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INTERFEROMETRIC LIMITS ON VERY SMALL-SCALE FLUCTUATIONS IN THE COSMIC MICROWAVE BACKGROUND

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ABSTRACT

Using the three-element interferometer at NRAO Green Bank, we have searched for fluctuations in the cosmic microwave background at 2695 and 8085 MHz. For the lower frequency, the synthesized beam was $\sim 13''$, and we found $\Delta T/T \sim (7.2 \pm 4.0) \times 10^{-2}$. At 8085 MHz, the beam was $\sim 4''$, and $\Delta T/T \lesssim 4.0 \times 10^{-2}$ at $\sim 90\%$ confidence.

Subject headings: cosmic background radiation — interferometry

I. INTRODUCTION

The origin and very early history of galaxies are important, but as yet unsolved, problems in cosmology. Many authors (Silk 1968; Sunyaev and Zel'dovich 1970; Sunyaev 1977, and references therein) have recognized that the analysis of small-scale intensity fluctuations in the cosmic microwave background may provide useful information relating to the origin of galaxies. To date, sensitive upper limits on intensity fluctuations are available only on angular scales $\gtrsim 3'$, which corresponds roughly to the mass of a cluster of galaxies (Caderni *et al.* 1977; Carpenter, Gulkis, and Sato 1973; Pariiskii, Petrov, and Cherkov 1977; Partridge 1980). Diffraction fixes a lower limit of $\sim 1'$ on such observations using filled-aperture radio telescopes. This *Letter* reports preliminary results of an attempt to measure fluctuations on a smaller angular scale, using radio interferometry.

In addition to permitting observations on smaller angular scales, interferometry can provide a two-dimensional image of fluctuations in the microwave background, unlike the usual observations which have employed drift scans. In principle, therefore, interferometry allows the determination of the morphology as well as the intensity of fluctuations. One pays a heavy price in sensitivity, however. Roughly speaking, the sensitivity is low because one examines "too many" independent regions on the sky, so that the integration time on each is small. This question is examined further in § III below.

This lack of sensitivity is particularly disappointing because the amplitude of fluctuations predicted by conventional theories of galaxy formation (see Boynton 1977; Sunyaev 1977) is small on these small angular scales. In spite of these difficulties—and in light of the very substantial uncertainties in the theory of galaxy formation—it seemed worthwhile to explore this new technique.

II. OBSERVATIONS AND DATA ANALYSIS

Our observations were made with the three-element NRAO[2] Greenbank interferometer on 1977 October 18–25 with baselines of 600, 1200, and 1800 m, and on 1978 March 28 to April 2 with baselines of 100, 1800, and 1900 m. Both *S*-band (2695 MHz) and *X*-band (8085 MHz) observations were made, with the latter emphasized in times of best weather. A bandwidth of 30 MHz was employed at both frequencies. The receiver temperatures at both frequencies were 125 K. Each individual measurement or subscan lasted 30 s.

By making raster scans of a strong unresolved source in both right ascension and declination, we directly measured the primary beam shape of the 85 foot (26 m) telescopes. It closely approximated a Gaussian. The measured values of the half-power beam width, corrected for delay loss and for phase wind during each 30 s integration, appear in Table 1.

A region at high declination, free of cataloged radio sources to a level of 0.2 Jy at 1400 MHz (Dixon 1978) was chosen for our map. The map center lay at R.A.(1950) = $3^{h}10^{m}00^{s}$, decl.(1950) = $80°08'00''$. A quick survey of this and adjacent regions, covering a square of $45' \times 45'$ centered on our map, revealed no *S*-band sources to a limit of about 40 mJy. We observed this field, with interruptions for calibrations, for 11 hours each night. Because the field was at high declination, the $(u - v)$-plane coverage was approximately a set of concentric circles.

The data were corrected and calibrated following standard NRAO procedures. The 30 s subscans were also individually inspected, and a few, for instance

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[2] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

TABLE 1

PRIMARY BEAM PARAMETERS

λ (cm)	BEAMWIDTH R.A. (arcmin)	BEAMWIDTH decl. (arcmin)	PRIMARY BEAM SOLID ANGLE (sr)	EFFECTIVE DIAMETER (m)	n_T
3.7......	5.77	5.35	2.96×10^{-6}	24.3	1440 ± 100
11.......	16.84	18.08	2.91×10^{-5}	23.3	1500 ± 100

NOTE.—Measured full beam widths at half-maximum, corrected for delay and phase wind, are given. The solid angle Ω of the main lobe of the primary beam was calculated assuming a Gaussian beam pattern. The effective diameter of the telescopes is calculated from equation (5). The baseline trace was calculated as in GMR, except that we have included a factor of 2 to account for the symmetry of the baseline trace in the $(u - v)$-plane. The number of resolution cells is n_T.

those taken during periods of high wind, were rejected. The individual 30 s subscans were vector-averaged in pairs to form 1 minute blocks of data. These visibility functions were then inverted to form brightness distribution maps of the field. The transforms were normally 512×512 arrays, and the maps covered $40' \times 40'$ for *S*-band and $16' \times 16'$ for *X*-band. All fluxes are tied to our primary calibration source, 3C 48, for which we take the *S*-band and *X*-band fluxes to be 9.0 and 3.3 Jy, respectively. The results reported here have both polarizations averaged together, and all data on all baselines combined. We did, however, examine subsets of the data to check for various systematic and instrumental effects and errors. No such effects which qualitatively affected our data were found; we will discuss this part of our work in detail elsewhere.

The *S*-band map revealed one very weak source. An extended 3.1 mJy source, roughly $2'' \times 5''$ with position angle 150°, was located at R.A.(1950) = $3^h12^m45^s$ and decl.(1950) = $80°13'.0$. No other significant sources were found at either frequency. Our upper limit for the detection of sources at *X*-band was about 2 mJy.

Following Goldstein, Marscher, and Rood (1976) and Goldstein, Turner, and Rood (1979) (hereafter GMR and GTR, respectively), each map was placed on an 8×8 grid, and the mean square fluctuation was calculated for each of these 64 grid points. We label these values MSF_{ij}. We also calculated a theoretical primary beam pattern B_{ij} which is a product of the Gaussian primary beam of the 85 foot telescopes (see Table 1), the baseline-weighted delay beam (see GMR), and the very small diminution caused by the 30 s averaging we used.

The MSF table for the *S*-band observations and the theoretical primary beam pattern B_{ij} are displayed in Tables 2 and 3, the corresponding results for *X*-band in Tables 4 and 5. The 8×8 MSF tables are, as expected, essentially noise. This noise has at least two components: (1) instrumental and atmospheric noise, which should be a uniformly distributed random variable, and (2) real sky noise due to unresolved sources and possible fluctuations in the cosmic microwave background. Real sky noise will be modulated by the primary beam pattern—that is, sky noise will not contribute much to the observed MSF where the primary beam pattern B_{ij} has a low value. Thus an estimate of the root-mean-square sky fluctuation σ may be found by minimizing the quantity

$$\sum_{i,j} \delta^2 \equiv \sum_{i,j} |\mathrm{MSF}_{ij} - (K + \sigma^2 B_{ij}^2)|^2 , \qquad (1)$$

where K is a constant which measures the mean square fluctuation due to instrumental and atmospheric noise.

Applying this procedure to the *S*-band data of Table 2 gives a marginally significant result:

$$\sigma = 0.40 \pm 0.22 \text{ mJy} . \qquad (2)$$

This value should be compared to the total rms fluctuation level of 0.57 mJy. The error in (2) is a fitting error given by $(\Sigma\delta^2/64)^{1/2}$ and has no direct relation to the standard deviation. As was found by GTR, the value of σ (*a*) is largely independent of the size of the map, (*b*) does not depend on the presence of sources (no change when the 3.1 mJy *S*-band source was cleansed from the data), and (*c*) is larger if the longer baselines are excluded.

The nonzero value of σ could be due to some instrumental effect that we have not yet been able to isolate, or possibly to individual unresolved sources (confusion). We will discuss this question in more detail in a later paper.

At *X*-band we obtain

$$\sigma = 0.005 \pm 0.12 \text{ mJy} . \qquad (3)$$

The total rms fluctuation level was 0.48 mJy. Neither this result nor those obtained from subsets of the data (e.g., with short baselines only) suggest to us that we have in fact detected real sky fluctuations at 8085 MHz. We prefer to regard our *X*-band result as an upper limit, and we adopt $\sigma \leq 0.2$ mJy at 8085 MHz. It is not easy to assign an exact confidence level to this result, but we believe it to be 90% or better.

III. CONVERSION TO BRIGHTNESS TEMPERATURE

In order to compare the results (2) and (3) with the intensity of the cosmic microwave background to estimate the fractional fluctuation $\Delta T/T$, we must convert the rms fluctuation values (2) and (3) to brightness temperature. The solid angle used for this conversion must take account not only of the main lobe of the synthesized beam but also of sidelobes, for these will make a significant contribution to σ due to the incomplete $(u - v)$-plane coverage. We use here the solid angle Ω_R defined by GMR, which gives qualitatively correct results. A more refined analysis will appear in a subsequent paper. We adopt

$$\Omega_R = \frac{\Omega}{n_T}, \tag{4}$$

where Ω is the primary beam solid angle (Table 1) and n_T is the number of independent samples in the $(u - v)$-plane, determined by integrating the baseline trace and then dividing by the effective diameter of the individual antennas (see GMR). The effective diameter is defined by

$$D = \left(\frac{4}{\pi\Omega}\right)^{1/2} \lambda, \tag{5}$$

and the values we determined are given in Table 1.

Were our experiment maximally sensitive to fluctua-

TABLE 2

THEORETICAL 40′ × 40′ PRIMARY BEAM PATTERN FOR THE 2695 MEGAHERTZ OBSERVATIONS

0.004	0.015	0.036	0.056	0.054	0.033	0.012	0.003
0.015	0.057	0.142	0.222	0.216	0.131	0.049	0.012
0.035	0.141	0.356	0.561	0.552	0.338	0.129	0.031
0.054	0.219	0.559	0.892	0.886	0.549	0.212	0.051
0.051	0.212	0.549	0.886	0.892	0.559	0.219	0.054
0.031	0.129	0.338	0.552	0.561	0.356	0.141	0.035
0.012	0.049	0.131	0.216	0.222	0.142	0.057	0.015
0.003	0.012	0.033	0.054	0.056	0.036	0.015	0.004

TABLE 3

OBSERVED ROOT-MEAN-SQUARE FLUCTUATIONS IN THE 40′ × 40′ MAP AT 2695 MEGAHERTZ[a]

0.9070	0.9821	0.9304	0.9549	0.9214	0.9379	0.9519	0.9574
0.9650	0.9643	0.9413	0.9359	0.9058	0.9670	0.9399	0.9919
1.0533	0.9424	0.9558	0.9439	1.0006	1.0587	1.0713	1.0394
0.9162	0.9431	0.9871	1.0166	1.2253	1.2254	1.1574	1.0224
0.9418	0.9953	1.0005	1.1785	1.2296	1.1733	0.9718	0.9419
0.9613	1.0232	1.2144	1.2166	1.1515	0.9049	0.9090	0.9086
0.9411	1.0337	1.1640	1.0229	0.9350	0.9321	0.9212	0.9624
1.0005	1.0630	0.9247	0.9439	0.9655	0.9019	0.8988	0.9342

[a] The fluctuations are normalized to the whole map mean of 0.57 mJy.

TABLE 4

THEORETICAL 16′ × 16′ PRIMARY BEAM PATTERN FOR THE 8085 MEGAHERTZ OBSERVATIONS

0.001	0.005	0.016	0.029	0.029	0.016	0.005	0.001
0.005	0.029	0.090	0.158	0.157	0.089	0.028	0.005
0.016	0.089	0.279	0.492	0.491	0.277	0.088	0.016
0.028	0.157	0.491	0.868	0.867	0.490	0.157	0.028
0.028	0.157	0.490	0.867	0.868	0.491	0.157	0.028
0.016	0.088	0.277	0.491	0.492	0.279	0.089	0.016
0.005	0.028	0.089	0.157	0.158	0.090	0.029	0.005
0.001	0.005	0.016	0.029	0.029	0.016	0.005	0.001

TABLE 5

OBSERVED ROOT-MEAN-SQUARE FLUCTUATIONS IN THE 16′ × 16′ MAP AT 8085 MEGAHERTZ[a]

0.9806	1.0172	0.9954	1.0082	1.0436	0.9801	0.9375	0.9857
0.9672	0.9904	0.9883	1.0350	0.9741	0.9834	1.0061	1.0385
1.0243	1.0028	0.9681	1.0266	0.9792	0.9508	1.0390	1.0093
1.0245	1.0408	1.0095	1.0620	1.0035	1.0119	0.9914	0.9801
1.0666	1.0432	1.0239	1.0253	0.9847	1.0047	0.9578	0.9934
1.0584	1.0187	0.9789	0.9588	0.9956	1.0175	1.0281	1.0547
0.9426	1.0102	0.9927	0.9968	1.0352	1.0215	1.0171	0.9696
0.9832	1.0405	1.0249	1.0474	1.0639	1.0058	1.0187	0.9939

[a] The fluctuations are normalized to the whole map mean of 0.48 mJy.

tions on angular scales $\gtrsim \Omega_R$, the brightness temperature fluctuations would be given by

$$\Delta T \approx \frac{\sigma \lambda^2}{2k\Omega_R} \,.$$

Our maximum sensitivity is limited, however, to fluctuations with angular size ϕ not much greater than the synthesized beam width (and therefore $< \sqrt{\Omega_R}$). The corresponding brightness temperature fluctuations are (Conklin and Bracewell 1967)

$$\Delta T = \frac{\sigma \lambda^2}{2k\Omega_R} \left(1 + \frac{\Omega_R}{\phi^2}\right)^{1/2} . \qquad (6)$$

In (6), Ω_R/ϕ^2 is the number of independent brightness fluctuations within the beam solid angle Ω_R. For $\phi \lesssim \frac{1}{2}(\Omega_R)^{1/2}$, (6) becomes

$$\Delta T \approx \frac{\sigma \lambda^2}{2k\phi \sqrt{\Omega_R}} \,.$$

The measured values of σ yield estimates of the largest brightness temperature fluctuations consistent with our observations. As fractions of the microwave background temperature, which we take to be 2.8 K, our results at 11.1 cm are

$$\frac{\Delta T}{T} \approx (7.2 \pm 4.0) \times 10^{-2} \left(\frac{13''}{\phi}\right) \quad \text{for} \quad \phi \lesssim 13'' \cdot$$

and at 3.7 cm are

$$\frac{\Delta T}{T} \lesssim 4.0 \times 10^{-2} \left(\frac{4''}{\phi}\right) \quad \text{for} \quad \phi \lesssim 4'',$$

with ϕ in seconds of arc.

IV. DISCUSSION

Because our $(u - v)$-plane coverage was essentially a set of concentric circles, we also sampled certain angular scales larger than the synthesized beam width. For larger angular scales ϕ, the brightness temperature fluctuations consistent with our observations continue to decrease with increasing ϕ, but not as steeply as $1/\phi$. A more detailed analysis, to be given in a subsequent paper, will permit us to assign specific upper limits to fluctuations at larger angular scales.

Because n_T was large in this experiment, our values of ΔT are not very sensitive; they are roughly equivalent to the earliest measurements of ΔT using filled-aperture telescopes. Substantial improvement is possible, though it is doubtful that interferometric limits on $\Delta T/T$ can be lowered by more than two orders of magnitude to be comparable to the best measurements using single antennas. We plan additional observations using systems with lower receiver noise, and more complete coverage of the $(u - v)$-plane at shorter baselines to increase Ω_R.

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REFERENCES

Boynton, P. E. 1977, in *IAU Symposium No. 79*, ed. M. S. Longair and J. Einasto (Dordrecht: Reidel).

Caderni, N., DeCosmo, B., Fabbri, R., Melchiorri, B., Melchiorri, F., and Natale, V. 1977, *Phys. Rev. D*, **16**, 2424.

Carpenter, R. L., Gulkis, S., and Sato, T. 1973, *Ap. J.* (*Letters*), **182**, L61.

Conklin, E. K., and Bracewell, R. N. 1967, *Nature*, **216**, 777.

Dixon, R. S. 1978, *Master Source List* (updated version of *Ap. J. Suppl.*, **20**, 1 [1970]).

Goldstein, S. J., Marscher, A. P., and Rood, R. T. 1976, *Ap. J.*, **210**, 321 (GMR).

Goldstein, S. J., Turner, K. C., and Rood, R. T. 1979, *Ap. J.*, **229**, 455 (GTR).

Pariiskii, Yu. N., Petrov, Z. E., and Cherkov, L. N. 1977, *Pizma Astr. Zh.*, **3**, 481 (English version in *Soviet A. J. Letters*, **3**, 263).

Partridge, R. B. 1980, *Ap. J.*, **235**, 681.

Silk, J. 1968, *Ap. J.*, **151**, 459.

Sunyaev, R. A. 1977, in *IAU Symposium No. 79*, ed. M. S. Longair and J. Einasto (Dordrecht: Reidel).

Sunyaev, R. A., and Zel'dovich, Ya. B. 1970, *Ap. Space Sci.*, **7**, 3.

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