THE ANISOTROPY OF THE MICROWAVE BACKGROUND: SPACE EXPERIMENT RELICT

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ABSTRACT

We carried out the first satellite experiment for searching the anisotropies of the microwave background. The main goal of the experiment was to obtain a radio brightness map of the sky at 8 mm. We obtained the direction and amplitude of the dipole component at 90% confidence level

$$\alpha = 11^h17^m \pm 10^m; \quad \delta = -7.5° \pm 2.5°; \quad T_D = 3.16 \pm 0.12 \text{ mK}.$$

The variance analysis gives the most stringent constraints on fluctuations of the relic background. For the model with the Zeldovich spectrum of primordial fluctuations we found an upper limit on the quadrupole as 1.6×10^{-5} at 95% level. We are first to obtain model-independent estimates of the first 15 multipole components. We obtained upper limits on correlation function of angular fluctuations

$\langle \Delta T_1 \Delta T_2 \rangle = 0.005$ mK^2 for the angular range from 20° to 160°. Intense galactic emission was observed over longitude interval from 90° to 270° and latitudes ±5°. The total flux from this longitude interval is approximately 56,000 Jy. The experiment studies confirmed that a space experiment gives a possibility to reach sensitivities high enough to estimate an anisotropy that is less than the values predicted by modern cosmological models.

INTRODUCTION

In the years since the discovery of the microwave background radiation searches for its anisotropy have brought very valuable information on the structure and evolution of the Universe. In spite of many efforts, the only determined deviations from the isotropy are the dipole anisotropy due to our motion through the background radiation

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(Henry 1971, Fixs n et al 1983, Lubin et al 1985) and departures from the isotropy toward rich clusters of galaxies (Birkinshaw et al 1984) thanks to the Sunyaev-Zeldovich effect (Sunyaev and Zeldovich 1970). The lack of any observed cosmological anisotropy on scales from seconds of arc to 90° and stringent upper limits on the fluctuations drastically restrict the choice of possible cosmological models. Theories predicting low values of fluctuations are preffered, e.g. inflationary models (Guth 1981, Starobinski 1980, Linde 1982, Rubakov et al 1982) and cosmological models according to which the missing mass is in the form of weakly interacting particles. Up to now, when analysing the large scale anisotropy, the main attention has been given to the quadrupole component. It was so because of relatively large expected amplitude of the quadrupole, its weak dependence on the presence or absence of secondary reheating of the Universe and because it was difficult to handle components of high order when analysing data of usual balloon experiments (Lubin et al 1985). Neverthless analysis of high harmonics now seems to be very important for two reasons. Firstly, a sum of multipoles or its combination like a correlation function may be a more sensitive test in finding fluctuations. Secondly, some cosmological models predicted breaks in the spectra of relic background fluctuations. Features of this kind occur in cosmological models with unstable neutrinos (Doroshkevich et al 1986, Kofman et al 1986) in models with small positive Λ-constant (Kofman and Starobinski 1985) and in two-stage inflation models (Linde 1985). So information on the spectrum of microwave background fluctuations could help us to discriminate between different cosmological models. For a given predicted spectrum of fluctuations the amplitude of the quadrupole may fluctuate 2-3 times from one sample to another and from the mean value predicted by a theory (Abbott and Wise 1984). Under such circumstances the spectrum of temperature fluctuations and sum of some large scale harmonics give values which have much smaller statistical deviations as compared with the quadrupole and so appear to be a more powerful statistics.

We present the results of multipole, variance and correlation analysis of the data obtained by RELICT experiment installed on the Prognoz-9 satellite. We would like to emphasize the following advantages of a space experiment in comparison with ground-based or balloon experiments: 1) it is possible to remove the systematic errors associated with the thermal emission of the Earth and its atmosphere; 2) a space experiment enables one to determine the level of instrumental noise to an extremely high accuracy and hence to use the method of variance analysis that gives the most stringent constraints on multipole components; 3) it is possible to increase essentially the total time of observations. We also note that a simple method of radiation cooling could be used to ensure 100 K temperature of equipment.

OBSERVATIONS AND DATA ANALYSIS

We have mapped most of the sky using an extremely sensitive 8 mm receiver with a degenerate parametric amplifier. The radio telescope was carried on board the high apogee satellite Prognoz-9 launched on July, 1, 1983. The RELICT mission was ended in February 1984. Prognoz-9 was the first satellite specifically designed for cosmological studies. The satellite was put into an eccentric orbit with the perigee 1,000 km, the apogee about 0.7 mln km, the inclination 65.5° and the period 27 days. These orbit parameters helped to reduce the effect of the Earth's and Moon's emission. Elyasberg and Eysmont showed the possibility of such an orbit. The satellite spins at 0.5 r.p.m. about its axis of symmetry which is directed to Sun. The radio telescope Relict has two antennas. One antenna is directed away from Sun and the other is crosswise directed and sweeps rapidly across the great circle of the sky. The receiver input is constantly switched over from one antenna to another. The output of the receiver is proportional to the difference between antennas temperatures. The sweeping of each great circle took about a week. The displacement of the rotation axis from the direction to Sun amounted to 7° per week. After correction the sweeping of the next great circle was performed. Thus the whole sky was covered in half a year. The data were recorded on a magnetic tape and subsequently transmitted to Earth.

The emission of the Moon and Earth contaminated the data. Fortunately it is not difficult to estimate the possible maximum contribution of the sources to the antenna temperature and to eliminate the contaminated data from subsequent data analysis. As a threshold we chose 0.5 mK.

The total number of measurements was 15 millions that made up 31 individual scans. 22 scans were used further analysis. Statistical weights of points within ±15° of the galactic plane were assumed to be equal to zero. The rest of the data covered about 70% of the celestial sphere. The data were smoothed by 7° Gaussian filter truncated at 14°. The smoothed r.m.s. variance was 0.2 mK. The smoothed radio brightness map is shown in Fig. 1.

Two methods of data analysis were used. The first one is the variance analysis which gives estimates of anisotropy for given spectra of fluctuations. We adopted the

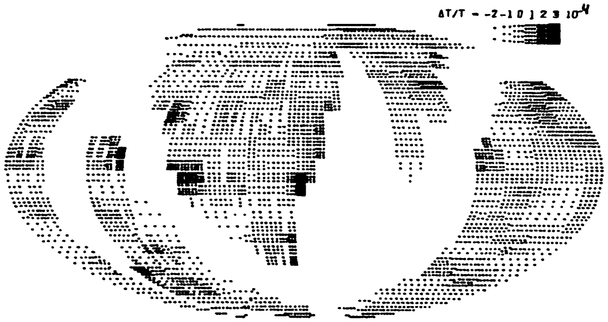


Fig. 1. Radio brightness map at 8 mm (the dipole component is subtracted). Ecliptical coordinates are chosen, zero longitude is on the right.

Zeldovich spectrum of primeval fluctuations and the spectrum of temperature fluctuations on the sky $1/\ell(\ell+1)$, where ℓ is the order of a spherical harmonic. The method was applied to the set of separate scans (Strukov and Skulachev, in preparation, Strukov et al, in preparation) and to the map of observed distribution of the temperature fluctuations on the sky.

The second method was the harmonic analysis. A numerical model which simulates main features of the experiment (such as the response of the receiver, the noise of the instrument and so on) and all stages of data reduction including incomplete coverage of the sky and inaccuracies of procedure was constructed. The model allows us to obtain upper limits on $\Delta T/T$ fluctuations by testing the passage of a given cosmological signal through the instrumentation and through all stages of data reduction and afterwards comparing it with the results for pure noise of the equipment. The approach was applied to both the variance and harmonic methods of analysis. Usually 100-200 samples were generated for confident estimates of signals.

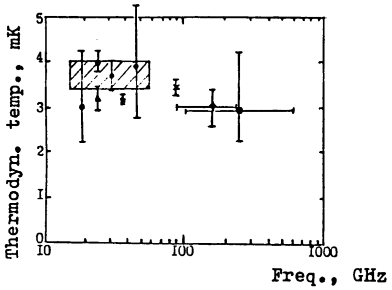
RESULTS

The dipole anisotropy

In our experiment we have received the dipole components with following parameters for the 90% confidence interval:

$$T_D = 3.16 \pm 0.12 \text{ mK}; \quad \alpha = 11^h 17^m \pm 10^m; \quad \delta = -7.5° \pm 2.5°.$$

For comparison we have presented the results of our work and those of other research groups in Fig. 2 and Table 1. The method by which the dipole component was determined is described in Strukov and Skulachev (in preparation), Strukov et al (in preparation).



● - Boughn et al 1981;
▲ - Fixsen et al 1983;
★ -'Relict';
x - Lubin et al 1985;
♦ - Lubin 1984;
■ - Lubin 1984;
▨ - Boughn et al 1981.

Fig. 2. Estimates of the dipole obtained by different groups.

Table 1

	Moscow (Relict)	Berkeley (Lubin et al 1985)	Princeton (Fixsen et al 1983)
δ, deg	-7.5 ± 2.5	-6 ± 1.5	-8 ± 2
α, hr	11.3 ± 0.16	11.2 ± 0.1	11.2 ± 0.1
T_D, mK	3.16 ± 0.12	3.44 ± 0.2	3.18 ± 0.2

The quadrupole anisotropy

We obtained the upper limit for the quadrupole component $C_2^2 = (\Delta T/T)_q = 1.6 \times 10^{-5}$ with 95% confidence for the cosmological models with the Zeldovich spectrum. The harmonic analysis gives a spectral independent estimate (for any spectrum of primordial fluctuations) of the upper limit on observed quadrupole component

$$(\Delta T/T)_q \leq 3 \times 10^{-5}.$$

Table 2 presents upper limits on quadrupole obtained with variance analysis for different types of cosmological spectra.

Table 2

Cosmological spectrum of $\Delta T/T$, C_ℓ^2	Angular resolution	R.m.s. fluctuations on the sky, mK		Upper limits	
		measured	noise ($\pm 2\sigma$)	quadrupole	$\sum_{C=2}^{25} C_\ell^2$
$\sim(2\ell+1)/\ell(\ell+1)$	7°	0.18	0.2 ± 0.02	1.6×10^{-5}	3.6×10^{-5}
$\sim$const	3.5°	0.31	0.32 ± 0.02	1.2×10^{-5}	5.7×10^{-5}
$\sim(2\ell+1)$	3.5°	0.31	0.32 ± 0.02	6.0×10^{-6}	7.0×10^{-5}

Multipole components

Table 3 presents the results of harmonic analysis of 10 multipole components. The first row is order of a sphere harmonic. The second row is the measured value of the amplitude of the spherical harmonic. The third row is the upper limit of the corresponding harmonic. Fig. 3 shows upper limits obtained by harmonic analysis for $\ell = 10$ and $\ell = 15$. Costraints obtained with variance analysis for different types of spectra are also presented. We should note that the results we presented would be taken without any correction because all necessary effects (like an antenna directivity, incomplete coverage of the sky and so on) already were taken into account. We determined the correlation function

$$\langle \Delta T_1 \Delta T_2 \rangle \leq 0.005 \text{ mK}^2.$$

The constraints on the correlation function are shown in Fig. 4.

Table 3

Harmonic, ℓ	2	3	4	5	6	7	8	9	10
Measured $(\Delta T/T)_\ell \times 10^5$	1	3	3	2	3	2.5	2.5	2	3
Upper limit of $(\Delta T/T)_\ell \times 10^5$	3	7	5.5	4	5	3.5	4.5	4.5	4.5

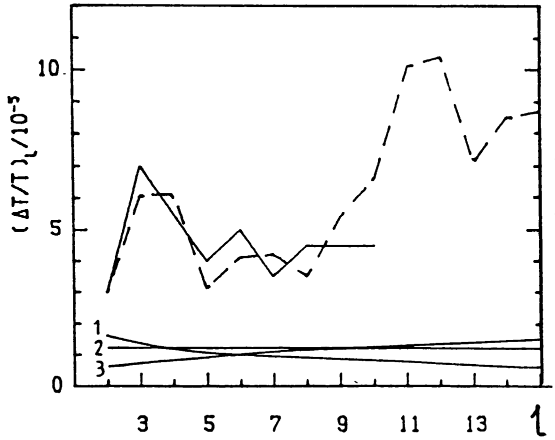


Fig. 3. Upper limits on spectral components. The full line - ℓ=10 (121 independent harmonics); broken line - ℓ=15 (256 harmonics). Curves labeled by numbers show constraints obtained for different kinds of $\Delta T/T$ spectra. The numbers correspond to spectra given in Table 2.

The galactic contribution

Intense emission is observed between galactic latitudes ±5° and longitudes from 90° to 270°. The total flux from this region is determined of 56,000 Jansky, twice that is calculated by Mezger (1978). The excess rsdiation may be explained by the emission from giant HII regions or some other sources with flat spectrum of radiation.

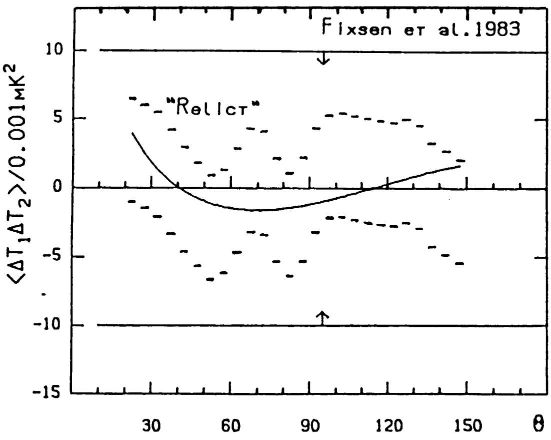


Fig. 4. Constraints on correlation function of the background fluctuations at 99% level of confidence. The full line presents correlation function for the spectrum $C_\ell^2 \propto (2\ell+1)/\ell(\ell+1)$ (Starobinski 1983) for which the quadrupole is $2\text{x}10^{-5}$.

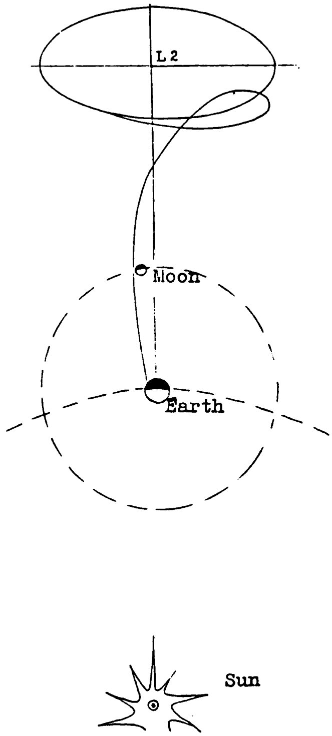


Fig. 5. The orbit of proposed experiment.

FUTURE PROSPECTS

The results of the RELICT experiment indicate that in order to detect the fluctuations of microwave background it is necessary in future experiments to improve the instrument sensitivity and take care of systematic errors due to the Moon, Earth and galactic emission.

The experimental studies carried out confirmed that the using of degenerate microwave parametric amplifiers in satellite-based radio mapping systems appears to be promissing. Laboratotry experiments have indicated that it is possible to construct millimeter-wavelength systems with noise temperature $T_{DSB} < 50$ K when the receiver module is cooled via the radiation loss of heat into space. That permits to detect or put upper limit for the quadrupole component with the 95% confidence level $(\Delta T/T)_q \leq 1\text{x}10^{-6}$

for models with the Zeldovich spectrum. The presence of rather intense radio emission along the galactic plane requires a multi-frequency experiment to study the anisotropy in the background radiation. We can avoid the thermal Earth's and Moon's emission by choosing a special orbit in the vicinity of the libration center L2 (see Fig. 5) (Boyarski 1986, Elyasberg and Tymokhova 1986, Elyasberg et al 1986). We are going to carry out an experiment in 4-5 frequency ranges from 20 GHz to 150 GHz.

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