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Infrared limit on the fine-scale anisotropy of the cosmic background radiation

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The cosmic-background anisotropy has been investigated at the angular scale of 25 minutes of arc by means of a special isotropometer at the alpine station of Testa Grigia (3500 m above sea level) through the atmospheric window 1.0–1.4 mm. We found an upper limit $\Delta T/T \lesssim 1.2 \times 10^{-4}$ at two standard deviations. Some physical implications about the origin and the rotation of superclusters and about the secondary ionization of plasma are discussed.

I. INTRODUCTION

The universe is permeated by a uniform background of electromagnetic radiation ranging from radio waves to γ rays. In recent years it has become increasingly apparent that fine-scale anisotropies of such a background contain as much information about the physical nature of the radiation as do the intensity and the spectrum. For instance, the study of the fine-scale fluctuations in the radio background (1–500 MHz) has proved that it is due to all the radio sources in the sky added together, and that the radio sources were more numerous in the past than they are now. Restrictive limits have been posed on the density and luminosity of the sources. In the frequency region 500 MHz–500 GHz a microwave background has been discovered by Penzias and Wilson,[1] and Dicke, Peebles, Roll, and Wilkinson,[2] and its existence apparently fitted perfectly in the framework of the hot big-bang theory. Because of the poor number of experimental data in cosmology, one can easily understand the importance of a detailed investigation of the properties of the microwave background, for instance, its angular distribution. Searches for the anisotropy of the background have been carried out in two regimes: on a large angular scale (θ~24 hours) and a small angular scale (θ~1°). Measurements at large scale[1-8] give us information about the anisotropy of the cosmological expansion and the motion of the solar system with respect to the frame at rest with the radiation.

In this paper we are involved with fine-scale anisotropies, which can tell us about the following phenomena:

(a) Density fluctuations of the primordial matter, which can be held responsible for the condensation of bound systems, such as galaxies, clusters, superclusters.[9-18] These fluctuations can be further divided into initially adiabatic perturbations (where both matter and radiation density oscillate), and entropy perturbations (where only the density of the matter oscillates). Both kinds of fluctuations can affect the isotropy of the microwave background.

(b) Vorticity perturbations, which might have produced density fluctuations and then the bound system, through the decay of turbulent eddies.[19-23]

(c) The secondary ionization of hydrogen, which is supposed to have occurred after the end of the plasma era. If it occurred inhomogeneously some anisotropy may have been induced in the background.[12,13,24,25,26]

(d) The contribution of discrete sources to the background. According to some models the entire microwave background would be due to emitting galaxies.[27-32] Small-scale measurements can set limits on these models.

Several investigators have contributed to the search for the fine-scale fluctuations.[1,4,33-42] Radio receivers have been used in the wavelength region between 3 mm and 4 cm with beamwidths between 80 arc sec and 15°. The upper limits found by these authors appear to be on the verge of a discovery. One would need the sensitivity to be higher by one order of magnitude.

As a consequence of the recent advances in detection techniques our interest has been turned toward the infrared region of the microwave background. The acquisition of such infrared data represents a natural extension in our knowledge of the properties of the microwave background measured in the radio region of the spectrum.

Two reasons suggest the choice of the millimetric region:

(1) Previous observations in the radio region are observing-time limited. The use of a wideband infrared bolometer could allow us to measure an anisotropy of 10^{-4} in about one hour of integration while the same accuracy with the best of radio systems in previous measurements would require several hours.

(2) The differential brightness arising from temperature fluctuations is described by a spectrum of the type

$$dI = I^\circ \frac{xe^x}{e^x-1}\frac{dT}{T}, \quad x=\frac{hc}{kT\lambda},$$

and it has a maximum around 1 mm of wavelength. An atmospheric window coincides with the maximum of the differential brightness allowing ground-based observations.

Thus the conditions are rather favorable to the measurements of cosmic-background anisotropies, although local anisotropies (dust emission in our galaxy in particular) may perturb them more than at 8 mm.

The selected beam width, $\theta = 25'$ corresponds to primordial fluctuations whose present characteristic length is of the order of 20 Mpc.

II. OBSERVATIONAL TECHNIQUES

The fine-scale isotropometer used in the present experiment consists of a germanium bolometer matched with a 150-cm flux collector, as shown in Fig. 1. The signal produced by the microwave background increases linearly with the throughput (AW cm^2 sr) to the detector. However, beyond a certain value of AW the photon fluctuations become an important additional source of noise (warm optical components, such as windows, mirrors, etc., contribute to this noise as well as the residual atmospheric emission). Therefore practical considerations limit the throughput at the value for which the detector becomes background limited. This condition is fulfilled in our case for AW = 1 cm^2 sr.[43] The sensitive element (a gallium-doped Ge bolometer having dimensions of $3 \times 3 \times 0.1$ mm) has been mounted in a spherical cavity of radius 5 mm, terminated with an $f/2$ cone (box A of Fig. 1).

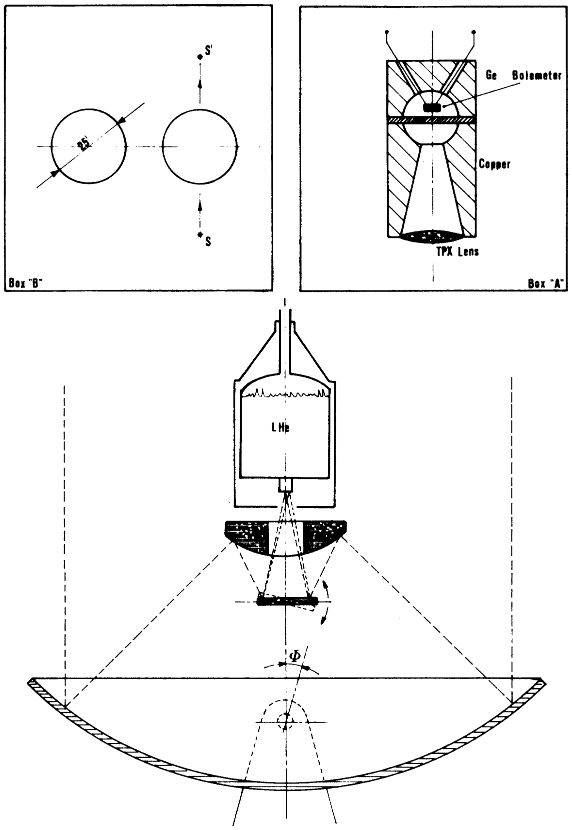

FIG. 1. Sketch of the isotropometer. The $f/2$ germanium bolometer is matched with a 150-cm flux collector by means of a hyperbolic mirror and a plane wobbling mirror. The wobbling mirror switches the 25′ field in the sky in a direction normal to earth's rotation (box B). A source in the sky would produce a signal positive or negative depending on its position with respect to the field of view. For long integration times the background anisotropies are thus canceled, and it is possible to measure the systematic effects produced by the atmosphere. Details of the detector are shown in box A (see also Ref. 43).

A combination of long-wave filters and narrowband meshes isolates the atmospheric window around 1 mm.[44] The measured noise-equivalent power (NEP) of the radiometer (detector plus filters) was found to be 1.5×10^{-13} W $Hz^{-1/2}$; about 40% of NEP is due to photon fluctuations. The measured responsivity at 1 mm was found to be 9×10^4 V/W. The radiometer has been mounted at the focus of the 150-cm flux collector. The responsivity of the isotropometer and its field of view have been measured using the moon and the sun as sources. The responsivity is $(4.5 \pm 0.5) \times 10^4$ V W^{-1} cm^{-2} sr^{-1} and the field of view 25 ∓ 2 arcmin at 20% of the peak. From these data we have evaluated the NET (noise-equivalent temperature) when observing the cosmic-background radiation, which is $(6.2 \pm 0.5) \times 10^{-3}$ °K $Hz^{-1/2}$. For comparison, a conventional telescope with a focal ratio ranging from $f/6$ to $f/10$ would require an integration time at least ten times larger in order to have the same sensitivity. The detector output is amplified and synchronously demodulated at the frequency of the wobbling plane mirror. The data are sampled every second.

An important atmospheric contribution to the signal is expected if the plane mirror does not wobble parallel to the horizon. An angular error $d\phi$ would produce a constant signal dI obtained by differentiating the Beer-Bouger law

$$dI = \epsilon I \sin\phi \cos^{-2}\phi\, d\phi,$$

where ϵ is the atmospheric emissivity, I is the intensity of a blackbody having the same mean temperature of the atmosphere, and ϕ is the angular distance from the zenith. In order to minimize dI we were forced to choose a dry site (small emissivity) and make observations at the zenith. We have carried out the measurements at the alpine station of Testa Grigia, 3500 m above sea level, during the winter season. Under favorable meteorological conditions the emissivity of the atmosphere was found to be as low as 1%.

When the telescope is pointed toward the zenith the maximum zenith distance is represented by the beam throw of ∓12.5 arcmin, so that the atmospheric effect dI can be written in terms of temperature dT as

$$dT = 3 \times 10^{-3} T_A d\phi,$$

where T_A is the temperature of the atmosphere at 1 mm (20–50 °K at Testa Grigia). The systematic effect produced by the atmosphere has been evaluated as follows (Fig. 2). The telescope was pointed toward various zenith distances and the output of the detector was integrated for one hour at each zenith distance. The motion of the earth smeared out the sky anisotropies so that the detected signal was due to systematic errors introduced by the instrument and/or the atmosphere. The dependence of the signal on the zenith distance discriminated between the two effects. The above procedure has been repeated many times, varying the position of the wobbling axis and carefully balancing the wobbling amplitude, until the minimum offset was obtained. During the observations the instrument was pointed toward the zenith and the wobbling direction was maintained normal to the earth rotation (box B, Fig. 1). A source would produce a signal constant in sign, when traveling from S to S' across the field of view. The earth rotation limited the observing time for each sky element to about 2 min, which allowed measurements of a minimum detectable anisotropy of $\Delta T/T = 2 \times 10^{-4}$ at one standard deviation.

III. THE MEASUREMENTS

The measurements were carried out during dry and clear nights in the winter. On ten nights we

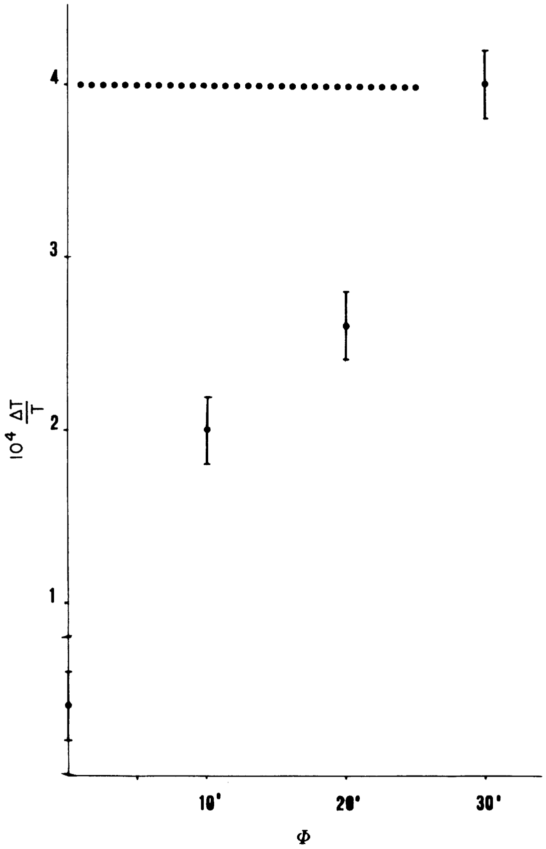

FIG. 2. Measurements of the instrumental offset plus the atmospheric effect, as illustrated in Fig. 1. The detector output is integrated for each zenith distance a time long enough to smear out the background anisotropies. The dependence on the elevation angle shows the atmospheric effect due to the angular error in the wobbling mirror. The dotted line indicates the sensitivity of the system when measuring the background anisotropies; each sky element is observed for two minutes at the zenith.

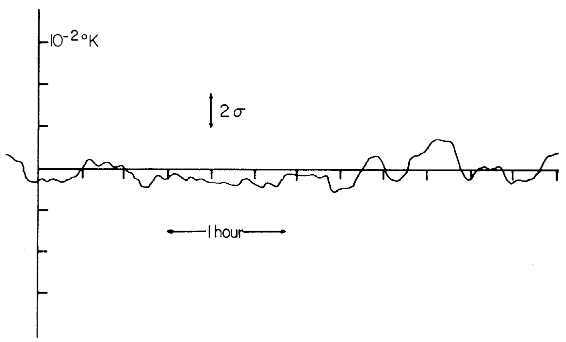

FIG. 3. Recorded output of the isotropometer during one night.

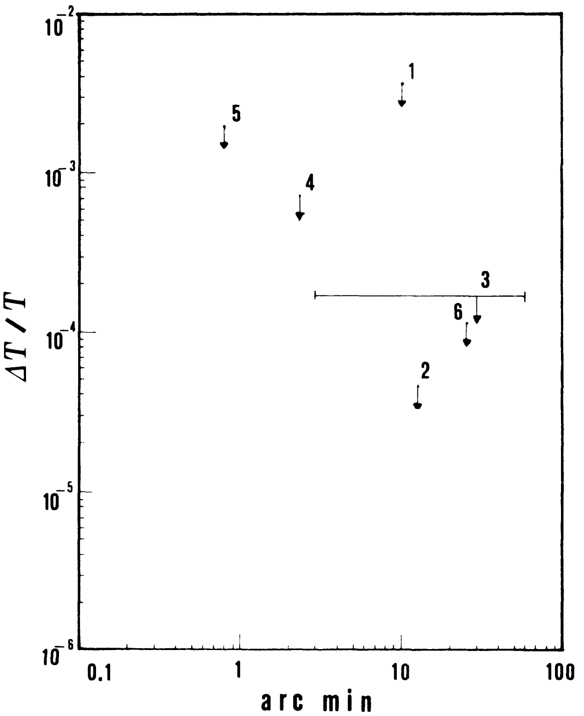

FIG. 4. Upper limits on the cosmic-background anisotropy at various angular scales. The measurements have been carried out at different frequencies, which are not quoted here. The numbers refer to the following authors: 1. Conklin and Bracewell (Ref. 35), 2. Parijskij (Ref. 40), 3. Parijskij (Ref. 42), Carpenter *et al.* (Ref. 41), 5. Boynton *et al.* (Ref. 38), 6. present work.

collected about six hours of useful data per night: 180 sky elements of $25' \times 25'$ were resolved and observed each night for two minutes per element. A typical output of the instrument is shown in Fig. 3. As can be seen from the figure, the standard deviation of one set of data is $\Delta T = 6 \times 10^{-4}$ °K corresponding to a maximum sky anisotropy $\Delta T/T = 4 \times 10^{-4}$ at two standard deviation. The data obtained in ten nights were averaged for each sky element. This procedure allowed us to reduce the upper limit for the sky anisotropy to 1.2×10^{-4} at two standard deviations. Therefore we can conclude that the background anisotropy at the wavelength of 1.2 ∓ 0.2 mm and at the scale $\theta = 25'$ has a probability less than 5% of being larger than $\Delta T/T = 1.2 \times 10^{-4}$ (see Fig. 4).

IV. DISCUSSION

In this section we shall derive some conclusions about the features of the perturbations expected to take place in a Friedmann universe. Our result gives upper limits to each of the different types of fluctuations considered in the Introduction. Let us examine in detail each case.

(a) Following Sunyaev and Zeldovich[13] we find that the background fluctuations are related to the amplitude of the adiabatic perturbations by

$$\Delta T/T \simeq 10^{-6}(1+27\Omega)(M\Omega^{-1}/10^{15}M_\odot)^{1/3}(1+Z_0)\,, \qquad (1)$$

where $\Delta T/T$ is the rms temperature variation, Ω is the ratio of the present matter density to the critical density of the universe, M is the mass associated with the half wavelength of the considered density perturbation, $M_\odot$ is the solar mass, and Z_0 is the red-shift such that the density perturbation $d\rho/\rho$ reaches the unit value (conventionally the date of birth of the proto-object). The angular scale is related to the mass M by the relation

$$\theta \simeq 10'(M\Omega^2/10^{15}M_\odot)^{1/3}\,. \qquad (2)$$

For M larger than the Jeans mass of adiabatic perturbations at the decoupling $M_j \simeq 10^{16}\Omega^{-2}M_\odot[1+(27\Omega)^{-1}]^{-3}$, that is, for θ larger than about $20'$, M should be replaced in Eq. (1) by the constant value M_j; the dependence of the fluctuations on the mass is frozen at this value. From Eqs. (1) and (2) and our result, we find the inequality

$$1+Z_0 \lesssim 2\,. \qquad (3)$$

This leads to the conclusion that superclusters of the scale of about 20 Mpc must have condensed rather recently in terms of the red-shift, if they were originated by adiabatic perturbations.

We should also consider that such perturbations could induce further anisotropy of the background, owing to Compton scattering of electrons during the recombination epoch.[13] The contribution due to this effect is

$$\Delta T/T \simeq 2 \times 10^{-5}(M\Omega^{1/2}/10^{15}M_\odot)^{1/3}(1+Z_0)\,. \qquad (4)$$

From our result an additional inequality comes out:

$$1+Z_0 \lesssim 3\Omega^{1/2}\,. \qquad (5)$$

Since Ω is not likely to differ too much from unity (the most probable value is 0.1), inequalities (3) and (5) are equally restrictive.

Entropy perturbations could affect the isotropy of the microwave background by means of the same mechanism of Compton scattering. Therefore inequality (5) holds for both adiabatic and entropy perturbations.

(b) Vorticity perturbations also could influence the anisotropy through Compton scattering. Anile and Motta[23] consider two extreme cases:

(i) Radiation was last scattered by vortices at the recombination epoch; then the following relation holds:

$$\Delta T/T \simeq \frac{\theta\Omega}{\pi}(1+Z_d)\omega_o/H_o\,, \tag{6}$$

where Z_d is the red-shift at the decoupling, H_o is the Hubble constant, and ω_o is the present value of the vorticity. Here and in the following formula θ should be expressed in radians.

(ii) The last scattering of radiation occurred at the secondary ionization of hydrogen (this phenomenon is assumed to take place at $Z_s < Z_d$). We have

$$\Delta T/T \simeq 25\Omega^{-1/6}(\theta/\pi\Omega)^{3/2}\omega_o/H_o\,. \tag{7}$$

Our result puts upper limits on the vorticity in those two cases: We find under the former assumption

$$\omega_o/H_o \lesssim 4\times10^{-5}\,\Omega^{-1} \tag{8}$$

and under the latter assumption

$$\omega_o/H_o \lesssim 5\times10^{-2}\Omega^{5/3}\,. \tag{9}$$

Assuming a value of H_o of 50 km sec^{-1} Mpc^{-1} we have

$$\omega_0 \lesssim 6\times10^{-17}\text{ rad day}^{-1} \tag{10}$$

$$\omega_o \lesssim 7\times10^{-14}\Omega^{5/3}\text{ rad day}^{-1}. \tag{11}$$

These results seem to exlude the existence of superclusters of 20 Mpc having angular velocity $\omega_o \gtrsim H_o^{-1}$, the so-called rapidly rotating superclusters.[45]

(c) Let us assume that a secondary nonequilibrium heating of plasma took place at the red-shift Z_s, and that the fluctuations of the electron temperature T_e were the same order of magnitude as the average T_e. Then the contribution to the temperature anisotropy of the microwave background is given by[12,13,24,26]

$$\Delta T/T \simeq y(x\coth\tfrac{1}{2}x - 4)\,, \tag{12}$$

where $x = hc/kT\lambda$ and

$$y = \int_0^{\tau(Z_s)} (kT_e/m_ec^2)d\tau\,. \tag{13}$$

Here m_e is the electron mass and τ is the optical depth for Thomson scattering. Since $x = 5.3$ in our case, we can derive an upper limit on y:

$$y \lesssim 10^{-2}\,. \tag{14}$$

The optical depth between reheating and us is not likely to be much larger than unity and might even be smaller. So the inequality (14) would imply $T_e \lesssim 10^6$ °K, if one assumes $\tau(Z_s) \sim 1$. Note that from measurements of the x-ray background the upper limit $T_e < 10^6(1+Z)$ °K was already established.[46,47]

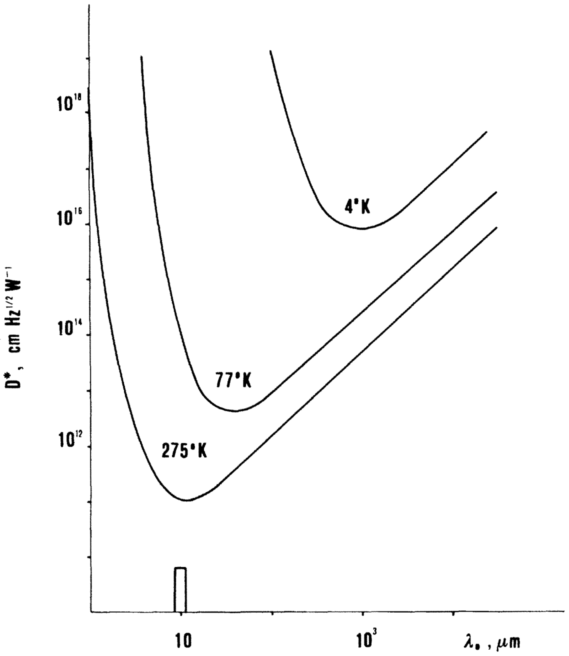

FIG. 5. Detectivity for a detector with a cold narrow-band filter under various backgrounds with 1 sr of field of view. At 1-mm wavelength the best available detectors are background limited for background temperatures larger than 50 °K.

(d) Most of the discrete source models of the microwave background proposed do not fit the available data on the fine-scale anisotropy, unless one assumes an unreasonably large number of sources.[30,48] The recent model proposed by Rowan-Robinson[32] is, however, consistent with such data. In particular, it is marginally consistent with Parijskij's upper limit[39,40] at a wavelength of 3 cm. In our case this model predicts an anisotropy $\Delta T/T \simeq 10^{-4}$, so it is also marginally consistent with our result. However, a difficulty of the model has been recently pointed out by one of us.[49]

V. CONCLUSIONS

We have found an upper limit of 1.2×10^{-4} for the microwave background anisotropy in the millimetric region. The physical implications of this limit have been discussed.

It is evident from the experimental details that our measurements are limited by the detector noise. The atmospheric effect at the zenith could allow detection of anisotropies as small as 10^{-5} °K, but an NEP smaller than 10^{-14} W Hz$^{-1/2}$ is required in order to measure such an anisotropy in two minutes. Both the intrinsic noise of the detector[50] and the practical limitation imposed by the quantum noise of the background can be reduced to this level. From Fig. 5 it is possible to see that the photon background is negligible for temperatures smaller than 50 °K. This condition is fulfilled by the atmosphere, but a very "clean" telescope is required in order to avoid emission from warm components. A special low-background isotropometer using a single, wobbling, off-axis mirror is under construction in our laboratory and will be used in future observations.

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