HAS THE UNIVERSE THE CELL STRUCTURE?

Mihkel Jôeveer and Jaan Einasto
Tartu Astrophysical Observatory
Tôravere 20244
Estonia, U.S.S.R.

1. INTRODUCTION

As demonstrated by de Vaucouleurs (1956, 1975a,b, 1976), Abell (1961), Karachentsev (1966), Kiang and Saslaw (1969) and others, clusters of galaxies as well as groups of galaxies have a tendency to form second-order clusters of galaxies, often called superclusters. Recent statistical studies by the Princeton group (Davis, Groth and Peebles 1977, Seldner and Peebles 1977a) have confirmed this result. Statistical studies, however, give little information about the internal structure of second-order clusters.

To get a clearer picture of the distribution of galaxies in space, we have studied the three-dimensional distribution of galaxies and clusters of galaxies. We have used recession velocities of galaxies and mean velocities of clusters as distance indicators supposing, following Sandage and Tammann (1975), that the expansion of the Universe is uniform.

2. OBSERVATIONAL DATA

The distribution of the following objects has been studied: Abell clusters of galaxies (Abell 1958), Zwicky clusters of galaxies (Zwicky et al. 1961-68), groups and pairs of galaxies, and single galaxies.

The second Reference Catalogue of Bright Galaxies (de Vaucouleurs, de Vaucouleurs and Corwin 1976) has served as the source of the radial velocities for galaxies. Radial velocities of the Abell clusters have been taken from a compilation by Corwin (1974) supplemented by some new determinations (Faber and Dressler 1976). Only nearby objects have been studied: Zwicky clusters belonging to the "near" distance class and galaxies having redshifts not in excess of 15 000 km s^{-1} have been used.

M. S. Longair and J. Einasto (eds.), The Large Scale Structure of the Universe, 241-251.

https://doi.org/10.1017/S0074180900144626 Published online by Cambridge University Press

3. SPATIAL DISTRIBUTION OF NEARBY GALAXIES AND CLUSTERS OF GALAXIES

To study the form of large-scale clusters, we compare the apparent distribution of these objects on the sky with successive cross-sections in space. To do this, the sky has been divided by parallel small circles into zones. The cross-sections of the space along the zones represent conic volumes with the Galaxy at the tip of the cones. This particular representation, used also by Fall and Jones (1976) in their study of the Rubin-Ford effect, has proved extremely useful in studying the spatial distribution of galaxies.

The overall large-scale distribution of galaxies was studied by dividing the sky into six cross-sections parallel to the celestial equator, each zone being 15° in width. The distribution of galaxies and clusters of galaxies in these sections exhibits the following features.

Clusters of galaxies are not randomly distributed but form long chains. Small groups of galaxies and galaxies have a tendency to form disk-like aggregates. These densely populated formations are separated from each other by big holes: regions of low space density of galaxies. The cross-sections between $\delta = -45^{\circ}$ and $\delta = +45^{\circ}$ show the presence of chains of clusters of galaxies in the Perseus, Coma, Hercules and Fornax regions. Big holes can be seen between the Local Supercluster and the Perseus chain of clusters, between the Coma and Hercules supercluster and in some other regions (Figure 1).

We have studied in detail the Perseus supercluster which is very favourably situated just behind a big hole and there is therefore probably very little confusion with foreground objects. Galaxies in the magnitude interval $12^{m}_{\cdot}0$ - $14^{m}_{\cdot}5$ in the Perseus region of the sky have been plotted in Figure 2. Giant galaxies in this apparent magnitude interval are at a distance of about 100 Mpc, if we adopt a Hubble constant $H = 50$ km s^{-1} Mpc^{-1}.

The most prominent feature in this figure is a chain of clusters of galaxies, which contains the Perseus cluster Abell 426, clusters A 347, A 262, NGC 507, NGC 383, and a number of groups of galaxies. We shall call this chain <u>the Perseus chain of clusters</u>. On the sky it covers a strip about 45° long and has half width about $1^{\circ}_{\cdot}5$. Practically all galaxies of the chain are located in a strip 4° wide (see Figure 2). All galaxies in this strip with known redshifts are plotted in redshift space in Figure 3. Data on some of the condensations in this strip are given in Table 1 (V_o is the redshift of the main galaxy, $\langle V_o \rangle$ the mean redshift of the cluster, σ_r - the velocity dispersion and n_{vel} - the number of galaxies with known redshifts). It is remarkable that the redshifts of the main galaxies are very close to the mean velocities of galaxies in the clusters with a very small rms scatter. We also note that most of the main galaxies are supergiant ellipticals with extended haloes, 6 of them being radio sources.

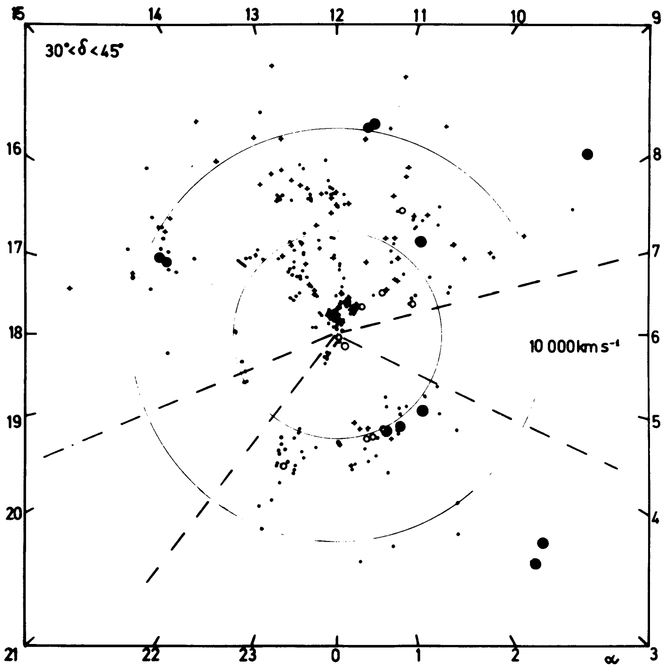

Figure 1. Cross-section of space in declination zone $30^{o} < \delta \leqslant 45^{o}$. Right ascension is used as the polar angle, redshift as the radius-vector. Abell clusters of galaxies have been plotted as filled circles, groups of galaxies as open circles, single galaxies as dots, Markarian galaxies as crosses. The Milky Way zone of avoidance is shown by broken lines.

https://doi.org/10.1017/S0074180900144626 Published online by Cambridge University Press

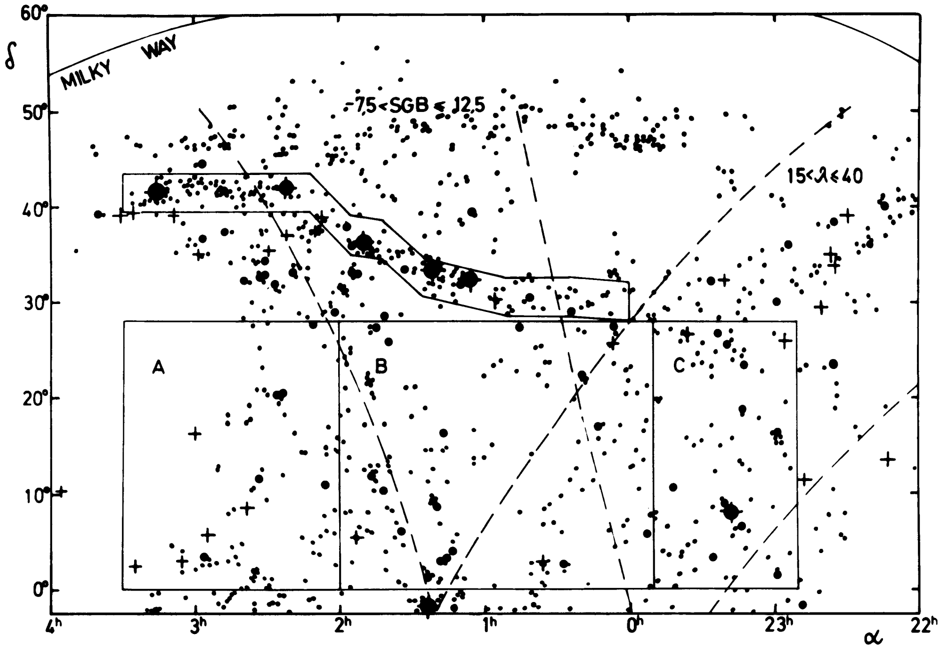

Figure 2. Distribution of galaxies in the Perseus region. In declination zones from 0° to 30° galaxies in the magnitude interval $12^{m}.0$ - $14^{m}.5$ have been plotted, in higher declination zones a somewhat fainter magnitude interval has been used to compensate for the increasing galactic absorption (Jôeveer, Einasto and Tago 1977). Bright elliptical and SO galaxies ($12.0 < m < 13.9$) have been plotted as small filled circles, radio galaxies in the redshift interval $2500 < V_{o} < 10\ 000$ as crosses, clusters of galaxies as large filled circles. The zone of width 4° associated with the Perseus chain of clusters of galaxies and Perseus supercluster disk areas A, B and C have been shown by solid lines and supergalactic zones by broken lines.

https://doi.org/10.1017/S0074180900144626 Published online by Cambridge University Press

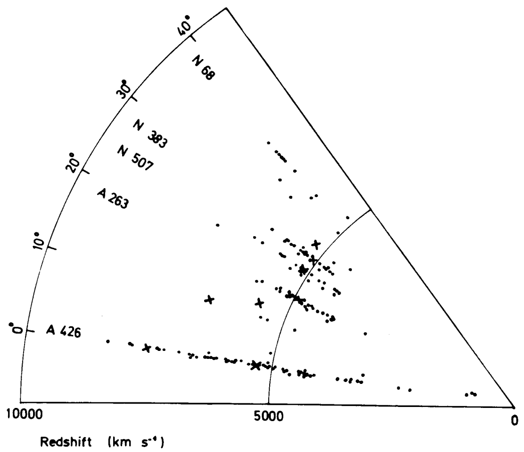

Figure 3. Distribution of available redshifts of galaxies in areas A, B and C (see Figure 2).

Table 1

Data on the Perseus chain of clusters of galaxies

Cluster	Main galaxy NGC	Main galaxy V_o (km s^{-1})	Cluster V_o (km s^{-1})	Cluster σ_r (km s^{-1})	n_{vel}	References
N 315	315	5218	-	-	1	
N 383	383	5095	5125	411	24	Moss & Dickens (1977)
N 507	507	5127	5113	658	14	Tifft et al. (1975)
A 262	708	5023	5031	438	33	Moss & Dickens (1977)
A 347	910	5315	5520	743	4	
N 1129	1129	-	-	-	-	
A 426	1275	5361	5490	1396	50	Chincarini & Rood (1972)
Field	-	-	5362	786	8	
Total		5190±132	5274±211		134	

https://doi.org/10.1017/S0074180900144626 Published online by Cambridge University Press

We note an interesting detail in the structure of the clusters of galaxies in the Perseus chain. As can be seen from the charts given by Zwicky et al. (1961-68), practically all clusters are elongated along the main ridge of the chain. This means that the clusters are either elongated like cucumbers or have flattened disks. We prefer the first explanation since in the last case all clusters would be oriented edge-on to the observer, which occurs with small probability.

Thus we conclude that the Perseus chain is essentially a one-dimensional formation.

Now we consider the region to the south of the Perseus chain between declinations $\delta = 0^o$ and $\delta = 28^o$. The distribution of radial velocities in three sections (denoted A, B and C in Figure 2) is given in Figure 4. We see that in the middle section B between $\alpha = 23^h\ 50^m$ and $\alpha = 2^h$ there is a strong peak with the mean redshift $\langle V_o \rangle = 5220$ km s^{-1}. Galaxies with velocities of about 5000 km s^{-1} are distributed over the whole area of the section. In the neighbouring areas A and C the redshift distribution is more or less uniform. It is apparent that in section B we see a thin layer of galaxies and groups of galaxies. This layer can be called the disk of the Perseus supercluster.

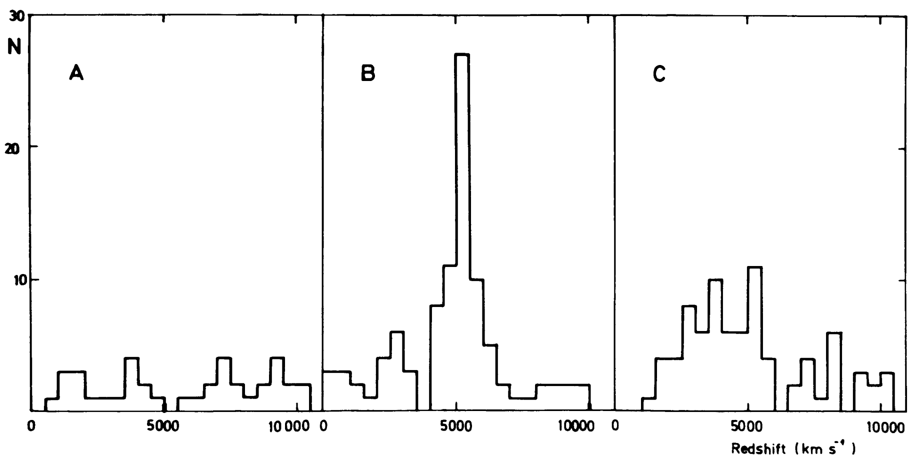

Figure 4. Distribution of available redshifts of galaxies in areas A, B and C (see Figure 2).

Along the eastern boundary of the disk of the Perseus supercluster a number of Zwicky clusters of galaxies and 5 radio galaxies are located between clusters A 426 and A 194. All these clusters and radio galaxies have redshifts about 5000 km s^{-1}.

To determine the extent of the disk in the southern and western direction, we have made cross-sections in supergalactic coordinates (Figure 5a) and in the western part of the Perseus supercluster in a coordinate system, perpendicular to the Perseus cluster chain

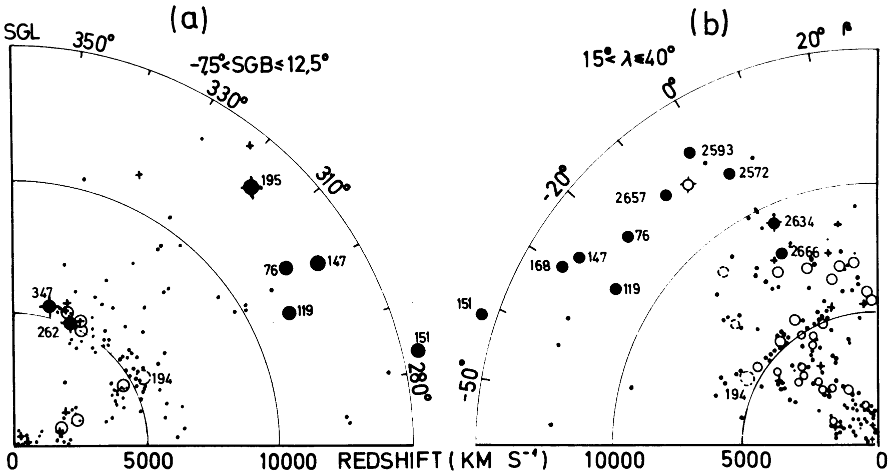

Figure 5. Cross-sections of the Perseus supercluster in Supergalactic coordinates (left) and in Perseus supercluster coordinates (right, for the definition of Perseus Supercluster coordinates see Jôeveer, Einasto and Tago 1977). Designations as in Figure 1. Abell cluster numbers have been indicated; some clusters just outside the zone limit have also been plotted by broken circles.

(Figure 5b). As seen from these figures approximately at SGL = 300° (near the cluster A 194) and in the region of the Pegasus cluster there exist bridges and chains of galaxies and poor clusters of galaxies which join the Perseus supercluster to the Local Supercluster. It is natural to consider these regions as the southern and western boundaries of the Perseus supercluster.

The distribution of galaxies and clusters of galaxies in the Perseus region as well as in other regions of the sky resembles cells. Cell walls can be considered as disks of superclusters. Along the intersections of cell walls chains of clusters of galaxies are located which encircle supercluster disks from all sides. Cell interiors are almost void of galaxies; they form big holes in the Universe with diameters of 100-150 Mpc. The cell structure can be considered third order clustering of galaxies (superclusters being second-order clusters).

4. COMPARISON WITH THE RESULTS OF OTHER AUTHORS

Chains of clusters of galaxies in the Perseus region of the sky are visible already on the maps of NGC objects (Meyer 1908). Similar chains of smaller size are visible on computer-processed maps based on the Shane-Wirtanen counts of galaxies prepared by a group of Princeton astronomers (Seldner et al. 1977). The limiting magnitude of the Shane-Wirtanen catalogue is 19^{m}, giant galaxies being visible to a distance of about 1000 Mpc. At this distance a chain of diameter of 100 Mpc has an apparent diameter 5^{o}. As can be seen from the maps published by Seldner et al. (1977), the smallest and most numerous chains have diameters just in this range.

5. MEAN MATTER DENSITY

The total luminosity of the Perseus chain of clusters is $7 \times 10^{13}L_{\odot}$ and the total luminosity of the disk of the Perseus supercluster is $6 \times 10^{13}L_{\odot}$ (Jôeveer, Einasto and Tago 1977). Adopting a mass-to-luminosity ratio of 200 for the chain (all clusters have elliptical main galaxies) and 100 for the disk (Einasto et al. 1976), we obtain $2 \times 10^{16}M_{\odot}$ for the total mass of the Perseus supercluster. The supercluster covers an area of 4000 Mpc^2. Adopting 15 Mpc for the mean thickness of the supercluster (in the thickest part around the cluster A 426 the thickness is about 20 Mpc), we obtain a volume for the supercluster 6×10^4 Mpc^3. If the mean diameter of the cells is 100 Mpc and the mean thickness of the cell walls is 15 Mpc, then cell walls fill about half of the total volume of space, the other half being formed by cell interiors - big holes. Thus the Perseus supercluster represents a volume of 1.2×10^5 Mpc^3. The mean matter density in this volume exceeds the critical density by a factor of 3. In the Perseus chain of clusters the mean density exceeds the critical value by 2 orders of magnitude.

In the Perseus region the density of clusters of galaxies is higher than on the average. However, the available data suggest that about half of all galaxies are located in clusters of galaxies. The density estimate of Ostriker, Peebles and Yahil (1974) and of Einasto, Kaasik and Saar (1974), $\Omega = 0.2$, is based on Shapiro's (1971) determination of the mean luminosity density. This density is an underestimate for two reasons. First, as indicated by Kiang (1976) in calculations of the effective volume of the sample, galactic absorption has not been taken into consideration. To correct for this effect, the density has to be multiplied by a factor of 2. Second, Shapiro omited the Virgo cluster with the aim of removing the influence of the local density enhancement. If half of all galaxies are located in clusters, then another factor of 2 must be applied and we obtain $\Omega = 0.8$. Similar estimates have recently been obtained by Seldner and Peebles (1977b) and Huchra (1977 private communication).

6. DISCUSSION

Summarising the observational evidence, we can say that the available data show that galaxies are not randomly distributed and do not form symmetrical, more or less spherical superclusters. Superclusters may have a form of distorted triangles, as in the case of the Perseus supercluster and they can be surrounded by chains of clusters of

https://doi.org/10.1017/S0074180900144626 Published online by Cambridge University Press

galaxies. Disks of superclusters intersect at right angles, forming walls of cells in the Universe. In cell interiors the density of galaxies is very small and there we see big holes in the Universe. The mean diameter of big holes as well as superclusters is $\sim$ 100 Mpc.

Numerical experiments show that cell structure cannot be formed by random clustering. We believe that this structure is primordial - that it was formed prior to the formation of galaxies and clusters of galaxies in the gaseous phase of the Universe after recombination. A theory of galaxy formation leading to the formation of cell structure principally with one- and two-dimensional gas layers has been proposed by Zeldovich and his group (Zeldovich 1970 and this volume, Sunyaev and Zeldovich 1970, Doroshkevich et al. 1977). The predicted diameter of cells is just of the order of $\sim$ 100 Mpc, as observed.

The density estimate obtained is, of course, uncertain, but the present work suggests that there exist systems with a characteristic scale of $\sim$ 100 Mpc where the density exceeds the critical value.

Note added after the symposium. Professor de Vaucouleurs drew our attention to the fact that the dense part of the Perseus chain of clusters was already discussed by Proctor in the 19th century. The presence of holes of various diameters was demonstrated during the symposium by B. Tully and W. G. Tifft. G. Chincarini showed that the foreground galaxies in the direction of the Hercules supercluster are located at distinct redshifts which are a natural consequence of the cell structure. The fact that clusters of galaxies, in particular the Perseus chain of clusters, form essentially a one-dimensional structure was also emphasized by W. G. Tifft.

REFERENCES

Abell, G.O., 1958. Astrophys. J. Suppl., 3, 211.
Abell, G.O., 1961. Astr. J., 66, 607.
Chincarini, G. and Rood, H.J., 1972. Astr. J., 17, 4.
Corwin, H.G., 1974. Astr. J., 79, 1956.
Davis, M., Groth, E.J. and Peebles, P.J.E., 1977. Astrophys. J. Lett., 212, L107.
de Vaucouleurs, G., 1956. In Vistas in Astronomy, ed. A. Beer, Pergamon Press, London, 2, 1584.
de Vaucouleurs, G., 1975a. Astrophys. J., 202, 319.
de Vaucouleurs, G., 1975b. Astrophys. J., 202, 610.
de Vaucouleurs, G., 1976. Astrophys. J., 203, 33.
de Vaucouleurs, G., de Vaucouleurs, A. and Corwin, H.G., 1976. Second Reference Catalogue of Bright Galaxies, University of Texas Press, Austin and London.
Doroshkevich, A.G., Saar, E.M. and Shandarin, S.F., 1977. Inst. Appl. Math., Moscow, Preprint No. 72.
Einasto, J., Jôeveer, M., Kaasik, A. and Vennik, J., 1976. Proc. Third European Astr. Meet., Tbilisi, p. 431.

Einasto, J., Kaasik, A. and Saar, E., 1974. Nature, 250, 309.
Faber, S.M. and Dressler, A., 1976. Astrophys. J. Lett., 210, L65.
Fall, S.M. and Jones, B.J.T., 1976. Nature, 262, 457.
Jôeveer, M., Einasto, J. and Tago, E., 1977. Tartu Astr. Obs. Preprint A-1.
Karachentsev, I.D., 1966. Astrofizika, 2, 307.
Kiang, T., 1976. Mon. Not. R. astr. Soc., 174, 429.
Kiang, T. and Saslaw, W.C., 1969. Mon. Not. R. astr. Soc., 143, 129.
Meyer, M.W., 1908. Das Weltgebäude, Leipzig and Wien.
Moss, C. and Dickens, R.J., 1977. Mon. Not. R. astr. Soc., 178, 701.
Ostriker, J.P., Peebles, P.J.E. and Yahil, A., 1974. Astrophys. J. Lett., 193, L1.
Sandage, A. and Tammann, G.A., 1975. Astrophys. J., 196, 313.
Seldner, M. and Peebles, P.J.E., 1977a. Astrophys. J., 215, 703.
Seldner, M. and Peebles, P.J.E., 1977b. Astrophys. J. Lett. (in press).
Seldner, M., Siebars, B., Groth, E.J. and Peebles, P.J.E., 1977. Astr. J., 82, 249.
Shane, C.D. and Wirtanen, C.A., 1967. Lick Obs. Publ., 22, 1.
Shapiro, S.L., 1971. Astr. J., 76, 291.
Sunyaev, R.A. and Zeldovich, Ya.B., 1972. Astr. Astrophys., 20, 189.
Tifft, W.G., Hilsman, A.K. and Corrado, L.C., 1975. Astrophys. J., 199, 16.
Zeldovich, Ya.B., 1970. Astr. Astrophys., 5, 84.
Zwicky, F., Wild, P., Herzog, E., Karpowica, M. and Kowal, C., 1961-1968. Catalogue of Galaxies and Clusters of Galaxies, 1-6, Cal. Inst. Techn., Pasadena.

DISCUSSION

Davis: Most of your redshifts are derived from the second reference catalogue of de Vaucouleurs and since the sky coverage of the catalogue is quite patchy, one must exercise caution in judging the reality of the holes between superclusters.

Einasto: Some of the distant holes may be due to the absence of data, of course. But the big hole between us and the Perseus supercluster is without any doubt real.

Rudnicki: Perhaps your results for the Perseus area need some corection. As I have shown in my paper on the Perseus cluster published in 1963 in *Acta Astronomica*, there is strong patchy galactic obscuration in this area.

Einasto: We have studied the effect of galactic obscuration (Jôeveer, Einasto and Tago, *Tartu astr. obs.* Preprint A-1 (1977)). In calculating luminosities differential obscuration has been taken into account. The presence of chains of clusters of galaxies is not due to the patchy obscuration.

Fessenko: Systematical devitations in the surface number density of so-called clusters of galaxies may reflect contamination of the observational material by zodiacal light. Also you do not take account of other (local) possible effects due to variability of observing conditions.

Einasto: We have studied the distribution of galaxies along the line of sight. It is apparent that zodiacal light will not affect the redshift distribution of galaxies.

Tinsley: Would Drs Turner or Gott like to comment on the discrepancy between the values of Ω obtained by them and by Dr Einasto?

Gott: Einasto has assumed a mean M/L $\sim$ 100-200. The best way to get the mean luminosity density is to count all galaxies in some large homogeneous region such as the Zwicky catalogue to the 15th magnitude. Davis, Geller and Huchra found $e_L \sim 6 \times 10^7\ L_\odot\ Mpc^{-3}$, while Gott and Turner found $e_L \sim 5 \times 10^7\ L_\odot\ Mpc^{-3}$ from a similar study. These properly average over superclusters and holes and avoid the contamination of the local supercluster which makes Shapiro's result 3 times higher. With the luminosity densities quoted above and Einasto's assumed M/L, one finds $\Omega = 0.07 - 0.18$.

Einasto: Of course the luminosity density in the vicinity of the Perseus supercluster is higher than the mean. Our estimate of Ω was based upon Shapiro's estimate of the luminosity density.

de Vaucouleurs: I would like to make a historical remark. The Perseus supercluster has been known for over 100 years. It was discovered by Proctor in 1870 and has since then been noted by many astronomers. So we are making progress!

Komberg: Have you tried to check the cell structure studied in your paper with X-ray surveys and 21 cm data? There are now data that show that superclusters are X-ray sources?

Einasto: This is interesting to do but we have not done it yet.

Huchra: I would like to emphasize once again a point stressed by de Vaucouleurs that the magnitudes and surface counts of galaxies should be corrected for absorption and note that it is now possible to so using the data on neutral hydrogen column densities in the Galaxy of Heiles et al. plus a value of the gas/dust ratio. In addition, conversion to a standard magnitude system could help remove or reduce the discordance in the values of ρ_L and thus Ω derived.

Peebles: The 21-cm map of Heiles shows very little correlation with the Lick counts at $b > 40^o$. Of course, this is a useful limit only if the dust follows the gas.