ACADEMY OF SCIENCES OF THE ESTONIAN SSR
DIVISION OF PHYSICAL MATHEMATICAL
AND TECHNICAL SCIENCES
STRUVE ASTROPHYSICAL OBSERVATORY

Preprint A-1 (1977)

THE CELL STRUCTURE OF THE UNIVERSE

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TARTU 1977

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Summary. The present report will be concerned with the three-dimensional distribution of galaxies and of clusters of galaxies. This distribution resembles cells: galaxies and clusters of galaxies are concentrated towards cell walls, in cell interiors the spatial density of galaxies is very low. The mean diameter of cells is about 100-150 Mpc for H = 50 km s^{-1} Mpc^{-1}. Rich clusters of galaxies are concentrated to cell edges and form long chains: loops and rings turning round the cells. Chains of clusters of galaxies and neighbouring cell walls form aggregates which can be called superclusters of galaxies. The cell structure has probably been formed before the formation of galaxies or simultaneously with galaxy formation.

The structure of the Perseus supercluster of galaxies is studied in detail. This supercluster is situated on the other side of the nearest cell at a distance of 105 Mpc from us and it has a form of a distorted triangle. It is surrounded by the Perseus chain of clusters of galaxies which consists of 8 individual clusters, the Abell clusters A 262, A 347 and A 426 among them and by other chains of clusters. The total mass of this supercluster is about 2.3×10^{16} $M_{\odot}$, two thirds of the mass is located in the Perseus chain of galaxies. The matter density in the region of the Perseus supercluster exceeds by a large margin the critical cosmological density. The mean matter density in the Universe, associated with galaxies, is estimated to be $\Omega = \rho / \rho_{crit} \approx 0.8$.

1. Introduction

Are galaxies randomly distributed in space or do they form distinct large-scale units? What structure have large-scale building blocks of the Universe if they exist? These questions are still a subject of controversy. The study of the apparent distribution of galaxies in the sky has given no definite answer, because it is difficult to eliminate projection effects, the effect of light absorption in the Galaxy and other disturbing factors. Some authors (Zwicky, 1967; Holmberg, 1974; Bahcall and Joss, 1976) argue that the large-scale distribution of galaxies is essentially a random one. Other authors (Abell, 1961; de Vaucouleurs, 1956, 1975 a,b, 1976; Kiang and Saslaw, 1969; Karachentsev, 1966; Davis et al., 1977) advocate the presence of distinct structures, superclusters of galaxies, having spheroidal shape.

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 as distance indicators, supposing following Sandage and Tammann (1975) that the expansion of the Universe is uniform.

In this study we were guided by the idea that aggregates of galaxies "remember" their history. As demonstrated by Rootsmäe (1943, 1961) and by Eggen, Lynden-Bell and Sandage (1962), the structure and kinematics of galactic populations tell us the story of their formation and evolution. The study of hypergalaxies * indicated that small-scale systems of galaxies also preserve tracks of their formation (Einasto et al. 1974). Large-scale systems of galaxies should remember their history even better since the crossing time in these systems is by many orders of magnitude greater than in the small systems. Thus, the study of the present structure of the Universe should give us information about the formation of large-scale aggregates of galaxies and should enable to check various theories of galaxy formation.

Our recent study indicated that the dynamics of clusters of galaxies and hypergalaxies is closely related with the dynamics of their main galaxies (Einasto et al. 1976a). This indicates that clusters (or protoclusters) of galaxies have been formed before the formation of galaxies. Zeldovich proposed a theory of galaxy formation which predicts the formation of large-scale protoclusters before the formation of individual galaxies (1970). According to this theory large-scale systems should have a disk-like form. For this reason we looked for the presence of disk-like superclusters of galaxies. Our preliminary study confirmed this expectation (Einasto et al. 1975). Further study indicated that superclusters are parts of larger aggregates which can be called cells of the Universe. In this paper we shall present the results of our study of the three-dimensional distribution of galaxies in the southern galactic hemisphere.

* We use the term hypergalaxies for groups of galaxies with one concentration center which consist of main galaxies, of surrounding clouds of dwarf companion galaxies and of intergalactic matter.

2. Observational data

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

Radial velocities of the Abell clusters of galaxies have been taken from a compilation by Corwin (1974) supplemented by some new determinations (Chincarini & Rood, 1972; Tifft et al., 1975; Moss & Dickens, 1977). All the Zwicky clusters of galaxies in the southern galactic hemisphere ($\delta \geqslant -2^\circ.5$, $b < 0^\circ$) have been checked on paper-print copies of the Palomar Sky Atlas for possible member galaxies with known radial velocities. If some probable members have been found, then their mean radial velocity has been assigned to the cluster. The Second Reference Catalogue of Bright Galaxies (de Vaucouleurs, de Vaucouleurs and Corwin 1976) has served as the principal source of the radial velocities for the Zwicky clusters as well as for galaxies. In the case of groups of galaxies the mean radial velocities were taken from the list compiled by Einasto et al. (1977a). Only nearby objects have been studied: the Zwicky clusters of the distance class "near" (Zwicky et al. 1961-68) and galaxies having redshifts not in excess of 15 000 km s^{-1}. In the case of the Abell clusters a higher redshift limit 30 000 km s^{-1} has been used.

3. Spatial distribution of nearby galaxies and clusters of galaxies in the Southern galactic hemisphere

In most previous studies of the large-scale distribution of galaxies and clusters of galaxies various statistical methods have been used. Recent statistical studies (Davis, Groth and Peebles 1977) give evidence of an abrupt break in the slope of the two-point spatial galaxy correlation function. This result can be interpreted as an indication for the presence of large-scale clustering of galaxies up to a certain maximum scale. Statistical studies give, however, no answer to the question which form has the large-scale clustering of galaxies. To derive the form of large-scale distribution we shall use in the present work an individual approach and try to derive the principal structural properties of the spatial distribution of galaxies in a particular region of space.

To study the structure of particular objects, we compare the apparent distribution of these objects in the sky with respective cross-sections of space. To do this, the area of the sky under consideration has been divided by parallel small circles into zones. The cross-sections of space along the zones presented in Figs 2 and 3 represent conic volumes with the Galaxy at the top of the cone. This particular way of representation, used also by Fall and Jones (1976) in their study of the Rubin-Ford effect, has proved extremely useful in the study of the spatial distribution of galaxies, since the ever decreasing completeness of data is partly compensated for by the increasing thickness of the conic section with growing distances from the observer. By experimenting with sections of different widths we found that best results will be obtained with sections about 15-20° in width (thin sections contain too small a number of objects, in wide sections the smoothing effect is too large).

This method gives a good representation of the true spatial distribution of galaxies. But its effectiveness decreases rapidly with increasing distance and with the growing incompleteness of radial velocity data. For this reason we have also studied the distribution of galaxies of given magnitudes in the sky. Suppose that galaxies are distributed uniformly in space and have a differential luminosity function of the form

$$\log \varphi(M) = a + b\,(M-M^*) \,, \qquad (1)$$

where a is a constant, M^* is the absolute magnitude of the knee-point and b the slope of the luminosity function. For $H = 50$ km s^{-1} Mpc^{-1} $M^* = -21.0$, $b_1 = 0.25$ for $M > M^*$ and $b_o = 1.4$ for $M < M^*$ (Holmberg 1969, Christensen 1974, Vennik 1977). Consider galaxies of apparent magnitude m. Let r_o be the distance corresponding to the distance modulus $m-M^*$. On these assumptions the galaxies of apparent magnitude m located in a given area, ω , of the sky are distributed according to the law

$$N(x)\,dx = c\,\omega\,r_o^3\,x^{\beta}\,dx \,, \qquad (2)$$

where $x = r/r_o$, c is a constant proportional to the space density of galaxies, and $\beta = 2-5b$. For $x \leqslant 1$ $(M > M^*)$ $\beta = 0.75$ and for $x > 1$ $\beta = -5$. We see that most galaxies of apparent magnitude m are located in the distance interval $0.3 \leqslant x \leqslant 1.25$

with a steep maximum at $x = 1$.

As can be seen from Fig. 1, clusters of galaxies form long chains. The most prominent chain of clusters seen in Fig. 1 contains the Perseus cluster Abell (1958) 426, clusters A 347, A 262 and the Zwicky clusters (Zwicky et al. 1961-68) 0107.5+3212, 0024.4+3014, 0013.6+2927. We shall call this chain the Perseus chain of clusters. To study this chain and the surrounding regions in greater detail, we have introduced new coordinates λ and β ; the equator of this coordinate system has been chosen so as to fit the Perseus chain as closely as possible. The cross-sections of the sky shown in Fig. 2 have been drawn in this coordinate system (the boundaries of the zones are indicated in Fig. 1). In Fig. 3 the cross-sections are given in supergalactic coordinates.

The comparison of Figs. 1, 2 and 3 shows that the Perseus chain of clusters of galaxies is a dense part of a very long serpentine of clusters. Near the cluster 0013.6+2927 the serpentine turns away from us. The next section contains clusters A 2666, A 2634 and A 2572. Here the serpentine bifurcates, one of its branches extends further and contains clusters A 2593, A 2626 and probably also clusters A 2589, A 2630 and A 2625 (redshifts unknown). The other branch turns to the south and contains clusters A 2657 and A 76. Here the serpentine makes a sharp turn to the northeast. The next section of it contains clusters 0055.0+1212, A 160, A 154, A 179, A 195, 0143.8+2323, the northern part of the cluster 0226.0+ +2600 and clusters A 376, A 407. Near the main cluster of the Perseus chain, A 426, two other less prominent chains of clusters of galaxies start. A shorter loop goes in the north-western direction and consists of clusters 0145.8 +4740, 0119.6+5035, 2352.1+4718, 2320.2+4309 and 2231.2 +3732. The last cluster joins this chain with the Perseus chain of clusters. The other loop goes from A 426 in the southern direction, containing clusters 0236.2+3249, the main body of the cluster 0226.0+2600 and clusters 0208.0 +1515, 0144.0+1230 and A 194. At A 194 the chain makes a sharp turn to the north-west, its next section consists of clusters 0032.6+0207, 0000.8+0452, 2347.5+0707, 2320.0+0845 (the Pegasus cluster) and 2259.6+0746. Here the southern loop joins the large aggregate of clusters of galaxies, constituting the western part of the Perseus serpentine.

As can be seen from Figs. 2 and 3, the majority of field galaxies are also concentrated towards areas populated by clusters of galaxies. The radial velocity data are unfortunately very incomplete and it is difficult to draw reliable conclusions on the distribution of the main body of the field galaxies. Figs. 2 and 3 indicate that in the central region of the sky under study clusters of galaxies strongly concentrate towards two distinct distances, about 100 Mpc (redshift $\sim$ 5000 km s^{-1}) and 250 Mpc (redshift $\sim$ 12 500 km s^{-1}). To study the distribution of galaxies at these distances, we have plotted histograms of galaxies along three vertical strips in Fig. 4. The upper part of the Figure ($12^m.0 \leqslant m \leqslant 14^m.9$) shows the distribution of galaxies at distances 50 to 150 Mpc, the middle part indicates the distribution at distances 100 to 200 Mpc. To study the possible effect of galactic obscuration, in the lower part of the Figure the histograms of numbers of very distant and extremely distant Zwicky clusters of galaxies have been given.

The histograms of numbers of galaxies demonstrate clearly that in chains of galaxies the average surface density of galaxies is significantly higher than in the neighbouring regions. These histograms also indicate that the space between the chains of galaxies is not empty but is also filled with galaxies. Here the surface density is about a third of that in the chains. Variations in the surface density of galaxies are real and do not reflect any variability of galactic obscurations. The histograms of the numbers of the distant clusters show only a smooth increase of obscuration with increasing declination (decreasing galactic latitude) as expected according to a cosecant law.

The whole picture resembles cells. In cell interiors the spatial density of galaxies is low. Clusters of galaxies are concentrated towards cell edges, field galaxies - towards cell walls. Most clusters of galaxies form long chains turning round the cells. One cell is located between us and the main concentration of galaxies in the Perseus region at the redshift level 5000 km s^{-1}, the next cell is situated just beyond it. The mean diameter of cells is 100 to 150 Mpc.

4. Structure of the Perseus supercluster

Second-order clusters of galaxies have often been called superclusters of galaxies. Usually by a supercluster a compact aggregate of clusters of galaxies has been meant.

The results of the previous section indicate that clusters of galaxies do not form compact aggregates. For this reason the definition of a supercluster is not a trivial one.

D e f i n i t i o n o f t h e P e r s e u s s u p e r c l u s t e r . Cells of the Universe resemble irregular polyeders: distorted cubes and octaeders. Clusters of galaxies form chains along the edges of the polyeders and encircle the cell walls from all sides. If we associate superclusters with cell walls, then only a half of their surrounding chains can be associated with particular cell walls if we want to avoid some chains being counted twice (the number of polyeder edges exceeds the number of walls). The same argumentation is valid if we start by defining a supercluster from a prominent chain of clusters. As seen from Figs. 1-3, cell walls, adjacent to a particular chain (a cell edge), form a considerable angle, often being located even perpendicularly. For this reason it is not appropriate to associate two adjacent cell walls with a particular chain but only with one of them.

In the case of the Perseus clustering of galaxies we regard the chain of clusters from A 426 to Zw 0013.6+2927 as skeleton of the Perseus supercluster. We consider the cell wall located at a distance of 100 Mpc and encircled from the northern side by the Perseus chain of clusters and from the southern side by the southern loop of clusters starting from A 426 (see previous section) as disk of the Perseus supercluster. We draw the eastern boundary of the supercluster along the line joining clusters A 426 and A 194.

Five radio galaxies are located on this line, all of them having redshifts of 5000 to 6000 km s^{-1}. The Perseus supercluster is seen almost face on, it covers an area from $\delta = 0°$ to $\delta = 32°-45°$ in declination and from $\alpha = 23^h50^m$ to $2^h - 3^h30^m$ in right ascension, having the form of a distorted triangle. As can be seen from the distribution of galaxies according to the redshift (Fig. 5'), in the supercluster disk area (western chain omitted) galaxies are strongly concentrated towards the redshift 5000 km s^{-1}. In the neighbouring areas the distribution is more or less uniform (here we look along the Perseus cell walls).

T h e s t r u c t u r e o f t h e P e r s e u s c h a i n o f c l u s t e r s . With the aim of studying the distribution of galaxies in the Perseus supercluster in more detail, we have plotted all galaxies in the magnitude interval of $12.0 \leqslant m \leqslant 14.5$ in Fig. 6. According to de Vaucouleurs, de Vaucouleurs and Corwin (1976), the mean galactic absorption in the disk of the Perseus supercluster is 0.3, the apparent magnitude 14.5 corresponds to the peak of galaxy distribution at $r_o = 110$ Mpc. At high declination zones we have used a somewhat fainter magnitude interval (see Figure caption) to compensate for the increasing galactic absorption.

The galaxy plot indicates that the Perseus chain of galaxies consists of 8 individual clusters of various richness, located at fairly regular intervals from each other. All the main galaxies of these clusters are supergiant elliptical galaxies, most of them being also radio sources (crosses in Fig. 6). Both supergiant elliptical galaxies and radio sources are strongly concentrated towards the main cluster, A 426, of the supercluster, many ellipticals and radio sources are also located along all other boundaries of the supercluster.

To determine the width of the Perseus chain of clusters, we have plotted in Fig. 7 a histogram of the numbers of galaxies at different declination zones in the interval $2^h15^m \leqslant \alpha \leqslant 3^h30^m$ (here the chain is parallel to the celestial equator). The histogram indicates the presence of a background at the N = 10-20 level and a strong peak at $\delta = 41^\circ.25$ with a dispersion of 1°, which corresponds to 2 Mpc at the distance of the supercluster. Practically all the galaxies of the chain are located in a strip 4° wide in declination. The galaxies the background also belong to the Perseus supercluster, forming a huge cloud surrounding A 426. Fig. 8 gives a histogram of the galaxies along the chain in the 4° strip. The declination of the mean ridge of the chain decreases in the western direction to 32°, the strip has been drawn ± 2° from the ridge. This histogram clearly shows the presence of condensation in the chain. Abell cluster numbers or NGC numbers of the main galaxies of these condensations have been indicated. We note that all the main galaxies of these clusters are supergiant ellipticals, 6 of them being radio sources. The surface density contrast between peaks and intermediate regions is of the order of 10.

Some data on the clusters of galaxies of the Perseus chain are given in Table 1. $\langle V_o \rangle$ is the mean redshift of the cluster and σ_r the respective radial velocity dispersion, n_v is the number of galaxies with known redshifts, A is the absorption according to de Vaucouleurs, de Vaucouleurs and Corwin (1976), m* is the apparant magnitude which corresponds to the knee-point absolute magnitude M* of the luminosity function, n* is the number of galaxies brighter than or equal to this limit, L is the total luminosity.

The luminosity has been estimated by integrating the luminosity function (1). First the number, n*, of galaxies brighter than or equal to M* was calculated. The total luminosity

$$L = n^* L^* \varkappa , \qquad (3)$$

where

$$\varkappa = b_o \left((b_o - 0.4)^{-1} + (0.4 - b_1)^{-1} \right) , \qquad (4)$$

$L^* = 3.6 \times 10^{10} L_\odot$ denotes the luminosity, which corresponds to $M^* = -21^m.0$, and b_o and b_1 signify the slopes of the luminosity function for the region of bright and faint galaxies respectively (see previous section). The value of the coefficient $\varkappa$ depends critically on the slope of the faint end of the luminosity function, for $b_o = 1.4$ and $b_1 = 0.25$ $\varkappa = 10$.

In the Table the mean velocity of main galaxies and of cluster velocity centroids is given, as well as their rms deviations (in parenthesis). The cluster N 68 was omitted since here the chain turns away.

The total luminosity of the Perseus chain can be estimated also in a different way, namely by using the total luminosity of the Coma cluster of galaxies as a reference point. We have found the distribution of galaxies according to apparent magnitude in the Perseus chain between $\alpha = 0^h$ and 2^h2^m (Fig. 9). This section includes cluster A 262 and other clusters located in the western part of the chain, where galactic absorption is small. In this area the number of foreground and background galaxies is small and the synthetic luminosity function resembles that of other giant clusters of galaxies (Oemler 1974). A similar distribution has been found for the Coma cluster, which is very close to the distribution in the Perseus chain. Adopting for the Coma cluster and the Perseus cluster chain distances of 138 and 105 Mpc, respectively, and the mean galactic absorptions 0.19 and 0.33, we have for the apparent difference in distance moduli $\Delta m = 0.45$. We note that at $M^* + 0.5$ the differential luminosity function has a small secondary maximum. In the Coma cluster this maximum is located at $m = 14.4$ (Rood 1969), in the Perseus chain at $m = 14.0$, which is in good agreement with expectations. The total number of galaxies in the Coma cluster $m \leq 15.7$ is $n = 220$, the interpolated number of galaxies $m \leq 15.25$ in the western half of the Perseus chain is 302. The number of galaxies in the eastern part of the Perseus chain is practically equal to the respective number in the western part, if we take into account the difference $0^m.4$ in galactic absorption (see the crosses in Fig. 9). Hence the total number of galaxies in the Perseus chain having $m \leq 15.25$ is 604 or 2.75 times the respective number in the Coma cluster. According to Rood et al. (1972) the total luminosity of the Coma cluster is $2.6 \times 10^{13}\ L_{\odot}$ (their value $1.37 \times 10^{13} L_{\odot}$ has been reduced to $H = 50$ km s^{-1} Mpc^{-1} and an absorption correction of $0^m.19$ has been applied). For the total luminosity of the Perseus chain we obtain $7 \times 10^{13}\ L_{\odot}$, which coincides with the value obtained above from the luminosity function. Adopting the mean mass to luminosity ratio $M/L = 200$ for systems of galaxies with elliptical main galaxies (Einasto et al.

1976b), we obtain for the mass of the Perseus chain 1.5×10^{16} $M_\odot$.

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 a l o n g the main ridge of the chain. This means that the clusters are either indeed elongated like cucumbers or have a form of flattened disks. We prefer the first explanation since in the last case all clusters would be oriented edge-on to the observer, a case of small probability. Bright galaxies in cluster A 194 also form a very elongated chain, directed exactly along the main ridge of the eastern boundary of the Perseus supercluster, towards cluster A 426.

To check the possibility of the presence of foreground and background galaxies, we have plotted in Fig. 10 the redshifts of all the galaxies in the 4° strip of the Perseus chain (polar angle is the new longitude λ). As expected for a physical one-dimensional chain, the distribution is symmetrical. It is noteworthy that most main galaxies of the clusters are radio sources and have very small relative velocities in respect of the mean cluster velocity (see Table 1).

T h e d i s k o f t h e P e r s e u s s u p e r c l u s t e r . The cross-section of the Perseus area along the supergalactic longitude (Fig. 3) shows that the disk of the Perseus supercluster is located at tangent to the celestial sphere, directed towards the Perseus chain. The mean velocity of galaxies in the whole disk area (Fig. 5, foreground and background galaxies omitted) is 5220 km s^{-1} with a formal dispersion of 630 km s^{-1}. The velocity dispersion in small groups is about 100 to 200 km s^{-1} (Einasto et al. 1976b), the dispersion caused by varying the mean distance of different parts of the disk may be of the order of 500 km s^{-1}. The dispersion caused by the thickness of the layer of galaxies may be estimated at 300-400 km s^{-1}. This estimate is confirmed by other data. As can be seen from Fig. 1, the diameter of the Zwicky Perseus cluster is about 12°, i.e. about 20 Mpc. It is apparent that the mean thicknes of the disk should be smaller. Only one layer of the groups of galaxies is situated on the periphery of the Local Supercluster. Here the thickness is equal to the diameter of the groups, i.e. ~ 3 Mpc. We adopt the mean thickness of the disk 15 Mpc.

The area of the disk ($\delta \geqslant 0°$, $\alpha \geqslant 23^h50^m$; northern boundary is the Perseus chain, eastern boundary is the chain of radio galaxies between A 426 and A 194) is 1150 square degrees or 3800 Mpc^2. Because the disk is situated face on, the counts of galaxies can be used as good indicators of the total number of galaxies in this area. The total number of galaxies in this area ($12.0 \leqslant m \leqslant 14.9$) is 460. In the eastern part of the area the absorption is by $0^m.4$ larger than in the remaining area. To correct for the absorption the number of galaxies in this area (144) is to be multiplied by 1.4 (on the basis of the luminosity function). So we estimate the total number of galaxies brighter than 14.9 in the supercluster disk area to be 520. We assume that a third of these galaxies are foreground and background objects (this number is estimated on the basis of radial velocity data, see histogram in Fig. 5). Thus the corrected number of galaxies of the disk is $m_{14.9} = 347$. The respective number of galaxies in the Perseus chain is 392. We conclude that about a half of all the galaxies in the Perseus supercluster are concentrated towards its skeleton, the Perseus chain, and the other half towards the disk. Adopting the value of 120 for the mass-to-luminosity ratio (in the disk the percentage of groups with spiral main galaxies is higher; for these systems we have M/L = 100, Einasto et al. 1976b), we obtain the mass of the disk 0.8×10^{16} $M_{\odot}$ and the total mass of the Perseus supercluster 2.3×10^{16} $M_{\odot}$.

The role of the main cluster of galaxies. It is well known that the Perseus cluster of galaxies, A 426, is peculiar in many respects. It has one of the highest velocity dispersions measured, it is a strong emitter of X-rays and contains a number of radio galaxies. Its main galaxy, NGC 1275, is a peculiar Seyfert galaxy.

This peculiarity is not surprising if we take into account the position of the cluster in the Universe. It is located at the "cross-roads" of many chains of clusters of galaxies: the Perseus chain of clusters, the northern and southern loops (see previous section) and probably a chain, which consists of radio galaxies and extends far away (see Figs. 1-3). All these chains are directed away from the Milky Way or are parallel to it. It is possible that this cluster is also a starting point of some other chains of galaxies, but these chains are obscured by the Milky Way. Thus this cluster is located in the corners of many cells of the Universe and sits in a very deep potential well.

5. The mean matter density in the Perseus supercluster region

The total volume of the Perseus supercluster is 4000x15= $= 6 \times 10^4$ Mpc^3, its mass being $2.3 \times 10^{16} M_\odot$. If the mean diameter of the cells of the Universe is 100 Mpc and the mean thickness of their walls is 15 Mpc, then all the walls (superclusters) fill about a half of the total volume of space, the other half being formed by cell interiors where the density of galaxies is at least by an order of magnitude smaller than in the cell walls. In order to estimate the mean mass density of the Universe in the Perseus supercluster region, the volume of cell interiors is to be taken into account, thus the Perseus supercluster represents a volume of 1.2×10^5 Mpc^3. In this volume the mean matter density is $2 \times 10^{11} M_\odot\, Mpc^{-3}$, which exceeds the critical cosmological density $\rho_{crit} = 6.9 \times 10^{10}$ $M_\odot$ Mpc^{-3} (for H=50 km s^{-1} Mpc^{-1}) by a large margin.

At the first glance this density estimate seems to be improbably high. However, we note that most of the mass of the Perseus Supercluster is located in the Perseus chain of clusters. This mass is well determined dynamically and cannot be very faulty. On the basis of the data given above the total luminosity of the disk of the supercluster is 6×10^{13} $L_\odot$. If we adopt the conventional mass-to-luminosity ratio for a mixture of spiral and elliptical galaxies M/L = 20 (Materne and Tammann 1976), the mass of the disk would be 1.2×10^{15} $M_\odot$ and the total mass of the supercluster

- 1.6×10^{16} $M_{\odot}$. Even in this case the mean matter density in the Perseus supercluster region exceeds the critical density twice (if the volume remains unchanged). It is interesting to note that in the Perseus chain of clusters as well as in normal clusters and groups of galaxies the mean matter density exceeds the critical cosmological density by a factor of 100.

Most of the mass in the Universe is concentrated in clusters and groups of galaxies. Clusters and groups of galaxies fill only a small fraction of space, about 1%. In the remaining space the density of galaxies is very small.

6. 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). They are better visible on the maps of the Zwicky galaxies (Peterson, 1974). Similar chains of smaller size are also visible on the Shane and Wirtanen (1967) equidensity contours of number densities of galaxies and even better on computer-processed maps based on the Shane and 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, which corresponds to the characteristic distance of r_o = 900 Mpc ($A = 0^m.3$). One would expect to see chains of clusters up to this distance. At this distance a chain of the true diameter of 100 Mpc has an apparent diameter 5°. As can be seen from the maps published by Seldner et al. (1977), the smallest and most numerous chains have just diameters of this range.

One of the most prominent cells in the northern galactic hemisphere seen on the maps is the one centred at $l^{II} = 30°$, $b^{II} = 55°$. Its corners contain the following Abell clusters of distance class 3 or nearer (in brackets the redshift is given, if available): the southern corner (Serpens-Virgo cloud by Shane and Virtanen 1967): 2029 (23300), 2048 (28250), 2052 (10530), 2055 (15885), 2063; the eastern corner (Hercules cloud): 2147 (11153), 2151 (10942), 2152 (13182); an intermediate corner: 2162 (9528); the northern corner (Corona cloud): 2065 (21650), 2022, 2079; the western corner: 1983 (13708), 1991. We see here an overlapping of cells, the nearest one is located at a distance of between 180 and 320 Mpc. The cross-sections drawn in two perpendicular directions through this region of the sky confirm the reality of these cells. In some other cases, for which radial velocity data are available, the reality of chains of clusters was also confirmed.

It is important to note that many loops of size 5° and located presumably at a distance of 900 Mpc are clearly visible. This high transperency of space confirms independently that the volume occupied by systems of galaxies is indeed a very small fraction of the whole volume of the Universe. The presence of filamentary patterns on scales of 5° to 15° has also been noted by Seldner et al. (1977). However, they state that "this visual impression may be misleading because the eye tends to pick out linear patterns even in random noise". Without doubt large and rich clouds of galaxies seen on the Shane-Wirtanen maps are probably strengthened by projection effects as it is the case for the Serpens -Virgo cloud. However, the majority of narrow chains of clusters of approximately equal size and richness are probably real physical structures.

7. Discussion

We ask first: can the picture, obtained above, be the result of various disturbing factors, such as galactic obscuration, incompleteness of observational data, etc.?

To investigate the effect of galactic obscuration, we have plotted in Fig. 4 histograms of distant Zwicky clusters in the region under study. The distribution of clusters is quite uniform, the number of clusters is smoothly decreasing with the decreasing galactic latitude. Chains of clusters of galaxies cannot be due to seeing windows. The reality of chains of clusters is also confirmed by the fact that all main galaxies of these clusters are supergiant ellipticals with extended halos (as seen on the prints of the Palomar Sky Atlas), they are also radio sources and have very small relative velocities in respect of the mean velocity of the cluster.

Incompleteness of radial velocity data makes it hard to study the structure of distant cells. The Perseus cell and the Perseus supercluster seem to be ideally situated: the Galaxy is located just on the other side of the cell and the Perseus supercluster is seen face on. The other favorable factor is the absence of a dense foreground and background of field galaxies (other cell walls). For this reason the incompleteness of radial velocity data is here not a crucial factor. But for the study of other cells and superclusters many new radial velocities are necessary.

Independent evidence for the presence of the cell structure was given by Chincarini and Rood (1976) and Chincarini (private communication). In their study of the Coma and Hercules superclusters they noted that foreground galaxies are not distributed randomly but form concentrations at distinct redshifts. This is what can be expected if galaxies are located in cell walls.

Summarizing the observational evidence, we can say that the available data do not support the idea that galaxies are randomly distributed or form more or less spherical superclusters. The majority of galaxies are concentrated into clusters of galaxies, forming long chains, turning round the cells of the Universe. The remaining galaxies are situated in small groups, located in cell walls. Superclusters have a form of distorted triangles and squares, they consist of cell walls and surrounding chains of clusters.

The next question is: can this structure have been formed as a result of a later density enhancement or was it formed prior to or during the formation of galaxies?

Sandage and Tammann indicated that the expansion of the Universe is not only uniform but also laminar, in other words the random velocities of systems of galaxies are small compared with the expansion velocity. If we adopt for the random velocity of systems of galaxies a value of 100 km s^{-1}, which is twice the velocity found by Sandage and Tammann for the random velocity of individual massive galaxies, then in 10^{10} years the systems will have moved only 1 Mpc from their initial place in respect of the uniformly expanding reference system. We conclude that systems of galaxies have not had time to change considerably their mutual configuration, in particular, to form cells of 100 Mpc diameter with interia almost void of galaxies.

Thus the cell structure should have been present at the time of galaxy formation. The only available time for the formation of the cell structure is the phase after the recombination of the hot primeval gas. A theory of galaxy formation which leads to the formation of a cell structure (mainly with one- and two-dimensional gas layers) of neutral gas before the formation of galaxies has been suggested by Zeldovich (Zeldovich, 1970; Sunyaev & Zeldovich, 1972; Doroshkevich et al. 1977). The predicted diameter of cells is of the order of 100 Mpc, as observed (Fig. 11).

Our last question concerns the matter density: how reliable is the density estimate of the Perseus supercluster region and how does it tell on the overall matter density of the Universe?

First of all we note that there exists additional independent information indicating a high matter density in the Perseus supercluster region. As demonstrated by Einasto et al. (1977b), the spatial density of the Abell clusters of galaxies is in a sphere of radius 75 Mpc, centered at A 262, about three times the mean density of the Abell clusters in a sphere with the radius of 180 Mpc (in this sphere practically all the Abell clusters have measured redshifts). The spatial density of poor clusters of galaxies, not included into the Abell catalogue, is also high in the Perseus supercluster region. The data of the present work indicate that a considerable fraction if not the majority of all galaxies are located in clusters of galaxies. For this reason it is not suprising that the mean mass density in the Perseus supercluster region is high.

We remind that current mean mass density estimates (Einasto, Kaasik and Saar 1974, Ostriker, Peebles and Yahil 1974) are based on Shapiro's (1971) determination of the mean luminosity density. Shapiro's luminosity density value is too low for two reasons. Firstly, as indicated by Kiang (1976), in calculations of the effective volume of space under study the galactic absorption has not been taken into consideration. To correct for this effect the density is to be multiplied by a factor of 2. Secondly, Shapiro omitted the Virgo cluster of galaxies to remove the influence of the local density enhancement. Our study indicates that the majority of all galaxies are located in clusters, for this reason another factor of at least 2 must be applied. Thus, instead of $\Omega = \rho / \rho_{crit} = 0.2$, we obtain

$$\Omega \approx 0.8 .$$

This density estimate is independent of the Hubble constant (both ρ and ρ_{crit} are proportional to H^2).

The uncertainty of this result, due to inaccuracy in the mass-to-luminosity ratio of systems of galaxies and in the luminosity density, is large, of the order 3 or more. To reduce the possible error much new data on both the spatial structure and the dynamics of large-scale systems of galaxies are necessary.

A similar estimate, using in principle the same idea but a completely different approach, has been recently obtained by Seldner and Peebles (1977).

Our density estimates as well as Seldner's and Peebles' one are conservative because only matter associated with galaxies and systems of galaxies has been taken into account. It seems to be very unlikely that the whole space outside of systems of galaxies (i.e. about 99% of the total space) is empty. It is very difficult to imagine a process of galaxy and supercluster formation which is effective enough to evacuate completely such large volumes as cell interiors are.

Data available at present are insufficient to solve the crucial problem whether our Universe is open or closed. But the results of this study indicate that even if the mean matter density is smaller than the critical one, there exist large-scale systems (characteristic scale 100 Mpc) where the density probably exceeds the critical limit.

Acknowledgements. Fruitful conservations with Professor Ya. B. Zeldovich and Drs A.G. Doroshkevich, B.I. Fesenko and I.D. Novikov are gratefully acknowledged. Many thanks are due to Professors P.J.E. Peebles and G. Chincarini for sending us preprints of their recent papers, to Dr E. Saar and to Messrs J. Jaaniste, A. Kaasik and A. Kivila, who took an active part in the early stage of this investigation, as well as to Miss K. Ahero, Mrs. H. Silvet, Mrs. M. Kõer and Mr. L. Kivimägi for their help in preparing the manuscript for print.

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Table 1. Data on the Perseus chain of clusters of galaxies

Cluster	Main galaxy NGC	Main galaxy V_o (km s^{-1})	$\langle V_o \rangle$ (km s^{-1})	σ_r (km s^{-1})	n_{vel}	A	m*	n*	L ($10^{12} L_\odot$)
N 68	68	5941	6784	458	8	$0^m.30$	$15^m.0$	23	8
N 315	315	5218	-	-	1	0.29	14.4	8	3
N 383	383	5095	5125	411	24	0.31	14.4	21	8
N 507	507	5127	5113	658	14	0.32	14.4	29	10
A 262	708	5023	5031	438	33	0.37	14.4	23	8
A 347	910	5315	5520	743	4	0.52	14.7	8	3
N 1129	1129	-	-	-	-	0.65	14.8	16	6
A 426	1275	5361	5490	1396	50	0.77	15.0	44	16
Field	-	-	5362	786	8	-	14.5	25	9
Total[1]		5190 (132)	5274 (211)		142			197	71

[1] Mean velocities of main galaxies and centroid velocities of clusters and their rms deviations (given in parenthesis) have been calculated omitting the cluster N 68.

Figure captions

Fig. 1. Distribution of the Abell and Zwicky clusters of galaxies in the Perseus region. Nearby Abell clusters ($R \leqslant 200$ Mpc) are denoted as filled circles, more distant ones as open circles. Contours of the Zwicky clusters located at small distances ($R \leqslant 200$ Mpc) are drawn with continuous lines, more distant clusters (of the distant class near) are contoured by dashed lines. The Perseus chain of clusters of galaxies forms a strip from Abell cluster 2572 to 426. In order to show the cross-section of space along this strip and the adjacent parallel strips, we have introduced new coordinates. The equator of the new coordinate system has been drawn through the densest part of the Perseus chain, the zero point of the new longitude λ is located at the point $\alpha = 22^h$, $\delta = 0°$. Zones of 15° in width and centered at new latitudes $\beta = 0°$, $\beta = -15°$ and $\beta = -30°$ have been indicated as zones A, B and C, respectively.

Fig. 2. Cross-section of space in latitude zones A, B and C (for definition of zones see Fig. 1). Longitude λ is used as the polar angle, the redshift as the radius-vector. Circles of radii 5000, 10 000 and 15 000 km s^{-1} have been drawn. Abell clusters of galaxies have been plotted as filled circles, Zwicky clusters and groups of galaxies have been plotted as open circles, single galaxies as dots, radio galaxies as crosses, Abell clusters, groups of galaxies and single galaxies of zones B and C, located in the southern hemisphere ($\delta < 0$), have also been plotted (not shown in Fig. 1).

Fig. 3. Cross-sections of space in the Perseus region of the sky in different supergalactic latitude zones (A: $-27^\circ.5 <$ SGB $\leq -7^\circ.5$; B: $-7^\circ.5 <$ SGB $\leq 12^\circ.5$; C: $12^\circ.5 <$ SGB $\leq 32^\circ.5$). For designations see Fig. 2.

Fig. 4. Histograms of numbers of galaxies of different luminosity (upper and middle figures) as functions of the declination zone of the Palomar Sky Atlas. Histograms have been compiled for three right ascension zones, each 18° wide, mean right ascension of each zone is indicated in the upper figure. In the lower figure histograms of numbers of very distant and extremely distant Zwicky clusters of galaxies in respective zones have been given.

Fig. 5. Distribution of available redshifts of galaxies in declination zones $0^\circ \leq \delta \leq 28^\circ$ (DDO dwarfs not included).

Fig. 6. Distribution of galaxies in the Perseus region. In the Palomar Sky Atlas zones centered at declinations from 0° to 30° galaxies in the magnitude interval $12^m.0$- $14^m.5$ have been plotted. In order to compensate for galactic absorption in higher declination zones different magnitude intervals have been used: in 36° zone $12^m.2$ - $14^m.7$, in zone 42° $12^m.5$- $15^m,0$, in 48° and 54° zones $13^m.2$ - $15^m.7$. Bright elliptical and SO galaxies ($12.0 \leq m \leq 13.9$) have been plotted as small circles, radio galaxies in the redshift interval $2500 \leq V_0 \leq 10\,000$ as crosses, clusters of galaxies as large filled circles (if they have more than 10 galaxies in the magnitude interval considered).

Fig. 7. Distribution of galaxies ($12.0 \leqslant m \leqslant 15.7$) across the Perseus chain in the interval $2^h15^m \leqslant \alpha \leqslant 3^h30^m$.

Fig. 8. Distribution of galaxies ($12.0 \leqslant m \leqslant 15.7$) along the Perseus chain in the 4° strip.

Fig. 9. Luminosity function for galaxies in the western half of the Perseus chain $0^h \leqslant \alpha \leqslant 2^h2^m$ (in this section galactic absorption is small). Designations: dots - integral luminosity function; open circles - differential luminosity function; crosses - integral luminosity function for the eastern section of the chain with significant absorption (corrected by differential absorption $m = 0^m.4$).

Fig. 10. Distribution of available redshifts along the Perseus chain.

Fig. 11. Typical distribution of point masses at the end of the gaseous phase of the evolution of the Universe according to a two-dimensional numerical experiment, carried out by Shandarin (Doroshkevich, Zeldovich and Sunyaev 1976). The numbers indicate the number of point masses in respective places. Initially point masses were located on knots of a regular frame (with small random shifts). The experiment shows the formation of a cell-like structure of density enhancements. Three-dimensional experiment gives similar results. For H = 50 km s^{-1} Mpc^{-1} and $\Omega = 0.1 - 0.3$ the mean present diameter of cells is about 100 Mpc (Doroshkevich and Shandarin 1977).

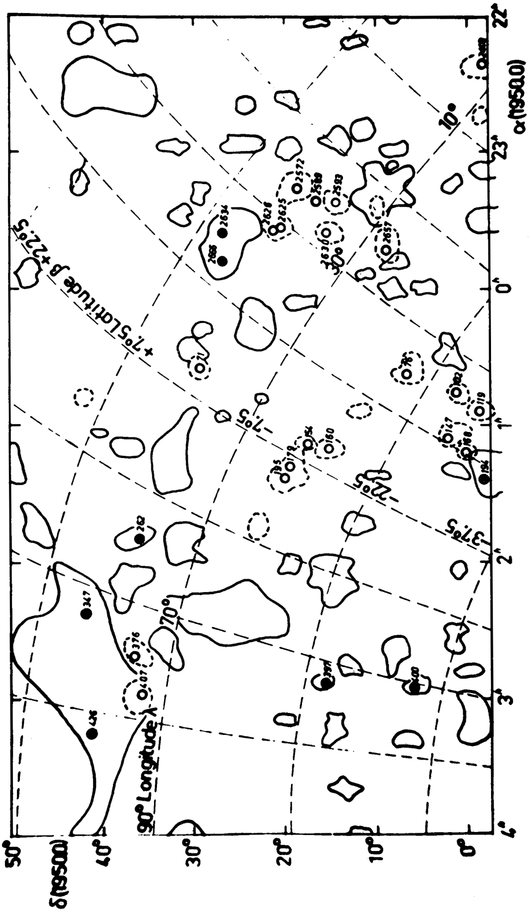

δ(1950.0)
α(1950.0)
+7°5 Latitude β
+22°5
-7°5
-22°5
-37°5
90° Longitude λ
70°
10°
30°
50°
40°
30°
20°
10°
0°
22h
23h
0h
1h
2h
3h
4h

Fig. 1

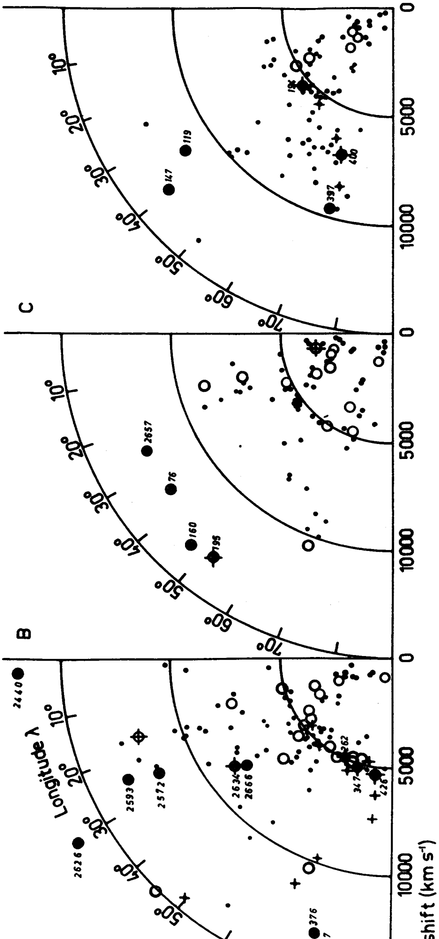

A
B
C
Longitude λ
Redshift (km s⁻¹)
0
5000
10000
15000
10°
20°
30°
40°
50°
60°
70°
80°
2440
2626
2593
2572
2634
2666
262
347
426
376
407
2657
76
160
195
119
147
400
397

Fig. 2

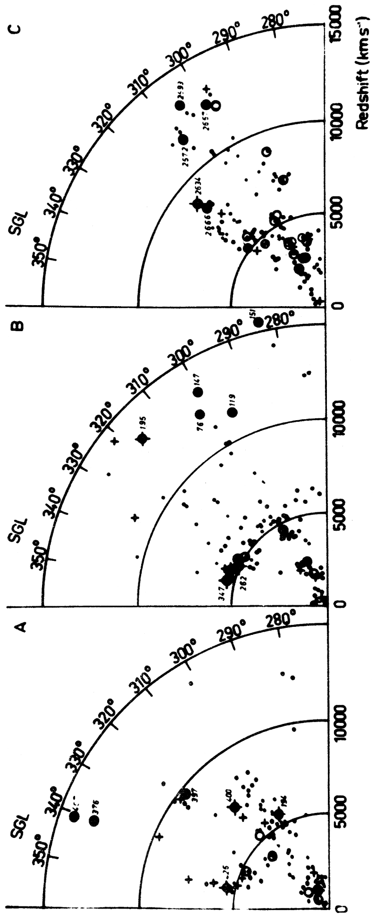
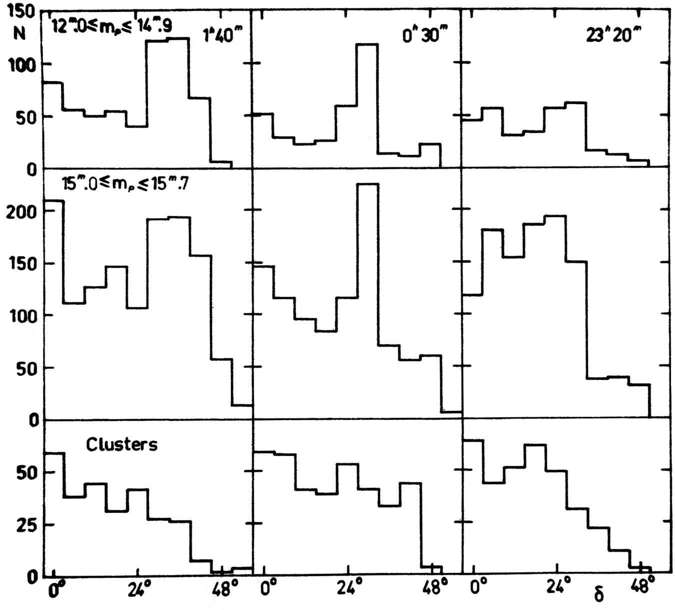

A
B
C
SGL
350°
340°
330°
320°
310°
300°
290°
280°
0
5000
10000
15000
Redshift (km s⁻¹)

Fig. 3



150
N
100
50
0
200
150
100
50
0
50
25
0
12ᵐ.0 ≤ mₚ ≤ 14ᵐ.9
1ʰ40ᵐ
0ʰ30ᵐ
23ʰ20ᵐ
15ᵐ.0 ≤ mₚ ≤ 15ᵐ.7
Clusters
0°
24°
48°
0°
24°
48°
0°
24°
δ
48°

Fig. 4

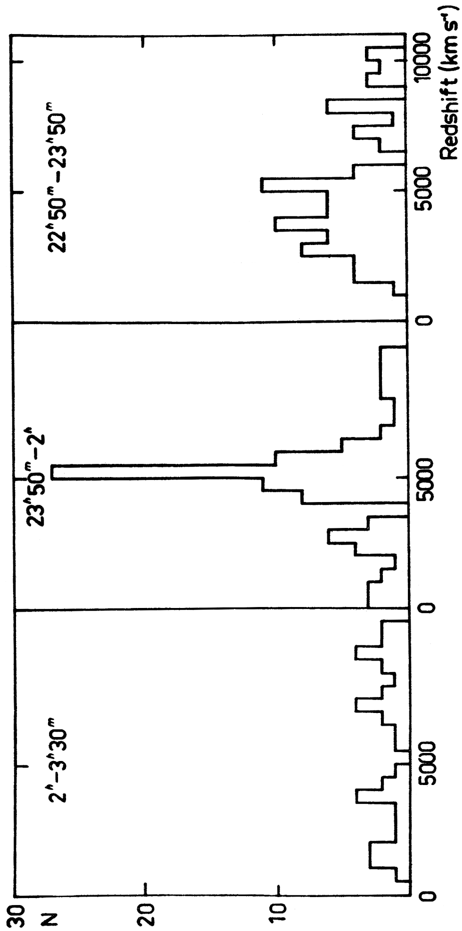

N
30
20
10
0
5000
10000
Redshift (km s⁻¹)
22h50m–23h50m
23h50m–2h
2h–3h30m

Fig. 5

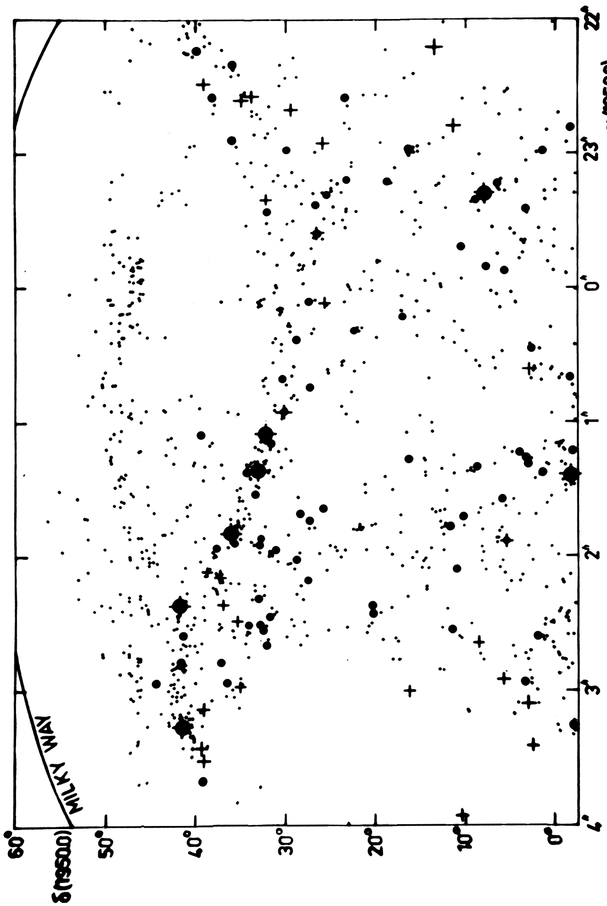


Fig. 6

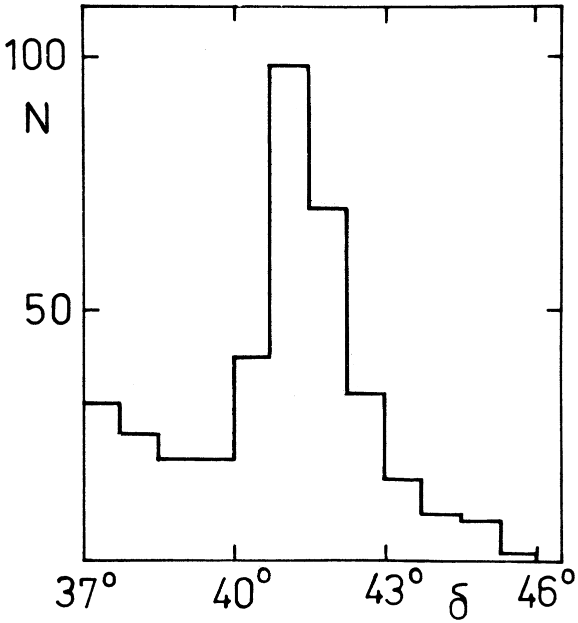


Fig. 7

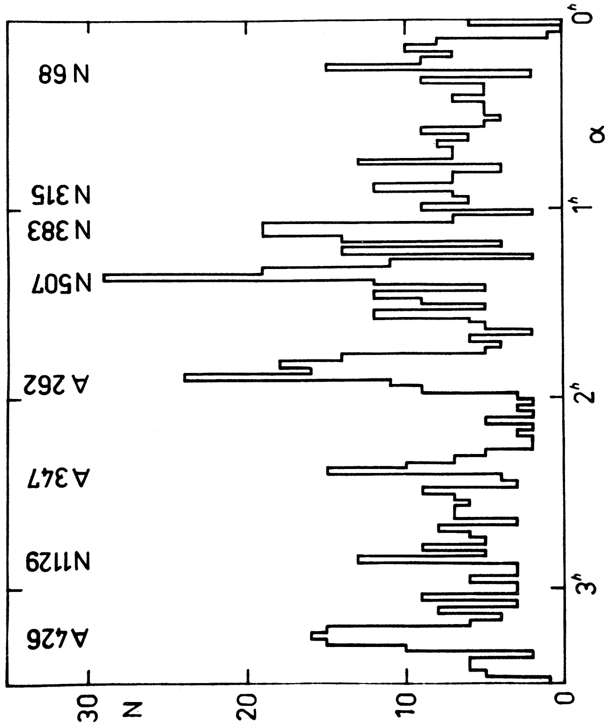


Fig. 8

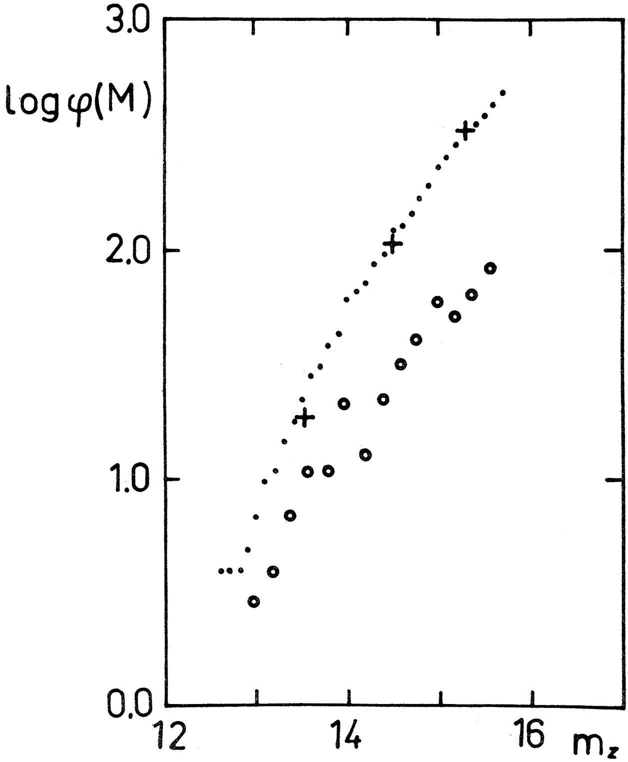


Fig. 9

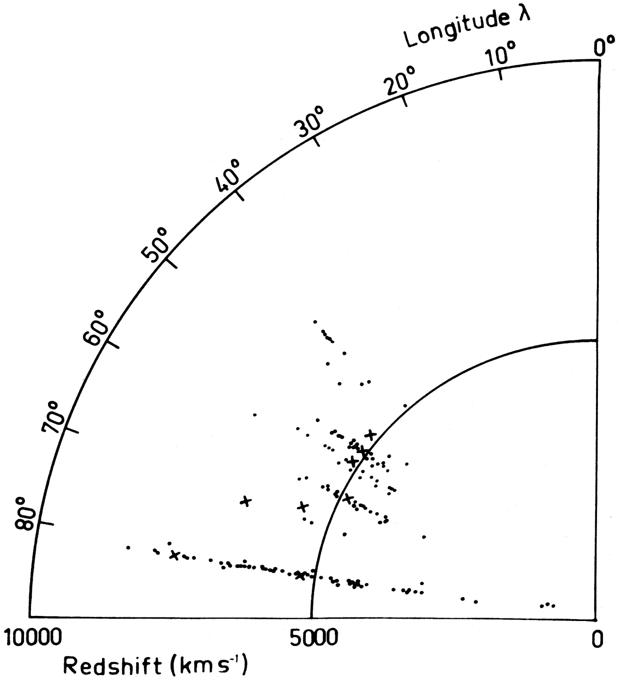


Fig. 10

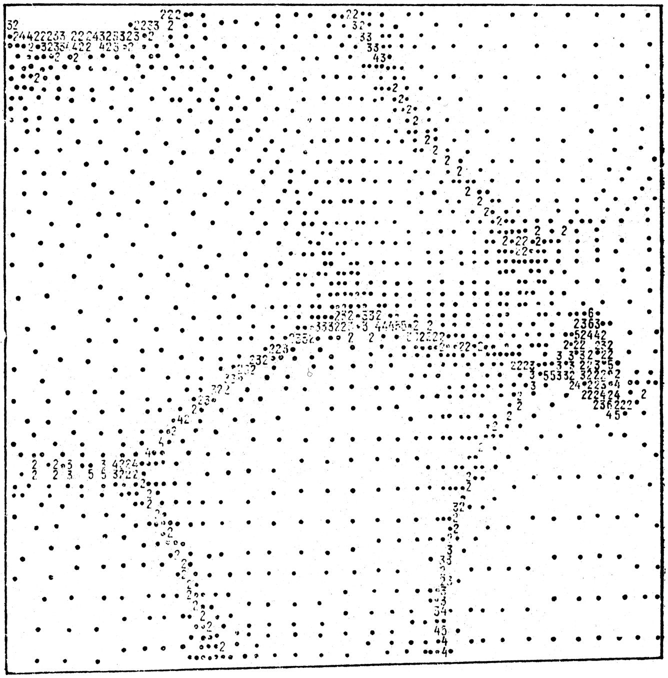


Fig. 11