LARGE DISTANCES, HIDDEN MASS AND FLUCTUATIONS OF THE RELIC RADIATION

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ABSTRACT. The problem of determining the fundamental constants of the Universe - H_o, q_o, Ω, Λ, hidden matter, and the primordial perturbation parameters is considered. The likelihood of finding new evidence for large-scale Δ T/T-fluctuations is discussed.

1. INTRODUCTION

In the past observational cosmology was a science concerned with the measurement of two numbers - the Hubble constant and the deceleration parameter. Now we can investigate more parameters, because of successes in investigations of the large-scale structure of the Universe. There are only a few observations in cosmology which crucially influenced the development of the science. They are first and foremost:

- The discovery of the recession of the galaxies by Hubble;
- The discovery of the relic microwave background radiation.

These discoveries confirmed the Friedmann model of the universe and the hot big bang. The next experiment on the list is now on the agenda. It is:

- The measurement of the large-scale angular Δ T/T fluctuations of the microwave background.

Theoretical predictions and current observational possibilities are of the same order ($\Delta T/T \sim 10^{-5}$). So, it may well be that the relic fluctuations on scales $\Theta \gtrsim 20'$* will be discovered soon. They could tell us a lot not only about the origin of galaxies but also about the processes in the very early Universe when the primordial cosmological perturbations (galactic embryos) were only forming.

One of the future experiments important for cosmology is:

- The use of Space radio interferometers with baselines much

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longer than the Earth's diameter. These may allow us to determine directly distances to other galaxies. This follows from a simple estimate for the maximum distance R_{max} to be measured by a interferometer with baseline L at a wavelength λ:

$$R_{max} = f \cdot L^2/\lambda \tag{1}$$

where $f \sim S/N$ is the numerical coefficient. For $\lambda \sim 1$ cm, $L \sim 2$a.u. $\simeq 3 \cdot 10^{13}$ cm, and $f \sim 10$, $R_{max} \sim 10^{28}$ cm, which is the cosmological horizon length scale.

Before we consider the current status of the $\Delta T/T$ problem we consider this latter argument in more detail.

2. SPACE INTERFEROMETERS

There are two proposals associated with large distances.

The first is to determine the curvature of the signal wave-front from a distant object which in fact, means to determine the parallax π. This may be done with the help of three or more satellites by measuring the delay time of the wave signal.

In the simple case in which it is assumed that heavy particles make up the missing mass (Novikov 1977)

$$\pi = \frac{H_o L}{2c}\left(4 - \Omega + \Omega^2 \cdot (\sqrt{1+\Omega z} - 1)^{-1}\left(1 - \frac{1-\Omega}{\sqrt{1+\Omega z}}\right)^{-1}\right) \tag{2}$$

where Ω is the total density of the Universe in critical density units. For the large redshift objects ($\Omega z \gg 1$)

$$\pi_\infty = \frac{H_o L}{c}(2 - \Omega/2) \tag{3}$$

π_∞ is independent of the redshift and allows us to determine Ω when the Hubble constant H_o is known. In the general case the parallax

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* See previous page.
According to conventional theories the scales $\Theta \sim 20'$ in $\Delta T/T(\Theta)$ are the scales most likely to be responsible for the formation of clusters and superclusters. Fluctuations on a scale of degrees are related to the structural correlations ~100-300 Mpc in the distribution of rich clusters (see Kopylov et al. 1984; Bahcall and Burgett 1986; Koo and Ellis in these Proceedings). Also a very important scale is $\sim 5^o$ which is the cosmological horizon at $z \sim 10^3$ (the hydrogen recombination epoch). The large-scale fluctuations ($\Theta > 5^o$) are of particular interest since they are expected to be the biggest. They are directly coupled to the primordial gravitational perturbations, and they are not smoothed by the secondary ionization and the hydrogen recombination dynamics.

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depends on the deceleration and the structural filling factor as well. Thus the shape of the diagram $\pi \leftrightarrow z$ gives us direct information about the fundamental constants of the universe.

The second proposal was recently discussed by Kardashev (1986), and he assumes that a long baseline interferometer can detect the motion of distant galaxies on a background of very distant objects. The relic radiation fixes the universal coordinate system in space-time, and any object moves relative to it. For example, our Sun has the absolute velocity v = 350 km/s in the direction $l \simeq 253^o$, $b \simeq 47^o$. Thus, relative to our laboratory system any remote object moves systematically (i.e. in addition to its random proper motion) in the direction of the antiapex with an angular shift depending on the distance and direction to the object. In a year the Sun travels $\sim 10^{15}$ cm giving a gain of a factor ~ 35 compared with the annual parallax (cf. L = 2 a.u. $\simeq 3 \cdot 10^{13}$ cm).* This effect grows linearly with time. While investigating angular shifts and redshifts we can extract information about the universal constants.

We do not discuss here statistical, absorption, gravitational and other problems (see Kardashev et al. 1973). Our aim is just to emphasize the possibility of determining the main cosmological parameters with help of space interferometers.

However, for now the most precise tool for the exploration of the universe is the study of fluctuations of the microwave background. Let us first recall the contemporary upper limits for $\Delta T/T$ in large scales, and then proceed to discuss the theoretical implications and the whole problem.

3. OBSERVATIONAL DATA FOR Δ T/T

Up to now, and after 21 years of investigation of the relic radiation, no fluctuations of its temperature have been found although they ought to exist on the level $\sim 10^{-5}$ because of the existence of superclusters. The best up-to-date limits on $\Delta T/T$ on scales $\Theta > 7^o$ are from the "RELIC" experiment that was carried out on the satellite Prognoz two years ago. This produced a sky-map at $\lambda = 8$ mm with a sensitivity $\sigma \simeq 0.2$ mK, which covered ~8.8 steradians. The final analysis of all of the observations is now complete (see Strukov and Skulachev 1986, Strukov et al. 1986, Klypin et al. 1986) and we summarize below that part which is of main interest here.

According to Klypin et al. (1986) the cosmological information can be listed under three headings:

1. Harmonic analysis. No $\Delta T/T$ signal was found at the 95% confidence level for the multipole components with the spherical

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* In a year one could measure systematic angular shifts for objects at $z \lesssim 0.01$ with angular resolution ~ $2 \cdot 10^{-6}$ arc sec (say, using as a baseline the Earth-Lagrange point ~ $1.5 \cdot 10^6$ km (Kardashev 1986).

harmonic index 1 = 2,3,..., 10. This leads to the following upper limits for the quadrupole and octupole anisotropies

$$(\Delta T/T)_2 < 3\cdot 10^{-5}, \quad (\Delta T/T)_3 < 7\cdot 10^{-5} \tag{4}$$

and $(\Delta T/T)_\ell < 5\cdot 10^{-5}$ for the higher harmonics (ℓ = 4,5,.., 10). The octupole amplitude (ℓ = 3) is less well-determined since the dipole component was subtracted in every scan before the analysis and harmonics with 1 > 10 are reduced by the antenna beamwidth and the method of analysis. Note that the quadrupole limit (ℓ = 2) is a factor of 2 less than that in the previous experiment (Fixen _et al_. 1983) and the large-scale background pattern is now outlined.

2. _Dispersion analysis_ was based on the background signal dependence

$$(\Delta T/T)_\ell \sim \frac{2\ell+1}{1(\ell+1)}, \quad \ell \geq 2, \tag{5}$$

which is valid for the flat primordial perturbation spectrum and the assumption that Ω = 1 with massive weakly interacting particles making up the missing mass. For the quadrupole amplitude this yields

$$(\Delta T/T)_2 < 2\cdot 10^{-5} \qquad \text{(95\% confidence limit)} \tag{6}$$

Note, that the upper limit in eq. (6) is model dependent (see eq. (5)) whilst the numbers in eq. (4) come purely from observation.

3. _The correlation function_ calculated from the noise sky map displays no statistically significant peaks:

$$< \Delta T_1 \cdot \Delta T_2 > \quad < \quad 4\cdot 10^{-3} \ \mathrm{mK}^2 \tag{7}$$

for angular scales $20^\circ < \Theta < 160^\circ$. This result adds no information to that obtained from the harmonic analysis.

These observational data put severe limits on the "market" of cosmological models which we now discuss.

4. COSMOLOGICAL MODELS

In Table I we present theoretical predictions for the quadrupole $\Delta T/T$ - amplitude (ℓ = 2) as measured by a 6° antenna and those for the small-scale structure function $\Delta T/T$ (Θ = 20') to be detected by the ideal antenna (Θ_a < 5'). The numbers are calculated for H_o = 50 km/s/Mpc, T_{BR} = 2.7°K, Ω = 1 and a flat spectrum for the primordial perturbations. The results are given for four different assumptions concerning the nature of the hidden mass.

The stable particle column (see Lukash _et al_. 1984) assumes the hot missing matter variant (ν - type particles). Here the primordial perturbations are normalized by assuming an r.m.s. density contrast ~ 1 at z = 3. The same numbers hold for the cold variant (axions or very heavy particles) if the correlation scale of the dynamical mass at z = 0 is ~ 30 Mpc.*

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TABLE I. Large and Small Scale Microwave Background Anisotropy Expected for Different Carriers of Hidden Matter

Δ T/T	Stable Particles	Decaying Particles	$\Lambda \neq 0$	Strings
Quadrupole	2×10^{-5}	2×10^{-5}	10^{-5}	10^{-5}
20' dispersion	10^{-4}	2×10^{-5}	8×10^{-5}	4×10^{-6}

In the second column we use the calculations of Kofman et al. (1986) and Doroshkevich and Khlopov (1985) for the decaying particle models. For the $\Lambda \neq 0$ model, the dynamical matter density in the form of axions was supposed to be 20% of the critical one (see Kofman and Starobinskii 1985). The data for the cosmological string model are due to Brandenberger and Turok (1985).

The large-scale Δ T/T fluctuations in all the models are seen to be of the same order of magnitude, and they are on the verge of the current observational limits (see Section 3). Detection of these fluctuations would be a crucial test of cosmological theory, since they bear direct information about the primordial gravitational perturbations on large scales which are not smoothed out by the recombination and secondary ionization dynamics.

A subtle point about the fluctuations in angles $\Theta \gtrsim 5^{\circ}$ is that the related density perturbations are still in the linear regime of the evolution now, i.e. they do not manifest themselves as a space structural pattern yet and we do not know their amplitude. Another parameter which the Δ T/T ($\Theta > 5^{\circ}$) fluctuations are sensitive to is the overall matter density Ω (see discussion on the spottiness in Section 5). Thus the large scale Δ T/T fluctuations can tell us primarily something about the primordial spectrum and Ω and secondarily something about the nature of the missing mass.

A different situation applies for the small scales ($10' < \Theta < 5^{\circ}$). These are related to the large-scale structure of the Universe which we now observe. However, the Δ T/T level at $\Theta \sim 20'$ drastically depends on the recombination and ionization processes. The numbers in Table I are given for the conventional recombination dynamics. If some unstable particles decay with small probability through the γ-channel at $z < 10^{3}$, they can quite easily reionize or draw out recombination of the cosmic hydrogen. This, in turn, decreases the small-scale Δ T/T

* If the correlation length is three times smaller (the Peebles correlation scale), then the quadrupole amplitude for the axion model is $\sim 5 \cdot 10^{-6}$; with biasing at $\sim 2\sigma$ (Kaiser 1984) the last number is less by a factor $\sim$ 1.5 (see Lukash 1987).

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- anisotropy by a factor ~50 (Dorosheva and Naselskij 1986). Thus $\Delta T/T$ fluctuations on small scales are a good test of the recombination and ionization dynamics at large redshifts.

5. DISCUSSION

In Table II we present the results of calculations of Lukash et al. (1984) for the dipole (in scales ~100 Mpc) and quadrupole anisotropies in the hot and cold missing matter models (without biasing) for different assumed power-law spectra of the primordial perturbations. It can be seen that the flat spectrum is a corner stone of the $\Delta T/T$ problem from the observational point of view. The white noise spectrum growing to larger scales is practically forbidden by the large-scale observations. On the other hand, decaying spectra which are most naturally predicted by the parametric amplification theory (Lukash 1980, Kompaneets et al. 1982) or in multi-inflationary universes (Kofman et al. 1985, Kofman 1986), decrease the expected value of $\Delta T/T$ on large-scales which would postpone the $\Delta T/T$ discovery.

TABLE II. Dipole ($\ell = 1$) and Quadrupole ($\ell = 2$) $\Delta T/T$ Amplitudes Expected for Different Primordial Spectra

Hidden Matter	ℓ	Flat Spectrum	White Noise	Decaying Spectrum
Hot	1	3×10^{-3}	5×10^{-3}	3×10^{-3}
	2	2×10^{-5}	4×10^{-4}	$< 10^{-5}$
Cold	1	10^{-3}	10^{-2}	10^{-3}
	2	4×10^{-6}	7×10^{-5}	$< 10^{-6}$

Another way to change the structure of the anisotropy at $5^o<\Theta<180^o$ is to put $\Omega \neq 1$. In open universes a qualitatively new effect arises. It is "spottiness": the large-scale $\Delta T/T$ pattern over the sky for $\Omega < 1$ represents an arbitrary superposition of cold and hot spots with angular dimensions $\Theta_o \sim \Omega$ independent of the perturbation wavelength (Novikov 1968, Lukash 1977, Lukash and Novikov 1985). As $\Omega \rightarrow 1$ the phenomenon disappears since the spot shape converts into the quadrupole structure, and any superposition of quadrupoles results in quadrupole structure again, i.e. the statistical effect fails. The spottiness brings about a relative gain in the multipole $\Delta T/T$ amplitude with $\ell_o \sim \pi/\Theta_o \sim \Omega^{-1}$. In other words the following result is found. If we fix the flat primordial spectrum and vary Ω from unity to lower values than the maximum expected, the $\Delta T/T$ anisotropy will shift from the quadrupole to a higher harmonic with $\ell_o \sim \Omega^{-1} > 1$. The normalization assumes that the $\Delta T/T$ amplitude will grow with Ω decreasing, which allows for the lower limit $\Omega \gtrsim 0.3$ established by the high harmonic upper $\Delta T/T$ limits ($\ell \sim 10$, see eq. (4)).

Of course, both factors, spottiness and primordial spectrum as well as the cosmological hidden mass model determine the large-scale $\Delta T/T$ structure. Only after we know the whole sky map for $\ell \lesssim 15$ can we answer all of the questions about the main cosmological parameters.

What are the observational possibilities as far as the detection of large-scale $\Delta T/T$ fluctuations are concerned?

First, we have the exciting result of Dr. R.D. Davies for $\Theta \sim 5^o$ in these Proceedings. This is in good agreement with the balloon data of Dr. Melchiorri (private communication) which are obtained on the same angular scales but at a much shorter wavelength. Both results still need verification, but let us assume for a moment that the background signal exists on the level $\Delta T/T \sim 2 \cdot 10^{-5}$ at $\Theta \sim 5-10^o$. Then we can normalize the primordial perturbations using this value in the correlation function of $\Delta T/T$. This is much more precise than the normalization by the density contrast since $\Delta T/T$ calculations are made using linear perturbation theory, and we do not need such poorly known quantities as the correlation radius for the dynamical mass, or the type of particle making up the missing mass. In doing this for the flat spectrum and $\Omega = 1$, we find from eq. (5) the following estimate for the quadrupole, $(\Delta T/T)_2 \sim 10^{-5}$ which is on the verge of detection. This problem was also discussed at the SAO Conference (USSR) in September 1986.

Another line of evidence comes from the large-scale motions (Collins et al. 1986, Burstein et al. 1986, and also the paper by Roger Davies in these Proceedings). If we assume the streaming velocity $v/c \sim 2 \cdot 10^{-3}$ on scales ~100 Mpc this will not contradict the dipole distribution of IRAS galaxies (Meiksin and Davis 1985, Yahil et al. 1986) if the density contrast in 100 Mpc is ~0.1 and the velocity vector correlates with the IRAS dipole. In this way we conclude that the microwave dipole anisotropy on these scales is totally determined by the cosmological "growing" mode of perturbations and $(\Delta T/T)_1 \sim 2 \cdot 10^{-3}$ purely from the velocity observations (Yudin 1986, cf. Table I). Again recalculating this result for the quadrupole $\Delta T/T$ anisotropy on the assumption of a flat spectrum and $\Omega = 1$ we get the same number $(\Delta T/T)_2 \sim 10^{-5}$.

We note that the two points at the diagram $\Delta T/T \leftrightarrow \Theta$ (at $\Theta_1 = 5^o$ and $\Theta_2 = 180^o$) give us the same estimate $\sim 10^{-5}$ for the quadrupole independent of any assumptions about the cosmological model. Thus the discovery of only quadrupole structure at this level would strongly confirm a flat spectrum for the primordial cosmological perturbations.

6. CONCLUSIONS

Our main conclusions are briefly summarized as follows.

1. Baryon models and $\Lambda \neq 0$ models with baryons or light massive particles as a dynamical hidden matter contradict the large-scale $\Delta T/T$ limits.

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2. Large-scale Δ T/T fluctuations may be detected in the satellite experiment with a sensitivity ~3-5 x 10^{-6}.

3. The flat primordial perturbation spectrum is a crucial test of the Δ T/T problem. The optimal range to search for Δ T/T is 20' < Θ < < 180^{o}.

If Δ T/T fluctuations are discovered at $\Theta > 5^{o}$ the spectrum of primordial perturbations as well as the total matter density in the Universe Ω could be determined.

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DISCUSSION

PARTRIDGE: In simple, low density, anisotropic cosmological models, there is a "hot spot" of scale $\Theta \sim \Omega$ radians. Has the map from the RELIC satellite been inspected for such a "hot spot?"

LUKASH: Individual hot or cold spots can exist if there were some peculiarities in the primordial spectrum. For example, if some wave vector in the initial perturbation amplitude was large in comparison with all of the others, then a spot will form with angular scale $\sim \Omega_{tot} < 1$ and with the large scale structure totally described by the Bianchi type V model. (The RELIC experiment was proposed in order to search for such spots in the sky.)

However, for example, for the Gaussian perturbation field, the sky pattern in the open universe represents an arbitrary superposition of the spots. In this case you cannot find separate spots, but instead the angular correlation scale, $\sim \Omega_{tot} < 1$. This is what we call the spottiness effect. It can be detected from the shape of the correlation function.

DEKEL: Could you please elaborate on the way you've normalized the spectrum of density fluctuations to obtain the various theoretical predictions for $\delta T/T$? In particular, shouldn't it depend on the type of dark-matter, the initial fluctuations, and on whether the galaxies trace the mass?

LUKASH: Thank you for the question since I did not have time enough to dwell on these points. The numbers for the stable particles were given for the hot scenario. Here the normalization is done by putting the r.m.s. density fluctuation equal to unity at $z = 3$, and $H_o = 50$ km/s/Mpc. For the very heavy particles the predicted $\Delta T/T$ values in different normalization procedures are a bit lower (see refs.) but still the $\Delta T/T$-fluctuations in large scales will be detected if the sensitivity is several units times 10^{-6}.

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