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A SEARCH FOR SMALL-SCALE STRUCTURE IN THE BACKGROUND RADIATION AT 6 CENTIMETERS

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ABSTRACT

We present the results of a search for angular structure in 6 cm radio emission of the sky on scales less than 1′. A deep VLA map of a field free of strong radio sources is found to contain structure beyond the expected contribution of faint discrete sources. This structure is unlikely to be due to purely instrumental effects, but we cannot rule out the possibility of contamination by sidelobes of the radio sources in the field. In terms of the microwave background temperature $T = 2.74$ K, emission on scales between 18″ and 160″ has rms fluctuations $\Delta T/T \approx 2 \times 10^{-4}$, with an upper limit of 4×10^{-4}.
Subject headings: cosmic background radiation — radio sources: extended

I. INTRODUCTION

Observations of anisotropy in the microwave background radiation (MBR), so far only in the form of upper limits on $\Delta T/T$, provide important information about the properties of the universe at early times (see Wilkinson 1986; Kaiser and Silk 1986; Partridge 1987 for recent reviews). Small-amplitude density perturbations responsible for the formation of galaxies and other bound systems will introduce fluctuations into the MBR at the epoch when the radiation last scatters from matter (Silk 1968). If the epoch of last scattering is at recombination, $z \approx 1000$, the amplitude of these fluctuations decreases sharply on angular scales $\theta < 10'$ (Bond and Efstathiou 1984), and most searches for MBR fluctuations have been carried out on scales 1′–1°.

There are, however, other scenarios for the introduction of fluctuations into the background radiation on small scales, as first noted by Hogan (1980). These models, which depend on the presence of ionized gas in bound structures such as galaxies at redshifts between 3 and 1000, raise the possibility of detectable fluctuations on arcsecond scales. Likewise, a new population of faint radio sources could produce fluctuations in the radio background on scales <1′.

A search for fluctuations at centimeter wavelengths on scales less than 1′ requires the use of aperture synthesis. The Very Large Array (VLA)[1] has been used by two groups to set upper limits on fluctuations in the background on scales $6'' \leq \theta \leq 60''$ (Fomalont, Kellermann, and Wall 1984; Knoke *et al.* 1984). These searches were limited by sources of systematic error peculiar to synthesis observations, particularly correlator offsets and crosstalk between antennas. In this paper we report further VLA observations employing a technique that largely eliminates these sources of error. In addition, we take a more careful look at the role played by radio sources too weak to be detected individually. Much of the work reported here parallels that of Kellermann *et al.* (1986), based on VLA observations made at about the same time as ours.

While some models predict significant fluctuations on scales of a few arc seconds, we have chosen to use the VLA in the D-configuration at 6 cm, giving a resolution of 18″, in order to maximize sensitivity to brightness temperature fluctuations. These observations are limited by receiver noise rather than source confusion, so sensitivity is maximized by using the most compact array.

II. OBSERVATIONS AND IMAGE PRODUCTION

We observed a field centered at R.A. = $3^h10^m00^s$, decl. = 80°08′00″ (1950), known to be free of 6 cm sources stronger than ~3 mJy. Windhorst (1987) has made optical observations of the region with the Palomar 5 m (200 inch) telescope, and confirms that no rich cluster of galaxies with members brighter than 24th magnitude is present. Observations were made in 1984 September with the VLA in the D-configuration, with antenna spacings between 40 and 1026 m. The center frequency was 4860 MHz, and the bandwidth was 100 MHz. We obtained 25 hr on our field, spread over three nights. We observed the calibration source 0212+735 for 4 minutes every 20 minutes, and used 3C 84, with an assumed flux density of 5.38 Jy, as a primary calibrator. The 8 hr integrations and high declination assured uniform and symmetric coverage of the *u-v* plane.

In order to minimize the importance of correlator offsets and antenna crosstalk which can produce spurious signals concentrated around the phase center of an aperture synthesis map, the phase center was offset 6′.6 north of the primary beam center, which is the position of maximum sensitivity. In addition, we threw out the data from any correlator whose average signal over 8 hr was unreasonably large, removed individual 30 s scans with values greater than 40 mJy, and edited the visibility data carefully to remove data from correlators and antennas which were excessively noisy. Altogether ~5% of the data were removed, primarily through excision of individual antennas. Our final images do not show the ringlike structure

[1] The VLA is a facility of the National Radio Astronomy Observatory, which is operated by Associated Universities, Inc., under contract with the National Science Foundation.

that limited previous observations (see Fomalont, Kellermann, and Wall 1984; Knoke *et al.* 1984).

The edited visibility data were Fourier transformed using natural weighting, in which the gridded *u-v* data are weighted according to the density of data points in the *u-v* plane, and the resulting images were deconvolved using the *clean* algorithm (Clark 1980). The synthesized beam is nearly symmetric with a FWHM of 18″, and a symmetric 18″ Gaussian was used to restore the clean components. Our procedure differs from Knoke *et al.* (1984) in that we restored the clean components before analyzing the images. This allowed a fairly deep clean to be performed without affecting the noise statistics. In order to include any sources falling in the first sidelobe of the primary beam, we made and cleaned maps covering a 43′ square. Pixels of 5″ were used for this map. We also produced images with 36″ and 60″ resolution by tapering the *u-v* data before transforming.

The 18″ image has an rms noise level, measured outside the primary beam pattern, in regions free of obvious sources, of 7.5 ± 0.1 μJy per beam. We adopt 40 μJy as our detection limit for discrete radio sources. The strongest source present has an uncorrected peak brightness of 1.8 mJy per beam, or 10% of the mean brightness of the 2.7 K microwave background (to which the interferometer does not respond). Besides 18 discrete sources, additional structure is present near the center of the map where the primary beam is greatest (see Fig. 1). The analysis described below is aimed at determining the level of fluctuations above that which can be attributed to the known population of radio sources.

III. ANALYSIS

Our general method of analysis is that described by Martin, Partridge, and Rood (1980) and Knoke *et al.* (1984): we distinguish between instrumental noise and real sky fluctuations by means of the different angular dependences of these effects. Instrumental noise appears in the visibility data with random phase and hence is distributed uniformly throughout the map (apart from a truncation very near the edge, which was excluded from our analysis). Any fluctuations of astronomical origin are multiplied by the primary power pattern and hence peak at the map center. We divide the inner 256^2 pixels of the full-resolution map into 64 square blocks of 160″ on a side and compute the brightness variance σ^2 in each block. This variance can be expressed as $\sigma^2 = \sigma_i^2 + P^2(\theta)\sigma_s^2$, where σ_i^2 and σ_s^2 are the variances due to instrumental noise and real sky fluctuations, respectively, and $P(\theta)$ is the primary power pattern, which we approximate as a Gaussian beam with full width at half-maximum equal to the measured FWHM of 9′.06 (Napier and Rots 1982). A least-squares fit to the measured variance as a function of P^2 yields estimates of σ_i^2 and σ_s^2, with uncertainties determined by the scatter among the measurements (Bevington 1969, p. 104). This technique determines the variance due to fluctuations on all scales between the resolution limit and the block size. As we show below, the

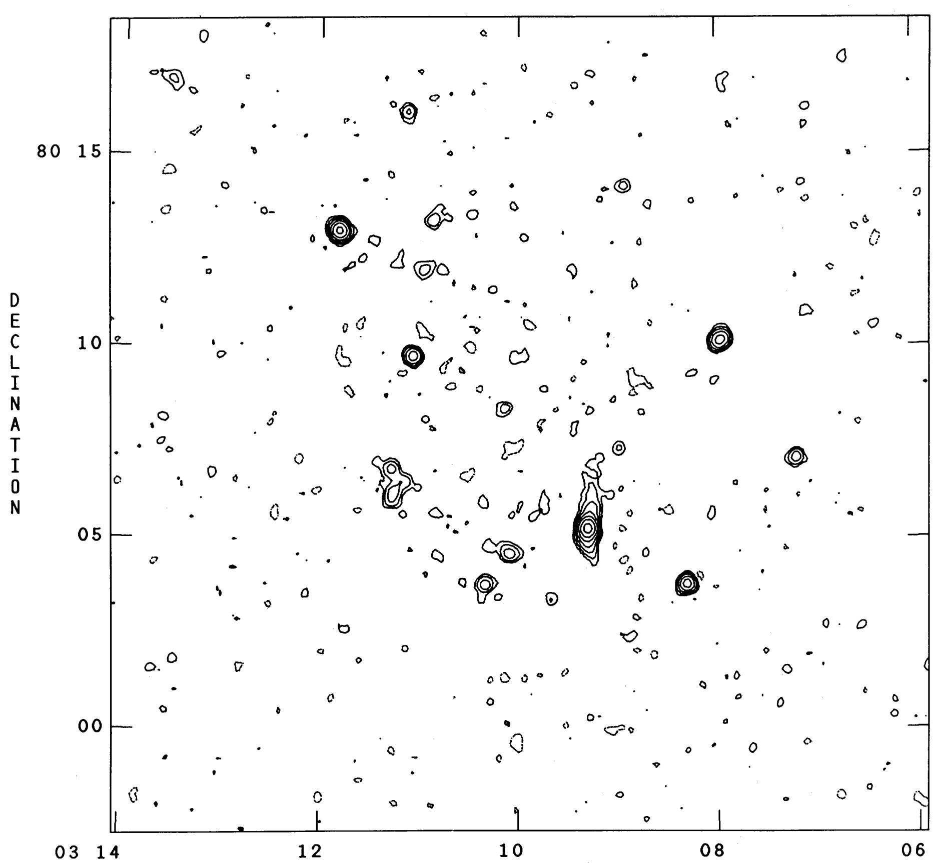

FIG. 1.—Central quarter of the map with 18″ resolution. Lowest contours are ± 20 μJy, and contours increase by factors of 2. Dashed lines are negative contours. No correction has been made for the primary beam, so sources away from the field center appear diminished. Phase reference position is 6′.6 north of the map center.

derived values of σ_s^2 depend on the largest angular scale sampled (the block size) as well as the resolution.

Discrete radio sources can contribute to σ_s^2. The contribution of the recognizable sources with peak flux $S_p \geq 40$ μJy per beam can be avoided by flagging and removing pixels inside and within 20″ of the 40 μJy per beam contour. Measurement of the variances, with sources removed in this way, yields a positive result for the excess sky fluctuations, $\sigma_s^2 = 57.3 \pm 5.6$ (μJy per beam)^2. This value of σ_s^2 yields a firm 95% confidence upper limit on fluctuations in the MBR, $\Delta T/T \leq 4.8 \times 10^{-4}$. (All results are listed in Table 1.) Analysis of a map of the circularly polarized emission, in which the instrumental noise level is the same but no sources are apparent, yields $\sigma_s^2 = 0.7 \pm 4.9$ (μJy per beam)^2. Maps of linearly polarized emission also give essentially null results. The lack of excess fluctuations in the polarized maps indicates that the fluctuations present in the total intensity map are not purely instrumental, but they may be related to faint sources with $S_p < 40$ μJy per beam.

We can avoid the effect of both these faint sources and the recognizable ones by considering only the negative fluctuations. For each block we plot the distribution of brightnesses, i.e., the number of pixels in each 2 μJy per beam brightness interval, and fit a Gaussian to the negative side of this distribution. (In fact, we extend the fit to +4 μJy per beam in order to determine it better.) In this approach we must assume that the distribution of brightnesses is Gaussian for real sky fluctuations as well as instrumental noise. With variances determined in this way we obtain $\sigma_s^2 = 50.7 \pm 11.4$ (μJy per beam)^2.

While this result is evidence of excess structure, it is still slightly contaminated by the convolution of the noise distribution with the source fluxes. For this reason, we attempt to take account of the sources by treating the observed distribution of sky brightnesses as a convolution of a distribution due to discrete sources and a Gaussian distribution representing noise and other fluctuations. We estimate the probability distribution of brightnesses due to discrete sources, convolve it with the Gaussian noise distribution, and determine the Gaussian parameters (amplitude, centroid, and standard deviation) that give the best fit to the measured distribution of brightnesses. These distributions are illustrated in Figure 2.

Our own data can provide only a crude estimate of the density of sources with flux density $S < 40$ μJy, so we use the results of Mitchell and Condon (1985) at 20 cm wavelength, and scale these to 6 cm assuming a mean spectral index $\alpha = 0.7$; i.e., $S \propto \nu^{-0.7}$. The 20 cm survey, also made with 18″ resolution, is limited by confusion rather than noise and hence is a much more sensitive determination of the distribution of brightnesses due to sources than our observation. Mitchell and Condon find a differential source count $dN/dS_{20} = 54S_{20}^{-2.2}$ over the flux density range 10 μJy $\leq S_{20} \leq$ 84 μJy. (Here and elsewhere, differential source counts are given in units of Jy^{-1} sr^{-1} when the flux density is measured in Jy.) When extrapolated to larger flux densities, this indirect estimate of the counts matches their direct counts at $S_{20} \geq 84$ μJy. When scaled to 6 cm, the source count of Mitchell and Condon becomes $dN/dS_6 = 20S_6^{-2.2}$ over the range 4.3 μJy $\leq S_6 \leq$ 37 μJy. The corresponding probability distribution of brightnesses is obtained following Condon (1974).

For each 160″ block of the map, the brightnesses are scaled by the appropriate mean attenuation (primary power pattern),

TABLE 1

RESULTS OF ANALYSES

Range of Angular Scales	Method	Instrumental Variance (μJy per beam)^2	Sky Variance (μJy per beam)^2	$10^4(\Delta T/T)$
18″–160″.........	Sources removed	59.5 ± 1.3	57.3 ± 5.6	4.4 ± 0.2
18″–80″..........	Circular polarization	64.0 ± 1.1	0.7 ± 4.9	<1.7
18″–160″.........	Fit to negative side	58.1 ± 2.6	50.7 ± 11.4	4.2 ± 0.5
18″–160″.........	Model[a] (estimate)	55.9 ± 1.2	19.6 ± 5.2	2.6 ± 0.3
18″–160″.........	Model (upper limit)	56.6 ± 1.2	38.4 ± 5.3	<4.0
18″–80″..........	Model (estimate)	49.4 ± 1.1	8.1 ± 4.9	1.7 ± 0.5
18″–80″..........	Model (upper limit)	50.0 ± 1.1	23.0 ± 5.0	<3.3
36″–160″.........	Model (estimate)	78.0 ± 5.0	76.8 ± 22.2	1.3 ± 0.2
36″–160″.........	Model (upper limit)	81.0 ± 5.5	168.2 ± 24.4	<2.1
60″–160″.........	Model (estimate)	138 ± 21	504 ± 100	1.2 ± 0.1
60″–160″.........	Model (upper limit)	146 ± 28	946 ± 125	<1.8

[a] Model results are obtained by fitting the measured histograms of brightnesses with a model distribution that is the convolution of a Gaussian and the probability distribution due to sources. The distribution due to sources corresponds to a differential source count $dN/dS \propto S^{-2.2}$.

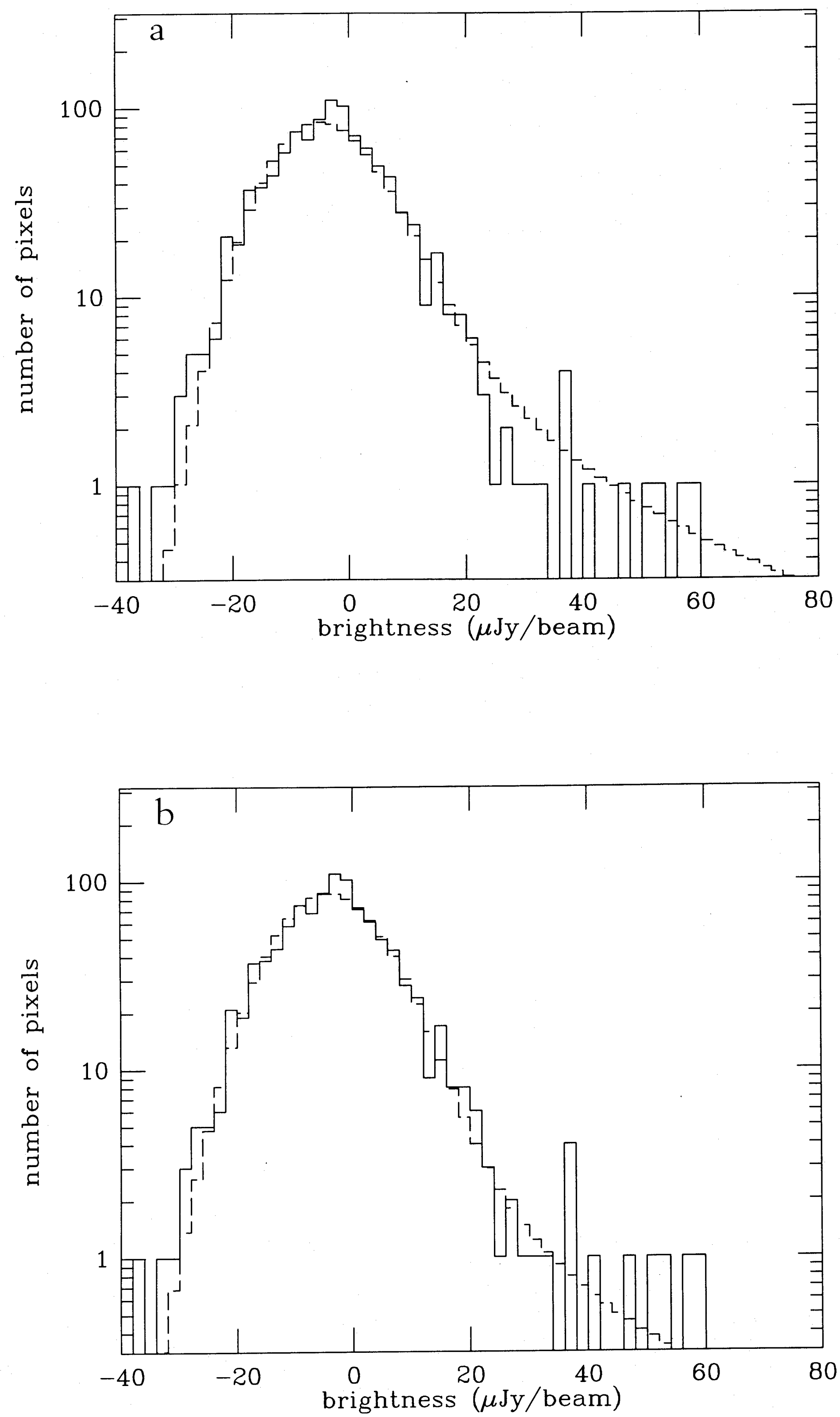

FIG. 2.—(*a*) Frequency distribution of observed brightness for the central block of 1024 pixels (*solid lines*), compared with a model fit (*dashed lines*). This region includes one recognizable source, with $S_p \sim 60$ μJy per beam. The model consists of a convolution of a Gaussian of variable centroid and width with a probability distribution due to sources, derived from the 20 cm source counts of Mitchell and Condon (1985). In this case, the standard deviation of the best fitting Gaussian is 7.4 μJy per beam. The same fitting procedure was applied to each of the 64 blocks covering the map shown in Fig. 1. (*b*) Same frequency distribution of observed brightness compared with a model fit with half the density of sources derived from Mitchell and Condon (1985). In this case, the standard deviation of the best fitting Gaussian is 8.2 μJy per beam.

convolved with a Gaussian, and fitted to the measured distribution. The results are used as before to determine the instrumental and sky fluctuations, and we obtain $\sigma_s^2 = 19.6 \pm 5.2$ (μJy per beam)^2. An example of the model fitted to the measured distribution is shown in Figure 2*a*.

While the 20 cm counts match the 6 cm counts (assuming $\alpha = 0.7$) near $S_6 = 1$ mJy, for $S_6 < 1$ mJy the 6 cm counts fall steeply while the scaled 20 cm counts remain closer to the Euclidean value. For $S_6 \leq 300$ μJy, the 6 cm counts of Kellermann *et al.* (1986) and Partridge *et al.* (1986) fall a factor of 1–3 below the direct 20 cm counts scaled with $\alpha = 0.7$. This discrepancy is apparent in the positive wing of the histogram shown in Figure 2*a*; the model curve falls above the observed distribution. Thus, by using the 20 cm results, we may overestimate the fluctuations due to sources and consequently underestimate the fluctuations due to other causes. The 20 cm results of Mitchell and Condon (1985) allow an uncertainty of roughly $\pm 25\%$ in source density. Varying the source density by this amount yields a range of estimates of the sky fluctuations 11 (μJy per beam)$^2 < \sigma_s^2 < 29$ (μJy per beam)^2. In order to obtain a conservative upper limit to the sky fluctuations, we take half the source density determined by Mitchell and Condon, i.e., $dN/dS_6 = 10S_6^{-2.2}$, a count that matches the direct 6 cm counts when extrapolated to $S_6 > 40$ μJy. The brightness distribution corresponding to this source count is convolved with a Gaussian noise distribution to produce the model shown in Figure 2*b*: note the better fit to the observed brightness distribution for $S > 20$ μJy per beam. With this model, the resulting 95% confidence upper limit on σ_s^2 is 47 (μJy per beam)^2.

An alternate method of analysis, which takes more explicit account of the contribution of discrete sources to the measured fluctuations, is to perform Monte Carlo simulations of brightness distributions due to sources. Fomalont and Kellermann (1987) simulate data based on a given differential source count, process these using the same software used on the measured data, and compare the two results to determine whether excess fluctuations are present in the measured data.

Finally, we investigate fluctuations on other angular scales by tapering the *u-v* data and altering the block size. We compute variances over 80″ blocks of the full resolution map to obtain measures of fluctuations on the 18″–80″ range, and over 160″ blocks of the lower resolution maps to obtain measures on 36″–160″ and 60″–160″ ranges. These results are listed in Table 1.

IV. DISCUSSION

The fluctuations we find are not obvious instrumental artifacts. By moving the phase reference position and removing suspect correlators we have eliminated the systematic problems that limited previous observations. The lack of excess fluctuations in polarized emission also rules out many purely instrumental effects that might have given rise to fluctuations.

Since the contribution of radio sources is concentrated in the central area of the map (within the primary beam pattern), any spurious fluctuations related to them would contribute to σ_s^2. Imperfect deconvolution (cleaning) could in principle result in fluctuations near the radio sources, so we have experimented with different amounts of cleaning. The value of σ_s^2 decreases as the number of clean components, N, increases, then becomes essentially constant for $8000 \leq N \leq 16{,}000$ for the 18″ resolution map and for $2000 \leq N \leq 16{,}000$ for the 36″ map. (10% of the flux of each component is removed in each iteration.) With this many components, we are cleaning nearly to the noise level of the maps, and a significant increase in the depth of cleaning would require cleaning almost every pixel. While sources fainter than the noise level of 8 μJy per beam have not been cleaned, their sidelobes, at a level of 0.1 μJy per beam or less, should have no appreciable effect on the measured variance. For the final analyses we use maps cleaned with 16,000 components at 18″ resolution, 8000 components at 36″ resolution, and 4000 components at 60″ resolution.

While our statistical treatment of fluctuations due to discrete sources should be valid for a large number of faint sources, one could question its validity when also applied to the few strong sources in our field. We have examined the possibility that this treatment of these sources causes the measured excess fluctuation. The recognizable sources were removed entirely, as described in § III, and the statistical analysis repeated. The resulting value of σ_s^2 is less than that determined with all sources present by 30% and 50% at 18″ and 36″ resolution, respectively; in neither case is the result consistent with $\sigma_s^2 = 0$. Since the theoretical probability distribution of brightnesses cannot be cut off at a limiting source flux density (Condon 1974), it is not strictly valid to remove the strong sources before comparing measured and theoretical distributions, so we do not include these results in Table 1. Removing these bright sources does, however, show that uncertainty in the density of bright sources is not responsible for all the measured excess fluctuation.

We have also searched for a spatial correlation between the density of discrete sources and the excess fluctuations. A positive correlation would suggest that the discrete sources increase the fluctuations in nearby regions of the map, possibly because of incomplete removal of their sidelobes. For this test we use the brightness variance σ^2 measured in each 160″ block of the full-resolution image with sources removed (as described in § III). We first look for a correlation between residual variance in each block (the difference between the measured variance and the best fitting model $\sigma_i^2 + P^2\sigma_s^2$) and mean brightness in the same block of the image with sources left intact. No significant correlation exists. Among the central 64 blocks the Spearman rank-order correlation coefficient (see, e.g., Press *et al.* 1986, p. 488) $r = -0.08$, indicating a 50% probability that the two quantities are uncorrelated and no suggestion of a positive correlation. When the same test is used on residual variance and peak (rather than mean) brightness, we obtain $r = 0.04$, indicating a 75% probability that these two quantities are uncorrelated. Thus we see no evidence that discrete sources influence the variance measured in nearby regions of the map.

Despite the lack of evidence that recognizable sources contribute to the excess fluctuations, we cannot rule out the possibility of this or other instrumental effects. To allow for this possibility, our results can be interpreted as upper limits on any true background fluctuations. We adopt as limits the 95% confidence upper limits obtained using half the source density extrapolated from Mitchell and Condon (1985), $dN/dS = 10S^{-2.2}$. These limits, for various ranges of angular scale, are listed in Table 1, along with our best estimates of the fluctuations, obtained using a source density equal to that extrapolated from Mitchell and Condon, $dN/dS = 20S^{-2.2}$.

Recalling that our apparent detection of fluctuations may be due in part to instrumental effects, we go on to discuss some interpretations of the measured fluctuations. If we increase the density of sources as far as possible within the limits of Mitchell and Condon (1985) ($dN/dS = 25S^{-2.2}$), our results imply a 5% probability that there is no excess sky fluctuation at 18″ resolution. For source densities equal to or less than Mitchell and Condon's best fit, this possibility is all but ruled out, and strongly ruled out if we extrapolate the 6 cm counts themselves.

It is possible that an as yet unknown population of faint sources contributes to the excess fluctuations. Kellermann *et al.* (1986) find evidence for a flattening of the 6 cm source counts below 100 μJy, i.e., more faint sources than extrapolation of the 0.1–10 mJy counts would suggest. Even these counts, however, are a factor of 3 lower than the source density we assume in the 25–100 μJy range. To account for the excess fluctuations we measure, the density of sources with $S_6 < 25$ μJy would have to be ~ 5 times the density obtained by extrapolating the direct counts of Kellermann *et al.*, assuming $dN/dS \propto S^{-2.2}$.

The fluctuations, if real, can also be interpreted as anisotropy of the MBR. For the full range of angular scales we sampled, 18″–160″, the measured sky fluctuation corresponds to $\Delta T/T = (2.6 \pm 0.3) \times 10^{-4}$. For more restricted ranges of angular scale, $\Delta T/T = (1.7 \pm 0.5) \times 10^{-4}$ for $18'' \leq \theta \leq 80''$, and $\Delta T/T = (1.3 \pm 0.2) \times 10^{-4}$ for $36'' \leq \theta \leq 160''$. One might consider galaxy-scale inhomogeneities at the epoch of recombination as the source of MBR fluctuations, since a $10^{11}\ M_{\odot}$ protogalaxy subtends an angle of $\sim 30''$ at $z \sim 1000$ for $\Omega_0 = 1$ and $H_0 = 100$ km s^{-1} Mpc^{-1} (Weinberg 1972, p. 570). A great deal of theoretical work argues against galaxy-scale fluctuations emerging from recombination with detectable amplitudes, so we consider instead more recent models involving the ionization of gas in bound structures at more modest redshifts.

Hogan (1980) estimated the microwave background fluctuations due to free-free emission and dust emission in a model in which cosmological structure builds up from small structures forming shortly after recombination. Either of these mechanisms can explain fluctuations as large as those we measure; in fact, for the parameters used in Hogan's calculation, the fluctuations are several times larger than we observe. A second scenario that produces appreciable anisotropy on small scales is explosive galaxy formation (Hogan 1984; Vishniac and Ostriker 1985). Here the mechanism responsible for the fluctuations is the Sunyaev-Zel'dovich effect (Zel'dovich and Sunyaev 1969), in which microwave photons inverse-Compton scatter off electrons in hot plasma. The effect is proportional to the line-of-sight integral of the electron pressure, and acts to reduce the observed temperature in the Rayleigh-Jeans region of the MBR spectrum. Vishniac and Ostriker calculate the magnitude of this effect under the assumption that explosive shocks stimulate the formation of an appreciable fraction of all galaxies. Anisotropy results from statistical fluctuations in the number of galaxies in a beam, and the angular dependence is that of a white-noise spectrum, $\Delta T/T \propto \theta^{-1}$ for θ larger than the size of a galaxy at large redshift, which is several arcseconds.

In a more recent paper, Ostriker and Vishniac (1986) have generalized their calculation of temperature anisotropies to any scenario for galaxy formation which involves heating and moving large quantities of gas. Both the Sunyaev-Zel'dovich effect and the bulk motion of hot gas produce temperature fluctuations, with a steeper angular dependence, $\Delta T/T \propto \theta^{-3}$. For a set of parameters adopted as standard by Ostriker and Vishniac, the latter effect dominates, and $\Delta T/T \sim 3 \times 10^{-5}(\theta/1')^{-3}$. That relationship is shown in Figure 3. There it is compared with our measurements for three ranges of angular scale, and the upper limit obtained by Uson and Wilkinson (1984) at $\lambda = 1.5$ cm with a 1.′5 beam. It is important to note, as Ostriker and Vishniac point out, that the θ^{-3} dependence will break down on sufficiently small angular scales, so their model can be made consistent with our tentative results.

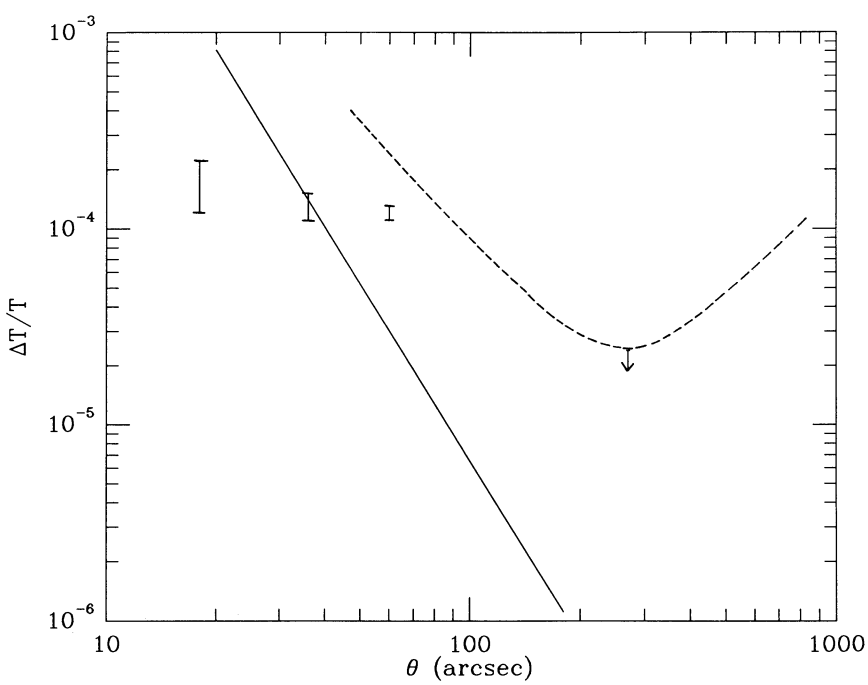

FIG. 3.—Results of our measurements over angular scales 18″–80″, 36″–160″, and 60″–160″ (*points with error bars*), and the results of Uson and Wilkinson (1984) at 1.5 cm with a 1.′5 beam and 4.′5 beam throw (*upper limit and dashed line*). The line with slope −3 is the prediction of Ostriker and Vishniac (1986) described in § IV. For such models with a strong inverse dependence on θ, the fluctuations depend on the resolution rather than size of the region sampled or beam throw; hence, our points are plotted at values of θ equal to the appropriate resolution.

V. SUMMARY

We have measured angular fluctuations on scales less than 1′ at 6 cm. We have not identified any instrumental effect capable of producing these fluctuations. There is, of course, a possibility of unknown instrumental effects in a measurement such as this near the sensitivity limit of the telescope. If the measured fluctuations are real, they are too strong to be produced by the known population of radio galaxies.

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REFERENCES

Bevington, P. R. 1969, *Data Reduction and Error Analysis for the Physical Sciences* (New York: McGraw-Hill).
Bond, J. R., and Efstathiou, G. 1984, *Ap. J. (Letters)*, **285**, L45.
Clark, B. G. 1980, *Astr. Ap.*, **89**, 377.
Condon, J. J. 1974, *Ap. J.*, **188**, 279.
Fomalont, E. B., and Kellermann, K. I. 1987, private communication.
Fomalont, E. B., Kellermann, K. I., and Wall, J. V. 1984, *Ap. J. (Letters)*, **277**, L23.
Hogan, C. J. 1980, *M.N.R.A.S.*, **192**, 891.
———. 1984, *Ap. J. (Letters)*, **284**, L1.
Kaiser, N., and Silk, J. 1986, *Nature*, **324**, 529.
Kellermann, K. I., Fomalont, E. B., Weistrop, D., and Wall, J. V. 1986, *Highlights Astr.*, **7**, 367.
Knoke, J. E., Partridge, R. B., Ratner, M. I., and Shapiro, I. I. 1984, *Ap. J.*, **284**, 479.
Martin, H. M., Partridge, R. B., and Rood, R. T. 1980, *Ap. J. (Letters)*, **240**, L79.
Mitchell, K. J., and Condon, J. J. 1985, *A.J.*, **90**, 1957.
Napier, P. J., and Rots, A. H. 1982, VLA Test Memo., No. 134.
Ostriker, J. P., and Vishniac, E. T. 1986, *Ap. J. (Letters)*, **306**, L51.
Partridge, R. B. 1987, *Rept. Progr. Phys.*, submitted.
Partridge, R. B., Hilldrup, K. C., and Ratner, M. I. 1986, *Ap. J.*, **307**, 46.
Press, W. H., Flannery, B. P., Teukolsky, S. A., and Vetterling, W. T. 1986, *Numerical Recipes* (Cambridge: Cambridge University Press).
Silk, J. 1968, *Ap. J.*, **151**, 459.
Uson, J. M., and Wilkinson, D. T. 1984, *Nature*, **312**, 427.
Vishniac, E. T., and Ostriker, J. P. 1985, in *The Cosmic Background Radiation and Fundamental Physics*, ed. F. Melchiorri (Bologna: Editrice Compositori), p. 137.
Weinberg, S. 1972, *Gravitation and Cosmology* (New York: Wiley).
Wilkinson, D. T. 1986, *Science*, **232**, 1517.
Windhorst, R. A. 1987, private communication.
Zel'dovich, Ya. B., and Sunyaev, R. A. 1969, *Ap. Space Sci.*, **4**, 301.

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