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THE LARGE-SCALE STRUCTURE OF THE UNIVERSE: MORE QUESTIONS THAN ANSWERS

Modern observations reveal an inhomogeneous distribution of matter. The large-scale structure of the Universe implies a distribution pattern of matter in space at the largest observable distances. In the latter half of the 20th century galactic clusters and superclusters – the largest type of galactic associations that contains thousands of galaxies were found as well as voids - areas almost without luminous matter. The suggestion that such hierarchy extends to arbitrary many levels further proved to be wrong. By the end of the past century the clusters of various shape from 'chains' to 'filaments' had been discovered. The filaments and voids can form extended relatively flat local structures, called the 'walls'. The first such observed object is the Great Wall CfA2 of about 500 million light-years across and only 15 million light-years thick. The latest discoveries are the Huge Large Quasar Group (November 2012) and the Hercules – Corona Borealis Great Wall (November 2013). In 1990s it was found that at distances of about 300 megaparsecs the Universe is closely homogeneous and represents an aggregate of filamentary clusters of galaxies, which are separated by voids of about hundreds of parsecs across. This paper discusses the problems of revealing, describing and studying such structures.

Keywords: galaxies, superclusters, walls, voids, large-scale structure.

1. Introduction

The large-scale structure of the Universe is a structure formed by giant stellar islands – galaxies and supergalaxies - at various spatial scales. Modern concepts of the large-scale structure are based both on study of single systems of galaxies and on statistical analysis of spatial distribution of galaxies located at different distances. The mere existence of such structure marks inhomogeneous nature of distribution of matter in the Universe up to the scales of hundreds of millions of light-years. The study of this structure is necessary for understanding of formation processes of galaxies and galactic clusters in the expanding Universe and their further evolution. Even sketchy knowledge of astronomical objects and their celestial and spatial attitude reveals that cosmic bodies are parts of systems of different sizes.

For the first time the eminent astronomer W. Herschel had considered an idea of the large-scale structure of the Universe. It was him who made such discoveries as detection of Uranus planet and its two moons, two moons of Saturn, revelation of infrared radiation and assumption concerning motion of Solar System through the space. Herschel built his own large telescope and made observations, and then he performed extensive estimation of celestial bodies of different brightness in certain regions of the sky and concluded that there are a lot of stellar islands in the space.

Later, in the early 20th century American cosmologist E. Hubble succeeded in proving that some nebulae are of structures differing from the Milky Way. So, it was reliably known that there are also various anagalactic star clusters. Soon research in that direction extended considerably our knowledge of the Universe. It turned out that along with the Milky Way there are dozens of thousands of other galaxies in the space. In an attempt to obtain a simplified map of the observable Universe scientists came across a remarkable thing that galaxies are unevenly distributed in the space and arranged into other structures of fabulous size.

2. Basic elements of observed space structures

All observed stars in the sky form a vast system – a galaxy. But what is its shape? Does it spread into infinity and how does Sun enter into it? English astronomer W. Herschel which came to be seen as author of many fundamental discoveries first attempted to find the answer to the question in the 18th century. To study the structure of stellar world, he proposed an original method (stellar statistics method) based on rigorous estimation of stars of different brightness in chosen regions of the sky and applied it with the use of the telescopes built with his own hand. Herschel came to the conclusion that our stellar world is spatially limited and made rough estimate of its size.

Indeed, galaxies proved to be basic 'brick elements' of the Universe, containing the most part of all the stars existing in nature, as well as large masses of interstellar gas. Modern large telescopes make it potentially available to observe many hundreds of millions of galaxies scattered all over the sky and located within 10-12 billion light-years away. The fact that galaxies, along with stars, are inhomogeneously distributed in the sky became clear even before their physical nature was ascertained. By means of the large telescopes it is possible to distinguish thousands of galactic clusters at different distances.

The structures formed of galaxies and supergalaxies are called the large-scale structures. The question of their existence and their properties is closely related to the fundamental scientific problem of the origin and evolution of the observable Universe.

The methods of observing were improved, the telescope sizes increased, as well as the size of the explored part of the Universe. In the early 20th century E. Hubble rigorously proved [1] the extragalactic nature of some nebulous formations. They turned out to be the huge stellar systems situated far beyond our Galaxy. Soon other galaxies were also discovered and the question of their spatial distribution arose.

Galaxies are combined into the clusters of about 4 Mpc in size. So, within the scales of millions of light-years galaxies are distributed inhomogeneously. For a while it was considered that structures at smaller scales always are a part of the larger formation and so on up to the infinitely large scales. Later, in the latter half of 20th century it has been found that it is wrong.

The average distance between the clusters is of 30 Mpc. Any cube with a side of 300 Mpc (as much as 10 billion light-years!) contains approximately 1,000 clusters. At these scales matter is already distributed homogeneously. But along with galactic clusters there are also larger irregularities 50-100 Mpc in size formed a large-scale structure of the Universe. Interestingly enough, the necessity for formation of such structures was predicted theoretically.

3. The most large-scale structures of the Universe

After discovery of the cosmic microwave background radiation in 1965 the theoretical attack on the riddles of the birth and evolution of the Universe began. One of the main issues is the way of formation of galaxies and their clusters from the initially almost homogeneous distribution of matter. Formation of these inhomogeneities requires for the initial compactions of matter, but they must be very small or temperature non-uniformities of relict radiation (discovered only in 1992, because until then their infinitesimal values were out of reach for observations) might be detectable.

On a theory developed by Ya. B. Zeldovich and his colleagues, just after recombination when in primary ionized matter of early Universe ions were combined with electrons, forming neutral atoms, from this neutral substance the inhomogeneities of the mass of about 10^{15} solar masses precipitate and begin to collapse. Moreover, this collapse is asymmetric. In addition, the flat objects (called the ‘pancakes’ because of shape) are formed. The substance of pancakes, while cooling down, will fragment into smaller clumps. Thus, galaxies are formed, and then – the stars. Pancakes are arranged randomly in the space, so the cell structure is formed with a cell size of about 50-100 Mpc and a wall thickness of 3-4 Mpc. In the cell nodes the large galactic clusters are located. The intersections of pancakes form the superclusters in the shape of filaments. Formation of pancakes and galaxies dates to epoch corresponding to redshift $z=4\div10$, or approximately 13 billion years ago. All these formations were discovered in the 80s as a result of the study of the spatial distribution of galaxies.

When the existence of galactic clusters was found out, the question arose, whether they form, in turn, more large-scale systems. And whether such hierarchy structural properties extend up to the infinity when any system is a part of another, and that one is a part of even larger system and so on? Science answers positively the first question and replies negatively to the second.

The ‘supercluster of galaxies’ term as applied to a system combining up to several dozens of single galactic clusters firmly came into general use. Now more than two hundred superclusters consisting of two and more single galactic clusters are detached.

The whole new level in the study of the large-scale structure was reached when obtaining redshift survey data for galaxies. It makes possible (for chosen region of the sky) 3d-mapping of space distribution of galaxies covering the distances of more than a billion light-years.

The distribution analysis of galaxies and their velocities led to the conclusion that superclusters cannot be considered as the same coupled systems, as the clusters, only a larger scale. As it turned out, superclusters are not the isolated ‘islands’ of the clusters or single galaxies, but simply the most dense areas of the complex, cellular or filamentary structure formed from galaxies and their systems in the space.

The question, whether the Universe is a cellular structure, was first raised in the 1970s by J. Einasto and his colleagues (Tartu Observatory, USSR). It proved to be that the most large-scale structure of the Universe really represents cells of different sizes made up from galaxies and supergalaxies. Galaxies and galactic clusters are concentrated to a kind of curved ‘walls’ of about 10 million light-years thick, cutting each other. Some of the ‘wall’ can be traced for hundreds of millions of light-years. Where the walls ‘merges’, there are especially a lot of galaxies (superclusters). These regions of enhanced concentration of galaxies form in the space a sort of long fibers (‘chains’ or ‘filaments’ [2]). Inside the cells between the walls there are ‘voids’, in which the density of galaxies at least ten times less than the average. Some kind of analogue of such a structure can be foam of soap bubbles. However, the distribution of galaxies along the cell ‘wall’, contrary to the distribution of soap solution in the bubbles, is very inhomogeneous, moreover, the cells do not exhibit shape accuracy. The size of large cells is several dozens of Mpc’s (over hundreds of millions of light-years), but there are also many smaller ones.

The ‘voids’ are among the largest objects in the space and occupy the greater part of space in the Universe [3]. The main feature of these structures is that the density of visible matter in voids is considerably less than its average density in the Universe. As the main elements of the large-scale structure voids are marked off by galactic filaments [4].

The average size of voids is 40 Mpc, but in the Universe there are more large-scale cavities - supervoids, the average diameter of which is 100 Mpc [5]. The voids can reach enormous sizes, which are able to impress not only astronomers, but also persons who are far from the science. So, diameter of the AR-LP 36 giant void – one of the largest known voids - is 400 Mpc. Whilst diameter of our Milky Way galaxy is just 0.03066 Mpc.

Long-term observation of the voids using the most advanced telescopes showed that the most common components in the voids are protogalactic clouds - the huge clouds, consisting of dust and gas, from which then galaxies are formed. Besides, according to 2014 data, astronomers from the University of Pennsylvania found in voids small distortions in the direction of the propagation of light, generated, as may be supposed, by ‘dark matter’. For this purpose it was used Data Release of the Sloan Digital Sky Survey (SDSS) for 40 million galaxies and 20 thousand voids [6]. Scientists believe that this is a specific form of matter which does not have self-electromagnetic field. For lack of this field observation of dark matter using modern available scientific methods becomes very difficult. However, applying the theories of indirect, special mathematical calculations and observations, researchers found evidence that this ‘matter’ actually exists.

Scientists still have much to learn of the nature of voids, their physical properties, composition and origin. These astronomical objects of the Universe are little-studied.

The filaments and voids can form extended relatively flat local structures, called the ‘great walls’. The nearest ‘wall’ goes a long arc through the southern constellations Hydra - Centaurus - Telescopium - Pavo - Indus. The constituent galaxies have radial velocities of several thousand km/s, and most of them are at distance of at least 20-30 million light-years away. This ‘wall’ contains the Virgo cluster, as well as all the Local Supercluster, at the periphery of which the Local Group of galaxies, including our Galaxy, are located. Since we are close to the edge of this ‘wall’, its constituent galaxies form a relatively narrow band in the sky, stretched for more than 180 degrees, a kind of that the Galaxy stars are concentrated in the band of the Milky Way. However, the number of single stars in galaxies is many times larger than the single galaxies in the cell walls.

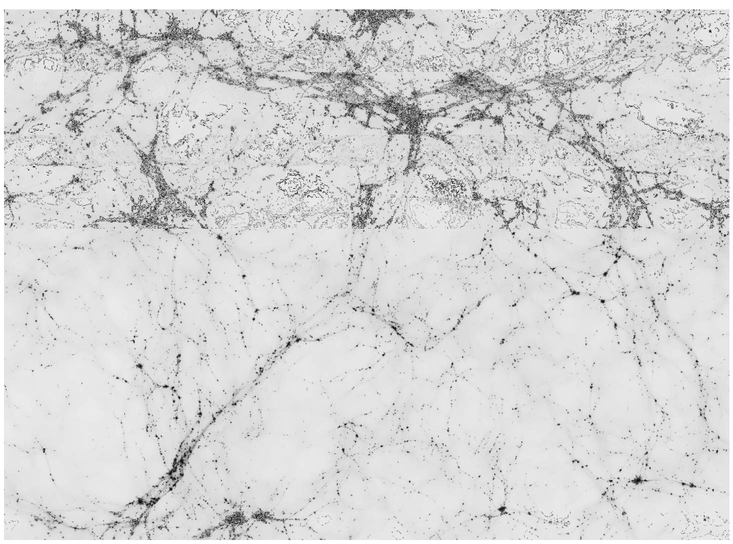

Fig. 1. Computer simulated image of a large-scale distribution of light sources (galaxies and quasars) in the Universe [7].

Another long ‘wall’, sometimes called the ‘Great Wall’ [8], which stretches a band for almost half of the sky, includes a rich well-studied cluster in Coma Berenices, located at the distance of about 300 million light-years away, in the center of other Supergalaxy.

One of the large clumps of galaxies, apparently formed from several clusters and located at the distance of about 200 million light-years away, was called the ‘Great

Attractor'. This name is due to the fact that in the 1980s scientists were able to detect and, most importantly, measure the gravitational influence of the compaction on the value of the velocities of galaxies in the surrounding space. Unfortunately, the study of 'attractor' is hindered by strong interstellar absorption.

In 2003 at the Anglo-Australian Telescope (in Australia) the program of redshift survey measuring of extragalactic objects, including very weak and distant, in certain selected regions of the sky was completed. As a result of the program the estimates of the distances for record large number (approx. 250 thousand) of single galaxies were obtained. Analysis of the distribution pattern of galaxies, carried out by these measurements in two opposite regions of the sky (near the North and South Poles of the Galaxy), revealed that the above-mentioned cellular structure can be traced to a distance of more than a billion light-years on each side, and, apparently, lengthens further out. Obviously, such is the whole structure of the Universe.

New research results say that the Universe is consists of not less than 200 billion galaxies. Analysis of 3d-model of distribution of galaxies the scientists perform suggests that the cell structure is observed at a distance of more than a billion light-years in any direction. This information suggests that at the scale of a few hundred million light-years any fragment of the Universe will have almost the same amount of substance. This proves that at these scales Universe is homogeneous. This important finding has to be considered when developing the cosmological evolution theory of the Universe.

Elements of the large-scale structure formed by galaxies continue to develop and vary nowadays. The relevant relative velocity of the motions of galaxies in multiple systems and groups is 100-200 km/s, in rich clusters - ten times as high. For hundreds of millions of years, configuration of galaxies in these systems must be changed beyond recognition, and for 1-2 billion years galaxy can travel a distance comparable to the size of the system. However, the total gravitational field of galaxies and the intergalactic medium provides the force of mutual attraction that holds galaxies, not allowing them scatter. Using the speed of galaxies within the system one can measure the mass and density of the substance that creates the wanted gravitational field. This, in turn, allows to come over from distribution of galaxies to estimates of density of matter, associated with galaxies, and conclude that the matter density distribution in space is inhomogeneous not only at small, but also at large scales. In November 2013, NASA astronomers discovered in the vastness of the space the surprisingly large structure, called the Hercules – Corona Borealis Great Wall [9,10]. It is so large that it would take at least 10 billion light-years to cross it completely from one remote side to another. The newly discovered cosmic structure of the Universe is about twice larger than the earlier record holder – the cluster, consisting of 73 quasars, discovered in November 2012. The latter astronomers called the Huge Large Quasar Group (Huge-LQG) or the Large Quasar Group [11, 12]. The range of the last record holder was of about 4 billion light-years. This is six times more than the Sloan Great Wall [13], which is 1.4 billion light-years long. Currently, astronomers say they do not have a clue as could be formed such a large group of galaxies.

4. Reasons for occurrence of the large-scale structures

An important feature that distinguishes couples, multiple systems, groups, clusters of galaxies, on the one hand, from the elements of the large-scale structure, on the other hand, is that the former are gravitationally bound entities (gravity restrains them from expanding and destruction), and the latter are not. Galaxies in superclusters within the cell walls continue to move away from each other due to the cosmological expansion of the Universe, as well they are also fulfilled the Hubble law (with minor amendments, taking into account the gravitational field of the 'walls' and single clusters). However, previously it has been suggested that the clusters is expanding gravitationally unbound systems, because the relative speed of movement of the galaxies in clusters were surprisingly large (often more than a thousand km/s). The weight of all the stars of all the galaxies in the cluster, as a rule, is not sufficient to keep the fast-moving galaxies together. The assumption that the rapid expansion of clusters might seem natural and only the great age of galaxies forced to look for other explanations. Needless to say, in the space between the galaxies there is also hot gas. In the clusters its mass is often greater than the total mass of single galaxies, but in many cases this is not enough to hold the galaxies together. There should be more weight, not emitting a light, the gravitational field of which plays a key role.

The study of the rotation of spiral galaxies, the distribution of velocities of galaxies in clusters and superclusters revealed that the greater part (perhaps up to 90%) of the total mass of the Universe is invisible and is found only by the gravitational effects on the observed objects [14]. This is so-called hidden mass of the Universe. Carriers of this mass can be weakly interacting particles with non-zero mass. The final conclusion of the presence of an invisible mass in the clusters was obtained, when it was discovered that the gravitational field of some of them reject passing through clusters light beams emitted by more distant galaxies. In the case of favorable location of galaxies beyond the cluster, their light beams bend and converge at a certain distance from the cluster as if they had passed through the glass lens of inferior quality. The gravitational field of the cluster can 'build' the image of distant galaxies. This effect is well-studied, it is called the 'gravitational lensing'. Observations have confirmed that the only galaxies, without a dark mass, cannot explain the strong gravitational field of clusters, and that the mass, causing a gravitational lens effect, is sufficient for the gravitational stability of the latter. Therefore, clusters of galaxies can be considered as the largest stable structures in nature (it is, of course, does not mean that their size or an internal structure does not change for billions of years). The dark mass nature is still under investigation, but it is already clear that this invisible environment should play an important role in the formation of the large-scale structures of the Universe. According to published in March 2013 observation data of the space observatory 'Planck' [15], interpreted in view of the standard cosmological Lambda-CDM model, the total mass-energy of the observable Universe consists of 4.9% of the ordinary (baryonic) matter, 26.8 % of dark matter and of 68.3% of dark energy. Thus, 95.1% of the Universe consists of dark matter and dark energy [16]. According to modern concepts, in the very early stages of the expansion of the Universe matter was distributed almost perfectly homogeneously. This can be seen, for example, from negligible amplitude of brightness inhomogeneities of the sky relic radiation that was emitted by usual gas at pre-galactic stage of expansion of the Universe (these heterogeneities were of thousandths of a per cent, and were discovered only in the 1990s, after many years of persistent searching. Gravity has the property to break the uniformity, to concentrate matter in single structures, to strengthen any density fluctuations. Gravitational forces gradually slowed the expansion of slight more dense areas, so initially small density inhomogeneities of matter were eventually grow rapidly, absorbing matter from more rarefied areas and become more 'contrast', continuing nevertheless to expand. So there was a large-scale cellular structure. In those areas where the density is particularly large, gravity could completely stop the expansion and change it to compress. Upon a time, these areas formed the galaxies, combined in a gravitationally bound system. Without the involvement of dark mass it would be very difficult to explain how for 13-14 billion years of expansion the subtle density inhomogeneities imprinted in the distribution of the brightness of the background radiation, proved to be able to grow so much that gave rise to the observed complicated structure formed by galaxies. The world of stars and galaxies, apparently, generally could not be occurred there, and the Universe would have remained unstructured, if the gravitational field of ordinary matter has not been strengthened by the presence of hidden mass.

5. Conclusions

This review demonstrates that the occurrence of the large-scale cellular structure from the original insignificant random perturbations of density in the expansion of the Universe confirmed by computer simulations. However, the models have several theoretical ‘scenarios’. Under certain initial conditions, admissible from physical standpoint, the numerical modeling enables to ‘play’ the process of formation of filaments and cells and single galaxies inside them. Whether such computer models are able to describe the real Universe wholly - an issue currently is under discussion. Anyway, the study of large-scale structure of the Universe proved to be a necessary link to understand how the world around us arose.

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