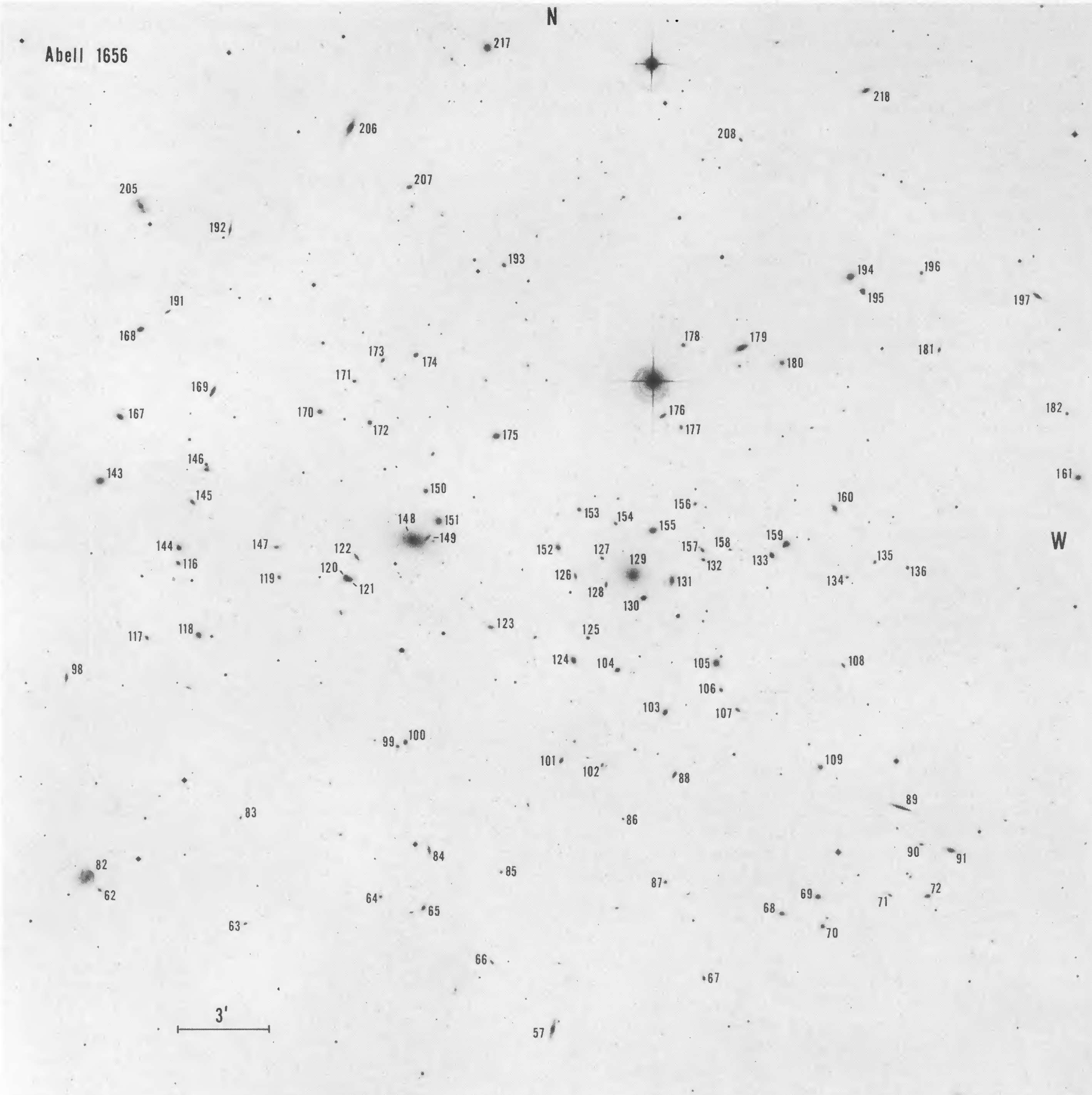

FIG. 1.—Enlargement of a section of a 103a-O du Pont plate of the central 0°.5 of the Coma Cluster. The numbers refer to the numbering system of Dressler (1980).

has an unusually high number of resolution elements along the dispersion (~ 1000), it is possible to obtain spectra from 4000 to 6000 Å covering the line-rich G band and Mg triplet regions, and still maintain an instrumental velocity width less than 100 km s^{-1}.

The Coma Cluster ellipticals are faint; therefore, it is desirable to open the slit as wide as possible. By using a 1200 lines mm^{-1} grating blazed at 5000 Å with a nominal dispersion of 0.6 Å per pixel, a 4″ × 4″ slit only degraded the instrumental resolution to an acceptable $\sigma = 85$ km s^{-1}. Since the slit was completely resolved at 5.5 pixels per FWHM, the data were oversampled by about a factor of 2. This means that the noise characteristics of the data are unusually good; i.e., the noise spectrum is closer to white because pixel-to-pixel correlations have been suppressed by oversampling. This, combined with the high signal-to-noise ratio (S/N) of the spectra, produces velocity dispersions that are very repeatable and consistent in different spectral regions.

Each of the 30 Coma Cluster galaxies was observed twice, in February of 1982 and March of 1983. The 4″ × 4″ slit is sufficiently large that atmospheric refraction effects are not very important, even at the large air mass (~ 2.0) of observations of galaxies in Coma made from Las Campanas. (Such effects are also alleviated by the fact that the effective wavelength of the image as viewed through the TV guider is ~ 5000 Å, which agrees well with the spectral region studied.) Each spectrum has a S/N $\gtrsim 20$ per angstrom, so that the final S/N of each Coma observation is $\gtrsim 28$. Integrations on each object required between $\frac{1}{2}$ and 2 hours to reach the desired S/N. Four examples of these Coma spectra with a range of velocity dispersion are shown in Figure 2, along with the stellar template.

The 23 Virgo ellipticals, observed in 1983 March, all have a S/N $\gtrsim 30$. Velocity dispersions are known to fall with radial distance from the nucleus in elliptical galaxies (Davies 1981; Illingworth 1983); therefore, it was decided to observe nearly the same spatial area in the Virgo ellipticals as was covered by the 4″ × 4″ slit for the Coma ellipticals. This was accomplished by drift scanning a 4″ × 16″ slit over the Virgo ellipticals in order to simulate observing the galaxy with a 16″ × 16″ aperture. By measuring the width of calibration arc and night-sky lines, it was determined that in all cases, less than 2% artificial broadening was introduced by this technique, so that the 4″ × 4″ and 4″ × 16″ slit measurements are directly comparable. As will be discussed later, the measured velocity dispersion of a typical nearby elliptical falls about 6% from a 4″ × 4″ area to a 16″ × 16″ area. This is not negligible in this type of study and must not be ignored.

Finally, special attention was given to the importance of choosing template stars with which to determine the velocity dispersions. The galaxies in question span a luminosity range of nearly 100, and it is now recognized that the average metal abundance of the stars producing the light varies systematically over that range. Inspection of such features as the Mg H and Mg *b* triplet lines indicate that the light of giant ellipticals is dominated by so-called SMR (super-metal-rich) stars, those stars with 2–3 times solar metal abundance. On the other end, the faintest ellipticals in this sample, at $M_B \approx -18$ ($H_0 = 50$), have spectra that appear metal poor compared with K0 giants of solar abundance. In the blue, in fact, many have spectra resembling main-sequence G-dwarf stars. In order to test the sensitivity of the velocity dispersion measurements to metallicity of the template, six K0 giants and three G dwarfs with a range of metal abundance from solar to SMR were observed to a S/N $\gtrsim 50$. Spectra of these stars were obtained through the 4″ × 4″ slit with the same setup as for the elliptical galaxies, except that the star images were trailed over the width of the slit so as to mimic the light distribution from a galaxy with zero velocity dispersion. When the Fourier technique was used to compare these stars with various galaxies, it was found that the velocity dispersions changed by less than 5% over the range of templates, while the line strength parameter "gamma" changed by a factor of 2. Apparently, determination of the velocity dispersion by the Fourier technique is quite *insensitive to the metal abundance of the template* and also insensitive to the spectral type of the template, as shown by Schechter and Gunn (1979). The small systematic effect on the velocity dispersion as a function of metal abundance (and thus with luminosity) that remains is unimportant in this work since the range of variation is the same for Virgo and Coma ellipticals. Therefore, a template formed by adding the spectra of BD +15°1544 and BD +29°2908, two giants with approximately solar abundance, was adopted for all measurements.

ii) *Accuracy of the Measurements*

The high S/N of these spectra, combined with their excellent noise characteristics, results in velocity dispersion measurements with a high degree of internal accuracy. The first comparison indicating this is made in Figure 3, where the velocity dispersions measured in the G band region (4200–4700 Å) and Mg region (4900–5400 Å) are compared. These pairs of measurements, each from a spectrum of S/N $\gtrsim 20$, agree well from very low to high velocity dispersions, with an implied accuracy of each measurement of better than 10%. A slight zero-point shift [in the sense that the σ(Mg) determination is systematically 10% higher] depends on the template used. These measurements are averaged together to form the adopted velocity dispersion for each spectrum. In Figure 4 the 1982 measurements are compared with the 1983 measurements. Again, the agreement is excellent and implies an accuracy of each measurement of about 7%. The final values of the velocity dispersion are therefore good to $\sim 5\%$, on the average, for both the Coma and Virgo measurements. There is a slight zero-point shift in Figure 4 that indicates that the 1982 measurements are systematically higher by 4%. This has been accounted for by adjusting them 4% lower before averaging the 1982 and 1983 data, so as to maintain consistency with the Virgo data, which was all obtained in 1983. The adopted values of the velocity dispersion are given in Table 1.

External comparisons with the velocity dispersions determined in other studies for objects in common with the present sample has become complex because of the extensive data now available. Since the present work rests exclusively on *internal consistency*, these comparisons are not particularly relevant. As an example, however, the "zero-point" of the L-σ relation, $\sigma(M_B = -21)$ as introduced by Whitmore, Kirshner, and Schechter (1979), is 208 km s^{-1} for this study, as compared with 237 for Faber and Jackson (1976), 201 for Schechter and Gunn (1979), 184 for Sargent *et al.* (1977), 237 for Whitmore, Kirshner, and Schechter (1979), and 220 for TDFB.

c) The Mg_2 *Index*

The Mg_2 index as defined in Faber, Burstein, and Dressler (1977) is a measure of metal abundance of the stars that

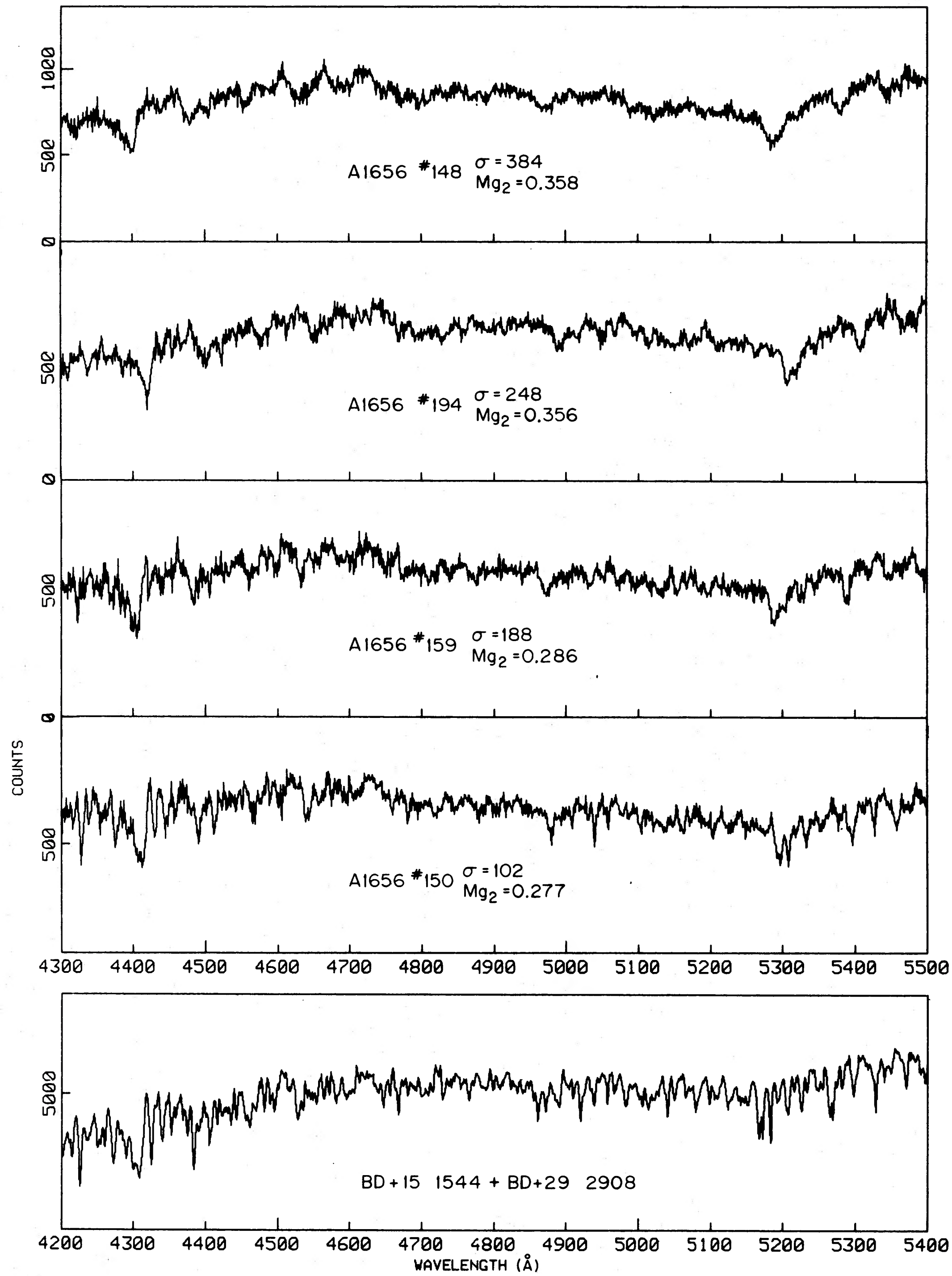

FIG. 2.—The spectra of four sample Coma ellipticals and the adopted stellar template. Each spectrum is the sum of the two spectra, each with S/N $\gtrsim$ 20 per angstrom. A range of velocity dispersion and Mg_2 strength is easily discerned by eye.

dominate the light of the galaxy, and is correlated with galaxy luminosity as shown in TDFB. The index measures the depression, expressed in magnitudes, of the intensity over the band 5157–5198 Å (in the rest frame) from a continuum line fit to two sidebands 4898–4959 Å and 5304–5358 Å. The depth of the central band is the combined effect of the broad Mg H feature and the Mg I *b* triplet and ranges from about 0.10 mag for metal-weak to 0.35 mag for metal-rich giants. The zero point of the system used here is in agreement with the values given in TFBD to $\sim \pm 0.002$ mag. Single measurements of the Mg_2 index using spectra with S/N $\gtrsim$ 20 are accurate to $\sim$0.010 mag, as demonstrated in Figure 5, where the 1982 and 1983 determinations are compared. The adopted values quoted in Table 1 are therefore good to $\sim$0.007 mag on the average, for both the Coma and Virgo data. These values include a slight correction, reaching

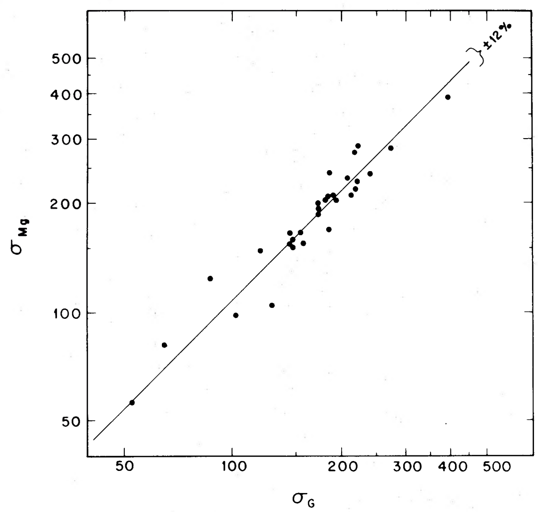

FIG. 3.—Comparison of the velocity dispersion measurements for the G band region with that for the Mg *b* region. Each point represents these two values for one of the S/N ~ 20 spectra of 1983 Coma data. The small scatter shows the high level of internal consistency.

a maximum of 2%, for the diminution of the central band due to the broadening by velocity dispersion. This correction was determined by artificially broadening standard stars (convolving with a Gaussian) and is completely negligible for $\sigma \leq 200$ km s^{-1}.

d) *Apparent Magnitudes*

The only photometric study that covers all 30 of the Coma ellipticals in the present work is that by Godwin and Peach (1977, hereafter GP). They present V_{25} magnitudes (total light within 25th magnitude isophote) for all but Dressler #194 (NGC 4860). This value was taken directly from Sandage and Visvanathan (1978). Dressler 120 and 121 were assigned different values from those quoted by GP since it was apparent from the large-scale du Pont plate that the ratio in brightness between the two components of this double system is approximately 2–3 to 1, and not as large as quoted by GP (who doubtless had trouble separating the two images on the lower resolution Schmidt plates). The GP magnitudes were summed and split between #120 and #121 assuming a difference of 1.0 mag.

Magnitudes for the Virgo ellipticals were taken from Sandage and Visvanathan (1978), who give photoelectrically measured V_{26} magnitudes for most of the Virgo ellipticals and 10 galaxies in Coma in common with GP. Comparison of the two studies indicates a slight zero-point adjustment of $V_{26} - V_{25} = +0.07$ (the GP values in Table 1 have been shifted by this amount) with very good point-by-point agreement, suggesting that the adopted magnitudes have a dispersion of $\sigma \approx 0.13$ mag. A few of the Virgo ellipticals were not studied by Sandage and Visvanathan but had *B* magnitudes listed in the *Revised Shapley-Ames Catalog* (Sandage and Tammann 1981). These values were adopted after correcting $B_T^{0,i} - V_{26} = 0.81$, which was determined from comparison of the 20 Virgo ellipticals common to both studies.

III. MOTION OF THE LOCAL GROUP TOWARD THE VIRGO CLUSTER

a) *The Data*

The relationship of velocity dispersion to luminosity is shown as log σ versus V_{26} for the Coma and Virgo ellipticals in Figure 6, and the relationship between Mg_2 and V_{26} is shown in Figure 7. When the apparent magnitude is used as the abscissa, it is easy to see that the relations are very similar for the galaxies of both clusters, and that the correlation is quite strong. One of the more striking features is that the relation between Mg_2 and luminosity is much stronger than in the TDFB sample. This will be discussed in more detail in § IV.

In the following discussion it will be assumed that the entire separation between the Virgo and Coma samples in both Figures 6 and 7 is due to the difference in distance to the two clusters. That is, it is assumed that there are no intrinsic differences in the distributions of these quantities; for example, the Mg_2 index is assumed not to be systematically higher or lower at a given luminosity in Virgo than in Coma. If subsequent studies reveal that the distances to the two

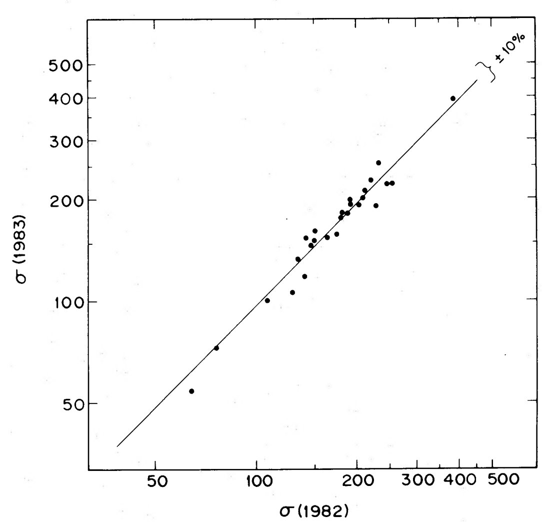

FIG. 4.—Comparison of the velocity dispersion measurements for 1982 with those of 1983 for the Coma ellipticals. The figure demonstrates that the final values are good to ~5%.

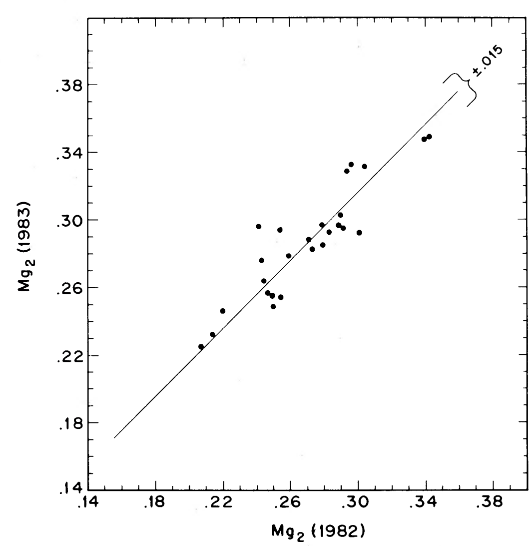

FIG. 5.—Comparison of the Mg_2 measurements for 1982 with those of 1983 for the Coma ellipticals. The figure demonstrates that the final values are good to ~0.007 mag.

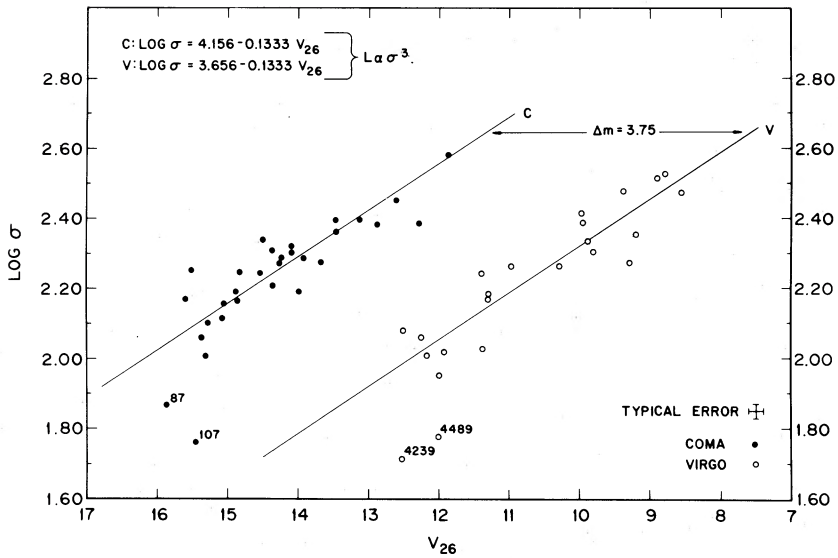

FIG. 6.—The log of the velocity dispersion vs. V_{26} for the Coma and Virgo ellipticals. The lines represent median fits, as described in the text, and are separated by 3.75 mag, indicating a distance ratio D(Coma)/D(Virgo) = 5.62. This implies a peculiar Virgocentric velocity of 311 km s^{-1}. Some of the more deviant points are identified.

clusters are not in the ratios implied by the data of Figures 6 and 7, then this would indicate that this assumption of universality is incorrect, and that there are systematic differences among clusters. This assumption can also be tested, of course, by obtaining and comparing similar data for other clusters whose Hubble velocities are sufficiently high that their distances can be unambiguously determined.

The separations between the two sequences, which represent the differences in distance moduli between the Virgo and Coma clusters, are found in this study to be 3.75 mag for the log σ versus V_{26} diagram and 4.00 mag for the Mg_2 versus V_{26} diagram. These values were determined in an unorthodox manner, but one that is much preferred over the usual technique of least squares fitting, which assumes Gaussian distributions. It is quite clear from Figures 6 and 7 that the distributions are distinctly non-Gaussian, since there are obvious asymmetries and a few very discrepant points that would receive inordinately high weight in a least squares fit. The procedure adopted was to combine the samples in each diagram with approximately the proper shift, estimate the slope of the best fitting line to all the data, and then turn this line into a median line, i.e., draw a line of the same slope which bisects each distribution. (Put another way, the trend has been determined by combining the data, and then the medians have been compared after the trend has been removed.) Though it is somewhat arbitrary to determine the slope of the line in this way, an advantage of this technique is that it does not depend critically on the slope that is chosen

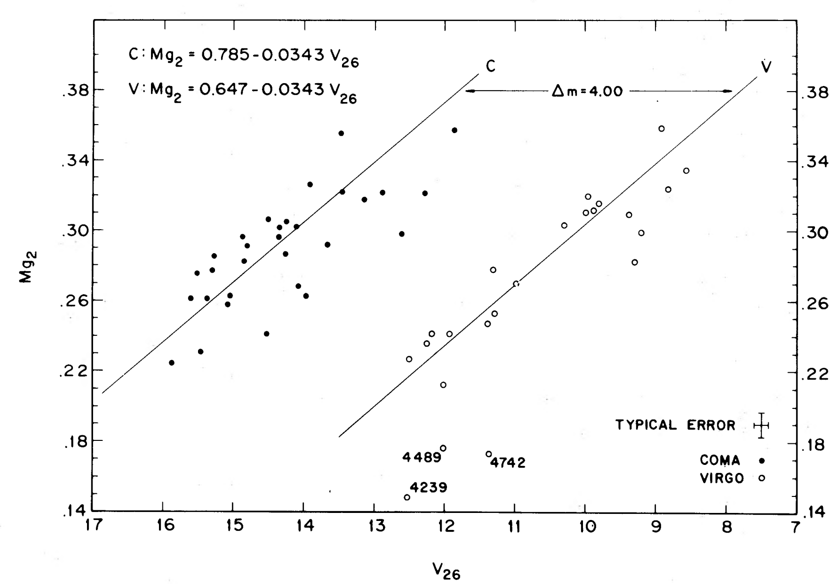

FIG. 7.—The Mg_2 index, a measure of metal abundance, vs. V_{26} for the Coma and Virgo ellipticals. The lines represent median fits, as described in the text, and are separated by 4.00 mag, indicating a distance ratio D(Coma)/D(Virgo) = 6.31. This implies a peculiar Virgocentric velocity of 147 km s^{-1}. Some of the more deviant points are identified.

and gives nearly the same answer for all reasonable choices. In fact, the assumption of a linear relationship is also probably unjustified, and thus it is equally reassuring that the adopted procedure is relatively insensitive to the curve chosen to describe the distribution of points.

The adopted slope of the line that best describes the log σ versus V_{26} relation of Figure 6 corresponds to $L \propto \sigma^3$, a stronger dependence of velocity dispersion with luminosity than the traditionally assumed $L \propto \sigma^4$. This "steeper" relationship was first proposed by Tonry (1981) for his own data on the Virgo ellipticals, a sample almost identical to the one studied here, and his work includes a brief discussion of the possible significance of the difference in slope in comparison with earlier work. It is quite possible, however, that the principal reason for the stronger relationship is that the other samples include mostly field galaxies, and errors in luminosity due to errors in distance will tend to reduce the strength of the correlation in just this way. On the other hand, the importance of the *value* of the exponent should not be overemphasized, since samples like those presented here and Tonry's give the distinct impression that the relationship is *not* a simple power law. It appears in Figure 6 that the relation becomes more shallow at high luminosity (see, e.g., Malmuth and Kirshner 1981) and perhaps even steeper at the lowest luminosities. This end is particularly uncertain, however, since it could well include rapidly rotating elliptical galaxies (Davies *et al.* 1983) or S0 galaxies, which are difficult to distinguish morphologically. Several possible examples of these types are noted on Figure 6.

Errors have been estimated using a Wilcoxon Distribution-Free Rank Sum Test (Hollander and Wolfe 1973), which can be used to determine a confidence interval for the determination of the medians of two samples. The uncertainty in Δm is nearly the same for the two determinations of Figures 6 and 7 and amounts to ± 0.18. (Though this nonparametric approach to error estimation is preferred, the use of Gaussian statistics gives a similar value for the uncertainty in the determination of the medians.) At first glance it seems surprising that Δm from the Mg_2 versus V_{26} relation is as well-determined as that from the log σ versus V_{26} relation, since the scatter from the median line appears smaller in the latter. The dispersion in the *abscissa* is all that matters, however, and this is very similar for the two relations. (The scatter perpendicular to the median lines is greater in Fig. 7 than Fig. 6, but the slope in the Mg_2-V_{26} plot is steeper, which strengthens the method.)

These values of Δm imply that the distance ratio D(Coma)/D(Virgo) is 5.62 for the log σ comparison and 6.31 for the Mg_2 comparison. These numbers, in turn, can be compared with the ratio of distances implied by the recessional velocities of the clusters using Schechter's (1980) linear Virgocentric flow model (with $\gamma = 2$) to determine the peculiar Virgocentric velocity V_V.[2] Applying this procedure with the values quoted above, and adopting V(Virgo) $= 967$ km s^{-1} (Kraan-Korteweg 1981) and V(Coma) $= 6890$ km s^{-1} (Rood *et al.* 1972),[3] yields $V_V = 311(^{+136}_{-120})$ from the log σ versus V_{26} comparison and $V_V = 147(^{+109}_{-103})$ for the Mg_2 versus V_{26} data. Weighting these two equally as is indicated by the Wilcoxon confidence intervals gives a mean value of $V_V = 229(^{+87}_{-79})$.

b) Discussion

There are numerous ways to measure the motion of the Local Group toward Virgo Cluster, and the results of such efforts have been reviewed in several papers. To simplify the following discussion, only the latest of these reviews, that by Davis and Peebles (1983, hereafter DP), will be discussed here. In Table 1 of DP the authors present a nearly complete summary of the methods used and values of V_V obtained in many studies. Since DP are primarily interested in the density parameter Ω, they make no serious effort to compare the value of V_V from the microwave measurements, which is well determined, with the numerous, less well determined values of V_V from optical methods, like the one in this paper. Also, the values selected by DP for their final V_V are chosen in a quite arbitrary fashion. Their value of $V_V = 400$ km s^{-1} is dominated by the microwave value itself, which has 4 times the weight of any of the other values DP included. DP exclude five of the nine best determined optical measurements (as judged by their associated errors) on the grounds that "we suspect that the local studies are the least reliable group."

The comparison of V_V (microwave) with V_V (optical) is an interesting and important one. Here the evidence is reviewed that these two numbers are not in good agreement. When this possibility is considered along with the large component of V_V (microwave) in a direction *perpendicular* to the centroid of the Local Supercluster, it seems likely that the pull of this nearby density enhancement does not account for a large fraction of the microwave dipole component. This, in turn, would imply that the density fluctuations that are accelerating both the Local Group and the Local Supercluster are farther away and of much larger scale. Since this is one of the more direct methods to evaluate the power spectrum of large mass scales, a distribution that is fundamental to both galaxy formation and cosmology, it is desirable to undertake such a critical comparison of V_V (microwave) and V_V (optical).

c) A Second Look at the Determinations of V_V

It seems unlikely from an inspection of DP's Table 1 that a convincing case can be made for any mean V_V based on the optical measurements, since the range of quoted values is inconsistent with their quoted errors. The object here is only to demonstrate that a lower value of V_V than implied by the microwave measurements is just as consistent with those data.

The problem, of course, is that the error estimates only reflect the seriousness of *random* errors; the more difficult-to-assess *systematic* errors are seldom included. An example of this can be made using data collected during the present work, which yields an *aperture correction* for comparing the internal velocity dispersions of nearby and distant E and S0 galaxies.

[2] The term *infall* has been adopted in many studies of this type to describe the velocity component of the Local Group in the direction of the Virgo Cluster. However, infall implies a gravitational acceleration, and the quantity actually measured with techniques like the one in this paper can include systematic (such as rotation of the Local Supercluster) or random motions; therefore, the nomenclature V_V (peculiar Virgocentric velocity) used by Davis and Peebles (1983) is preferred. The values for V_V derived here can be compared directly with what is loosely called the "infall velocity" in studies where this distinction is not clearly drawn.

[3] The Virgo velocity is also very close to the value of 980 km s^{-1} adopted by Davis and Peebles, which comes from Mould, Aaronson, and Huchra (1980) but uses the Yahil, Sandage, and Tammann (1977) solution for the reduction of heliocentric velocities to the centroid of the Local Group. The Coma velocity is a compromise between the $V_C = 6950$ value of Tifft and Gregory (1976) for a more extended 3° sample and a value of $V_C = 6850$ km s^{-1} for the present sample of 66 E and S0 galaxies in the Coma core region.

It was realized that a 4″ × 4″ aperture for the Coma galaxies would sample a much larger volume than the same aperture used on Virgo galaxies. As mentioned in § II*b*(i), the general decline in measured velocity dispersions with radial distance requires that the Virgo galaxies be observed with apertures that are effectively 4 or 5 times as large. As described earlier, such measurements can be made by drift scanning a long slit over the galaxy. During the 1982 and 1983 observing seasons, such drift scans were made on 43 nearby ($V \sim 1000$ km s^{-1}) ellipticals and eight S0's in the Virgo and Fornax clusters, and in the field. The same galaxies were also observed with 4″ × 4″ apertures centered on the galaxies, in order to estimate the average error that would result if only small-aperture measurements were made. These data are shown in Figure 8, where the small-aperture measurements σ_S are plotted against the large-aperture measurements σ_L. Figure 8 shows that, as expected, the velocity dispersions measured through the large apertures are systematically lower than those through the small apertures. The magnitude of the effect is -9% ($\pm 2\%$) for 13 field ellipticals, -10% ($\pm 3\%$) for nine Fornax ellipticals, and -3% ($\pm 3\%$) for 21 Virgo ellipticals, yielding an average of -6% ($\pm 2\%$). The effect seems to be larger for the S0 galaxies, amounting to -19% ($\pm 3\%$), though more data are needed here. Tonry and Davis (1981) did *not* include this aperture effect in their determination V_V from the comparison of Virgo ellipticals and S0's to a field sample which is, on the average, 3 times more distant. They used a 3″ × 12″ slit, and the ratio of the large to small aperture size for their sample is closer to 3 than 4, so that the data of Figure 8 are not directly applicable. If one makes the conservative assumptions, however, that a 4% correction is needed for the ellipticals, and a 6% correction is needed for the S0's, this implies 0.20 and 0.30 mag shifts, respectively, for the ellipticals and S0's, since $L \propto \sigma^{4.5}$ in their sample. This seemingly small effect lowers their values of V_V from 470 to 320 km s^{-1} for the elliptical galaxies and from 416 to 203 km s^{-1} for the S0 galaxies. The correction could well be larger, resulting in even lower values of V_V.

Table 2 is a compilation of the 10 best determinations of V_V (quoted errors less than 100 km s^{-1}) regardless of technique or domain, with the corrected Tonry and Davis values and the new value from this study, which is completely independent of previous determinations. The unweighted mean of these 10 determinations is 297 km s^{-1} with a standard deviation of 114 km s^{-1}. Thus, one is able to arrive at a value considerably lower than V_V (microwave), and one that is consistent with the errors quoted by the authors if it is true that the *systematic errors* are comparable in size to the *random errors*. Including seven additional determinations whose quoted errors are 50% larger lowers the value for V_V even further.

As was stated previously, it is impossible to make a compelling case for one value or the other when the sources of systematic errors in the determinations are largely unknown. There is, at this point, insufficient information to decide which values should be included in a determination of the mean of V_V, and how these should be weighted. The author of this

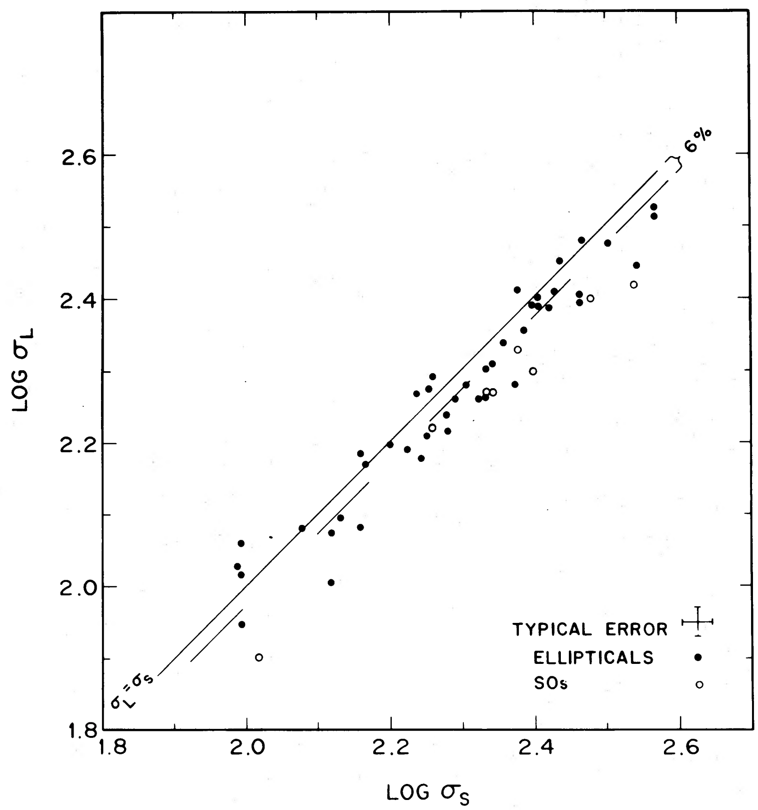

FIG. 8.—The comparison of velocity dispersion measurements through small apertures (4″ × 4″) with those for large apertures (synthesized 16″ × 16″, see § II) for 43 nearby ($V \sim 1000$ km s^{-1}) ellipticals and eight nearby S0's. An average decrease of 6% from the small to large aperture measurements is apparent, although individual cases can be much larger. (Within the errors, no galaxy shows an increasing velocity dispersion with radius.) This seemingly small effect is important in comparing the velocity dispersions of nearby and distant galaxies, as discussed in § III.

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TABLE 2

V_V MEASUREMENTS

DP No.	Method	V_V[a] (km s^{-1})		Reference
4	M_H-ΔV at $CZ \sim 2500$	450	±55	Hart and Davis 1982
11	L-ΔV at $CZ \sim 5000$	520	±75	Aaronson *et al.* 1980; Mould, Aaronson, and Huchra 1980
12	L-σ at $CZ \sim 5000$; E	320[b]	±75	Tonry and Davis 1981
13	L-σ at $CZ \sim 5000$; S0	203[b]	±75	Tonry and Davis 1981
14	B_T at $CZ \sim 1000$	175	±60	de Vaucouleurs and Peters 1981
15	B_T-ΔV at $CZ \sim 1000$	197	±40	de Vaucouleurs *et al.* 1981
16	Local: RSA	220	±75	Sandage and Tammann 1981; Yahil 1981
18	IR-ΔV: Δm for Fornax and Virgo	316	±80	Aaronson *et al.* 1982
19[c]	IR-ΔV: flow model	331	±41	Aaronson *et al.* 1982
	L-σ, L-Mg_2: Coma vs. Virgo	242[d]	±80	This paper
		297	±36	$\sigma = 114$

[a] The quoted values have been adjusted by Davis and Peebles to conform with the Yahil, Sandage, and Tammann 1977 solution for the conversion of heliocentric velocities to the centroid of the Local Group.

[b] Corrected for aperture effects as described in § III.

[c] DP #19 and #20 are different analyses of the same data.

[d] A correction of +13 km s^{-1} has been added to the value quoted in the text to account for the adopted Virgo velocity.

paper naturally prefers the scheme suggested here, since this mean value agrees well with the results of this paper, while the DP value is some 2 σ away. The point of this exercise, however, was only to show that although there is still great uncertainty in the determinations of V_V (optical) from relatively nearby galaxies, it may well turn out that a large fraction of the $V_V = 410$ km s^{-1} measured from the microwave dipole anisotropy is not due to local gravitational accelerations (scales $\lesssim 30$ Mpc). This is further supported by the equally large component of the microwave anisotropy that is perpendicular to the vector point at Virgo. DP suggest that this component of the motion can be accounted for by departures from spherical symmetry in the Local Supercluster; but it could also be due to large mass concentrations farther than Virgo but closer than the Coma Cluster. In any event, it appears possible, if not likely, that the microwave dipole anisotropy will not be explained by the pull of the Local Supercluster alone. Since this would be very informative as to spectrum and distribution of mass on large scales, it would be unwise to sweep the disagreement under the rug in order to make all the numbers compatible.

IV. THE SECOND-PARAMETER QUESTION

Both metal abundance, as measured by the spectral line strength (Faber 1973), and central velocity dispersion depend primarily on luminosity for elliptical galaxies. (It is probably more sensible to consider galaxy mass as the principal parameter, but the relative constancy of mass-to-light ratios allows one to think of the more easily measured quantity as the fundamental one.) TDFB measured velocity dispersions and Mg_2 indices for 24 elliptical galaxies using high S/N spectra and demonstrated these correlations of L, σ, and Mg_2. Though the L-σ relationship is quite strong for their sample, the L-Mg_2 correlation is very weak. TDFB did, however, find a strong relationship between the scatter in these two relations in the sense that galaxies with velocity dispersions that are higher than the mean at a given luminosity also have Mg_2 indices that are too large; that is, they are more metal rich. This correlation of residuals, called the "delta-delta diagram" in TDFB, implies that, in addition to luminosity, at least one more parameter is needed to describe the properties of elliptical galaxies. There is also an indication in their work that these residuals are connected with galaxy ellipticity in the sense that round ellipticals have higher velocity dispersion and Mg_2 than flat ellipticals at a given luminosity.

Some of these conclusions have been challenged by Tonry and Davis (1981), who, for a much larger sample, confirm the L-σ and L-metallicity relations but find only a weak correlation among the residuals. Furthermore, Tonry and Davis find no correlation of these residuals with galaxy ellipticity. However, their metal abundance determinations have significantly larger internal errors than the TDFB Mg_2 determinations, and so the analysis by Tonry and Davis is not decisive. The delta-delta relationship is also investigated by Efstathiou and Fall (1983), who, in principal component analysis of the TDFB sample plus 13 low-luminosity ellipticals, conclude that the distribution of points in the M_B–log σ–Mg_2 space is approximated by a canted plane. Such a distribution will show a correlation among the residuals in the planes onto which it is projected. Although Efstathiou and Fall thereby support the TDFB claim of at least two parameters, they find no evidence that the second parameter is related to galaxy ellipticity and instead suggest that mass-to-light ratio is more likely correlated with the residuals of metal abundance and velocity dispersion. Other candidates for the second parameter are considered by de Vaucouleurs and Olson (1982).

The data presented here for the Coma and Virgo ellipticals show a relationship between luminosity and velocity dispersion that has comparable scatter but is steeper than those of TDFB and Tonry and Davis. In comparison to the L-Mg_2 relationship of TDFB (or Efstathiou and Fall) the relationship in this paper has a similar scatter, but again the trend is *much stronger*. In fact, the L-Mg_2 relationship rivals the L-σ relationship as a distance indicator. Why is the correlation so much better in the cluster sample? Measurement errors are not the problem.

The apparent magnitudes for the TDFB sample are at least as good, and the Mg_2 indices are more accurate. There are other possibilities: (1) the TDFB sample is small and unrepresentative; (2) the correlations are intrinsically better for cluster ellipticals; (3) there are substantial errors in the determinations of distances to the field galaxies that are required to turn their apparent magnitudes into luminosities; (4) mass, not luminosity, is the proper independent variable, and the connection between the two, the mass-to-light ratio, has a larger dispersion in the field sample.

Before trying to evaluate these possibilities, it is instructive to look at the delta-delta diagram for the *cluster* sample, which is plotted in Figure 9. At first glance it is obvious that no very tight relationship exists as in TDFB. On the other hand, one's impression is that there is some residual correlation in the same sense as in TDFB. Confidence in this conclusion, however, begins to evaporate as soon as the data are scrutinized more closely. The Coma ellipticals form a scatter diagram in which most of the scatter is cosmic and not due to measuring errors. There is no clear trend. The most deviant point, #107, can be seen on Figure 1 to be the best candidate for an S0 that should have been deleted from the sample. The Virgo ellipticals overlay the Coma sample, except for four points, NGC 4697, NGC 4742, NGC 4239, and NGC 4489. Two of these, NGC 4239 and NGC 4489, lie about 5° from the Virgo center, and thus near the edge of what is traditionally considered the Virgo Cluster proper. They are quite close together in the sky and have nearly the same radial velocities of about 900 km s^{-1}. These two are in the "triple value region," where it is difficult to determine reliable distances. If instead of including NGC 4239 and NGC 4489 in the Virgo Cluster proper, one puts them at roughly 50% of the Virgo distance, they will still have a 900 km s^{-1} recessional velocity due to their own infall to Virgo. This means that they would be intrinsically fainter by as much as 1.5 mag, which would explain their large residuals in the L-σ and L-Mg_2 diagrams and their positions in the delta-delta diagram. The other two deviant galaxies, NGC 4697 and NGC 4742, are members of the Southern Extension of the Virgo Cluster. They, too, have very similar velocities, of order 1200 km s^{-1}, and lie in a region where distance determinations are somewhat ambiguous (although the situation seems not to be as bad as for NGC 4489 and NGC 4239). Furthermore, in a strict sense, they are not members of Virgo since they lie outside the 6° radius and probably should not be included in a comparison with the Coma sample, which is strictly confined. Without these four questionable galaxies, there is no compelling evidence of a correlation between the L-σ and L-Mg_2 residuals in the cluster sample.

In summary, the residuals in the L-σ and L-Mg_2 relations are about the same size in both the cluster sample and the TDFB field sample, but the relationships are steeper in the

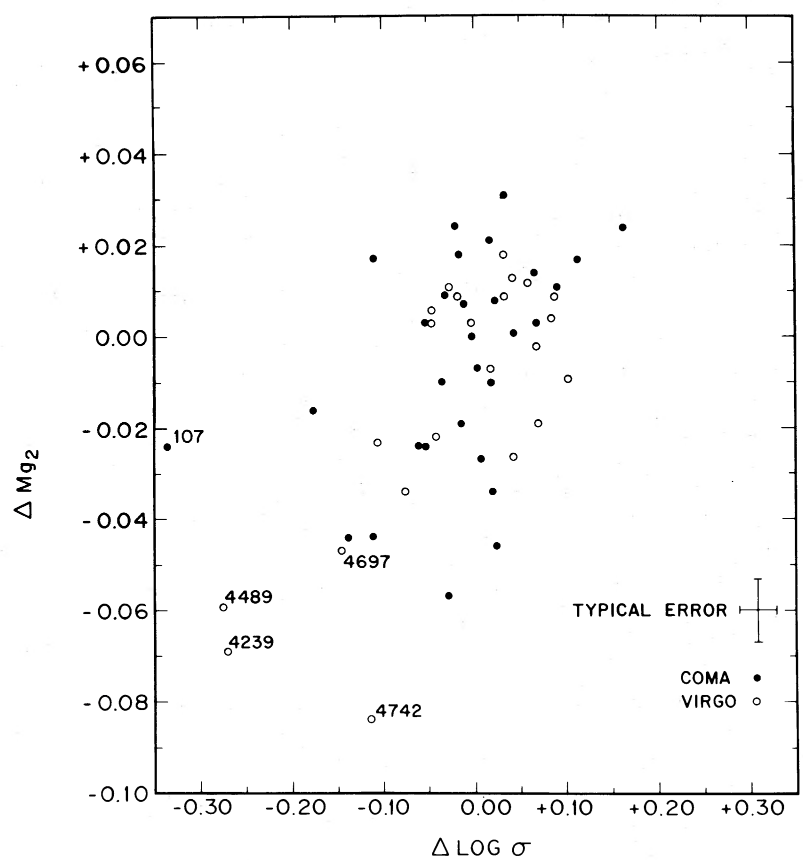

FIG. 9.—The residuals of the log σ vs. V_{26} plot (Fig. 6) vs. the residuals of the Mg_2 vs. V_{26} plot (Fig. 7)—the delta-delta diagram of TDFB. No strong correlation like that in the TDFB sample is seen, but a weaker trend seems apparent. On closer examination, however, there are reasons to be suspicious of all the identified points in the lower left (see § IV), and without these there is little or no evidence of a correlation of the residuals.

cluster sample, especially in L versus Mg_2. If there is a trend in the delta-delta diagram, it is much weaker than that found by TDFB for the field sample.

Let us now return to the four possible explanations of the stronger L-Mg_2 relationship for the cluster sample than the TDFB sample. The most likely explanations for the difference are that the TDFB sample is small and unrepresentative, or that cluster ellipticals are intrinsically different from field ellipticals. The former will become known as the results of a new study (Faber *et al.* 1984) with a sample 10 times the size of TDFB are analyzed, and more observations of clusters will be necessary to confirm the latter possibility. If it is eventually resolved that cluster ellipticals form a more coherent sample of objects with stronger correlations of L-σ-Mg_2, perhaps because of a common environment of formation and similar evolutionary histories, an important clue to the role of environment in the development of elliptical galaxies will have been found.

The more speculative explanations are also worth considering. The absence of a strong delta-delta relation for the cluster sample makes the explanation that there are substantial errors in the luminosities of the field galaxies seem particularly attractive. Such errors, which would most likely come from errant distance determinations, would explain the degradation of both the L-σ and L-Mg_2 correlations and would generate a correlation between the residuals of these two relations. (A cluster sample is immune to such problems, of course, since the galaxies in any given cluster are at roughly the same distance.) TDFB anticipated this objection to the delta-delta relation and pointed out that the "distance error vector" in the delta-delta diagram is not well aligned with the relationship, indicating that distance errors are not responsible for spreading the points. This defense is unsatisfactory, however, since the direction of the vector depends on the slopes in the L-σ and L-Mg_2 diagrams and the latter of these is extremely poorly determined. If the slope of the L-Mg_2 relation is steeper, as found here, the vector aligns quite well with the distribution of points.

A further indication that there is a problem with using galaxy luminosity as the independent variable can be seen in Figure 8 of Tonry and Davis (1981). The correlation in their field sample of log σ versus metallicity, two distance-*independent* quantities, is noticeably better than the correlation of metallicity and luminosity.

With the stage thus set to understand the differences between the field and cluster relations in terms of luminosity errors that result from incorrect determinations of distances to field galaxies, it is disappointing to report that this explanation is unlikely. The sense of the effect is fine, but the degree of the effect is not. Distance errors of factors of 2 are required to generate the delta-delta diagram of TDFB, and these are not forthcoming if the velocity field in the Local Supercluster is anything like the linear Virgocentric models. Assuming such a model and a value of $V_V = 300$ km s^{-1}, 14 out of 24 of the TDFB galaxies are sufficiently distant from the Local Supercluster that their Hubble velocities should give accurate measures of their distances to better than 10%. Only a few of the galaxies in the TDFB sample could conceivably have errors of the order required to generate the delta-delta diagram. Unless the local velocity field is much different from that supposed and contains additional irregularities of $\gtrsim 500$ km s^{-1}, which seems at this point very unlikely, the cause of the difference in the field and cluster samples must be found elsewhere. This uncertainty could be resolved, of course, by studying a field sample well beyond the Local Supercluster, but such a project will face additional problems of assigning group membership and obtaining reliable morphological classifications.

The final and most speculative explanation follows from Efstathiou and Fall's (1983) suggestion that the residuals from the L-σ and L-Mg_2 relations correlate better with mass-to-light ratios (M/L) than galaxy ellipticity. Suppose that there are, in fact, tight correlations of velocity dispersion and metal abundance with galaxy *mass*, but since only *luminosity* has been measured, the relationships are degraded, and delta-delta diagrams are produced by variations in M/L. In order to explain the difference between the field and cluster samples, M/L would have to vary significantly (factors of 2–3) in field galaxies, but little for the cluster galaxies. This might happen, for example, if star formation continued for $\sim t_{\rm Hubble}$ in field ellipticals but ended early in the clusters. Similarly, cluster ellipticals might have been the products of early mergers (before the cluster velocity dispersion became high enough to prevent them), but field ellipticals might be the result of more recent mergers of star-forming galaxies.

This variation might be checked by a more careful determination of M/L for each elliptical that has a large residual in the L-σ-Mg_2 space, by measuring $\sigma = f$(radius) and the luminosity profile. Integrated colors and color gradients, particularly in the UV and IR, and population syntheses of spectra might be able to show differences in the stellar populations that are indicative of M/L variations. This is probably a "last resort" explanation and would be the most difficult to test.

V. SUMMARY

Studying the internal kinematics of galaxies in rich clusters is appealing since the galaxies are at a uniform distance from the observer, and they share a common evolutionary history. It is possible within the limitations of present technology to measure velocity dispersion and line strength indices for ellipticals in relatively nearby clusters with uncertainties that are smaller than the cosmic scatter in the relationships. Unfortunately, the time required for such observations is long, particularly for the many interesting clusters with $V \gtrsim 10{,}000$ km s^{-1}. Furthermore, the radial dependences of velocity dispersion and line strength within ellipticals will need to be well understood in order to correct for the different areas sampled in galaxies at different distances.

It has been demonstrated in this study that observations of this type and of sufficient accuracy can be made, and that the relationships between galaxy luminosity, velocity dispersion, and the Mg_2 index are quite strong. These parameters seem to be better correlated for cluster galaxies than for field galaxies, but the samples are small at this time and therefore subject to considerable uncertainty. In particular, the L-Mg_2 relation appears much stronger in the Coma-Virgo sample, and the delta-delta relation, the correlation of the residuals of the L-σ and L-Mg_2 relations found for field ellipticals, is weak or absent in the cluster sample. The most likely explanations for these differences between field and cluster samples are small-number statistics or a genuine difference between cluster and field ellipticals. Another simple explanation for these differences is that the distances to field galaxies are poorly known, but this hypothesis seems untenable with the present data. M/L variations could also be responsible, but this speculation may be very difficult to test.

Assuming that the L-σ and L-Mg_2 relations are not systematically different from Coma to Virgo, the relations can be used to derive a relatively accurate peculiar Virgocentric velocity for the Local Group of $V_V = 229$ (± 80) km s^{-1}. This completely independent value compares favorably with the results of many other optical studies which indicate a low value of V_V, and one that is significantly less than $V_V = 410$ km s^{-1} determined from the dipole anisotropy in the microwave background. The equally large velocity component in a direction *perpendicular* to the center of mass of the Local Supercluster may be further evidence that a significant fraction of the Local Group motion is *not* due to gravitational pull of the Supercluster. The comparison of the Local Group motion relative to the microwave background with its motion relative to nearby galaxies and clusters is a strong test of the spectrum and distribution of large mass scales, and therefore deserves careful study and rigorous scrutiny.

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