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АКАДЕМИЯ НАУК ЭСТОНСКОЙ ССР
ОТДЕЛЕНИЕ ФИЗИКО-МАТЕМАТИЧЕСКИХ И ТЕХНИЧЕСКИХ НАУК

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GIANT VOIDS IN THE UNIVERSE: AN EYEWITNESS STORY OF GALAXY FORMATION

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ABSTRACT

Recent observational data indicate that most galaxies are concentrated towards superclusters which consist basically of galaxies and clusters of galaxies. Giant volumes between superclusters are almost empty of visible objects.

Modern theories of galaxy formation predict the formation of superclusters and giant voids. Large-scale structure changes very slowly, thus the currently observed structure reflects the whole history of galaxy formation and of structural evolution. The astronomers' task is to decode this eyewitness story.

1. INTRODUCTION

According to the traditional picture based on the study of the apparent distribution of galaxies on the celestial sphere, galaxies are distributed more or less randomly, showing a moderate tendency to clustering. Statistically the clustering tendency can be expressed in terms of the galaxy covariance function [1]. The use of modern sensitive detectors has made it possible to determine redshifts of galaxies in large quantities. The redshift, interpreted as the speed of the expansion of the Universe, is proportional to the distance of the galaxy from the observer. Combined with the apparent position on the sky, it is now possible to derive a three-dimensional distribution of galaxies in space.

The results of recent studies of the three-dimensional galaxy distribution are surprising. The vast majority (80-90 %) of galaxies are concentrated towards strings of galaxies, groups and clusters of galaxies [2-6]. Neighbouring strings form a connected network which conventionally can be called superclusters [3]. Superclusters fill only a small fraction of the total space (less than 10 %), the remaining space between strings and superclusters contains almost no luminous matter [3, 6]. The diameter of voids between superclusters reaches 100 h^{-1} Mpc, where h is the Hubble constant in units of 100 km s^{-1} Mpc^{-1} [3, 7], and such voids make up more than 90 % of the total volume of the Universe.

This picture, particularly the presence of giant voids, differs completely from earlier expectations. It is not surprising that these observations raise two questions. First, is it necessary to revise the fundamental cosmology, the Friedman-Lemaitre model of the Universe? And the second question is, what does the observed structure tell us about the formation of galaxies?

Observed random velocities of groups and clusters perpendicular to the neighbouring string network are very small, of the order of < 100 km s^{-1} [6]. During the whole Hubble time a galaxy with such a small velocity could travel a distance, less than 1 Mpc. Thus the presently available structure should reflect the history of its formation and evolution. Superclusters as a whole may have larger random velocities [1, 8, 9], however this will not alter the conclusion that the structure of the Universe changes very slowly.

2. IS THE OBSERVED STRUCTURE COMPATIBLE WITH THE FRIEDMAN-LEMAITRE MODEL?

Voids having a volume of about one million cubic Megaparsec seem to be very large. The comparison of large voids found so far indicates that this is just the characteristic volume of voids between superclusters [3, 7], smaller voids seem to be subunits inside the big ones.

In an expanding Universe the diameter of voids expressed in redshift units remains constant (in the case of a non-decelerating Universe), thus we can adopt as a first approximation $\Delta z = 0.03$. Let us assume that the cellular structure was formed at $z = 3-10$, as indicated by a comparison of densities in various structural elements and by the cut-off of quasar redshifts at $z = 3.5$ [3, 10]. If this is the case, then within the horizon our Universe should contain $10^6 - 10^7$ cells.

Presently there is little or no evidence for the presence of still larger structural units in the Universe. Cell dimensions in comparison with the Universe as a whole are still small, thus we see at present no need for a revision of the fundamental principles of cosmology. Confidence in the classical model is further strengthened by the fact that the observed structure can be reproduced using a numerical simulation based on the Friedman-Lemaitre model, as well as by small temperature fluctuations of the microwave radiation.

3. TWO SCENARIOS OF GALAXY FORMATION

At the present time it is difficult to infer the type, spectrum and amplitude of initial perturbations from general physical principles.So theorists consider all possibilities. The most developed scenarios of the formation of the large-scale structure are based on two different assumptions about the character of perturbations in the pre-decoupling era.

According to one of the scenarios at an early stage both matter and radiation density were perturbed. These perturbations are called adiabatic because the entropy distribution (the ratio of baryons to photons) was uniform ([11] and references herein).

In the other case it is supposed that the matter density was perturbed but the radiation density was not. These perturbations are known as isothermal ones since in this case temperature was the same everywhere [12, 13].

The principal difference between these two scenarios lies in the scale of post-decoupling perturbations.

Adiabatic fluctuations on scales smaller than a characteristic mass 10^{13}-10^{15} $M_\odot$ were damped due to photon viscosity [14]. After decoupling one finds no fluctuations on scales smaller than this limit. Perturbations of the scale 10^{13}-10^{15} $M_\odot$ had the largest amplitude, thus under- and overdensities of this scale developed first. This theory suggests that large-scale structures, giant voids and protosuperclusters were the first objects to form, while the Universe was still in the gaseous phase. According to this scenario, galaxies and clusters of galaxies formed in dense regions after the gas collapsed and cooled. The formation started at a relatively late epoch, $z = 3$-10.

According to the isothermal scenario, small-scale density fluctuations were not damped. As a consequence, the mass of the first objects to be formed was determined by the respective Jeans mass after decoupling, 10^5-10^6 $M_\odot$. Thus globular cluster sized objects were the first primordial building units formed soon after decoupling, $z \sim 10^3$. During the subsequent evolution gravitation was the principal driving force. Larger building blocks, galaxies and clusters of galaxies, were built up step by step by gravitational clustering.

Numerical simulations have been carried out in the framework of both scenarios. Surprisingly enough, simulations based on completely different assumptions show similarity of essential feature [15-17]. The principal structural elements, such as rich clusters and huge voids, do form in all simulations. There are differences in details, but they are not large and much work is to be done before we understand them quantitatively.

4. THE STRUCTURE OF THE UNIVERSE AND THE CATASTROPHE THEORY

The present-day structure of the Universe had to develop from initial post-decoupling perturbations. Initial perturbations had a velocity field either from the very beginning or this field would develop during the subsequent evolution. The evolution of a velocity field had one important consequence. As the velocity field developed into nonlinear stage, singularities were built up by the concentration of matter into surfaces, lines and points of intersection of particle trajectories (caustics). Singularities of this kind are studied in a mathematical theory known as the catastrophe theory [18, 19].

Different types of fields have different kinds of singularities. As it was demonstrated by Lifshitz [20], perturbations of a potential type (rot $\vec{v} \equiv 0$) grow with time, so we shall consider only the evolution of perturbations of this type. The evolution of singularities of this type of fields has been recently studied by Arnold and coauthors [21]. It has been found that pancake-like singularities known in the catastrophe theory as lips formed first as suggested earlier by Zeldovich [22]. At a later epoch pancakes intersected and formed a fairly regular cellular structure. Matter continued to flow toward the pancakes and their intersection lines, thus the density of singular surfaces, lines and points (intersection of several pancakes in cell corners) was steadily growing. All this happened during the gaseous phase of the evolution of the Universe. This phase ended with a continuous network of high density gaseous sheets, strings and knots. Dense gas regions were excellent places for star formation, and it is natural to expect that star and galaxy formation started here.

5. OBSERVABLE DIFFERENCES EXPECTED IN DIFFERENT FORMATION SCENARIOS

Let us first consider the isothermal scenario. As we noted earlier, in this case dominant post-decoupling perturbations had a scale corresponding to a mass of 10^6 $M_\odot$. Cluster-like objects formed very quickly after decoupling and most of the primordial gas went into stars at an early stage [23]. Large-scale structures, such as superclusters and large voids, were due to large-scale perturbations, which needed much more time to develop. Galaxies should have a tendency towards clustering, but could be found everywhere between clusters and strings. Strings should be shorter and not connected with other structural elements, voids should have moderate sizes.

All these expectations have been confirmed by respective numerical simulations [15, 16].

Let us now consider the adiabatic scenario. As already pointed out, in this case small-scale perturbations were damped. As a consequence the Universe evolved much more slowly and was gaseous for a long time. Accordingly cellular structure and voids had a larger scale and formed later. In contrast to the isothermal scenario, large-scale structural building blocks (clusters and groups of galaxies) formed along the initially continuous pre-existing network of strings and knots. The density of gas between the strings was small and its temperature was high. Thus no galaxies should have been formed outside the strings and knots [24]. Some gas (and dark matter) is still in "empty" areas, because it is difficult to evacuate these large regions completely [3], but this gas should have had primordial abundance. In this case the further evolution of the cellular structure was due to gravitational clustering and Hubble expansion. Numerical simulations [17] have demonstrated that after some time the cellular structure would be destroyed and clumps of still larger masses than superclusters would be formed, as is the case also in the isothermal scenario. The speed of this evolution and, consequently, the duration of the cellular phase depend on several factors: the epoch of the formation of the cellular structure, the density parameter, etc. During the cellular phase the string network should be maintained. Due to expansion, originally continuous strings should be broken into pieces. These pieces must point to each other, in other words, they should lie along the same line as a dashed curve. Rich clusters of galaxies should be centres of several strings, since they were formed in cell corners.

It is well known that most of the mass in the Universe is in some hidden form [25]. If this dark matter is made of heavy neutrinos then the scenario of galaxy formation will be similar to the adiabatic one [26-28]. Possible role of supernova explosions to the formation of large-scale structure was studied by Ostriker and Cowie [29].

To summarize, the expected differences are of two types:

(1) the composition of the gas outside superclusters, and (2) the fine structure of superclusters and "empty" areas.

Gas layers in cell walls can be studied using absorption line spectra of distant quasars as suggested by Oort [30]. Here not only the presence of gas but also its chemical composition is important.

Geometrical properties of alignment of galaxies and clusters of galaxies can be best studied in our vicinity. Very accurate redshifts are needed, but modern 21-cm and optical observations supply data of sufficient accuracy. Here three problems still make a straightforward interpretation of observations difficult: (1) dynamical velocities of galaxies in clusters and in groups, (2) the real gravitational redistribution of galaxies, and (3) dynamical velocities of clusters as a whole [9].

We also note the importance of studying "empty" areas. So far the attention of astronomers has been concentrated on rich clusters and other prominent features. The study of empty areas needs coverage of large areas in the sky up to a fairly faint apparent magnitude, thus demanding much observing time. But the basic differences between different formation scenarios are expected to be just here.

Several authors [3, 6, 31] have already used geometrical arguments to give support to the adiabatic scenario. The opponents have noted, especially in private discussions, that the arguments are qualitative and descriptive. We agree with this criticism. The tests should be impersonal and quantitative. So far no convincing tests have been suggested.

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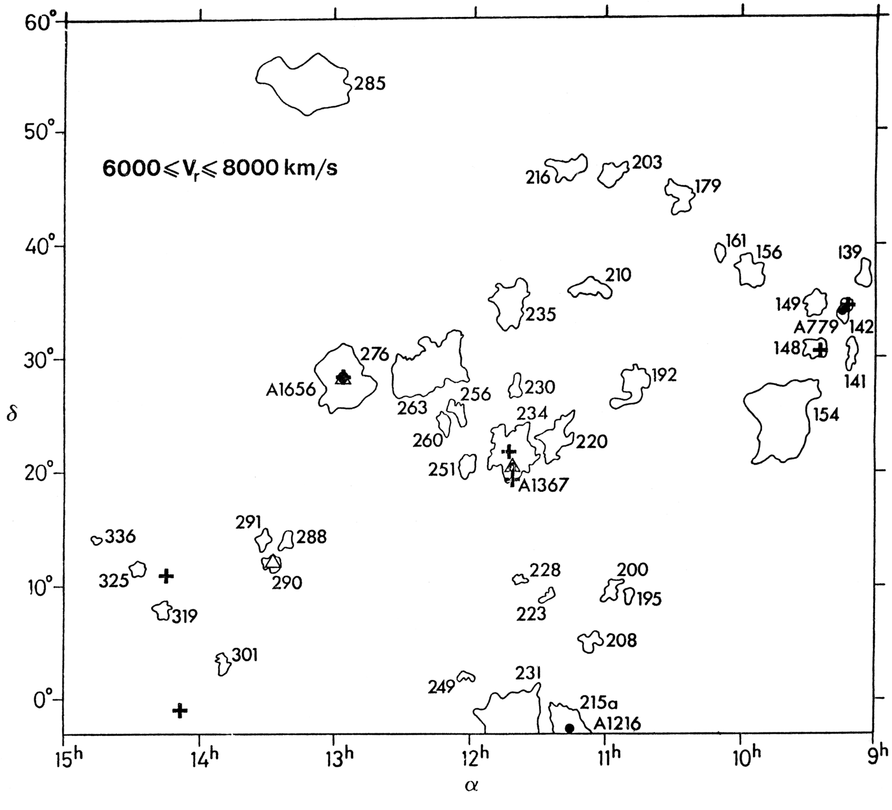
FIGURE CAPTIONS

Fig. 1. Distribution of Zwicky [32] clusters of galaxies near the Galactic North Pole: (a) between distances 60-80 Mpc, (b) 80-110 Mpc, and (c) 110-150 Mpc for Hubble constant H = 100 km $s^{-1}Mpc^{-1}$ [33]. Clusters have been numbered according to Uppsala Catalogue of Galaxies [34], rich clusters are denoted by filled circles, respective Abell Catalogue [35] numbers are also given. Crosses indicate radio galaxies, triangles extended X-ray sources.

These figures demonstrate that most clusters of galaxies form chains. At different distances the chains are located at different places. Clusters 234 (A 1367), 251, 256, 260 and 276 (A 1656) form the main chain of the Coma supercluster. A number of other superclusters is also seen. Big empty areas are clearly visible.

Fig. 2. Plots of galaxies in YZ-plane in thin X sheets [36], Z-axis is directed toward the supergalactic pole, Y-axis approximately to the Coma cluster, our Galaxy lies at the centre. Galaxies of different absolute magnitudes have been plotted by following symbols: (¤) brighter than -21.0, (Δ) $-21.0 \leq M_B < -19.5$, (X) $-19.5 \leq M_B < -18.0$. (+) $M_B \geq -18.0$.

Figures show a network of galaxy strings. Near the supergalactic plane (the plane of the Local Supercluster, Z = 0) strings are closely located. Between the Local Supercluster (X = 0, Y = 10, Z = 0) and the Coma supercluster (X = 0, Y = 67, Z = 10) a continuous network of strings is located. Diameters of empty areas far from the supergalactic plane are larger than near rich clusters, the density of galaxies is smaller. Here only bright galaxies have been observed so far which makes the identification of strings difficult (note that strings between Virgo and Coma clusters contain basically only dwarf galaxies).



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216
203
179
161
156
139
210
235
149
A779
142
148
141
276
A1656
263
256
230
192
154
234
260
220
251
A1367
291
336
288
325
290
319
228
200
223
195
208
301
249
231
215a
A1216
60°
50°
40°
30°
20°
10°
0°
δ
15h
14h
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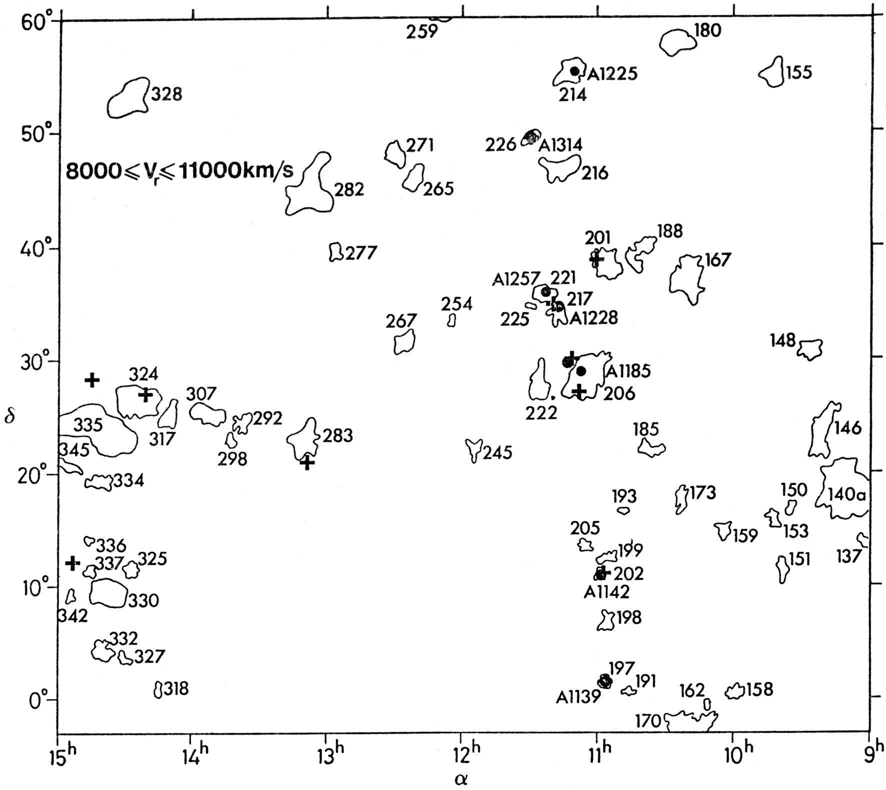
10h
9h
α

Fig. 1a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60°
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40°
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δ
15h
14h
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10h
9h
α
259
180
A1225
214
155
328
226
A1314
271
216
282
265
201
188
277
167
A1257
221
217
254
225
A1228
267
148
324
A1185
206
307
222
335
292
317
185
146
283
345
298
245
334
193
173
150
140a
205
153
159
336
199
337
325
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A1139
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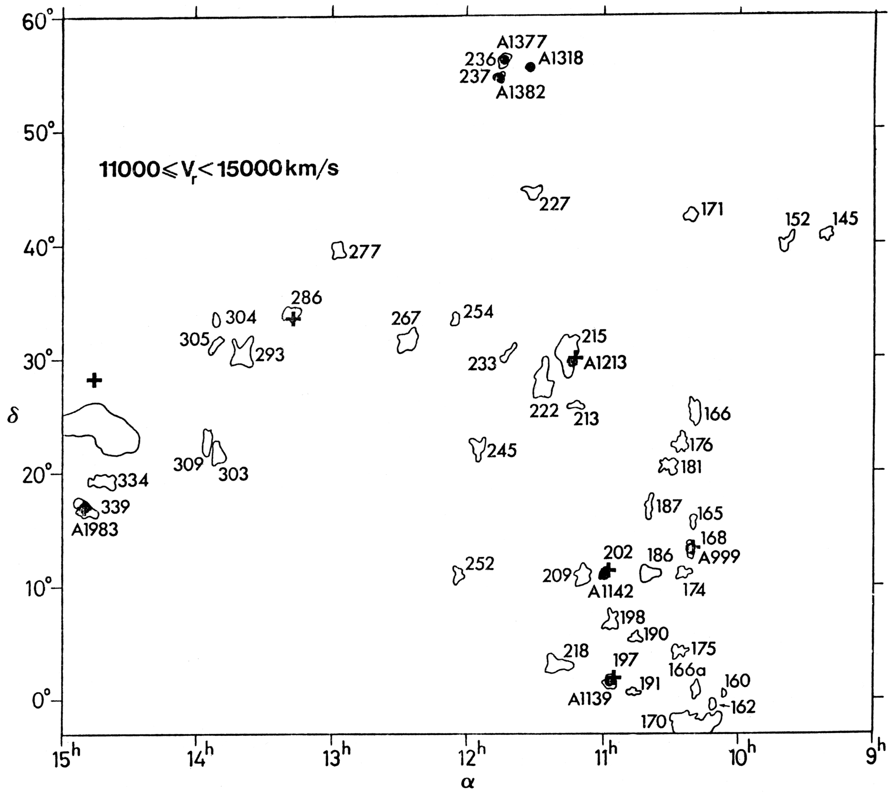
170

Fig. 1b



60°
50°
40°
30°
20°
10°
0°
δ
15h
14h
13h
12h
11h
10h
9h
α
11000⩽V_r<15000 km/s
A1377
236
A1318
237
A1382
227
171
152
145
277
286
304
305
293
267
254
233
215
A1213
222
213
166
245
176
181
309
303
334
339
A1983
187
165
168
A999
202
186
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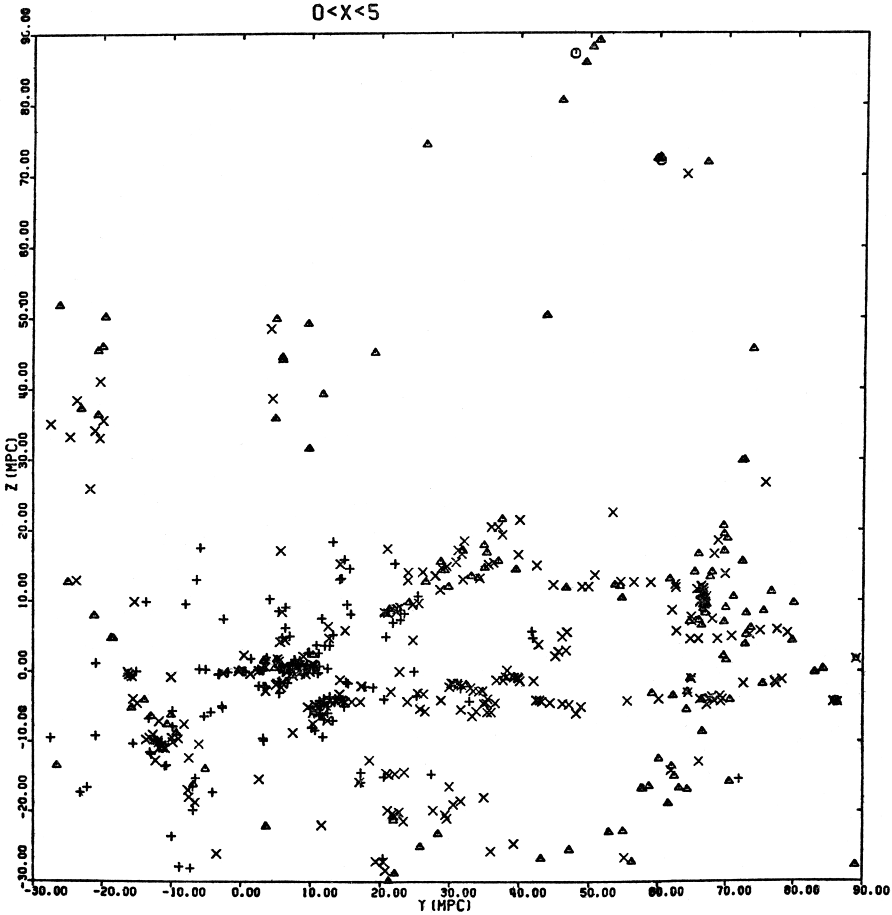
197
166a
160
191
A1139
162
170

Fig. 1c



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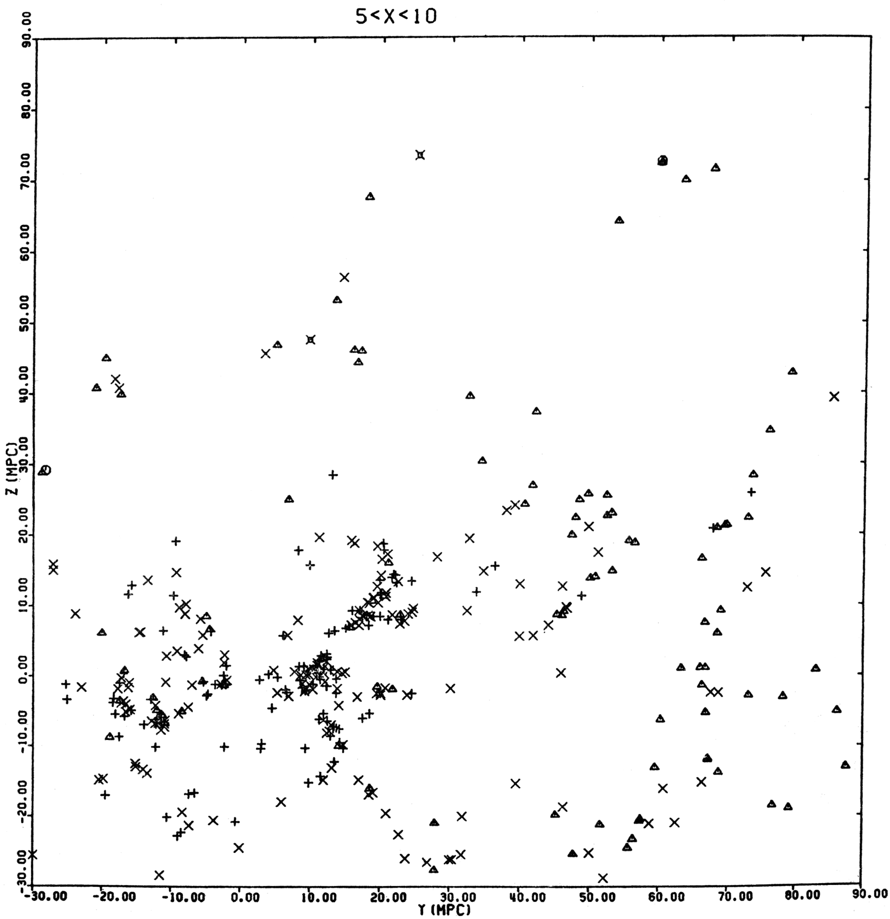
80.00
90.00

Fig. 2a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0.00
-10.00
-20.00
-30.00
-30.00
-20.00
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Fig. 2b

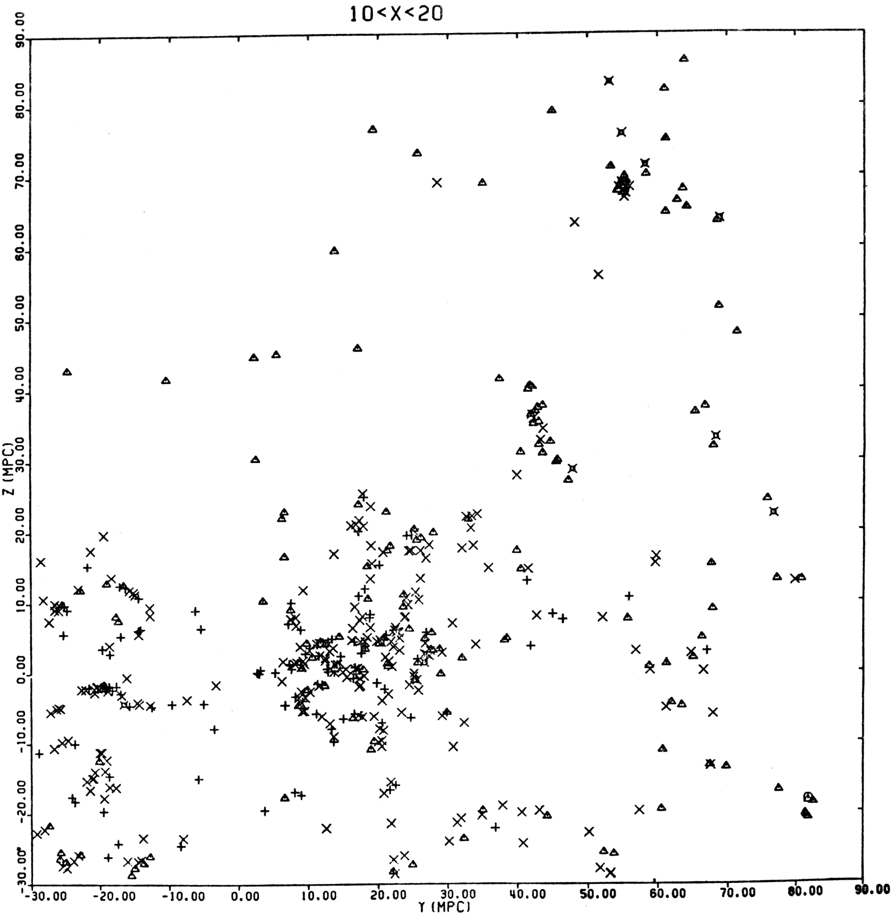
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Fig. 2c

УДК 523, 855

Огромные пустоты во Вселенной: рассказ "очевидца" об образовании галактик.

Я. Б. Зельдович, Я. Эйнасто и С. Ф. Шандарин

Рассматриваются основные наблюдательные данные о структуре Вселенной: наличие больших каверн, где отсутствуют скопления галактик и число галактик очень мало, а также сверхскоплений, состоящих из взаимосвязанной системы цепочек галактик и скоплений галактик. Описываются энтропийная и адиабатическая теория образования галактик и теория катастроф в применении к образованию структуры Вселенной. Рассматриваются ожидаемые различия в структуре согласно двум теориям и возможные наблюдательные тесты.