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NEW LIMITS ON SMALL-SCALE ANISOTROPY IN THE MICROWAVE BACKGROUND[1]

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ABSTRACT

We have searched for small-scale anisotropy in the cosmic microwave background using the maser receiver and 140 foot (43 m) telescope of the National Radio Astronomy Observatory, operating at a frequency of 19.5 GHz. The half-power beamwidth was 1'.5. Beam switching by 4'.5 was used in order to minimize variable contributions from ground and atmospheric emission and from the instrument. Our data set an upper limit of $(\Delta T/T)_{\rm rms} < 4.5 \times 10^{-5}$ at the 95% confidence level on fluctuations at the 4'.5 scale.

Subject heading: cosmic background radiation

I. INTRODUCTION

Shortly after the discovery of the microwave background radiation, Peebles (1967) pointed out that observation of fluctuations at small angular scale in this remnant of the early universe would provide direct information about the power spectrum and characteristic lengths and masses of the initial density fluctuations.

A number of observers have attempted to measure small-scale anisotropy in the microwave background at different angular scales and frequencies, but so far no such anisotropy has been detected. Limits on $(\Delta T/T)_{\rm rms}$ of 10^{-4} have been attained only by using many hours of integration and by paying careful attention to systematic effects. Equipment and techniques have now reached a level of sophistication such that considerable time and effort must be invested to gain a factor of 2 or 3 in sensitivity. For a comprehensive review of the observations, see Partridge (1983; see also Lasenby and Davies 1983).

Since December of 1980, we have been searching for small-scale anisotropy in the microwave background at an angular scale of a few arc minutes. Our first result was $(\Delta T/T)_{\rm rms} < 1.1 \times 10^{-4}$ (Uson and Wilkinson 1982). This *Letter* reports improved limits based on observations made in December of 1982 and May of 1983 using an improved observing strategy. A detailed discussion of the observations with a careful analysis of statistical and systematic effects will be published elsewhere (Uson and Wilkinson 1984).

II. OBSERVATIONS

We used the NRAO[2] 140 foot (43 m) telescope with the *K*-band maser receiver (Moore and Clauss 1979) tuned to 19.5 GHz. The bandwidth was about 370 MHz, and total system noise varied from 50 K to 70 K for the data used. The beam efficiency was 55% as measured by on-off scans of the moon. The half-power beamwidth was 1'.5.

The observations were made during 1982 December 27–31 and 1983 May 16–20. In December, the weather was never ideal, the sky being cloudy most of the time. Data taken during periods when cumulus clouds moved through the beam were very noisy and have been discarded. In May, the Sun shone onto the telescope primary and subreflector. Therefore, we decided to use only data taken between sunset and sunrise. All together, a total of 112 hours of data (out of 211 assigned hours) were used to get the result reported in this *Letter*.

Twelve fields chosen at declination 86°51' and right ascension $1^{\rm h}30^{\rm m}$, $3^{\rm h}30^{\rm m}, \ldots, 23^{\rm h}30^{\rm m}$ (epoch 1950) were measured. The beam was switched 4'.5 by nutating the secondary reflector at a rate of 3.33 Hz in order to minimize variable contributions due to atmospheric, ground, and telescope emission. The beam is switched along a fixed direction in the sky, making an angle of 112°.5 (east of north) with the hour circle of the field being observed. Each field is alternatively observed with the "+" beam (ON position) and the "−" beam (OFF position) in order to cancel the effects of slow drifts in the differential ground pickup and atmospheric gradients. Thus, the radiation temperature of the field position is compared to the mean of the radiation temperatures of two reference positions—REF1 (westerly) and REF2 (easterly)—4'.5 away.

The observing procedure was similar to the one used in our previous observations (Uson and Wilkinson 1982) with two modifications. Most importantly, the time spent in the OFF (REF1-FIELD) and ON (FIELD-REF2) positions was increased to $4^{\rm m}\,48^{\rm s}$ each. This gives the best possible cancellation of a systematic effect due to differential ground pickup because the telescope moves through nearly the same range of hour angle for each observation in an ON-OFF pair (see eq. [2]). The second change was inspired by the fact that, while the sensitivity to a possible sky signal in each field is proportional to the square root of the time that the field is observed, the overall sensitivity to a fluctuating sky signal is inversely proportional to the fourth root of the number of independent fields observed, for a given total observing time. Therefore, we reduced the number of observed fields from 24 to 12. Each

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field (and associated reference areas) was observed for about 2 hours on each day, between hour angles -2^h22^m and -0^h22^m. The ground effect is minimal in this range because the beam throw is horizontal at -1^h22^m.

III. DATA ANALYSIS AND RESULTS

We measure two sets of data for each field:

$$\delta T_{ON} = T_{FIELD} - T_{REF\,2} \tag{1a}$$

and

$$\delta T_{OFF} = T_{REF1} - T_{FIELD}, \tag{1b}$$

where T_{REF1} and T_{REF2} correspond respectively to the westerly and easterly reference positions. Values of T have been corrected to thermodynamic temperature and for the 55% beam efficiency of the telescope. The second level of switching ($\sim$ 0.2 minute^{-1}) gives the quantity measured for each field:

$$\Delta T_{FIELD} = (\delta T_{ON} - \delta T_{OFF})/2$$
$$= T_{FIELD} - (T_{REF1} + T_{REF2})/2. \tag{2}$$

Figure 1 shows the results for each of the 12 fields observed. $\overline{\Delta T}_{FIELD}$ is averaged over each 2 hour integration and then over all days observed. The error, $\bar{\sigma}_{FIELD}$, is estimated from the scatter in the measurements of each field. The variation of $\bar{\sigma}_{FIELD}$ from point to point is mainly due to the different number of days over which each field was observed. The weighted mean of the points in Figure 1 is $\overline{\Delta T}_{AVG} = (56 \pm 50)$ μK, and none of the 12 points differ significantly from the mean. We conclude that none of the observed fields show an anisotropy greater than 0.5 mK.

A more sensitive test is that used by Boynton and Partridge (1973). Here one asks whether there is evidence for a true statistical sky signal, σ_{SKY}, which has increased the scatter among the values of $\overline{\Delta T}_{FIELD}$ by more than what one expects from the scatter of the data from individual fields. This test

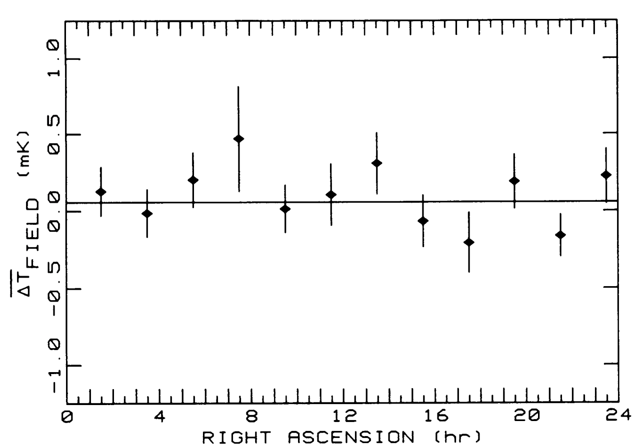

FIG. 1.—Final averages for observed fields. The solid line indicates $\overline{\Delta T}_{AVG}$, the overall weighted average. $\overline{\Delta T}_{FIELD}$ is the difference in thermodynamic temperature between the field (1'.5 in diameter) and the average of two reference positions, 4'.5 away (see eq. [2]).

requires an especially accurate assessment of the errors in Figure 1 (Lasenby and Davies 1983). The day-to-day scatter in the values of ΔT_{FIELD} averaged over 2 hours, ΔT^i_{FIELD}, could be larger than expected from the standard deviation σ^i_{FIELD} derived from the scatter of the data in those 2 hours; we are asking for exceptional day-to-day reproducibility of the entire system. Unfortunately, we do not have enough observations (days) on each field to constitute a good statistical test. Therefore, we use all of the observations to compute an instrumental χ^2. The weighted square residuals $(\Delta T^i_{FIELD} - \overline{\Delta T}_{FIELD})^2/(\sigma^i_{FIELD})^2$ are added. This χ^2 does not contain any sky signal as the residuals are computed with respect to the corresponding average for *each* field. The value of χ^2 is 50.3 with 48 degrees of freedom which indicates that our errors are accurately estimated.

Since σ_{SKY} contributes to T_{REF1} and T_{REF2}, as well as to T_{FIELD}, the rms residual in $\overline{\Delta T}_{FIELD}$ due to a true sky signal is (from eq. [2]):

$$\sigma^2_{rms} = (4\sigma^2_{SKY} + \sigma^2_{SKY} + \sigma^2_{SKY})/4 = \tfrac{3}{2}\sigma^2_{SKY}, \tag{3}$$

if σ_{SKY} is uncorrelated in the two beams. Our observing procedure is thus a probe of σ_{SKY} with $\sqrt{1.5}$ efficiency.

Applying the Boynton-Partridge (1973) statistics to our results gives:

$$\sigma_{rms} = (0.2 \pm 9.2) \times 10^{-5}\ \text{K}, \tag{4}$$

and, therefore, the statistical sky signal is:

$$\sigma_{SKY} = (0.1 \pm 7.5) \times 10^{-5}\ \text{K}. \tag{5}$$

Using 2.7 K for the temperature of the background radiation gives (in conventional notation):

$$(\Delta T/T)_{rms} < 4.8 \times 10^{-5}, \tag{6}$$

at the 95% confidence level.

Finally, combining these data with the data obtained for the same fields in December of 1981 (Uson and Wilkinson 1982) gives a limit

$$(\Delta T/T)_{rms} < 4.5 \times 10^{-5}, \tag{7}$$

at the 95% confidence level.

It is noteworthy that, owing to our improved observing strategy, analysis of these data is relatively simple and straightforward. For example, no systematic effect (with telescope position) is fitted and removed (see Uson and Wilkinson 1982). With the new ON-OFF procedure, no residual ground effect is detectable in the data; that is, ΔT_{FIELD} is not correlated with hour angle. Furthermore, the day-to-day scatter in ΔT_{FIELD} is consistent with the noise in the 2 hour observations; $\bar{\sigma}_{FIELD}$ is not inflated by long-term fluctuations in a systematic effect. The small value for the grand average of all data [$\overline{\Delta T}_{AVG} = (56 \pm 50)$ μK] attests to the effective cancellation of systematic effects. Finally, the result in equation (5) comes within a factor of 1.8 of the ideal value calculated from system temperature, bandwidth, and total integration time.

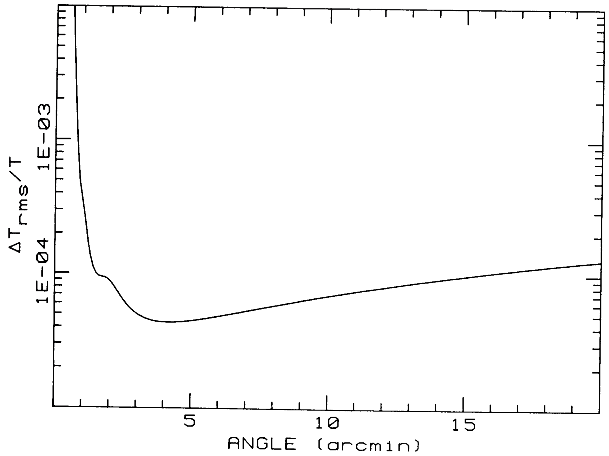

FIG. 2.—The 95% confidence upper limits implied by this measurement under the assumption of monochromatic angular fluctuations. The angle corresponds to the separation between "hot" and "cold" spots, i.e., it is equal to half the wavelength of the fluctuations.

This excess noise is due to weak, but fast (up to 30 Hz), fluctuations in maser gain and to fluctuations in the atmospheric gradient on time scales of the beam switching period.

IV. DISCUSSION

The final result, expressed in equation (7), follows the common trend of these kinds of measurements: as observing techniques are improved, the experiments yield more stringent upper limits, but no anisotropy is detected. Any such experiment is normally sensitive over a certain range of angular scales, and the limits implied by the result depend on what power spectrum is assumed for the underlying sky anisotropy. The observing procedure provides us with an "instrumental transfer function."

We have computed the limits on sky anisotropy implied by our measurement under the assumption that *all* this anisotropy is the result of a superposition of (spatially) monochromatic sine waves with random orientations and phases; so if *all* the anisotropy is due to fluctuations at a single angular scale, our measurement places a limit on the amplitude at that angular scale. The 95% confidence limit in the range from 1′ to 20′ is shown in Figure 2. The experiment is mostly sensitive at an angular scale of 4′.5, but the fluctuations on scales between 1′.5 and 15′ must be less than 1 part in 10^4.

A more realistic approach is to assume a reasonable power spectrum for the sky fluctuations and evaluate the limits that our measurement imposes on possible models. Several authors have calculated the expected anisotropy in the microwave background for various initial conditions (see Wilson and Silk 1981, and references therein). One assumes that the initial density perturbations are of the form $(\delta\rho/\rho)^2 \propto k^n$ and fixes the amplitude of the spectra by matching the evolved matter autocorrelation functions to the observed clustering of galaxies. If we compare the result in equation (7) to the predictions of Wilson and Silk (see also Wilson 1983), our measurement rules out almost all possible models of adiabatic fluctuations; only the model with $n = 4$ and density parameter $\Omega = 1$ barely survives. Predictions based on isothermal fluctuations are close but still below our limits, except models with $n < -0.4$ and $\Omega < 0.1$, which are excluded. Of course, isothermal models may be saved by introducing a recent epoch of reionization of the matter.

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