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NEW LIMITS ON MICROWAVE BACKGROUND ANISOTROPY AT SMALL ANGULAR SCALES

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ABSTRACT

We have used the Very Large Array to examine a small piece of blank sky for possible angular variations in the temperature of the cosmic microwave background. This experiment differs from previous aperture synthesis studies in using a much shorter wavelength, 2 cm instead of 6 cm. As a result, these data yield finer spatial resolution and virtually eliminate radio source contamination, which has complicated the interpretation of the earlier work. The 95% confidence limits on sky variance obtained are $\Delta T/T < 6.3 \times 10^{-4}$ with 5″.3 resolution, and $\Delta T/T < 1.6 \times 10^{-4}$ with 18″ resolution. Comparable limits are obtained on polarized fluctuations on 18″ scales.

Subject heading: cosmic background radiation

I. INTRODUCTION

As cosmological theory has grown to incorporate more comprehensive and realistic models of galaxy formation, it has become clear that the earliest work, which was based on a highly idealized linear theory, may have excluded the most important sources of microwave background anisotropy. One example is radio source contamination; at long wavelengths, emission from moderate-redshift ($z < 5$) radio galaxies and quasars dominates over all other sources of anisotropy including the classical effects predicted by linear theory from the epoch of recombination at $z = 1000$ (Danese, De Zotti, and Mandolesi 1983). Similarly, it could be that at all angles and wavelengths (but especially at small angles) the high-redshift fluctuations, which in modern theories can have a very small amplitude, are swamped by various effects occurring at lower redshifts, $5 < z < 1000$. While it may be cause for discouragement that signals from the highest redshifts are unobservable, any anisotropy created at intermediate redshift carries information about cosmic evolution during those periods and is thus interesting in its own right.

The current experiment was designed to probe a number of intermediate-redshift effects which might be associated with the formation of galaxies, all of which have spectra which, unlike the nonthermal emission from radio galaxies themselves, increase at shorter wavelength. These include Comptonization from hot shocked gas (Hogan 1984), Doppler scattering from nonlinear collapsing protogalaxies (Ostriker and Vishniac 1986; Vishniac 1987), and thermal emission from the hot dust which may be responsible for generating the recently discovered submillimeter excess radiation (Matsumoto *et al.* 1988; Bond, Carr, and Hogan 1989). Unlike the classical linear anisotropy introduced at the recombination era, in which small-scale anisotropy is smeared out by scattering, these intermediate-redshift processes are generally expected to produce values of $\Delta T/T$ which increase at smaller angular scales, and they are therefore the natural targets of aperture-synthesis background imaging. For the purpose of setting limits on this type of effect in an aperture-synthesis experiment, the double benefit carried by high frequencies (better angular resolution and weaker nonthermal contamination) more than offsets the cost of noisier receivers at short wavelength. This is particularly true since the experiments at 6 cm have proven in practice to be limited not by receiver noise but most probably by the anisotropy caused by numerous faint discrete sources (Partridge 1988).

II. OBSERVATIONS AND ANALYSIS

We observed a region of the sky essentially free of sources at 2 cm wavelength using the Very Large Array (VLA)[1] in the D array. Our observations were centered at R.A. = $8^h41^m42^s$ and decl. = $+44°42'45''$ located in a region deeply mapped at 1.4 GHz by Windhorst *et al.* (1985) and at 4.9 GHz by Donnelly, Partridge, and Windhorst (1987). No 21 cm sources with flux density > 200 μJy lay within 2′.5 of our field center; the half-width at half-maximum of the primary beam at 2 cm was 1′.5. Our field center was chosen so that the brightest (~ 1 mJy) 21 cm sources within $\sim 5'$ were placed in the null of the primary beam. No 6 cm source with $S > 160$ mJy lay in the primary beam pattern of our observations at 2 cm.

Our observations were carried out over several nights of good weather in the summer of 1987. A total of ~ 24 hr (or 400,000 visibility records) on the sky was obtained. We calibrated our data using 3C 286, assuming for it a flux of 3.45 Jy at our observing frequency of 14,940 MHz. As a phase calibrator, we employed 0917+449, with a 2 cm flux of 1.02 Jy. We edited the visibility data carefully to exclude data from those antennas shadowed by others or subject to interference, and from those correlators exhibiting excess noise.

An important advantage of aperture-synthesis over filled-aperture measurements (e.g., Readhead *et al.* 1989) is that most systematic sources of noise do not mimic an apparent sky signal. Slowly varying sources of background emission, such as sidelobe pick-up from the ground, cancel out in an aperture synthesis map. Atmospheric emission will add slightly to the

[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.

system noise, but the major effect is to introduce phase errors in the measurements made by pairs of antennas in the array. In this work, in the D configuration and in good weather, the typical phase errors were below 5°.

The visibility data were transformed to maps using standard VLA algorithms, with cells of 1".5; 512^2 maps were made, but only the inner 256^2 was analyzed. This inner quarter of the map was thus roughly 4 times the solid angle of the primary beam at 2 cm. Inspection of the map revealed the presence of five weak sources (or more probably noise spikes). None of these sources corresponded in position with sources detected at 21 or 6 cm. The rms noise of the map was 28 μJy over the effective solid angle of the synthesized beam. No artifacts such as grating rings or other instrumental effects were visible in the map.

We also constructed maps based on *tapered* data, that is, *u-v* data to which a weighting function had been applied to approximate a Gaussian synthesized beam at a particular scale. In the untapered, full resolution map, the synthesized beam width $\theta_{1/2}$ at half-maximum was 5".33 × 5".18, which we approximate as 5".3. Tapering was used to obtain synthesized beam widths of 10" and 18". For these tapered maps, the cell sizes were 3" and 5", respectively. We also made maps at 18" resolution in Stokes parameters *Q*, *U*, and *V* (linear and circular polarization); these are expected to produce zero sky signal and are a measure of system noise and stability.

All maps were deconvolved using the CLEAN algorithm. For a pure-noise map free of point sources, the final sky variances are unaffected by CLEANing, since the Fourier transform of the true synthesized beam differs from that used by CLEAN only slightly except for phase differences. We find that at 2 cm CLEANing indeed makes little difference in the results and is probably unnecessary except to confirm the lack of point sources. With the loop gain set at its usual value of 0.1, negative CLEAN components began to appear after fewer than 10 iterations, confirming that sources are almost entirely negligible compared to noise. We stopped the CLEAN operation after 20–25 iterations in all cases, since CLEANing noise only shifts fluctuation power around in phase and was observed to make little difference in our final results.

We then examined the maps to determine whether the variance in the measured values of flux was greater at the center (where the primary beam response was high) than at the edges (where the primary beam response ≈ 0). Excess variance at the center would be expected either from weak discrete sources or from fluctuations in the microwave background. The analysis employed the technique used in earlier VLA searches for fluctuations (Martin and Partridge 1988). The map is divided into square blocks 48" (or in some cases 50") on a side; the variance of the brightness per synthesized beam in each block is expressed as a sum of instrumental noise and a sky contribution proportional to the amplitude of the primary power pattern in that block; and a least-squares fit to the whole map then yields estimates of both instrumental and sky variances. We made no correction for the presence of weak sources, except to drop one $\sim(48'')^2$ region with an unusually high mean flux which may have contained a weak 2 cm source; including this region makes little ($<\frac{1}{2}\,\sigma$) difference in the final results.

III. RESULTS

The results of this analysis appear in Table 1, which gives the estimated values for both the instrumental variance (col. [3]) and the excess variance which we ascribe to the sky (col. [4]), with 1 σ errors in the estimate of the latter. The lower limit on the range of angular scales of sky fluctuations which contribute to the measured sky variance is determined by $\theta_{1/2}$ and the upper limit by the size of the blocks used in the analysis. If the sky fluctuations are uncorrelated on scales exceeding $\theta_{1/2}$, so each synthesized beam is independent, then we just measure the rms sky fluctuations on this scale. With the possible exception of the Stokes parameter *Q* map, our results reveal no significant evidence for the existence of sky fluctuations.

If we ascribe any sky variance we detect entirely to fluctuations in the microwave background, we may convert the values taken from column (4) of Table 1 (expressed in μJy beam^{-1}) to values of $\Delta T/T$ as follows:

$$\frac{\Delta T}{T} = \frac{S\lambda^2}{2kT\Omega_s} \times 10^{-32} ,$$

where $\Omega_s = 1.13\theta_{1/2}{}^2$ is the solid angle of the synthesized beam, which we approximated as a Gaussian. The upper limits in column (5) were found in this way, with *T* taken as 2.75 K; we calculated 95% confidence level, one-sided, upper limits.

The angular scale of our most heavily tapered map (18") matches the angular scale of the 6 cm observations of Martin and Partridge (1988) and of Fomalont *et al.* (1988). Their values of $\Delta T/T$ are $(1.7 \pm 0.5) \times 10^{-4}$ and $\lesssim 1.2 \times 10^{-4}$, respectively. Thus our 2 cm results are in general agreement with earlier, longer wavelength work where the presence of sources makes substantial corrections to the final values of the sky variance necessary. The indication from these new results is that the true sky fluctuations on 18" scales probably lie

TABLE 1

RESULTS OF THESE 2 CENTIMETER OBSERVATIONS

Polarization (1)	Range of Angular Scale (2)	Instrument Variance (μJy beam^{-1})^2 (3)	Sky Variance[a] (μJy beam^{-1})^2 (4)	Inferred Upper Limit on $\Delta T/T(10^{-4})$[b] (5)
I[c]	5".4–48"	780	-24.0 ± 70.7	≤ 6.3
I[c]	10–48	1184	-43 ± 217	≤ 3.2
I[c]	18–50	2272	388 ± 735	≤ 1.6
Q	18–50	2561	1061 ± 738	≤ 2.7
U	18–50	2256	89 ± 550	≤ 1.8
V	18–50	2449	-507 ± 626	≤ 1.3

[a] Errors are 1 σ.
[b] Upper limits at 95% confidence level.
[c] One block containing a source not included in the analysis.

below the value detected by Martin and Partridge, and the most likely explanation is contamination by unresolved sources in the 6 cm work. (It is also possible but less likely that true microwave background fluctuations were present in their field but at an unusually high level.) Our shorter integration time has not allowed us to set formal limits quite as low as those given by Fomalont *et al.*, but since the limits we quote are achieved without the need for any subtraction of a model-dependent source contribution, the systematic uncertainties are perhaps better understood.

The limits on small-scale variance in the untapered map ($\theta_{1/2} = 5''.3$) are the best direct limits ever placed on fluctuations on such small angular scales, representing more than an order-of-magnitude improvement over previous work (Knoke *et al.* 1984). These limits complement better limits on $\Delta T/T$ on larger angular scales (e.g., Readhead *et al.* 1989) and comparable limits at still higher frequencies (Kreysa and Chini 1989), in constraining models of pregalactic events.

Because of the relatively low frequency, our results are not as useful as other recent experiments (especially Kreysa and Chini 1989) in constraining submillimeter-background anisotropy (see Bond, Carr, and Hogan 1989 for a quantitative discussion). However, our high angular resolution is useful in constraining Doppler-scattering anisotropy from motions of lumpy high-z gas along the line of sight. If N_θ lumps of gas appear in each beam, then an rms anisotropy $\Delta T/T \simeq N_\theta^{-1/2}\tau\sigma_V/c$ is produced, where $\tau = 0.04\Omega_{\rm H\,II} hZ^{3/2}$ is the mean cosmic optical depth, σ_V the one-dimensional peculiar velocity dispersion of the lumps, and $Z = (1 + z)$. Assuming that all the gas is compressed into spherical lumps as numerous as L_* galaxies ($n \simeq 10^{-2}h^3$ Mpc^{-3}) and the same diameter as the beam [$L = 15h^{-1}$ kpc $(\theta/5'')(Z/10)^{-1}$], we would have $N_\theta \simeq 0.6Z^{-1/2}(\theta/5'')^2$. Since our results imply that $\Delta T/T \lesssim 6 \times 10^{-4}(\theta/5'')^{-1}$, we have the constraint

$$\sigma_V \lesssim 333 \text{ km s}^{-1} (\Omega_{\rm H\,II}/0.1)^{-1}h^{-1}(Z/10)^{-2} .$$

Clearly our limits will be useful for constraining theories in which galaxy spheroids form at moderately high redshift. The small synthesized beams allow one to probe galactic scales directly without need for extrapolation to larger angles.

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