THE STATE OF THE COSMOLOGICAL MODEL: OBSERVATIONS AND THEORY

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ABSTRACT. The main points and trends of observational and theoretical cosmology that influence and form the understanding of the Universe are reviewed.

Key words: cosmology

1. Introduction

The modern situation in revealing the true cosmology is considered. The investigation of the anisotropy of the relic CMB radiation ensures a basic channel of the information about our World. The continuing progress in the technology of deep-sky galactic surveys has resulted in impressive knowledge on the large scale structure in the Universe as well as its evolution back to high redshifts. Both $\Delta T/T$ and LSS experiments complement on supercluster scales and thus disclose the underlying cosmological model. To be brief, the model is found today up to accuracy 10-20 % which is a great progress since what we had 10-15 years ago when the discussions were at best on the level of a factor two. A great hope of the cosmologists is related with the development of ground and space based $\Delta T/T$ and far Universe observations which will help to delimit and determine the cosmological model up to a few per cent in the nearest future.

2. Basics of the LSS Formation

The seeds of the visible *Large Scale Structure* in the Universe are the *Cosmological Density Perturbations* which grow due to gravitational instability in the late, cold period of the Universe history when the expasion is dominated by *Cold Dark Matter* ($z < 10^5$). These primordial CDPs must have been created at the inflationary Big Bang epoch, as after the end of inflation the Universe was radiationally dominated and hence absolutely gravitationally stable against small perturbations of matter density and gravitation field. The CDPs existed in the hot Universe evolution period like the longwave 'gravitating sound waves' propagating across the relativistic matter with a constant amplitude. The CDPs started growing only after the equality epoch when the matter pressure decayed. The required CDP amplitude for galaxy clusters could form by now has therefore been predicted on the level $\delta \sim 10^{-5}$ which was finally confirmed by COBE (Bennet et al. 1996) on this same level but at two orders of magnitude larger scale (that in turn appeared to be in a successful consistency with another famous prediction known as the *Harrison-Zel'dovich* scale-invariant perturbation spectrum).

This optimistic situation has produced a great impetus for the observational and theoretical cosmology extending dramatically by continuing progress in the improved technology of deep-sky surveys and CMB temperature detections. The ultimate goal was to reconstruct the model parameters and CDP power spectrum from Mpc up to the horizon scale, the scope straighforwardly related to the high energy physics at inflation thus capable of being observationally tested today.

Three points should be emphasised in connection with the problem of LSS formation: theoretical, model, and observational.

The first point means that the LSS formation in the Universe is as fundamental problem as the creation of the Universe as a whole: both features, the small CDPs and the Friedmann background (the *Cosmological Principle*), were produced in the unique process of inflation in the very early Universe. The theory works at very high energies ($\sim 10^{13}$ GeV) whereas the observations occur in a low-energy limit ($\sim 10^{-4}$ eV). To provide a fair comparison in such a situation we need a model to know how perturbations evolved during the whole history of the Universe. Therefore, any confrontation in cosmology between theory and observations appears model dependent.

To determine the model we need priorities and parameters. The former assumes gravitational instability as the principal mechanism of the CDP dynamics on large scale, and Gaussian primordial perturbations with random spatial phases. The latter assumes knowledge of the current time when the structure is observed (H_0), the abundance of cosmic matter components (Ω_m, Ω_Λ, Ω_ν, Ω_b) and *Cosmic Gravitational Waves* (T/S), and the nature of dark matter (e.g. relic scalar field, cold/hot dark matter, the number of species of massive neutrinos and relativistic particles). Today, cosmologists venture the following approach: if the dark matter model is postulated as fairly simple (with just a few model parameters) then the recovering of both the CDP power spectrum and the cosmological parameters can be provided by observational data on $\Delta T/T$ and LSS.

Below, I discuss the model under such a conventional probability sense. There is no principal restrictions on the way: any theory could be tested to the limit if we had enough data. The more data are available the less uncertainties remain in the theory and more parameters can be determined. Actually, we are now in the beginning of data collection. Cosmologists have started the model restoration exercise taking simple theories and confronting them with the observational data available. The development progresses with an increasing number of model parameters. Theory goes from simplicity, however Nature appears complex.

3. Dark Matter Models

Until recently there were two basic theories claiming to approach the corner stones of the LSS formation: inflation and defects. While being very much different in their grounds on galaxy seeds – the linear Gaussian scalar perturbations in one case and the non-linear non-Gaussian cosmic defects (strings, monopoles, textures) in other case – both models presented the fundamental inevitable perturbations produced in the very early Universe: the parametrically amplified quantum vacuum fluctuations of the inflaton and the topological defects left after phase transitions in the early Universe, respectively.

However, the simplest defect model normalised by the CMB fluctuations proved to fail to meet the LSS formation (Watson 1997). The reason is that the nonlinear matter perturbations generate all three types of the metric fluctuations - *Scalar, Vortex* and *Tensor* ones, which all contribute to the Sachs-Wolfe $\Delta T/T$ anisotropy on large angular scale, so the resulting S-mode amplitude proved to have had insufficient power to develop the observed galaxy distribution.

By now only the inflation theories have got through ordeals of fitting the LSS and $\Delta T/T$ requirements. The principal quest here is the predicted Gaussian nature of small CDPs, which faces a satisfactory consistency with the real distribution of galaxies on scales $\sim 20\ h^{-1}$ Mpc (e.g. Juszkiewicz & Bouchet 1996). The only obstacle to testing reliably this important feature of the CDP seeds is the restricted depth of the available galaxy surveys.

Deep galaxy surveys would also be highly welcome for clarifying another challenge of the modern cosmology: the fractal model attacking persistently the cosmological principle. The point is that huge voids seen in the galaxy distribution spatial fields extend up to scales $\sim 100\ h^{-1}$ Mpc which is close to catalogues' sizes, thus leaving a room for discussions on the value of the homogeneity scale (Sylos Labini et al. 1997). Nevertheless, I would like to stress that the fractal challenge is still a question for the distribution of optical galaxies rather than for the total mass of the Universe. The latter should be pretty homogeneous on scales larger than tens of Mpc to fit the beautiful Hubble diagrams, to say nothing on the uniform microwave and X-ray backgrounds testifying the cosmic homogeneity on larger scales.

Thus, we consider only models backed on the inflationary theories. The main tool for the Gaussian perturbations is the second moment of their spatial distribution related to the power spectrum:

$$\langle \delta^2 \rangle = \int_0^\infty P(k) k^3 dk = \int_0^\infty \Delta_k^2 \frac{dk}{k}. \qquad (1)$$

The dimensionless CDP spectrum Δ_k^2 has a simple meaning of the variance of density contrast in the scale k (the wave number) within the scale band $dk \sim k$, it is evidently additive ($\delta^2 \sim \Sigma \Delta_k^2$).

Before passing to discussion on the spectrum observational reconstruction let me sketch briefly the situation with the model parameters.

4. Cosmological Parameters

It seems that the longstanding strong debate on H_0 is approaching to its end and we are going to learn the value of the Hubble constant during nearest years. Today, two methods seem very promising: measuring Cepheids in distant galaxies and the supernovae type Ia method. I would not like to fix here the number since it is not yet time for any consensus between the groups about systematic and selection bias effects for all methods employed. For us, it is important to note that the matter dominated cosmological models (with the critical dynamical density, $\Omega_m = 1$, and negligible Λ-term) are consistent only with small Hubble constant ($H_0 < 65\, km\, s^{-1} Mpc^{-1}$) regarding the low limit for the age of the Universe coming from globular clusters.

A more optimistic point stands for determination of the matter content in the Universe. At the first glance the situation looks similar: again we have two groups of experiment resulting in different conclusions. However, here the consensus is possible.

The first experiment deals with megaparsec scales – galaxy halos, groups and X-ray clusters, – $l < l_D$ where the dynamical scale in the Universe is $l_D \sim 10 h^{-1} Mpc$ (the scale of the richest collapsing clusters). The assumption on the hydrostatic equilibrium within cluster cores yields a low dynamical mass responsible for the formation of the gravitational potential on Mpc scale:

$\Omega_m \sim 0.3$. Another important observation is a large fraction of baryons inside X-ray clusters reaching somehow $\sim 20\%$ within scale ~ 1 Mpc:

$$\frac{M_b}{M_m} \sim 0.2, \quad (2)$$

which is also consistent with the low matter density involved dynamically in small scales (as $\Omega_b \leq 0.1$ due to the primordial nucleasynthesis, and M_b/M_m may be $\sim \Omega_b/\Omega_m$ on the dynamical scale).

Another experiments dealing with LSS ($l > l_D$) hints that the Universe may be matter dominated ($\Omega_m > 0.5$). There are few arguments for it (still more model dependent ones in comparison with the small-scale arguments):

- the existence of substructures in the majority of galaxy clusters evidencing that the clusters are just forming systems, which is possible only in the Universe dynamically close to the critical density;
- the large coherence velocities obviously of the cosmological origin, allowing the reconstruction of the total density contrast (and as a consequence, consistency with the 'standard' model $\Omega_m > 0.5$ and the galaxy biasing factor $b \simeq 1$);
- the essentially Gaussian nature of the linear primordial cosmological perturbation pattern when it is recovered (by returning back in time from the actual non-linear distribution of matter density and velocity) in a matter-dominated universe ($\Omega_m \sim 1$);
- the weak gravitational lensing confirming high dynamical mass abundance around some X-ray clusters;
- the lensing argument on the fraction of splitting quasars, (still much dependent on the model assumptions);
- the evolutionary argument on the galaxy clusters number density (still under discussion);
- the geometrical argument from the distant supernovae type Ia, (still much to be clarified on systematic effects);
- the point coming from $\Delta T/T$ anisotropy (mainly, the location of the first acoustic peak).

The last three points got some important turns in the recent time which I cannot help mentioning here.

It is the ENACS identification of the nearby galaxy clusters (by the dispersion velocities of their optical galaxies, Mazure et al.1996) that has shown the previous underestimation of the Abell cluster abundance. At the moment we may state the consistency of the cluster number density evolution with redshifts for the $\Omega_m/sim1$ Universe. At least, the low evolution argument that for many years has been considered as a basic argument in favour of the low density Universe, is not any more as strong as it has seemed.

The breakthrough in the problem of the model geometry restoration is being done today using the classical Hubble diagrams (the redshifts *vs* apparent magnitudes) composed for distant supernovae of type Ia (Perlmutter et al. 1998). Contrary to galaxies, such sources look amazingly standard candles which is well supported by the distance measurements to nearby supernovae. Tested by distant supernovae, the deviations of the Hubble diagram from the linear law hint upon the real geometry of the Universe. Currently, the predictions are close to a halh-to-half matter-vacuum Universe ($\Omega_m \sim \Omega_\Lambda \sim 0.5$). However, this supernovae method is still young and careful analysis of the systematic effects is required to make it trustable.

Reconstruction of the cosmological parameters from CMB temperature fluctuations reminds one an exercise since the strongest effect comes from the location and amplitude of the first acoustic peak (the Sakharov oscillation) whose observational detection leaves much to be desired. However, without discussing here the numbers, it is worthwhile recalling the *tendency* for the model parameter constraints resulting from all $\Delta T/T$ data available in the literature (e.g. Lineweaver & Barbosa 1997): they favor low H_0 (~ 0.5) and high Ω_b (~ 0.1) and Ω_0 (> 0.5 , $\Omega_0 = \Omega_m + \Omega_\Lambda$). The low density open Universe ($\Omega_0 < 0.3$) is rejected by current $\Delta T/T$ data. It is also interesting that the high Ω_0 values are welcome by the Ly_α forest data.

Finally, a possible reconciliation between the DM experiments on small and large scales can be the following: some fraction of dark matter in the Universe is distributed on large scales and does not enter the galaxy halos and groups.

How can it be arranged?

Today we have purely theoretical ideas on such a possibility. The most frequently discussed are models with *Mixed Dark Matter* (cold+hot, with the hot particles like massive neutrinos with a few eV rest mass and the corresponding density parameter $\Omega_\nu \in (0.2, 0.4)$), non-zero Λ-term ($\Omega_\Lambda \in (0.5, 0.7)$), and a combination of both (the ΛMDM models). In all cases CDM particles form a dynamic structure on Mpc scales, while on large scales there is an additional contribution coming from light neutrinos or/and vacuum density (the Λ-term affects the cosmological expansion rate). A sceptical point concerning these and other cosmology models which are considered today as possible candidates for the real Universe is as follows: all of them are multi-parameter and thus non-minimal models; the more parameters is involved, the better comes the situation with data confrontation.

Does the latter tell us that we miss something important in our discussion on the formation of the Universe structure? May be. I can only conclude here saying than none of the models under discussion meets all the observational tests. Say, regarding previous examples, for $\Lambda \neq 0$ models one can expect a large fraction of old (relaxed) galaxy clusters and lensed quasars, whereas the MDM models require $H_0 < 65\, km\, s^{-1} Mpc^{-1}$ and too a small abundance of X-ray clusters and high-redshift quasars. Probably, the dark matter can exist in the form of relic scalar field left after inflation or in some other exotic form which requires special analysis.

In such a situation the observational verifications become extremely important. The principal test here is the LSS evolution in the early Universe.

5. The spectrum of density perturbations

The cosmological models of LSS formation discussed today are aimed to fit the observational data at $z = 0$. Thus we cannot distinguish between the models without going into their evolution at medium and high redshifts where the models demonstrate their essential difference.

Two main experiments promote a snow ball progress in the reconstruction of the CDP spectrum, which was impossible in previous years: $\Delta T/T(\theta > 1')$ and direct investigation of the evolution and hierarchy of LSSs. The reason for stimulating such a progress is that these two experiments confront and overlap each other: the $\Delta T/T$ investigations go nowadays to small comoving scales up to $l \sim 10\ h^{-1}$ Mpc (recall the corresponding angular scale in arcmin $\theta \sim lh$), and, at the same time, we observe a developed structure of clusters, filaments, voids, and superclusters reaching the scales $\sim 100\ h^{-1}$ Mpc.

Any reasonable assumption on the "formation" of large voids and superclusters in Gaussian perturbation theories inevitably leads to $\Delta T/T$ predictions at $\sim 1^0$ capable of current detection. It is a great puzzle that namely this scale specifies the horizon at the decoupling era and therefore the angular scale of the first acoustic peaks. Its existence was predicted by theory long ago. Now, the time for observations came: it is just on agenda, a matter of the improved instrument's technology and foreground separations that will precisely determine the acoustic peak parameters and ultimately prove and determine the theory.

We are aware of the cosmological temperature anisotropy on large scale and have some information on the whole spectrum of the CMB fluctuations (Hancock et al. 1998). Fortunately, the small angular scales ($\theta < 1^0$) can be effectively tested from the Earth's surface. A hope is that such terrestrial instruments as SK, CAT, VSI, TOCO, BUMERANG, RATAN-600, combined with balloon experiments as well as the MAP and Planck Surveyor satellites, will provide a sensitivity advance sufficient for the cosmological model reconstruction.

Meanwhile, the situation with the CDP spectrum looks rather dramatic. On large scales ($\sim 1000\ h^{-1}$ Mpc) the fundamental spectrum is small in amplitude and consistent with the HZ slope:

$$\Delta_k^2 \sim k^{3+n_S}, \quad n_S = 1.1 \pm 0.1. \tag{3}$$

However, on smaller scales ($\leq 100\ h^{-1}$ Mpc) the power should be boosted as we observe rich structures in spatial distribution of galaxies, clusters, Ly_α systems, and distant sources like quasars. The latter is especially important. We live in the period of decay of quasar and star formation activities (Boyle & Terlevich 1998). We thus have a unique opportunity to observe these numerous early sources tracing the past dynamics of LSS formation. This would be extremely informative as the LSS perturbation amplitude, being still less than unity today at $l \sim 100\ h^{-1}$ Mpc, was ever lower in the past, which predicts a strong inverse evolution of such huge systems as superclusters and voids.

It seems that quasars, the active galactic nuclei of distant galaxies, form the LSS at medium redshifts ($z \sim 1-2$) which is provided by their correlation function and the existence of large QSO groups recalling in properties (the comoving size and abundance) the local superclusters (Komberg et al. 1996). Actually, distant bright quasars may originate in merging galaxies in protoclusters, and thus can trace the sites of enhanced matter density at medium and high redshifts analogous to how galaxy clusters trace them in the near space. In case of matter dominated Universe the dynamical formation of these early LSSs suggests that the spectral amplitude on superclusters scale ($\sim 100\ h^{-1}$ Mpc) should be comparable and pretty close to that on cluster scale ($\sim 10\ h^{-1}$ Mpc), i.e. the CDP spectrum is nearly flat between those scales (Komberg & Lukash 1994):

$$\Delta_k^2 \sim k^{0.9 \pm 0.2}. \tag{4}$$

This estimate for the spectrum shape is also backed by the local observations of galaxy and galaxy cluster distributions (Guzzo 1991, Peacock 1996, Einasto et al. 1997).

A strong break in the spectrum slope from the HZ asymptotic (3) to the flat part (4) should have happened at supercluster scale ($\sim 100 - 150\ h^{-1}$ Mpc) which is obviously a real feature of the fundamental CDP spectrum. This 'signature of the God' in the primordial spectrum demands its explanation in physics of the very early Universe.

I cannot help mentioning another connection of the very early Universe with the primordial perturbation spectrum. This is a possibility to have high abundance of cosmic gravitational waves contributing to large-scale CMB anisotropy.

There are at least two reasons for such discussion.

The first one is theoretical. Inflation theory is not discriminative to any of the perturbation modes if inflation occurs at GUT energies (Lukash & Mikheeva 1997): both S (CDP) and T (CGW) modes can be produced with similar amplitudes and thus comparable contribution to the CMB anisotropy,

$$\left(\frac{\Delta T}{T}\right)^2_{10^0} = S + T. \quad (5)$$

The second reason comes from observations. If the scalar perturbation spectrum is 'blue' ($n_S > 1$) then a non-zero T/S¿0 is required to reconcile the COBE $\Delta T/T$ measurement with the galaxy cluster abundance.

The problem of T/S is fundamental but can be treated at the moment only theoretically. A serious discussion on the observational detection of T/S could be launched after CMB polarization measurements, which would require the instrumental sensitivity $\sim 1\mu K$ currently non-reachable.

6. Conclusions and Tendencies

As never before, the cosmologists are close to recovering the real model of our Universe and the post-recombination CDP spectrum directly from observations, both $\Delta T/T$ and LSS, and to creating an exciting link to the physics of the very early Universe. We are going to gain the data from the advanced ground and space based CMB explorers as well as huge surveys of spatial distribution of galaxies, to delimit the cosmological model with unprecedented precision.

The list of current conclusions may be incomplete:

- the extreme open models ($\Omega_0 < 0.3$) are rejected by CMB and cluster evolution data;
- the distant supernovae Ia may be used to restoring the spatial geometry of our Universe;
- the current data on the acoustic peak indicate small H_0 ($\leq$ 65 $km\ s^{-1}$Mpc^{-1}) and large Ω_b (~ 0.1) and Ω_0 (> 0.5);
- the slope of the fundamental CDP spectrum is consistent with HZ ($n_S \simeq 1$);
- the CMB and LSS data indicate a break in the CDP spectrum slope at scale $\sim 100 - 150$ Mpc, which requires *new physical* explanation;
- the T/S problem cannot be ignored and needs careful treatment.

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