THE PHYSICAL PROPERTIES OF LARGE SCALE SYSTEMS FROM OPTICAL OBSERVATIONS

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Holmberg's (1937) analysis of the distribution of double and multiple galaxies provided what may have been the first hint of a local inhomogeneity of greater scale than that of the Local Group. The idea of a Local Supercluster was subsequently revived by de Vaucouleurs (1953, 1956, 1958). The analyses of others, as well as the continuing study of de Vaucouleurs himself (1976 and references cited therein) have now effectively established the reality of the Local Supercluster. Several other more remote inhomogeneities, or "clouds" of galaxies, were described by Shane and Wirtanen (1954). The writer (Abell 1958) found the distribution of rich clusters to be clumpy, and published a finding list of several apparent superclusters (Abell 1961).

For the most part, however, our knowledge of large-scale inhomogeneities in space is based on statistical analyses of the distribution of galaxies and clusters of galaxies (e.g., Abell 1974; Kalinkov 1972; Davis *et al.* 1977 and references cited therein). These statistical investigations suggest that matter is clustered on at least two different orders, and possibly on a continuum of scales up to 50 to 100 Mpc (for $H = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$). What we call "superclusters" are evidently these systems of clusters of galaxies, groups of galaxies, and possibly individual galaxies, such systems of which have characteristic diameters of 50 to 100 Mpc. As useful as the statistical approaches are, however, it is of obvious interest to review what we know about the structures and dynamics of individual superclusters.

1. THE LOCAL SUPERCLUSTER

Both de Vaucouleurs (1976) and Jones (1976) have carefully re-examined the Local Supercluster, but largely on the basis of existing data. Considerable new data have recently been gathered for galaxies in a large portion of the Local Supercluster by Abell and Eastmond (Eastmond 1977 and references cited therein). From extrafocal Palomar Schmidt plates covering 158 deg^2 centered on M87, Eastmond has determined total magnitudes for approximately 3000 E and S0 galaxies, complete to

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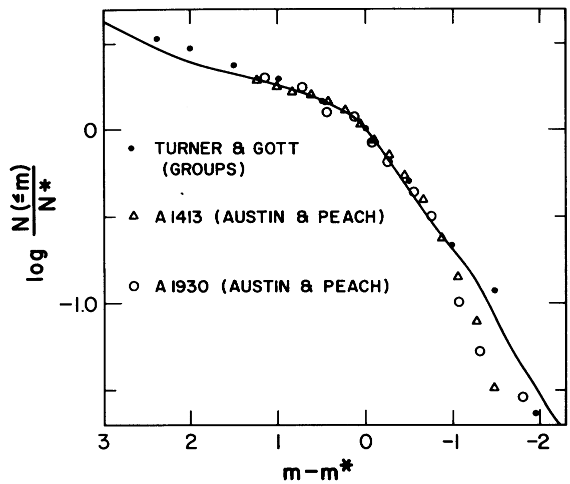

Fig. 1. Integral luminosity functions for galaxies in nearby groups and in two rich clusters, fit to that of the Coma cluster (solid line).

the limit $m_v = 16.5$, by the method of Abell and Mihalas (1966). In addition, Eastmond made step-scale magnitude estimates for all galaxies to the limit $m_v = 14.0$ on red prints of the 52 Palomar Sky Survey fields covering the region $\alpha = 11^h\ 30^m$ to $13^h\ 50^m$ and $\delta = -27\frac{1}{2}°$ to $26\frac{1}{2}°$. Eastmond calibrated his step-scale estimates against photometry by Holmberg (1958) and also against the extrafocal photometry in the central cluster region, and finds the statistical mean error of a single magnitude estimate to be 0.3 mag. Finally, Eastmond made DDO luminosity-class estimates for all Sb and Sc spirals in the 52 fields.

Eastmond then examined the Hubble diagram for the spirals of known radial velocity and distance moduli obtained from his magnitude and DDO-type estimates. Although the sample was heavily weighted with Virgo cluster spirals, there was nevertheless a striking correlation of velocity with distance. Yet, nearly all of the galaxies observed are within the Local Supercluster; thus Eastmond's finding suggests that the supercluster is expanding.

To examine the kinematics of the Local Supercluster more quantitatively, Eastmond arbitrarily selected, within the large region surveyed, several small regions where the relatively high surface density of bright galaxies suggested the likelihood of physical associations. Following Eastmond's notation, we identify those apparent groups of galaxies with letter designations. The next goal is to derive mean velocities and distances for the galaxies within each group.

We estimate the distance of each group from a plot of the integral luminosity function of its elliptical galaxies. It is now well established that the elliptical galaxies in rich clusters have a

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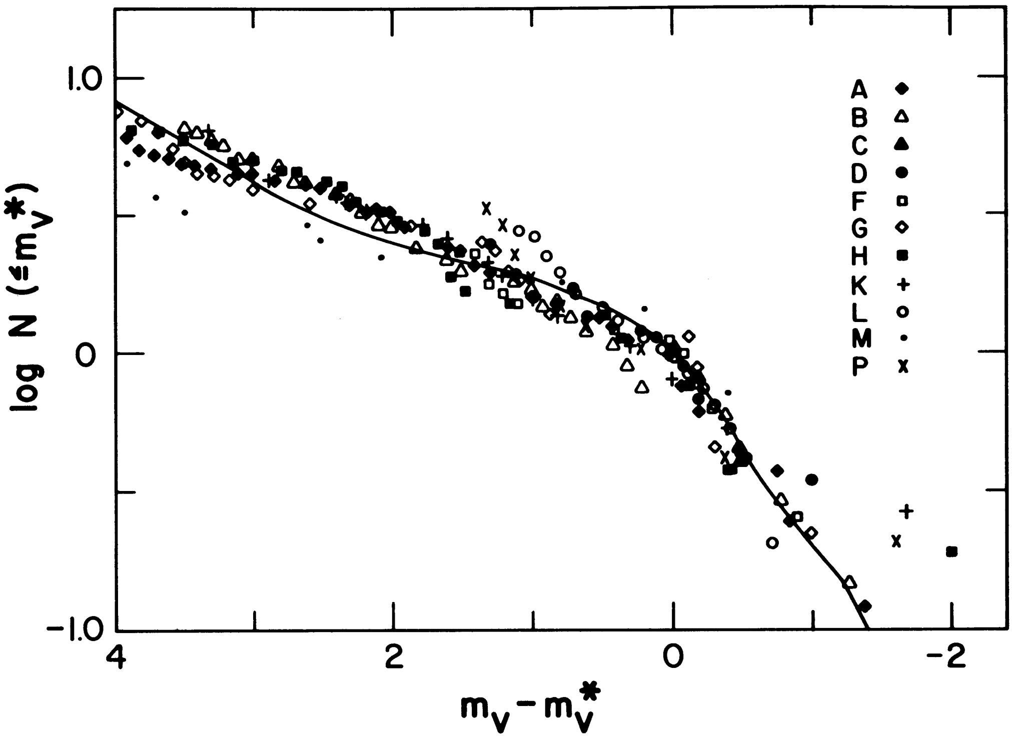

Fig. 2. Integral luminosity functions for elliptical galaxies in 11 Eastmond groups, all fit to that of the Coma cluster (solid line).

characteristic luminosity function. Figure 1 shows the integral luminosity function of the Coma cluster ellipticals, from Abell (1977), super-imposed on the luminosity functions for two other clusters observed by Austin and Peach (1974) and Austin *et al* (1975). The luminosity function for *all* galaxies in nearby groups, as determined by Turner and Gott (1976), is also shown. Evidently, perhaps fortuitously, even spirals seem to satisfy the same luminosity function, but to keep the present sample as pure as possible, we consider only ellipticals in the groups studied here. We estimate relative distances of the groups by the horizontal shifts necessary to match their elliptical galaxy luminosity functions.

Figure 2 is a composite of the luminosity functions for 11 of Eastmond's groups, prepared by the writer from the individual magnitudes given by Eastmond. The plot for each group has been shifted vertically (to take account of differences in richness) and horizontally (to take account of different distances). The smooth line is the luminosity function for the Coma cluster. The writer defines a particular point in the Coma luminosity function to designate a magnitude, m_v*. The horizontal shift of the function for each group required to achieve a

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TABLE I

Group	α (1950)		δ		m_v^*	$<V_r>$ (km s^{-1})	n
A	12^h20^m	to 12^h35^m	+11°00'	to +14°30'	10.0	896	33
B	12 14	12 23	+ 5 00	+ 7 00	12.1	2274	9
C	11 58	12 06	+ 1 00	+ 3 30	∿14.1	5859	7
D	12 41	13 05	- 5 00	-11 00	12.3	3992	7
F	12 44	13 02	-11 00	-16 00	12.5	4192	2
G	12 35	12 59	+ 9 00	+14 00	10.1	977	17
H	12 12	12 35	+ 7 00	+11 00	10.5	1012	17
K	12 14	12 35	+14 30	+19 00	10.7	942	9
L	13 08	13 22	-15 30	-18 00	12.9	2285	5
M	12 23	12 56	- 1 00	+ 5 30	9.8	1081	26
P	13 12	13 29	- 9 30	-15 30	12.6	2576	2

fit to the Coma cluster determines m_v^* for that group. For some of the poorer groups the data are few, and the fits are poorly determined; yet it is gratifying that the procedure works as well as it does, despite some uncertainty (up to 0.5 mag) in determining m_v^*.

Radial velocity data for many of the Eastmond groups were very sparse or absent. Consequently, new radial velocities were observed for 142 galaxies with the Cassegrain scanner of the 3-m telescope at the Lick Observatory in 1975-76. These new data permitted us to obtain mean radial velocities for each of the 11 Eastmond groups surveyed. In some cases, foreground and background galaxies were rather obviously present in the field; Those with velocities differing by more than 2000 km s^{-1} from the mean were not used in calculating mean group velocities.

The data obtained are summarized in Table I. Successive columns give the group designation, the range of α and δ that define each group, the value adopted for m_v^*, the mean radial velocity for each group, and the number of galaxies used in computing the mean velocity. The Hubble diagram for the groups is shown in Figure 3.

Also shown in Figure 3 is a point representing the Coma cluster m_v^* = 14.5; $<V_r>$=6952km/s). The straight line has the cosmological slope of 0.2. Within the uncertainties of the observational data, all points are consistent with a uniform expansion of the Local Supercluster (containing Groups A, B, G, H, K, L, M, and P), the more remote groups (C, D, and F), and the Coma cluster. In other words, despite the apparent reality of the Local Supercluster as a spatial inhomogeneity, there is no evidence for any local inhomogeneity in the Hubble flow--a result in agreement with Sandage and Tammann (1974) from their observations of the Virgo cluster alone. Evidently, the Local Supercluster is not gravitationally bound; moreover, within uncertainties (perhaps 20%) it expands as rapidly as the universe in general.

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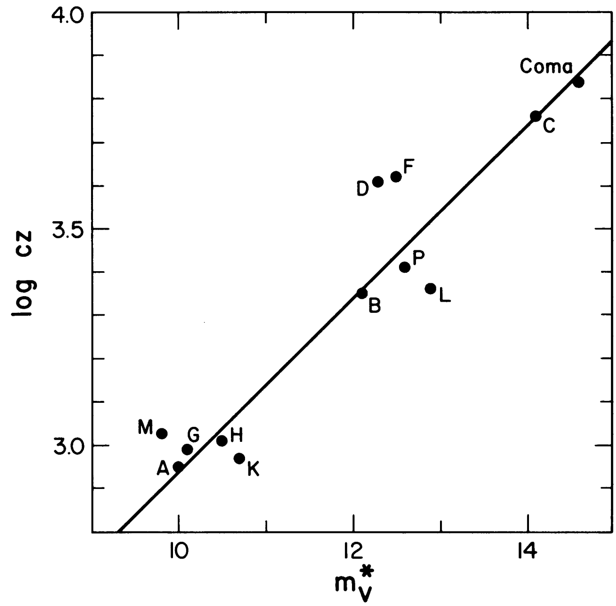

Fig. 3. Hubble diagram for Eastmond groups and the Coma cluster.

2. THE COMA SUPERCLUSTER

Observations of the distribution of galaxies in the dense core of the rich regular Coma cluster (e.g., Abell 1977) suggest that at least some dynamical evolution has taken place and that the cluster appears to have been stable for at least a good fraction of a Hubble time. Thus there is no reason to doubt that this and other similar systems are gravitationally bound. Yet, all galaxies in the field of the cluster do not share the structure of the dense Coma core. In particular, Abell has shown that the spirals exhibit almost no central concentration to the cluster center, even though most of them have radial velocities that would suggest that they are members of the Coma cluster. It is as if there were a highly concentrated, negative-energy core of E and SO galaxies embedded in a cloud of other galaxies, including the spirals in the same field, which are not gravitationally bound to that core; that is, the Coma cluster core appears to be a bound concentration within a larger supercluster, which may not be gravitationally bound. Tifft and Gregory (1976) arrive at a similar conclusion.

So do Chincarini and Rood (1976), who have obtained spectra of 50 of the 52 galaxies brighter than m_p=15.1 in Cluster 16 in Zwicky-Herzog (1963) field 158. They find that galaxies in the field have velocities near 1000 km s^{-1}--evidently members of the Local Supercluster--near 4000 km s^{-1}--members of the NGC 4169 group--or near 7000 km s^{-1}--like that of the Coma cluster. Chincarini and Rood conclude that most of the objects in Cluster 16 are members of the Coma supercluster (but up to 14° away

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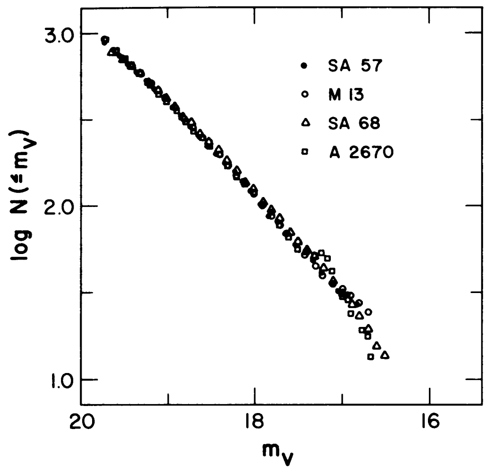

Fig. 4. Number-magnitude relation for field galaxies in four fields.

from the center of the Coma cluster itself), and that the entire system includes a semi-relaxed Coma core with dynamical history, which merges into an outer non-relaxed supercluster expanding with the Hubble flow. They also suggest as did Abell (1961) that cluster Abell 1367, 41 Mpc distant, belongs to the same supercluster.

3. GROUPS OF RICH CLUSTERS

Rood (1976) has attempted to delineate physical groups of clusters in the Abell (1958) catalog by imposing the criterion that the space density of clusters in such a group must be at least 100 times that of the clusters in general. With this criterion he identifies 5 definite groups of clusters belonging to Abell distance classes 0 to 2 and 39 probable groups in distance classes 3 and 4. In fact, 41% of the clusters in distance classes 0 to 2 are in such groups. Because radial velocities are available for all distance class 0 to 2 clusters, Rood was able to estimate linear separations of the clusters in each group by assuming that the groups expand with the normal Hubble flow. To test this assumption, Rood notes that if the clusters within a group are oriented at random, their mean radial separation, $\langle R \rangle$, should be related to their mean transverse separation, $\langle T \rangle$ by $\langle R \rangle / \langle T \rangle = 2/\pi = 0.64$. For the 11 clusters of distance classes 0 to 2 in the 5 groups, the observed value is $\langle R \rangle / \langle T \rangle = 0.53 \pm 0.20$. In short, the Rood analysis, while hardly definitive, is consistent with the picture that clusters tend to group in superclusters, but that the superclusters are expanding with the universe.

4. IS THERE AN END TO THE HIERARCHY?

The statistical studies of Peebles and others indicate correlations

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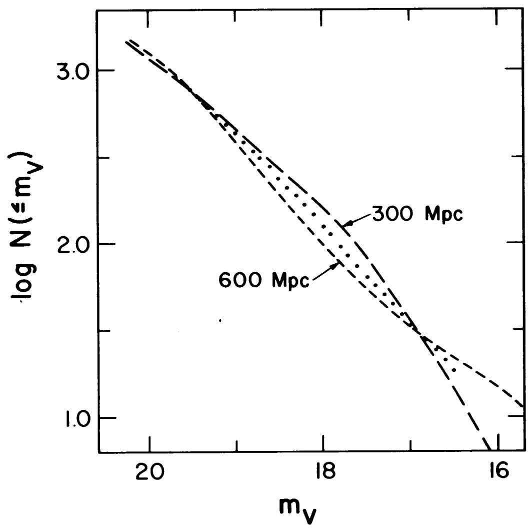

Fig. 5. Observed number-magnitude relation for field galaxies (dots), compared to two different superclustering models.

in the positions of galaxies and clusters over a distance of up to 100 Mpc, but are not conclusive over larger scales. Other studies, however, suggest that the correlations do not extend to very much greater distances, and that, in particular, a hierarchical universe probably does not exist.

One such study is that of Webster (1976), who concludes that faint radio sources are distributed with remarkable isotropy. If most of those sources are radio galaxies, Webster's analysis rules out spatial density fluctuations of as much as 10% over a scale of 1000 Mpc; the study is, in other words, entirely consistent with the existence of superclusters of the sort discussed here, but not with very much larger inhomogeneities. Similarly, the observed isotropy of the microwave background, if the usual interpretation is assumed correct, rules out an indefinite hierarchy of clustering.

Direct observations of the isotropy of optical sources are provided by Rainey's (1977) counts of galaxies to various limiting magnitudes. Rainey made counts of galaxies as a function of magnitude to the limit m_v=19.5 in three widely separated fields (around Selected Areas 57 and 68 and in the field of M13), each of approximately 1 deg^2. Rainey's counts for his three fields are superimposed in Figure 4. His data are supplemented with counts by Mottmann and Abell (1977) of galaxies in a 0.226 deg^2 field near cluster A2670. Counts by Brown (1976) to several limiting magnitudes are also highly consistent with those shown in Figure 4.

The agreement of the number-magnitude relation of galaxies in widely separated directions in the sky suggests a remarkable isotropy in the distribution of faint galaxies, but it remains to be shown that it rules out large inhomogeneities in the galaxy distribution. To this end, Rainey has calculated theoretical number-magnitude relations for several models of galaxy distribution. Figure 5 shows the observed (composite) distribution compared with that for two models of large-scale superclustering, both of which assume typical Friedmann cosmologies, and a galaxian luminosity function like that of Figures 1 and 2. In each superclustering model, the galaxies are presumed to be distributed roughly uniformly in systems with the diameters indicated, with similar distances separating superclusters. According to Figure 5, even inhomogeneities of size 300 Mpc should result in easily observable distortions of the observed number-magnitude relation. These data and calculations suggest that inhomogeneities in the universe much larger than 100 Mpc probably do not exist.

REFERENCES

Abell, G. O.: 1958, *Astrophys. J. Suppl.* 3, pp.211-288.
Abell, G. O.: 1961, *Astron. J.* 66, pp.607-613.
Abell, G. O.: 1974, *IAU Symp.*63, pp.79-92.
Abell, G. O.: 1977, *Astrophys. J.* 213, pp.327-344.
Abell, G. O. and Mihalas, D. M.: 1966, *Astron. J.* 71, pp.635-641.
Austin, T. B., Godwin, J. G., and Peach, J. V.: 1975, *Monthly Notices Roy. Astron. Soc.* 171, pp.135-142.
Austin, T. B. and Peach, J. V.: 1974, *Monthly Notices Roy. Astron. Soc.* 168, pp.591-602.
Brown, G. S.: 1976, University of Texas, Austin (Ph.D. Thesis).
Chincarini, G. and Rood, H. J.: 1976, *Astrophys. J.* 206, pp.30-37.
Davis, M., Groth, E. J., and Peebles, P. J. E.: 1977, *Astrophys. J. (Letters)* 212, pp.L107-L111.
de Vaucouleurs, G.: 1953, *Astron. J.* 58, pp.30-32.
de Vaucouleurs, G.: 1956, *Vistas in Astronomy* 2, pp.1584-1606.
de Vaucouleurs, G.: 1958, *Astron. J.* 63, pp.253-266.
de Vaucouleurs, G.: 1976, *Astrophys. J.* 205, pp.13-28.
Eastmond, T. S.: 1977, University of Calif., Los Angeles (Ph.D. Thesis).
Holmberg, E.: 1937, *Ann. Obs. Lund,* No. 6.
Holmberg, E.: 1958, *Medd. Lunds, Ser. 2* 13, No. 128.
Jones, B. T.: 1976, *Monthly Notices Roy. Astron. Soc.* 174, pp. 429-447.
Kalinkov, M.: 1972, *Proc. 1st Eur. Astron. Meeting, Athens,* 3, pp.142-161.
Mottmann, J. and Abell, G. O.: 1977, *Astrophys. J.* (in press).
Rainey, G. W.: 1977, University of Calif., Los Angeles (Ph.D. Thesis).
Rood, H. J.: 1976, *Astrophys. J.* 207, pp.16-24.
Sandage, A. R. and Tammann, G. A.: 1974, *Astrophys. J.* 194, pp.559-568.
Shane, C. D. and Wirtanen, C. A.: 1954, *Astron. J.* 59, pp.285-304.
Tifft, W. G. and Gregory, S. A.: *Astrophys. J.* 205, pp.696-708.
Turner, E. L. and Gott, J. R.: 1976, *Astrophys. J.* 209, pp.6-11.
Webster, A.: 1976, *Monthly Notices Roy. Astron. Soc.* 175, pp.71-83.
Zwicky, F. and Herzog, E.: 1963, *Catalogue of Galaxies and Clusters of Galaxies* Vol. II, California Institute of Technology, Pasadena.

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DISCUSSION

Chincarini: Since George Abell referred to my preliminary work on the various contributions to the cosmic luminosity, we have the following results, based on Oemler's total cluster luminosity determination and estimates for groups.

Object	$L/L_\odot$ (Units 10^{12})	Total luminosity $L_\odot Mpc^{-3}$	Notes
Cluster Richness 5	17	1.78×10^4	
4	(11.75)	7.24×10^4	
3	6.85	4.79×10^5	
2	5.96	2.4×10^6	
1	3.28	4.2×10^6	
0	> 2.45	$> 2.5 \times 10^6$	uncertain
Groups outside the Local Supercluster	≈ 0.2	$> 3 \times 10^6$	very uncertain
Groups and galaxies in Superclusters	≈ 0.2	$\sim 3.3 \times 10^7$	very uncertain

Adding all contributions and, depending on the relative weighting of the contributions, we find $1.5 \times 10^7 \leqslant L_{cosmic} \leqslant 4.6 \times 10^7\ L_\odot\ Mpc^{-3}$.

Abell: In connection with the Universal mass density, there are about 4000 great clusters (richness 1 or greater) within z = 0.2. If cluster masses are typically $4 \times 10^{15}\ M_\odot$, all great clusters contribute only $\Omega = 0.004$. To have $\Omega = 1$, there must therefore be 250 times as much matter outside of the great clusters as within. Hubble, Minkowski, and others have estimated that about one tenth of the visible galaxies are in great clusters; Abell has made a similar estimate. The numbers are, of course, highly uncertain, but it seems unlikely that the number of non-cluster galaxies can be high enough to make Ω much greater than 0.1.

Ostriker: A word on your calculation of Ω. The luminosity and mass in great clusters can be made larger and larger as one defines their radius to be larger and larger. Correspondingly, the fraction of the cosmic luminosity (and mass) in clusters is larger. But the total cosmic light (or mass) density calculated should be invariant if one is careful to be consistent in the two calculations.

Abell: Of course, I fully agree.

Jaakkola: What has happened to your earlier observations? At the Uppsala symposium you presented a diagram in which the Virgo cluster fell

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distinctly above the mean Hubble line and later Dr Gudhus has obtained similar results. Now you have obtained a Hubble relation in which the Virgo cluster contradiction has been removed.

Abell: At Uppsala I was using the published mean radial velocity for all galaxies in the Virgo region. In the diagram presented here, I use the mean velocity of the elliptical and S0 galaxies within 3^{o} of M87; that velocity is about 1000 km s^{-1}. For that tight group of galaxies there is no discrepancy with the mean Hubble line.

Fall: From your Hubble diagram for groups within the local supercluster, what would you say is the maximum allowable deceleration with respect to the centre of the Virgo cluster?

Abell: I certainly could not rule out a local perturbation of 20%, but do not think it could be as high as, say, 50%

Silk: If you were to use distance indicators suggested by other workers (Sandage - Tammann etc.), what is the corresponding spread in the luminosity function that you have derived?

Abell: For the great and distant clusters (Coma and beyond) the difference in modulus between that found from the brightest galaxy, m_1, and from the luminosity-function fitting, m*, can be as great as a full magnitude. The dispersion in m^*-m_1 is about 0.3 mag. However, for elliptical galaxies in groups, studied here in the Virgo region, we could not use m_1 because most of the groups have small numbers of ellipticals and they are nearly always contaminated by foreground and background galaxies.

Peebles: From the cross correlation of Lick counts with Abell clusters M. Seldner and I find that the mean number of galaxies, in excess of random, at $1.5 < hr < 30$ Mpc from an Abell cluster centre, is $\sim$20 times the number at $r < 1.5\ h^{-1}$ Mpc. Taking $\sim$2 Abell clusters per supercluster on this scale one finds $\sim$10 times as many galaxies in the supercluster as in the great clusters, in agreement with Abell's estimate.

Abell: That is encouraging.