THE THEORY OF LARGE-SCALE STRUCTURE OF THE UNIVERSE: LOCAL PROPERTIES AND GLOBAL TOPOLOGY

A.G. Doroshkevich, S.F. Shandarin, Ya.B. Zeldovich
Keldysh Institute of Applied Mathematics
USSR Academy of Sciences, Moscow 125047, USSR

ABSTRACT

Properties of the large-scale distribution of galaxies are considered. Particular attention is paid to properties of the large-scale structures such as anisotropy of superclusters and the existence of large regions practically devoid of galaxies. Another question discussed in detail is the link between superclusters and formation of a network or cellular structure. An explanation of the latter is proposed in the frame of the fragmentation scenario. The role of the neutrino rest mass is discussed.

1. INTRODUCTION

The theory that will be considered here is based on the big bang model and the idea that physical processes before decoupling leave us with small amplitude longwave perturbations in cold gravitating matter. These conditions are fulfilled in the flat universe because of photon viscosity. Later, arguments concerning the small MBR temperature fluctuations and the matter density appearing to be much less than the critical value are shown to reveal a quantitative discrepancy, leading to the idea of a neutrino-dominated universe.

In this case the wavelength of surviving perturbations is determined by the neutrino travel distance, which is limited because the neutrinos are no longer relativistic at a temperature before decoupling.

Luckily, the two scenarios (baryon- or neutrino-dominated Universe), very different physical ideas, are leading to very similar structural properties. Many ideas worked out in 1970-1978 in the frame of baryon dominance remain valid for the neutrino model. Of course, the exact value of the neutrino mass and even its nature remain to be confirmed by particle physicists.

We will discuss only the rather late epoch, ($z < 10$), when density perturbations become nonlinear, $\delta\rho/\rho \sim 1$ and the structure acquires features, many of which exist at present. The long previous evolution of small perturbations guarantees that only growing modes existed. Therefore, perturbations must be random and smooth and of potential type (rot $v = 0$).

G. O. Abell and G. Chincarini (eds.), Early Evolution of the Universe and Its Present Structure, 387–391.

https://doi.org/10.1017/S0074180900039413 Published online by Cambridge University Press

2. OBSERVATIONS

Observational data about the large-scale structures are discussed in detail by many others and are well summarized by Oort (see this volume). Perhaps the most striking features of the large-scale galaxy distribution are the following: Most galaxies belong to superclusters; superclusters occupy only about 10% of the volume; the other space is practically devoid of galaxies; superclusters are highly asymmetric unrelaxed structures; superclusters are not isolated from each other but probably form a network of cellular structure. Typical sizes of the structure reach 100 Mpc or even more. The two-point correlation function for galaxies is much less than 1 on these scales (Peebles 1980).

3. SCENARIO FOR STRUCTURE FORMATION

In the scenario under consideration, perturbations were small for a long time after decoupling. The smallest perturbed scale was about $M_C \simeq (10^{14} - 10^{15})\ M_\odot$, which is much greater than Jeans mass M_J ($M_C >> M_J$) of neutral gas and/or cold neutrinos. This means that gas pressure is unimportant for evolution of the perturbations prior to formation of the first objects. Zeldovich (1970) has argued that the beginning of collapse in a medium with low pressure is one-dimensional. This results in the formation of so-called pancakes with masses of about $M_C \simeq (10^{14} - 10^{15})\ M_\odot$.

The pancakes are bounded by the shock waves (gas component), the multistream regions with high neutrino density. Once formed, the pancakes remain gravitationally bound.

Later, it became clear that pancakes are the large-scale objects formed first but they are not the only ones. Catastrophe theory provides a full list of all structures of the generic types (Arnold, Shandarin, Zeldovich 1982) forming at the nonlinear stage. There are two-dimensional (pancakes), one-dimensional (filaments or strings) and zero-dimensional (clusters) structures in the list. Structures of the generic types are those elements from which the large-scale structure is built. They are extremely anisotropic, so in this scenario anisotropy of superclusters is explained quite naturally.

Numerical simulations of the structure formation in this scenario were done in two-dimensional (Doroshkevich *et al*. 1980) and three-dimensional cases (Klypin and Shandarin 1981). They have known that at some stage soon after pancake formation regions of large density form a single network structure.

Galaxies are formed inside pancakes and higher order singularities in a rather complicated process. Gas heated by shock waves first cools to ~ 10^4 K (Sunyaev, Zeldovich 1972); thereafter, it fragments (Doroshkevich, Shandarin, Saar 1978). The rarefied gas outside pancakes is heated and ionized by pancake radiation. Probably no galaxies are formed in this gas, which would explain the voids (Zeldovich, Shandarin 1982).

4. GLOBAL TOPOLOGY OF THE STRUCTURE

Let us consider this question in detail. Recently, many observers (see this volume) pointed out that many superclusters link each other in a single network structure; however, the lack of quantitative technique to study this problem makes it difficult to establish this objectively. The widespread, two-point correlation analysis gives much interesting information about the galaxy distribution (Peebles 1980); however, it gives little help in answering the question concerning pattern recognition. The question about the global topology of the structure was raised by Zeldovich (1982). If superclusters really occupy only about 10% of the total volume and the majority of galaxies belong to them, it is surprising that superclusters form a connected system.

To explain it, let us consider an epoch prior to pancake formation. At this stage perturbations are small and one easily can find that there are four types of fluid element behavior: i) contracting along all three directions; ii) contracting along two directions but expanding along the third one; iii) contracting along only one direction; and iv) expanding in all three directions. Here contraction or expansion mean peculiar motion in comoving coordinates with the mean Hubble flow; i.e., it is superimposed on the general expansion. To form a pancake, it is enough to contract along only one direction and as was shown by Doroshkevich (1970) about 92% of the matter contracts along at least one direction. At the stage of small perturbations, this matter forms one connected region because it occupies also about 92% of the volume.

The eight percent of the "to be rarefied gas" is occupying disconnected islands in the sea of "to be compressed gas." These islands, devoid of galaxies, remain disconnected when their volume has increased to more than 50%, just due to their expansion. Topology is preserved. It is a cell structure if galaxy formation is strong enough after one-dimensional compression; it is a net if higher order singularities are needed. In all cases the cell and/or net structure remains gravitationally unstable, it is an intermediate asymptote, which will be disrupted after a time of the order of (several) ages of the Universe.

Recently, Shandarin (1982) proposed a new quantitative method to recognize the patterns in observations. The method is based on ideas of percolation theory (see, for example, B.I. Shklovski, Efros, 1979) and is particularly sensitive in distinguishing between network or cellular structure on the one hand and isolated clumps of galaxies on the other. It can be used for both two- and three-dimensional distributions.

Cut out in space a cube with size L, containing N galaxies within it. Draw a sphere of radius r around each galaxy. If there is another galaxy within the sphere, we shall call the two galaxies connected. All connected galaxies form a cluster. The number and sizes of clusters depend on the radius r. At small r, clusters are numerous but small; at large r, the number of clusters decreases and sizes grow. There is a critical radius r_c when a cluster is linking the opposite sides of the cube. In terms of percolation theory, percolation arises. The condition of percolation is usually expressed in terms of a dimensionless parameter $B = 4/3\ \pi\ N(r_c/L)^3$, which is a mean number of galaxies within a sphere of percolation radius r. If galaxies were distributed independently with a Poisson distribution, percolation would arise at $B_{Poisson} \simeq 2.7$ (Kurkijarvi 1974; Pike and Seager 1974; Skal and B.I. Shklovski 1973). It is clear that if the galaxy distribution tends towards a network, percolation would arise along the network more easily.

https://doi.org/10.1017/S0074180900039413 Published online by Cambridge University Press

than in the Poisson case: $B_{network} < B_{Poisson}$. In the opposite case, if galaxies are concentrated towards isolated clumps, percolation would be impeded between clumps: $B_{clumps} > B_{Poisson}$.

Below we give the first estimates of percolation parameters for four different distributions. For details see Shandarin (1982) and Einasto et al. (this volume). The first distribution (A) is a real distribution of galaxies within a cube with size 80 Mpc (H=50), taken from the Huchra sample. Three others are model distributions. One of them (B) is taken from the Klypin and Shandarin (1981) three-dimensional numerical simulation in the adiabatic scenario; the second (C), is a realization of Poisson distribution; and the third (D) is hierarchical distribution constructed in accord with the prescription by Soneira and Peebles (1978).

	Type of Distribution	Number of Objects	Percolation Parameter
A	Galaxies (observational sample)	866	0.8
B	Adiabatic model	753	0.7
C	Poisson	850	3
D	Hierarchical model	819	7

These values definitely show that in both observational and adiabatic samples there are filamentary structure. The hierarchical sample, where isolated clumps dominate, gives a value of B far from that observed. This analysis, in its present form, disproves clumps but was not discriminate between cellular or network structure. However, in principle, this method can distinguish between these two possibilities if one will also study percolation problems in "empty" regions. Summarizing, the observations favor the adiabatic scenario. The new ideas of Ostriker and Cowie about the role of explosions remain to be analyzed.

REFERENCES

Arnold, V.I., Shandarin, S.F., Zeldovich, Ya.B. 1982, Geophys. Astrophys. Fluid Dynamics, 20, 111.

Doroshkevich, A.G. 1970, Astrofisica, 6, 581.

Doroshkevich, A.G., Shandarin, S.F., Saar, E. 1978, M.N.R.A.S., 184, 643.

Doroshkevich, A.G., Kotok, E.V., Novikov, I.D., Polyudov, A.N., Shandarin, S.F., Sigov, Yu.S. 1980, M.N.R.A.S., 192, 321.

Klypin, A.A., Shandarin, S.F. 1981, Pr-t No. 136, In-t Appl. Math. Acad. of Sciences USSR.

Kurkijarvi, J. 1974, Phys. Rev., B9, 770.

Peebles, P.J.E. 1980, The Large-Scale Structure of the Universe, Princeton University Press.

Pike, G.E., Seager, C.H. 1974, Phys. Rev., B10, 1421.

Shandarin, S.F. 1982, Pis'ma v Astron. Zh.

Shklovski, B.I., Efros, A.L. 1979, Electronic Properties of the Alloyed Semiconductors, Moscow.

https://doi.org/10.1017/S0074180900039413 Published online by Cambridge University Press

Skal, A.S., Shklovski, B.I. 1973, FTP, 7, 1589.
Soneira, R.M., Peebles, P.J.E. 1978, Astron. J., 83, 845.
Sunyaev, R.A., Zeldovich, Ya.B. 1972, Astron. Astrophys., 20, 189.
Zeldovich, Ya.B. 1970, Astron. Astrophys., 5, 84.
Zeldovich, Ya.B. 1982, Pis'ma v Astron. Zh., 8, 195.
Zeldovich, Ya.B., Shandarin, S.F. 1982, Pis'ma v Astron. Zh., 8, 131.

Discussion

Thompson: For your three-dimensional simulation which produced a filamentary structure, what did you assume for the model's initials conditions?

Shandarin: In our simulations we started from random but smooth (on short scales) perturbations of a potential type. These initial conditions are typical for the adiabatic or fragmentation scenario of structure formation.

Bonometto: How many points were used in your simulation and which numerical technique did you use?

Shandarin: We used a fast Fourier technique with a total number of particles of $32^3 \approx 3.277 \times 10^4$. The number of cells was the same.

B. Jones: The Lick catalogue is two-dimensional; whereas, the numerical simulations of both the pancake theory and isothermal theory are three-dimensional. Is it possible to use the percolation coefficients to compare these or is it essential to have a three-dimensional picture of our universe such as is provided by the redshift surveys?

Shandarin: Yes, it is possible. However, in the two-dimensional case, a critical value of the percolation parameter, B_c, is different. $B_c^{(2)} \approx 4.1$, but $B_c^{(3)} \approx 2.7$.

https://doi.org/10.1017/S0074180900039413 Published online by Cambridge University Press