1977ApJ...213..345G

THE ASTROPHYSICAL JOURNAL, 213:345–350, 1977 April 15

THE COMA I GALAXY CLOUD

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Received 1976 September 2; revised 1976 October 6

ABSTRACT

The Coma I cloud of galaxies, an outlying component of the Local Supercluster, has been surveyed in redshift over an unprecedented range of luminosities. Using the redshift-defined sample of galaxies, we derive the Coma I cloud's structure, density, luminosity function, and component morphological types. In addition we present statistically significant evidence that the Coma I system is rotating.

Subject headings: galaxies: clusters of — galaxies: redshifts — luminosity function

I. INTRODUCTION

The term *galaxy cloud* refers to the loose but extensive associations of galaxies which have been observed in the outer parts of the Local Supercluster. In order to determine exactly which galaxies are members of any particular cloud, large numbers of galaxy redshifts must be obtained. Consequently, the general properties of these clouds are poorly understood. The Coma I cloud is an excellent candidate for detailed study. It is one of the mass concentrations within the Local Supercluster; it has a mean redshift of 980 km s^{-1} and a distance of 13 Mpc (Hubble constant = 75 km s^{-1} Mpc^{-1} assumed hereafter). Turner and Sargent (1974) have shown that Coma I is probably a bound system—an important distinction since only 13 of 44 groups in the Local Supercluster proposed by de Vaucouleurs (1976) and studied by Turner and Sargent appear to be bound. Finally, Coma I lies near the north galactic pole where galactic obscuration is minimal.

The analysis of Coma I presented in this paper is made possible by a recently completed magnitude-limited survey of galaxy redshifts covering a large area of the sky (~250 square degrees) near the north galactic pole. Using this homogeneous redshift survey, we can easily eliminate all problems associated with foreground and background contamination. The Coma I galaxies provide a complete sample of galaxies covering a range of 4.7 mag in m_p from the brightest member NGC 4725 with $m_p = 10.2$ to the survey limit at $m_p = 14.9$ (magnitudes from Zwicky and Herzog 1963, hereinafter CGCG).

In § II we briefly describe how the Coma I galaxies were selected, and then we list the basic properties of the galaxies in this sample. In § III we determine the cloud's properties including the mean density of galaxies, the cloud's location in the Local Supercluster, the galaxy luminosity function, and the distribution of morphological types. We then discuss the dynamics of the Coma I galaxies, and present evidence for a systematic redshift effect which can be interpreted as rotational motion. Finally, in § IV, we discuss the implications of these results.

II. DATA

The Coma I cloud lies in the foreground of the supercluster containing Coma (A1656) and A1367. This fortuitous circumstance means that the Coma I cloud was included in the large redshift surveys of this region. There have been three coordinated surveys. Tifft and Gregory (1976) studied in galaxies within 6° of the Coma cluster center, Chincarini and Rood (1976) studied a large area to the northwest of the Coma cluster, and another survey currently in progress (Gregory and Thompson 1977) studies the entire supercluster region between A1656 and A1367. Redshifts are also available for a few of the brighter galaxies in this area from the catalog of de Vaucouleurs and de Vaucouleurs (1964).

Figure 1 shows the region of the sky (*dashed lines*) over which the above-mentioned surveys were made. For reference, the locations of the distant rich clusters A1656 and A1367 are also shown. With a few exceptions that are noted below, the individual symbols represent all known galaxies in this area with $m_p \leq 14.9$ and $V_0 \leq 2000$ km s^{-1} (hereafter all redshifts will be given in units of km s^{-1}). Those galaxies which seem to be members of the Coma I cloud are shown as filled circles. The two filled circles superposed on crosses represent members with $m_p = 15.0$. If a galaxy's membership in the Coma I cloud was uncertain (for reasons which will be explained shortly),

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† Operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

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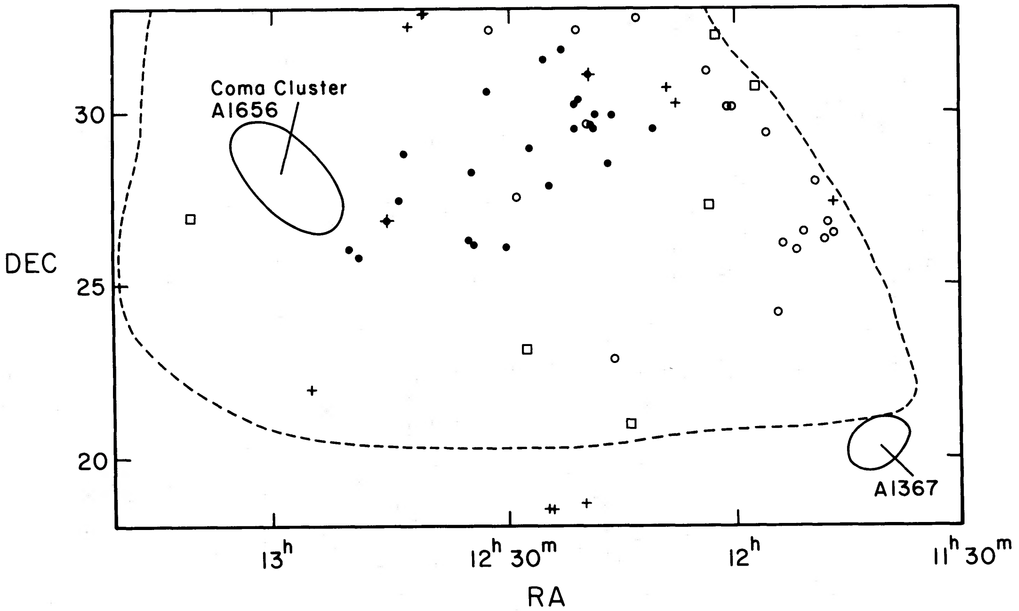

FIG. 1.—The distribution on the sky of the Coma I cloud. Galaxies with certain membership are marked with filled circles or filled circles with crosses (for two galaxies fainter than the $m_p = 14.9$ redshift survey limit). Possible outlying members are shown as open squares and known members of other mass concentrations in the Local Supercluster are shown as crosses. The region of near completeness in the redshift surveys is included within the dashed curve, and the positions of the more distant rich clusters Coma (A1656) and A1367 are indicated.

it is shown as an open square. The open circles represent the 18 galaxies in the area with unknown redshifts. Finally, the 10 galaxies shown as crosses are all located near the border of the survey area. Nine of these are known or suspected members of the CVn I group, the CVn II group, or the Virgo cluster (de Vaucouleurs 1976). The tenth cross represents NGC 3900; its redshift $V_0 = 1702$ is $3.5S_{v \cdot p}$ (analogous to the standard deviation; $S_{v \cdot p}$ will be defined in § III) from the mean redshift in the northwest part of the cloud, and therefore it will not be considered in the following analysis.

Table 1 presents the basic data which will be used to determine the fundamental properties of the Coma I cloud. Column (1) gives the galaxy identification; NGC numbers have been used for all but the last three galaxies, and these are identified by their listing in the CGCG, the first three digits indicate the field number and the last three digits the sequential number of the galaxy in the field. Column (2) contains the galaxies' morphological types. These were obtained from the glass copies of the Palomar Sky Survey, consulting for the brighter galaxies the types listed in the Bright Galaxy Catalog (de Vaucouleurs and de Vaucouleurs 1964). Column (3) gives the photographic magnitudes as listed in CGCG. Column (4) contains the redshift determinations all reduced to a reference system at the galactic center. The sources of these redshifts are listed in column (5). If more than one redshift determination is available, we use an unweighted mean. One of the galaxies shown in Figure 1 as a questionable member (Zw 160160) is not included in this table, since we show in § III that there is no dynamical evidence that it is actually a member of Coma I, whereas the other questionable members have dynamical properties consistent with membership.

It is quite likely that Table 1 is a complete list of the brighter Coma I galaxies. From the sample of 457 galaxies in the survey area which have redshifts determined, only 30 are possible or certain members of Coma I. This means that of the remaining 18 unobserved galaxies only $(18/457) \times 30 \approx 1$ is likely to be a member of Coma I. This is probably an overestimate, since six of the unobserved galaxies seem to be concentrated in a loose cluster of the type found by Tifft and Gregory (1976) between the Local Supercluster and Coma.

III. RESULTS

a) Structure of Coma I and Location in the Local Supercluster

The galaxies in the Coma I cloud are concentrated in what appears to be an elongated system with a position angle of about 120° (visually estimated). There seems to be a slight density enhancement around NGC 4274, but the rest of the members are uniformly distributed to the southeast of this slight enhancement. Although de Vaucouleurs (1976), using incomplete data, stated that there were two concentrations in the Coma I cloud—one around NGC 4274 and the other around NGC 4565—the existence of these two concentrations is not obvious in Figure 1.

Because the boundaries of the cloud are difficult to specify, there are a number of outlying objects with uncertain membership. More complete redshift data

TABLE 1

Coma I Galaxies: Basic Data

I.D.	Type	m_p	V_0 (km s^{-1})	V_0 Ref*
N 4020†	Scd	13.2	800	CR
N 4062†	Sb	11.9	744	CR
N 4080†	S	14.0	722	CR
N 4173	Sd	13.7	1093	CR
N 4204†	SBd	14.3	690	GT
N 4245	SBO^+	12.4	882	BGC
N 4251	SO	11.5	1000	BGC
N 4274	SO/a	11.1	761	BGC
N 4278	E	11.2	622	BGC
N 4283	E	13.1	1078	BGC
N 4308	E	14.3	602	CR
N 4310	SO^+	13.5	895	CR
N 4314	SBO/a	11.5	879	BGC
N 4359	Sd	13.9	1174	CR
N 4393	SBcd	13.8	829	CR
N 4414	Sbc	10.9	720	BGC
N 4448	SO/a	11.9	687	BGC
N 4455†	Sb	13.0	588	GT
N 4494	SO^-	10.7	1305	BGC
N 4525	Scd:	13.0	1136	CR
N 4559	Sc	10.7	852	BGC
N 4562	dSO	14.6	1340	TG, CR
N 4565	Sc:	10.3	1171	BGC
N 4670‡	SO:p	12.6	1167	CR, BGC
N 4725	Sb	10.2	1164	CR, BGC
N 4747	Im_p	13.2	1216	CR
158082§	Sm_p	15.0	1009	CR
159067	S:p	14.7	993	TG
159074§	E	15.0	869	CR, BGC

*CR = Chincarini and Rood (1976) or references therein
GT = Gregory and Thompson (1977)
BGC = de Vaucouleurs and de Vaucouleurs (1964)
TG = Tifft and Gregory (1976) or references therein

†questionable membership in Coma I
‡Haro 9
§fainter than uniform survey limit

on nearby galaxies might show that these objects belong to other condensations, and we agree with de Vaucouleurs's (1976) statement concerning CVn II that "the assignment of outlying objects to this cloud rather than to other overlapping or adjacent clouds or groups (CVn I, Coma I, M101) is to some extent a matter of interpretation." For the purpose of our analysis, any galaxy separated from its nearest neighbor by more than $2\overset{\circ}{.}5$ ($\sim$0.6 Mpc) will be considered to be a questionable member of the cloud.

The central barlike structure of the Coma I cloud has a minor axis of 4° (0.9 Mpc) and a major axis of 10° (2.3 Mpc). A characteristic radius for the cloud is therefore $r = 1.4$ Mpc, and its volume is approximately 12 Mpc^3. Within this volume there are 24 bright galaxies. By assuming that $M/L = 7$ for spirals, $M/L = 30$ for S0 galaxies, and $M/L = 50$ for ellipticals, we can convert the magnitudes listed in Table 1 to mass estimates. The total mass of the Coma I galaxies with definite membership is $2.5 \times 10^{12}\ M_\odot$, and the mass density of the entire cloud is 1.5×10^{-29} g cm^{-3}.

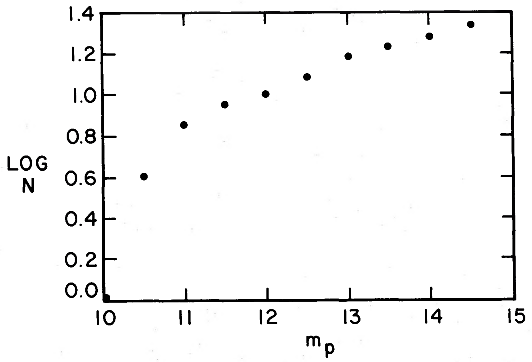

FIG. 2.—Luminosity function for the Coma I galaxies with definite membership. Less restricted cases also show a relatively small number of faint galaxies.

The Coma I cloud has a mean redshift ($V_0 = 980$), nearly identical to that of the Virgo cluster core. If we assume that the Local Supercluster is centered on the Virgo cluster, the radial position of Coma I in the Supercluster is 13 Mpc sin 16° = 3.6 Mpc, where 16° is the angular separation of Virgo and Coma I.

b) *Luminosity Function*

The sample of galaxies in Table 1 is perfectly suited to a luminosity function analysis. All foreground and background galaxies have been eliminated, and the sample is complete to a relatively faint absolute magnitude ($m_p = -15.7$). Figure 2 shows the integrated luminosity function, treated as a sum in 0.5 mag bins, for the 22 certain members of Coma I with $m_p \leq 14.9$. The general form of the luminosity function is consistent with that found for rich cluster samples (Abell 1976; Oemler 1974); there is a steep rise at the bright end followed by a break at $m_p \approx -21$ and a less steep linear portion at the faint end. Although the brighter end of the luminosity function contains too few galaxies to define a meaningful slope, we find for the fainter end a slope $\beta = [\Delta \log n(\leq m_p)/\Delta m_p] = 0.13 \pm 0.01$; adding seven of the questionable members gives $\beta = 0.16 \pm 0.01$. (This error is purely formal; the real error in β may be as large as ± 0.03 because we do not know the total membership with absolute certainty.) The luminosity functions of rich clusters generally have larger values of β. Four clusters studied by Abell (1976) have $\beta = 0.25$, and 15 clusters studied by Oemler (1974) have $\beta = 0.29 \pm 0.09$. The two clusters in Oemler's sample with the shallowest slopes (A1656 and A2670) have $\beta \approx 0.15$. In order for Coma I to have β as large as 0.25, the total population would have to be increased by a factor of $\sim$2 to $N = 50$.

c) *Galaxy Morphology*

Spiral galaxies are the dominant constituent of the Coma I cloud. There are only four ellipticals and four genuine S0 galaxies listed in Table 1. Two additional objects have been tentatively classified as S0. One of these is the peculiar object Haro 9, and the

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other (NGC 4562) is an intrinsically faint disk system with low surface brightness which has been listed as a "dwarf S0." The remaining 13 galaxies (59% of the 22 definite members with $m_p \leq 14.9$) have some semblance of spiral structure; counted with these 13 galaxies are three objects with very smooth spiral arms classified as S0/a. It is interesting to point out that the brightest galaxy in the Coma I cloud is a spiral and that the brightest elliptical member is the seventh brightest in the group, a full magnitude fainter than the brightest spiral.

d) *Systematic Redshifts*

In a discussion of the Coma I cloud, de Vaucouleurs (1976) points out that the group of galaxies surrounding NGC 4274 has a lower mean redshift than the galaxies near NGC 4565. Since our complete sample shows no evidence for two distinct groups, the best test for systematic redshifts is a linear regression analysis.

The position of each galaxy was projected onto a line of p.a. = 120° (the cloud's major axis), and regression solutions of redshift V_0 onto projected position p were calculated. Since the outlying galaxies have questionable relationship to the main body of Coma I, two cases were tested. Case I places no further restrictions on membership. The total number is $N = 30$, and this includes all galaxies in Table 1 plus Zw 160160, which lies farther than any other galaxy in Figure 1 from its nearest neighbor and is only 1° from the border of the surveyed area. Case II places stringent restrictions upon membership. Only the 22 galaxies shown as filled circles in Figure 1 are included. Not only are the six outlying galaxies excluded, but the two galaxies with $m_p = 15.0$ are also dropped, since they are fainter than the uniform survey limit. We can state *a priori* that the best definition of the total membership of Coma I lies between these two extreme cases. It is probably more restrictive than case I for the following reasons: in Figure 1 there are 13 galaxies with $m_p \leq 14.9$ lying outside the barlike main body of Coma I, but within the borders of our surveyed region. Of these 13, seven have previously been shown to be members of CVn I or CVn II. Thus, for each of the remaining six galaxies, there is at least a 50% probability that each is not a member. Case II is certainly too restrictive, since two galaxies which are members have been excluded.

Table 2 gives the results of the regression analysis. Column (1) identifies the case. Columns (2) and (3) give the magnitude of the slope and the uncertainty, respectively, for the regression lines. Column 4 gives $S_{v.p}$ which measures the dispersion of the points about the linear regression solution. Figure 3 shows redshift versus p. The symbols are the same as in Figure 1. The solid line shows the regression solution for Case II. The slope of the regression lines in Table 2 differs from zero (no systematic effect) by 1.91 (case I) and 2.82 (case II) times the associated uncertainty. The uncertainties listed in Table 2 are analogous to one standard deviation in a normal distribution, so levels of statistical significance are 3% (case I) and 0.2% (case II). The solution to case I is strongly affected by Zw 160160. All possible cases which do not include this galaxy show regression solutions significant at the level of 1% or less. In view of this galaxy's position at the extreme eastern boundary of our survey, we believe that Zw 160160 is probably an outlying member of one of the other mass concentrations of the Local Supercluster. Hence the level of significance for the systematic redshifts in Coma I is probably 1–0.2%

TABLE 2

REDSHIFT REGRESSION ANALYSIS

Case (1)	Slope (km s^{-1} degree^{-1}) (2)	Uncertainty (km s^{-1} degree^{-1}) (3)	$S_{v.p}$ (km s^{-1}) (4)
I........	20.0	10.5	207
II........	41.5	14.7	191

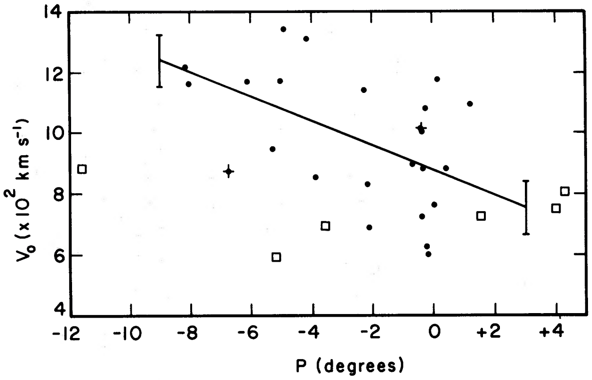

FIG. 3.—A plot of redshift versus p, the projected position of Coma I galaxies onto the major axis of the cloud. Symbols for galaxies are the same as in Fig. 1. The line represents the linear regression solution for case II with 1 σ error bars shown. The individual galaxies have redshift uncertainties of ±100 km s^{-1}.

It is natural to suspect that the two ends of the cloud may be at different distances, and that the redshift difference reflects, at least in part, the Hubble flow. With the data available it is impossible to discount this explanation entirely, but we have compared the luminosity functions for each end of the cloud. To account for a 300 km s^{-1} redshift difference, the galaxies on the southeast end of the cloud should be brighter by 0.7 mag than the galaxies on the northwest end. In fact the two luminosity functions are nearly identical; but since the number of galaxies in each sample is rather small, the comparison is not definitive. Even so, the median magnitudes of the two samples differ by only 0.1 mag, and if either of the two samples is brighter, it is the sample with the larger redshift; a regression solution of m_p on p shows m_p decreasing from the low redshift end to the high at 0.06 ± 0.11 m_p degree^{-1}.

e) *Virial Analysis*

For the virial analysis, we use the method described by Materne (1974). The individual redshifts are assumed to have, on the average, an uncertainty $\sigma(v) = 100$, and rather than calculating the velocity dispersion relative to the mean redshift of the cloud, we calculate the dispersion relative to the regression fit for case II. By assuming that the mass-to-luminosity ratio (M/L) is 7 for spirals, 30 for S0 galaxies, and 50 for E galaxies, we find the total mass of the 22 definite members to be $2.5 \times 10^{12}\, M_{\odot}$. The total potential energy is $\Omega = -5.3 \times 10^{59}$ ergs. The kinetic energy is the sum of the random component $T_{\sigma} = 20 \times 10^{59}$ ergs, and the rotational component $T_R = 0.3 \times 10^{59}$ ergs. For less restrictive cases, mass and energy differ from these values by less than 5%. According to this calculation, $\Omega + T > 0$, implying that the cloud is not bound, but we have been conservative in choosing our values of M/L. Trial solutions of the virial analysis were made with increased values of M/L, and marginal stability was obtained by increasing the spiral galaxy M/L to 100. Large values of M/L might be expected for spiral galaxies if the massive halo hypothesis is correct. We can only conclude that the virial discrepancy for Coma I seems to be no larger than results obtained for other groups, clouds, and rich clusters of galaxies (cf. Rood, Rothman, and Turnrose 1930; Field and Saslaw 1971; Rood *et al.* 1972).

IV. DISCUSSION AND CONCLUSIONS

The virial analysis, if interpreted literally, indicates that the Coma I cloud is not a bound system but only a transient subcondensation that will soon disperse. If so, we should only use the observations in the previous section to show the general characteristics of galaxies in the outer parts of the Local Supercluster. But since the virial discrepancy for the Coma I cloud is no greater than the discrepancies found for groups and rich clusters, and the harmonic crossing time for Coma I is only $\sim\frac{1}{4}H^{-1}$, it seems fair to proceed further with the discussion and ask what implications can be drawn if Coma I is a bound system and the systematic redshifts imply rotation.

The Coma I cloud is located in a region of the Local Supercluster where the mass density gradient is quite large (Jones 1976). It also seems that Coma I is just *exterior* to the region which contains a mass density equivalent to the Einstein–de Sitter critical density $\rho_0 = 2 \times 10^{-29}$ g cm^{-3}, so that the Coma I system will never fall into the Virgo cluster potential well (Jones 1976). These observations may be important in explaining the possible rotation of the Coma I cloud. A very rough estimate of the tidal torque produced by the Virgo cluster core indicates that the Coma I cloud rotation might be explained by some type of tidal interaction with the nearby massive Virgo cluster inhomogeneity. If we assume, for the purposes of calculation, that the Coma I cloud acts as a solid body with a length $l = 2.3$ Mpc (10°) located at $R = 3.6$ Mpc from the center of the Virgo cluster core, we can calculate the tidal torque N using the equation $N = F \times l/2$, where F is the differential force between the two ends of the cloud. One end of the cloud is a distance $r_1 \approx R + \frac{1}{2}l\,(\sin 30°)$ from the Virgo cluster core, and the other is at a distance $r_2 \approx R - \frac{1}{2}l\,(\sin 30°)$, so the differential force is

$$F = GM_{\rm Virgo}(M_{\rm cloud}/2)(1/r_2^2 - 1/r_1^2)\,.$$

Since the torque can be equated to the rate of change of the angular momentum

$$N = \dot{J} = \tfrac{1}{2}M_{\rm cloud}\dot{v}l/2\,,$$

then

$$\dot{v} = GM_{\rm Virgo}(1/r_2^2 - 1/r_1^2)\,.$$

By assuming that the torque acts for one Hubble time H^{-1} and that $M_{\rm Virgo} = 3 \times 10^{13}\, M_{\odot}$, we find that the rotational velocity for the Coma I cloud, at the $\pm 5°$ points, is 80 km s^{-1}. If the problem is analogous to the origin of galaxy angular momentum, it is likely that the torques were larger in the earlier stages of the Universe (cf. Peebles 1969). The energy involved in rotational motion is very small; this is consistent with the findings for Coma (A1656) by Gregory (1975) and by Gregory and Tifft (1976) where some of the implications of cluster rotation are discussed. It is a curious fact that the position angle along which systematic redshifts are most strongly seen in Coma (A1656) is nearly the same as that found here for Coma I. But the regression slopes have opposite signs, so that the side receding in Coma I is that which is approaching in Coma (A1656).

The importance of our derivation of the luminosity function of Coma I lies as much in our method as in the numerical values obtained. Previous studies which cover as large a range in magnitudes have been possible only for composite groups (e.g., Turner and Gott 1976), or for very rich clusters (e.g., Oemler 1974). In the former none of the individual groups has been completely surveyed in redshift, and in the latter the observations must extend to such faint apparent magnitudes that few redshifts are available. In both cases background corrections must be made and the sizes of such corrections are inherently uncertain.

Coma I is unique in the wide range of luminosities over which it has been completely surveyed. We hope that other groups and clouds within the Local Supercluster can soon be surveyed in the same manner, for it is important to determine if the small values of β are common to such aggregates. Complete redshift surveys are time consuming, but the rewards have been worthwhile so far. The surveys described in § II have provided verifications for the existence of a supercluster linking Coma (A1656) and A1367 (Gregory and Thompson 1977), and for the lack of a significant field of isolated galaxies (Tifft and Gregory 1976). In addition Peebles (1976) has suggested a number of other interesting applications for complete samples of galaxy redshift data.

S. A. G. is grateful for support from a Faculty Fellowship from the Research Foundation of the State University of New York and for support from National Science Foundation grant AST 74–22597.

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