ANISOTROPY OF THE MICROWAVE BACKGROUND AND COSMOLOGICAL DARK MATTER

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ABSTRACT. Both large and small-scale $\Delta T/T$ anisotropies of the microwave background are reviewed in the context of the modern theories of the Universe structure origin. A number of primordial perturbation spectra and various types of cosmological missing mass are considered. Theoretical predictions are compared with the observational data. Importance of the $\Delta T/T$ measurements on large angular scales ($\theta > 5°$) is emphasized.

This year we observe the 20th anniversary of the microwave background radiation discovery which so splendidly confirmed a hot model of the Universe. Much has been done since then to study the degree of isotropy of the relic background. The experiment is already close to $\Delta T/T \sim 10^{-5}$. However, no angular variations of temperature beside the dipole component due to the motion of the Earth relative to the relic background [1], have been observed yet. Cosmological models with missing mass considered today predict the presence of fluctuations $\Delta T/T \sim 5\times10^{-6}$ brought about by the embryos of the observed Universe structure. Thus it may well be that we are now on the verge of a new discovery which may confirm the validity of our concepts not only about the origin of galaxies, but also about the processes occurring in the Very Early Universe at the time primordial perturbations were only forming.

The modern theoretical and observational cosmology predicts that there were small primordial density and coupled gravitational perturbations in the early Universe. There also exists dark matter, whose nature is still unknown. The primordial perturbations start growing at the redshift $z_{eq} \sim 10^4$ and on due to the gravitational instability, become large and form the large-scale structure of the present Universe. Evolution of the small perturbations and the structure formation process depend upon the parameters of cosmological missing mass. However to detect these fundamental parameters from the observed structure is quite a difficult task due to nonlinear gas dynamical processes which accompanied the formation of galaxies.

Observation of the microwave background anisotropy provides an independent and much more accurate test of the processes which led to

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the formation of the Universe structure. Being small at the beginning, the primordial inhomogeneities perturbed the relic radiation which had been propagating freely since $z < 10^3$. These perturbations must manifest themselves at present as angular variations of the microwave background temperature.

Theoretical calculations of the $\Delta T/T$ fluctuations are carried out within the framework of linear theory. These calculations are simple and reliable. The $\Delta T/T$ amplitude is determined unambiguously by the primordial inhomogeneities and by the dynamics of their growth in the early Universe. Furthermore, the large-scale $\Delta T/T$ distribution is affected by the overall space curvature of the present Universe. Perturbation theory predicts for the open Universe ($\Omega_{tot} = \rho/\rho_{cr} < 1$) the existence of a characteristic correlation $\Delta T(\theta)/T$ structure with angular scale $\theta_c \sim \Omega_{tot}$. This structure is referred to as "spottiness". The discovery of the spotty structure (or its absence) in the $\Delta T/T$ large-scale anisotropy will enable a conclusion about the total matter density of the Universe, including the dark mass. To gain this sort of information in any other way is quite difficult.

Thus the measurements of the relic radiation anisotropy provide direct information about the primordial cosmological perturbations and about the parameters of the missing mass which govern the evolution of these perturbations.

On the other hand, the background anisotropy explorations are stimulated today by the theories of the Very Early Universe. Different theories predict different primordial perturbation spectra and different types of missing mass carriers. In particular, the standard inflationary theories predict both a flat primordial adiabatic perturbation spectrum and the overall matter density $\Omega_{tot}=1$. Thus, comparison of theoretical predictions for $\Delta T/T$ with the observational data provides a unique opportunity to test the theories of the Very Early Universe [2].

We shall outline below models to be considered and then proceed to the $\Delta T/T$ results. All figures are given for $H_0 = 50$ km/s/Mpc and $T_\gamma = 2.7°$.

1. COSMOLOGICAL MODELS

The most attractive theoretically is a neutrino-dominated model of the Universe, since it has no free parameters and provides a natural cutoff in the primordial perturbation spectrum at wavelengths less than the supercluster scale. The laboratory experiment [3], which set the lower limit on the rest mass of the electron neutrino $m(\nu_e) > 10$ eV, has stimulated comprehensible investigations of the cosmological model with massive stable neutrinos [4]. Standard ν - models face well-known problems [5]: 1. Rapid nonlinear evolution ($z_s < 1$). 2. Small part of matter converted into galaxies ($M_{vir}/M_{gal} \sim 50$). 3. Large correlation scale of the dynamical structure (~ 20 Mpc). 4. Large peculiar velocities of galaxies. One can see that discrepancy between theory and observations is of the order of 2. We do not know yet how galaxies form and the relation between the distribution of galaxies and that of dynamical mass in clusters. Furthermore, according to [6] the observational correlation scale of galaxies may increase from 10 Mpc to 20-30 Mpc. Thus, there are no convincing proof to turn down the ν - model until these aspects of the structure are clarified (for difficulties due to $\Delta T/T$ anisotropy see below). However we have serious arguments to consider alternative models, which try to overcome the above difficulties.

The missing mass is considered to consist of weakly interacting particles. Here we list the alternative models according to how well they are developed: (a) Models with unstable particles ($z_\tau \simeq 4$-10) [7]. (b) Axion models and models with supermassive relic particles ($m_R > 1$ KeV). (c) Models with Λ - term. (d) Open models $\Omega_{tot} < 1$. Although the alternative models somewhat reduce the contradictions of the ν - model, some subtle contradictions still remain. For example models (b) poorly account for the homogeneous component of missing mass ($\Omega_h \simeq 0.8$), the age for models (a) is $\sim 10^{11}$ yr. The situation can be improved by adding a small Λ - term, or by rejecting eq. $\Omega_{tot} = 1$ at all and turning to open models.

The idea of models (a,c,d) is as follows: by introducing several additional parameters to slow down the evolution at the nonlinear stage and to decrease the gas temperature in superclusters. Models (a,c,d) present a fine adjustment to the experimental data. Decay of massive neutrinos into collisionless particles ($\tau_{dec} \simeq 10^{16} - 5\cdot10^{16}$s) or the beginning of Λ - term or space curvature domination must be timed to the nonlinear stage triggering. In addition such a small required value of the Λ - term ($\Lambda = \rho_{vac} < \rho_{cr} \simeq 10^{-47}$ GeV^4) is a puzzle for the elementary particle physics [8]. In this respect, the models (b) would be more natural. The physical nature of supermassive particles is not so much important. They may be primordial black holes, monopoles, gravitinos and so on. What matters, in fact, is that they became nonrelativistic long before the recombination epoch. In this case the perturbation spectrum does not fall at shorter wavelengths, which results in a more smeared structure.

2. PRIMORDIAL PERTURBATIONS

A field of primordial perturbations is described by a random function $q = q(x)$ with Gaussian distribution of amplitudes. By definition:

$$\langle q_{\underline{k}}\, q_{\underline{k}'}\rangle = 2\pi^2 q_k^2 \delta(\underline{k} - \underline{k}'),\ \langle q^2\rangle = \int_{-\infty}^{\infty} q_k^2 \, d\ln k, \tag{1}$$

where $q_{\underline{k}}$ is the Fourier transform of q ; $\langle\ldots\rangle$ means the average over the state of the q - field; one-parameter family of q_k is called a primordial spectrum; k is a modulus of the wave-vector. For comparison, we give the relation of the gauge-invariant q - function to metric perturbations $h_{\alpha\beta}$ in the synchronous reference system (t, x^α):

$$h_\alpha^\beta = q\delta_\alpha^\beta + 0\ (t^2 q_{,\alpha}^{,\beta}) \tag{2}$$

When relic nonrelativistic particles dominate the expansion, their density spectrum is as follows:

$$\delta_k = \frac{1}{20} (k\eta)^2 q_k \ \Psi \ (k) \qquad (3)$$

where $\langle\delta_R^2\rangle = \int \delta_k^2 \ d \ \ln k$, $\eta = \int dt/a$, $a = a(t)$ is the scale factor. The transfer function Ψ (k) monotonically decreases with k growing ($\Psi(0) = 1$), its shape depends on the dark matter model considered.

We explored three simplest spectra of the primordial perturbations:

$$q_k \sim k^n \ , \ n = \begin{cases} -1 \\ 0 \\ 1 \end{cases} \qquad (4)$$

The growing spectrum ($n = -1$, white noise) is taken from general considerations. The flat spectrum ($n = 0$) is predicted by standard models of the inflationary Universe [9]. The decaying spectrum ($n = 1$) originates in the parametric amplification theory [10], the scale of exponential cutoff in short wavelengths ($k^{-1} < 20$-600 Mpc) is an arbitrary model parameter. A combined spectrum with the changing slope $n = 0 \to 1$ is also allowed.

In the neutrino models the Ψ - function decays abruptly for large k [11], which allows for a simple spectrum normalization:

$$\langle\delta_R^2\rangle = 1 \qquad \text{at} \qquad z = z_s \qquad (5)$$

where at the redshift z_s the structure of the Universe emerges. The following results are given for $z_s = 3$.

In models (b) the Ψ - function damps rather slowly; Ψ (k) $\sim k^{-2} \ln k$ [12], which results in the logarithmic increase of the density perturbation growth at small scales. This demands a more subtle normalization of the primordial spectrum which is the weakest point of the linear theory (b). Further on we normalize the correlation function ξ (r) $= \langle\delta_R(0) \ \delta_R(r)\rangle^{1/2}$ by the correlation scale $r_c = 10$ Mpc ($\xi_c = 1$, $z = 0$) which corresponds to the formation at $z = 3$ of objects with masses $\sim 10^{12} \ M_\odot$ [13].

In models (a,c,d) subsequent evolution of the $\delta_k(\eta)$ function with massive particles no longer predominant at late stages, should be taken into account [14,15].

3. FORMATION OF ΔT/T ANISOTROPY

The possibility to compare theoretical $\Delta T/T$ calculations with observations is based on hypothesis (1), which is predicted by almost all theories of the Very Early Universe. In fact, the reason is that the primordial perturbations originate from quantum (or thermal) fluctuations which obey, by definition, the Gaussian law of distribution. The latter allows a theoretical estimate of the confidence level for predicted quantities, originating from the fact that we observe one of possible realizations of the Universe.

The theory gives $\Delta T(\underline{e})/T$ amplitude as a function of the unit vector $\underline{e}$ along the line of sight. We can use it to calculate the correlation function

$$\xi\ (\theta) = \left\langle \frac{\Delta T}{T}(\underline{e})\ \frac{\Delta T}{T}\ (\underline{e}')\ \right\rangle^{1/2} \tag{6}$$

and the root-mean square temperature fluctuation

$$\frac{\Delta T}{T}\ (\theta) = \left\langle \left(\frac{T(\underline{e}) - T\ (\underline{e}')}{T}\right)^2 \right\rangle^{1/2} = (2(\xi(0) - \xi(\theta)))^{1/2} \tag{7}$$

which depend on the angle between the observation directions, $\cos\theta = \underline{e}\cdot\underline{e}'$. The ergodicity theorem allows identifying eqs. (6), (7) with the observed distributions, where the average is taken over all directions on the celestial sphere, with the fixed angle θ. For confrontation, one should take into account the antenna beamwidth θ_a which averages all fluctuations at $\theta < \theta_a$. (To make estimates, $\xi(\theta_a)$ function should be substituted in eq. (7) for $\xi(0)$).

The other way is to employ harmonic analysis (dipole component is subtracted):

$$\frac{\Delta T}{T}(\underline{e}) = \sum_{l=2}^{\infty}\ \sum_{m=-l}^{l}\ a_{em}\ \Psi_{em}\ (\underline{e}), \tag{8}$$

where $\Psi_{em}\ (\underline{e})$ are spherical functions. For the predicted multipole anisotropy and dispersion we have:

$$\left(\frac{\Delta T}{T}\right)_l = \left(\sum_{m=-l}^{l}\ a_{em}^2\right)^{1/2},\ \xi\ (\theta_a) \simeq \left(\sum_{l=2}^{[\theta_a]^{-1}}\ \left(\frac{\Delta T}{T}\right)_l^2\right)^{1/2}. \tag{9}$$

Hydrogen recombination dynamics in the Universe is well investigated [16]. Cosmic plasma becomes transparent for relic photons

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at $z_{rec} \simeq 10^3$ during the interval of redshifts $\Delta z/z \simeq 0.1$. The recombination scale and the transparent width correspond to the angles $\theta_{rec} \sim 5°$ and $\theta\Delta \sim 10'$ on the celestial sphere ($\Omega_{tot} = 1$, $\Lambda = 0$).

For scales $\theta > 10'$ we can treat the recombination as an instantaneous process and explicitly calculate background anisotropy:

$$\frac{\Delta T}{T}(\underline{e}) = -1/2\ e^\alpha e^\beta \int_{\eta_{rec}}^{\eta_0} \dot{h}_{\alpha\beta}\, d\eta + (\dot{v} + e^\alpha v_{,\alpha})_{\eta=\eta_{rec}} \qquad (10)$$

where $\dot{h}_{\alpha\beta}$, $\delta_b = 3\dot{v}$ and $u_b^i = (1; -v_{,\alpha}/a)$ are metric, baryon density and velocity perturbations in the synchronous, co-moving with relic particles, reference system; all the functions are taken on the light-cone; $(^\cdot) = \partial/\partial\eta$; $(,\alpha) = \partial/\partial x^\alpha$. The first term in the right-hand-side of eq. (10) is due to the gravitational field perturbations [17]. The second and third terms represent distortions and motions of the sphere of the last scattering of photons, due to baryon density [18] and velocity [19] perturbations. On scales $\theta < 10'$ the recombination process via which the cosmic plasma transforms from the opaque to transparent state, should be taken into account.

The correlation scale of the ξ (θ) function appears to be $\theta_c \sim 20'$ [16]. At $\theta > 20'$, the dominant contribution in the relic-particle models comes from the integral (10), two next terms are essential for models (c,d).

In models with unstable particles the hydrogen recombination process may well be essentially slower due to a possible secondary ionization of plasma by the products of decay. This leads to weaker small-scale fluctuations $\Delta T/T$ ($\theta < 5°$) [20].

For large-scale calculations ($\theta > 5°$) only the integral in eq. (10) is important with the lower integration limit vanishing. Thus, $\Delta T/T$ predictions in this region do not depend at all on the recombination and secondary ionization dynamics, they are directly linked to the primordial metric perturbations.

4. RESULTS FOR $\Omega_{tot} = 1$

Fig. 1 presents the results of $\Delta T/T$ (θ) calculations for ν- and b-models with n = 0. The upper curves correspond to an ideal antenna, whereas the middle ones show an expected $\Delta T/T$ for the antenna beamwidth $\theta_a = 5°$ [2]. The dotted curves show the expected level of fluctuations in small and large angular scales when secondary ionization of cosmic plasma is taken into account [20]. (It is assumed here that massive neutrinos decay with $\sim 10^{-9} - 10^{-8}$ probability over the period of $10^{14} - 10^{16}$ s by producing γ - quanta with energy $10 - 10^2$ eV). Arrows ($\downarrow$) show the experimental restrictions [21-24]. Arrows ($\uparrow$) show the increasing large-scale anisotropy in model (b) due to possible growth of the correlation scale of galaxies. If $\xi_c \sim 30$ Mpc [6], then $\Delta T/T$ ($\theta \geq 5°$) fluctuations in ν- and b-models become of the same order.*

* P.D.Naselskij, private communication.

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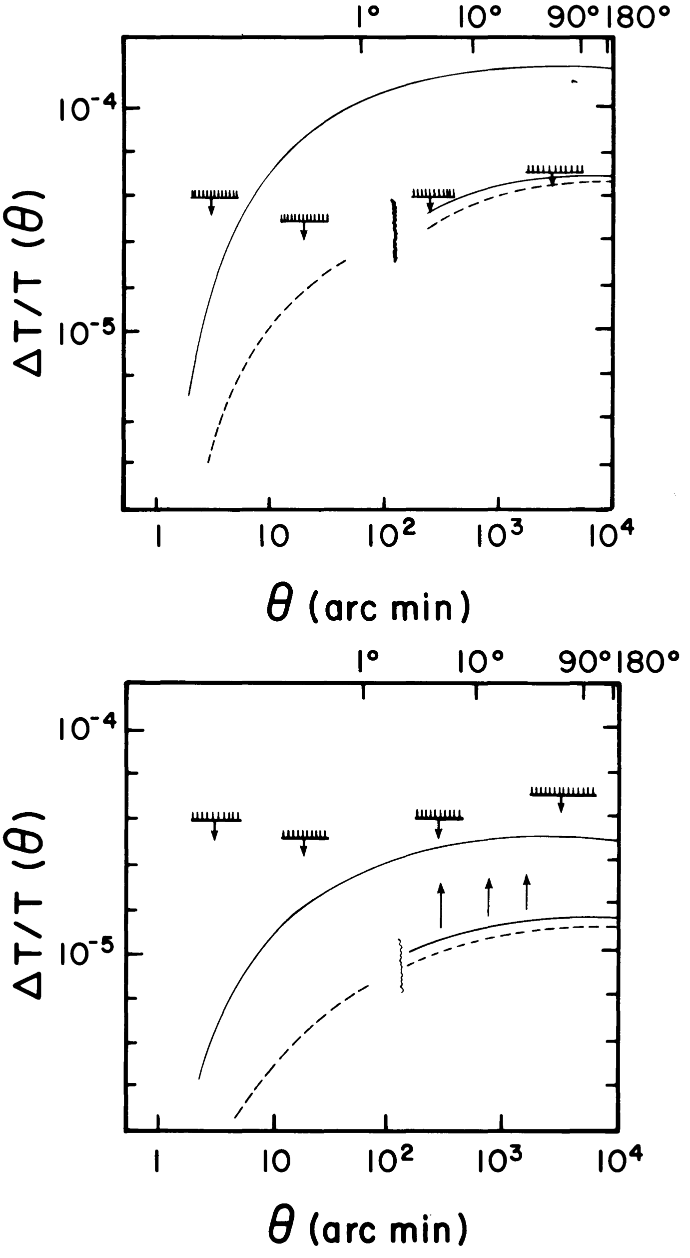

Fig. 1. The anisotropy of the microwave background ΔT(θ)/T in stable neutrino model (upper panel) and in axion or very heavy particle model (lower panel). Observational restrictions: (4.5') [21]; (10') [22]; (6°) [23]; (10°-90°) [24].

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Dark mass $\Delta T/T$	ν	a	b	c	Baryons; stable ν with $\Lambda\neq 0$
$l = 2$ $((2\times10^{-5})$	2×10^{-5} [2,31]	2×10^{-5} [14]	4×10^{-6} [13,2,31]	10^{-5} [15]	$>5\times10^{-5}$
ξ (6°) (5×10^{-5})	5×10^{-5} [2]	5×10^{-5} [14]	10^{-5} [2]	2×10^{-5} [15]	$>10^{-4}$
ξ(20')	10^{-4} [16]	2×10^{-5} [25]	2×10^{-5} [16,31,32]	8×10^{-5} [16,15]	$>10^{-4}$
ξ(20') secondary ionization	$\sim10^{-6}$ [20]	-	$\sim2\times10^{-7}$ [20]	-	-
UW (3×10^{-5})	10^{-5}	3×10^{-6}	3×10^{-6}	2×10^{-5}	-
P (10^{-5})	5×10^{-5}	10^{-5}	10^{-5}	4×10^{-5}	-

Table I. $\Delta T/T$ anisotropy in different models of dark matter (n=0, $\Omega_{tot}=1$, ν - stable neutrinos, a - decaying neutrinos, b - axions or very heavy particles, c - models (b) with $\Omega_\Lambda = 0.8$). Observational data are given in parentheses (large-scale $\Delta T/T$ restrictions for quadrupole (l=2) and dispersion ξ(6°) [24] and small-scale $\Delta T/T$ restrictions of [21] (UW) and [22] (P)).

	l	n = 0	n = -1	n = 1
ν	1	10^{-2}	1.5×10^{-2}	10^{-2}
	2	2×10^{-5}	4×10^{-4}	$<10^{-5}$
b	1	2×10^{-3}	3×10^{-2}	2×10^{-3}
	2	4×10^{-6}	7×10^{-5}	$<10^{-6}$

Table II. Dipole (l=1) and quadrupole (l=2) $(\Delta T/T)_l$ amplitudes for different spectra of primordial perturbations.

In models with decaying neutrinos ($\tau_{dec} \simeq 1\text{-}5 \cdot 10^{16}$s, $z\tau \simeq 4\text{-}10$, $m_\nu \simeq 40\text{-}150$ eV) the level of small-scale fluctuations $\Delta T/T$ becomes lower by a factor of ~ 4 [25]. At large scales, $(\Delta T/T)_l$ anisotropy increases by a factor of 3 for $l < z_\tau$ (and is of the same order for $l > z_\tau$) compared to the models with stable neutrinos with the same m_ν, this may provide a test for the decaying neutrino model (a) [14]. The quadrupole component $\Delta T/T$ (l=2) recalculated for the experiment [24] (n=0), is as follows [14]:

$$(\frac{\Delta T}{T})_2 \simeq 8 \cdot 10^{-5} \, (\frac{24 \text{ eV}}{m_\nu}) \; . \tag{11}$$

The amplitude (11) becomes less than quadrupole anisotropy in the standard model ($2 \cdot 10^{-5}$) only if $m_\nu > 100$ eV. In models with Λ-term ($\Omega_\Lambda \simeq 0.8$) the amplitude of small-scale $\Delta T/T$ fluctuations increases by a factor of about 4, whereas large-scale fluctuations almost double [15,16]. The data about expected $\Delta T/T$ for n = 0 are summed in table I (the observational restrictions are given in parentheses). The last two lines show the value of $\Delta T/T$ for the experiment [21]

$$(\frac{\Delta T}{T})_{UW} = [2(\xi(1.5') - \xi(4.5')) - 1/2(\xi(1.5') - \xi(9'))]^{1/2}$$

and the expected value of $\Delta T/T$, which is compared to the experiment [22]

$$(\frac{\Delta T}{T})_P = [2(\xi(4.5') - \xi(9'))]^{1/2} \; .$$

Table II shows dipole and quadrupole components of $\Delta T/T$ for the ν- and b-models for various kinds of spectra [2].

5. SPOTTINESS

A radically new effect in the large-scale $\Delta T/T$ structure occurs in an open Universe. In this case the Universe 3-space curvature results in a new correlation scale $\Theta_c{}' \simeq \Omega_{tot}$ [26-28].

The spotty structure effect may be qualitatively explained as follows. The field of random primordial perturbations $q(\underline{x})$ is homogeneous on the average, that is, the distribution does not depend on the $\underline{x}$ point. In the Lobachevski space (3-space of the homogeneous model) such fields may be presented as a random superposition of a full set of eigenfunctions, each with constant amplitudes over the space. These functions are plane-wave analogs in the Lobachevski space [27].

Each of such waves forms a "spot" in the large-scale $\Delta T/T$ distribution with an angular dimension $\Theta_0 = 2 \tan^{-1} (\exp(-h\eta_0)) \simeq \Omega_{tot}$; here $h\eta_0$ is the ratio of today's horizon (η_0) to the curvature radius (h^{-1}). With $h > 0$ ($\Omega_{tot} < 1$) the random distribution of spots (with the fixed q_k spectrum) yields a statistical distribution $\delta T/T$ (θ) with the correlation scale $\theta_c' \simeq \theta_0$. If $h = 0$ ($\Omega_{tot} = 1$) the spot degenerates into a quadrupole structure ($\theta_0 = \pi/2$), and the spotty-structure effect is not present, since any superposition of quadrupoles is again a quadrupole.

The correlation scale θ_c' also depends on the primordial spectrum, hence if $\Delta T/T$ anisotropy over the range $\theta > 5°$ is found both the spectrum q_k and the total density of matter Ω_{tot} can be determined.

6. CONCLUSIONS AND DISCUSSIONS

The basic conclusions for the flat model of the Universe (Ω_{tot} = 1) and the flat spectrum of primordial perturbations ($n = 0$) is as follows.

1. The standard model of the inflationary Universe with massive neutrinos (both stable and decaying) as missing mass contradicts the large scale $\Delta T/T$ limits [2]. The mismatching factor here is ~2 thus the final conclusion is only possible if the accuracy of measurements is improved.
2. The minimum predicted anisotropy level $\Delta T/T$ limits ($\theta > 6°$) may be detected if the RELIC experiment [24] sensitivity is improved to $\sim 6 \cdot 10^{-6}$.
3. The $\Lambda \neq 0$ models with baryon or stable neutrino missing mass disagree with current observations.
4. All models except those in item 3 do not contradict the limit [21], however, stable neutrino models and all models with $\Lambda \neq 0$ contradict the data [22].
5. The secondary ionization reduces $\Delta T/T$ ($\theta > 1°$) to the level $< 8 \cdot 10^{-6}$ [20]. A test for secondary ionization is to measure polarization which may reach here several tens percent with respect to $\Delta T/T$ anisotropy [29].

The flat spectrum ($n = 0$) is a crucial test in the $\Delta T/T$ problem. White noise ($n = -1$) practically contradicts the present - day observations while decaying spectra ($n \geq 1$) reduce the expected level of large-scale $\Delta T/T$ fluctuations. Note that spectra falling toward longer waves are predicted by the theory of parametric amplification of perturbations [10] and by inflationary theories of isothermal perturbations [28].

The optimal range of search for $\Delta T/T$ is $20' < \theta < 90°$. In case $\Delta T/T$ is detected at the angular scales $\Delta > 5°$ the spectrum of primordial perturbations q_k and the total matter density in the Universe Ω_{tot} could be determined [2].

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DISCUSSION

SILK: Could you give us some more details about the RELIC microwave background experiment, particularly about the confidence level of the measurements?

LUKASH: The first results of the RELIC experiment are as follows. The best scans cover about a fifth or a quarter of the sky. For these, contamination from the Moon and the Galaxy is less than 0.5 μK. The satellite was at about 10^6 km from the Earth and the scans were each about seven days long. During this length of time, the rotation of the satellite caused each point on the sky to be measured 10^6 times. This gives the very high sensitivity of the results. Each scan consists of observations of 120 points, where each point measures an area of the sky of ~6°×6°, the beamwidth of the antenna. On any scale ~6° or greater, the deviations from isotropy are found to be less than $\Delta T/T = 5\times10^{-5}$. If we assume that the primordial fluctuations were flat, this gives an upper limit to the amplitude of the quadrupole of 2×10^{-5}. This figure is a purely observational result not dependent on any theoretical assumptions.

LUBIN: What is the confidence level of the limit on fluctuations on the 6° scale? What is the value of the directly measured quadrupole?

LUKASH: There isn't a direct measure of the quadrupole term. The limit I gave is for temperature fluctuations on scales from 6° to 90°, but of course applies to any multiple harmonic, including the quadrupole term. If you assume Gaussian fluctuations, the upper limit on the quadrupole term is 5×10^{-5}. If you assume a flat spectrum, the limit drops to 2×10^{-5}. The confidence level of these values is 95%.

BURKE: When I look at the all-sky RELIC data, I agree that you have the accuracy you have quoted on 6° scales. But on the 90° scale I can see large-scale irregularities beyond the dipole term which look as though they are associated with the Galaxy. That is, there are fluctuations in the brightness of the background which are not the dipole term, but which have a scale larger than 6°, and which look as though they are along the galactic plane. I think that it is very hard to get an accuracy of 5×10^{-5} on the 90° scale when you can already see irregularities on a scale of ~60°.

LUKASH: Yes, of course, you are right. But as I said in my talk, data from only about a quarter of the sky were used to set the quoted limit. It was not found from the all-sky data. The influence of the Galaxy is quite subtracted from this result.

WILKINSON: The reason you can't get the large-scale measurement out of the RELIC data is that the sidelobes of the antenna are too large. For example, the Earth and Moon are seen even when the antenna is pointed far away from them. So there will be a lot of large-scale contamination in the RELIC data. I think that this is why you have to extrapolate from the 6° scale given by the antenna beamwidth to larger scales.

LUKASH: I agree, but the limits on the quadrupole and octupole anisotropies that I gave are quite adequate.

USON: I shall not discuss the validity of the results by Parijskii that you quote as he is not here to argue about them. But I would like to point out that when they were presented three years ago at IAU Symposium 104, there was quite a bit of controversy about them. The general consensus was that before they could be accepted, a thorough description had to be published. I have not seen this; has it been published yet?

LUKASH: Yes, the latest publication I know is that by Korolkov, D. V., and Parijskii, Yu. N. (1985), Communications of Special Astrophysical Observatory, 41, 42, 43. I'm still not sure what theoretical quantity should be compared with their results.

PEEBLES: You've given a very clear description of the value of $\Delta T/T$ expected from primeval adiabatic perturbations. Have you also considered the possibility of primeval isocurvature perturbations in which density is constant?

LUKASH: Yes. An analysis of the spectrum of isocurvature perturbations on all scales has been made by Starobinski and colleagues. If you take a flat spectrum, the predicted amplitude for isocurvature perturbations will be at least six times greater than that predicted for adiabatic perturbations. So in any case you should choose another spectrum for isocurvature perturbations. Alex Szalay has already mentioned the work of Kofman and Linde, who proposed an inflationary model in which they could get isocurvature perturbations which have a flat spectrum up to some scale and then an abrupt decay. This model is good for describing large-scale fluctuations.

FELTEN: You mentioned results of Kofman and Starobinski for a model with nonzero Λ. Are these limited to a specific model? For example, were they derived for a model with flat space and $\Omega_0 \approx 0.2$?

LUKASH: Yes. They consider flat space with arbitrary Ω due to Λ, but the figures I mentioned are for $\Omega_0 \simeq 0.2$ and $\Omega_\Lambda \simeq 0.8$.

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