LARGE SCALE STRUCTURE OF THE UNIVERSE

Introduction

J. EINASTO
Tartu Observatory, EE-2444 Tõravere, Estonia

The changes of main paradigms on the structure and evolution of the Universe are reviewed. Two puzzles of the modern cosmology, the mean density of matter and the regularity of the Universe on large scales, as well as the possibility to solve these puzzles by the introduction of more complicated form of inflation, are discussed.

1 Changes of paradigms in cosmology

Until mid-70’s it was generally believed that galaxies form clusters and groups, and the remaining field galaxies are more-or-less randomly spaced in the Universe. In late-70’s and early 80’s this simple picture was radically changed. It was found that field galaxies form elongated chains or filaments, clusters also are often located along chains; they form together filamentary superclusters of galaxies. The space between such filaments is devoid of any visible galaxies. This new picture was reviewed by Zeldovich, Einasto and Shandarin and Oort.

The distribution of galaxies and clusters was confronted with theoretical predictions by Zeldovich et al. It was found that this distribution has some similarity with the distribution of particles found in the adiabatic theory of structure formation developed by Zeldovich and collaborators. According to this scenario the structure evolution is determined by the dominating dark matter population of the Universe. If this population is due to massive neutrinos as it was expected in early 80’s, then perturbations on small wavelength are damped, and the large-scale structural units, such as superclusters, will form first. Matter flows from low-density regions which have positive gravitational potential, to high-density regions forming gravitation wells, and builds up pancake-like superclusters. In low-density environment the contraction of matter to form galaxies is impossible, and the matter remains in some pre-galactic form. Superclusters and voids form a continuous network of alternating high- and low-density regions; the mean diameter of voids between rich clusters of galaxies is about 100 $h^{-1}$ Mpc.

Zeldovich et al. noticed also some problems with the neutrino dominated Universe: in such picture only very rich superclusters form and there are no systems of galaxies of intermediate richness; and, as a result, voids should be completely empty. The observed structure is more complicated: there exist intermediate sized systems of galaxies that form rarified filaments between superclusters. This failure of the neutrino-dominated Universe seems to be fatal; and it is overcomed by a new candidate for the dark matter introduced by Peebles. It is called cold since in contrast to hot neutrinos particles of cold dark matter (CDM) have much lower velocities. In CDM dominated Universe the formation of fine structure is not damped and systems of galaxies of intermediate size can form. All modern structure formation scenarios are based on cold dark matter.
2 Puzzles of modern cosmology

The golden age of the theory of CDM Universe was 80’s. Numerical simulations made within the standard CDM scenario with critical density Universe were in much better agreement with observations than simulations based on the HDM hypothesis. However, some weak points in the standard scenario were found. It gives too low power on large scales if normalised to small scales. The solution of the problem was the introduction of models with a mixture of hot and cold dark matter, or low Ω models with or without a cosmological constant. These models can be characterised by the parameter \( \Gamma = \Omega h \) which determines the position of the maximum and the power index of the spectrum on galactic scales. The standard model has \( \Omega = 1 \) and \( h = 0.5 \) which gives \( \Gamma = 0.5 \); in new models the preferred value is \( \Gamma \approx 0.25 \), hence for \( h \geq 0.6 \) it follows that \( \Omega \leq 0.4 \). Direct dynamical density estimates also support low density values. The case of a low-density Universe with a non-zero cosmological constant was recently reviewed by Ostriker and Steinhardt.

On the other hand, methods based on the study of the cosmic velocity field yield higher values for the density parameter, and the problem is still open for discussion. A number of talks in our workshop are devoted to the discussion of the velocity field using new data and methods of analysis.

Another cloud in the blue sky of the CDM-scenario has appeared recently. Superclusters and voids are formed by density waves of wavelength which corresponds to the scale of the supercluster-void network. According to the classical paradigm on the formation of the large scale structure the distribution of density waves is Gaussian, thus the distribution of high- and low-density regions should be random. It was a great surprise when Broadhurst et al. found that the distribution of high-density regions in a small area around the northern and southern Galactic pole is fairly regular; high- and low-density regions alternate with a rather constant step of 128 \( h^{-1} \) Mpc. Bahcall and others have confirmed that these overdensities are part of extended supercluster-like structures.

This discovery rises the question: Has the Universe some regularity on large scales, and if yes, what it means in terms of the structure formation scenario?

Deepest available sources of information on the distribution of matter on large scales are rich clusters of galaxies, catalogued by Abell and collaborators, and the APM survey of galaxies and clusters in the southern Galactic hemisphere. Analyses of these datasets are now available.

The 3-dimensional distribution of high-density regions as defined by very rich superclusters of galaxies was found to be fairly regular resembling honeycombs or 3-D chessboard with the same step as found by Broadhurst. This regularity can be described by the correlation function of rich clusters of galaxies and by the power spectrum of clusters. The cluster power spectrum and the distribution of clusters in rich superclusters shall be presented in my talk during this workshop.

The results of other independent analyses of Abell and APM clusters also show the presence of a surprisingly sharp maximum in the power spectrum. Three-dimensional reconstruction of the power spectrum of 2-D distribution of galaxies of the APM survey indicates again a rapid transition from the positive spectral index on large wavelengths to negative index on galaxy scales. The comparison of
the power spectra with models based on CDM scenario with the scale-free initial power spectrum has shown that serious disagreement remains – it is impossible to find a set of cosmological parameters which yields a model in agreement with new data on the power spectrum.

Fluctuations of the temperature of the cosmic microwave background radiation have been recently measured. The peaked power spectrum of matter determined from optical observations has been translated to the angular CMB spectrum assuming a certain set of cosmological parameters. Results of such comparisons show that the peaked power spectrum is in agreement with CMB data, but it cannot identify a model of structure formation in a unique way. Within the framework of the classical scale-free initial power spectrum it is extremely difficult to find a set of cosmological parameters that satisfies all constraints.

3 Is there light on the other end of the tunnel?

We come to the conclusion that the present modernised CDM model of the structure formation is in serious trouble. However, it seems that the situation is not hopeless. All CDM models considered so far are based on the assumption that inflation produces a scale-free initial power spectrum, \( P_0 \sim k \). This simple hypothesis is not the only possibility. Already more than ten years ago more complicated variants of the inflation scenario were suggested which predict a non-scale-free initial power spectrum. One of such variants suggested by Starobinsky was recently compared with CMB observations. The results are promising – with a non-scale-free post-inflational spectrum it is possible to satisfy simultaneously constraints posed by optical and CMB observations.

Presently a series of new experiments is planned, both on the Earth and in space. We all look forward to see the results of these experiments that certainly will give us much more accurate data on the power spectrum in different regions and epochs. Whatever the answers to our questions are, one is sure: the spectra on large scales give us information on the structure of the Universe in the earliest epochs of its evolution.

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