A SEARCH FOR ANISOTROPY IN THE COSMIC MICROWAVE RADIATION AT MEDIUM ANGULAR SCALES

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ABSTRACT

We report the results from a search for anisotropy in the cosmic microwave radiation (CMR) at angular scales 0.5° to 5°. No temperature fluctuations are detected; however, the data place limits on intrinsic CMR anisotropy. We express the limits in terms of two models which describe the temperature fluctuations. For models specified by a Gaussian-shaped correlation function the fluctuation amplitude is found to be $\Delta T_{\text{rms}}/T \leq 1.1 \times 10^{-4}$ at 1.1; for models with monochromatic fluctuations $\Delta T_{\text{rms}}/T \leq 7.5 \times 10^{-5}$ at 1.7. These limits satisfy the likelihood ratio test at the 95% confidence level. The implications of the results for large-scale structure formation scenarios are discussed.

Subject heading: cosmic background radiation

I. INTRODUCTION

The goal of searches for anisotropy in the cosmic microwave radiation (CMR) is to detect temperature fluctuations that are expected to arise from inhomogeneities present at the time of decoupling of the radiation from matter when the temperature of the universe was $\sim 4000$ K. These expected inhomogeneities are thought to be the precursors to structure seen in the present-day universe. With the exception of a dipole effect with amplitude $\sim 3$ mK and tentative detections at angles of 5°–8° (Davies et al. 1987; Melchiorri et al. 1981) the CMR appears uniform to better than $\Delta T/T \sim 10^{-4}$.

The most sensitive experiments to date (Uson and Wilkinson 1984a, b; Readhead et al. 1988) are at 5–5 arcminutes and employ low-noise ground-based radio telescopes and long integration times. Experiments at this angular scale are sensitive to anisotropies arising from the seeds of structure on the scale of clusters of galaxies.

Large-scale maps of the CMR have been made from balloon platforms (Fixsen, Cheng, and Wilkinson 1983; Lubin et al. 1985) and from the Prognoz 9 satellite (Strukov, Skulachev, and Klypin 1988) to avoid atmospheric noise, which worsens with increasing angular scale. These experiments use large beams ($\geq 3°$) to scan over most of the sky, measuring the dipole effect and searching for anisotropies with angular scales $>1°$.

There remains a relatively unexplored region from 0.5° to 5° which is difficult to observe from the ground because of atmospheric effects. However, several recent theoretical scenarios predict residual fluctuations in the CMR with coherence lengths in this angular range (Juszkiewicz, Górski, and Silk 1987; Peebles 1987). Also, in the absence of inflation, the CMR photosphere is divided into regions of several angular degrees that are not causally connected (Weinberg 1972). We present here the results from a ground-based experiment in the 0.5°–5° angular range.

II. OBSERVATIONS

Measurements of the CMR were made with a low-noise interferometer that is described in detail elsewhere (Timbie and Wilkinson 1988). The instrument is designed specifically for ground-based anisotropy measurements at intermediate angular scales. It employs two SIS heterodyne receivers tuned to a center frequency of 43 GHz. This frequency lies within an atmospheric window and near a minimum between the radio and thermal dust emissions of our Galaxy.

The beam pattern and observation scheme are displayed in Figure 1. The symmetric beam pattern and the second level of beam switching (wobble) help eliminate effects from atmospheric fluctuations, which have limited the sensitivity of ground-based measurements except at small angular scales (Partridge 1988). The relative phase between the two interferometer channels is adjusted to produce a symmetric interference pattern; the three central lobes of the beam profile are similar to the pattern achieved by a single-beam antenna undergoing "chopping and wobbling" (Uson and Wilkinson 1984a, b). This pattern has no response to large-scale spatial gradients in the atmospheric emission; thus atmospheric noise (which is greatest on large scale) is reduced compared to that measured by the asymmetric beam pattern. Also, the interferometer has no response to large uniform sources (sky or ground), so it is immune to slow temperature drifts in these sources. Finally, the entire interferometric beam is "wobbled" at constant elevation every 10 s from one side of the north celestial pole (NCP) to the other, and a difference is formed between the integrated "west" and "east" signals ($T_W - T_E$). This procedure subtracts long-term drifts in the instrument output arising from (1) slow changes in the second and higher spatial derivatives of atmospheric emission and from (2) drifts in instrument gain and offset. Wobbling also allows observation of each sky patch every 12 hr, thus reducing confusion of true sky signal with any residual diurnal effects on the instrument.

The interferometer is calibrated, and the beam efficiency is checked, approximately every 8 hr, by sweeping a small, ambient temperature blackbody target through the beam. The overall calibration error is estimated to be $<25\%$; drift in calibration or beam shape over 8 hr is $<10\%$. At 43 GHz we can use the Rayleigh-Jeans approximation for both the 2.7 K and 300 K blackbody spectra.

The noise of the interferometer determined by this calibration varied over the course of the observations between 13 mK/s$^{1/2} < \Delta T_{\text{rms}} < 15$ mK/s$^{1/2}$. These values represent the instrument's sensitivity to the difference between the antenna
temperature of the central, positive interference lobe and the two negative lobes. The values account for the efficiency of the symmetric beam (77%). The system temperature of each of the two SIS receivers was measured daily; at the entrance to the antennas the system temperature of one receiver was typically 65–75 K and the other was 75–103 K, depending mainly on the tuning of the mixers. The sky temperature was measured a few times on clear days and found to be 23 ± 1 K at 0° zenith angle. Of this, 2.7 K is from the CMR, ~18 K is from O2 emission, and ~2 K is from water vapor emission. At the 38° zenith angle of the NCP, the sky contributes ~28 K of antenna temperature. Combining these receiver temperatures, the sky temperature, beam efficiency and the bandwidth (500 MHz) gives (see Timbie and Wilkinson 1988) values for ΔT_m that correspond well with those measured directly and reported above.

Observations were made during 1987 January and February in Saskatoon, Saskatchewan (52° 14' N, 106° 37' W). Saskatoon was chosen as an observing site because its climate is cold, clear, and dry during the winter months. Precipitable water in January and February has a mean value of 4 mm and on the coldest days it drops to ≤2 mm (Hay 1970; Environment Canada 1983). The mean temperature for these months is −17°C. The relatively high latitude of the site makes observations of the NCP region less troubled by sidelobe spill-over to the ground on the north horizon. Also, the Sun appears only in the far backlobes of the antenna pattern.

After several weeks of preparation, the interferometer was ready to collect data between 1987 January 28 and February 11, a period of approximately 350 hr. During this time 156 hr of data were recorded; of the remaining time, 35 hr were required for maintaining the instrument (primarily refilling the helium bath) and the rest were lost to extended periods of precipitation or heavy cloud conditions, when the instrument was covered and turned off. Although clear, cold weather generally provided the best (lowest sky noise) observing conditions, excellent data were also obtained during periods that were partly cloudy or overcast with high altitude clouds.

III. DATA REDUCTION

The 156 hr of raw data were edited to remove periods of excessive noise due to atmospheric fluctuations or instrument instability. First, periods of gross noise (σ ≥ 10σ_INS) were discarded by inspection, leaving 139 hr. Most of the discarded time corresponds to the presence of heavy clouds or the arrival of new weather systems. Some occurred in periods when the temperature of the pumped helium bath was changing. Next, a program computed the standard deviation of wobble-differenced data (one point every 20 s) for data in 5 minute segments and discarded any segment with standard deviation from the mean of the segment greater than 3 times that expected from instrument noise alone. This procedure, intended to eliminate short periods of radio interference (e.g., aircraft transmitters), removed 11 hr of data and is not excessively restrictive; a noise threshold of 10 σ in this program still cut 9 hr of the data. Noise in the remaining 128 hr of data is consistent with stable instrument performance and negligible atmospheric fluctuations, even though approximately 10%–20% of the final data were obtained during partly cloudy to overcast conditions. The rest of the time the sky was clear. The remaining data were organized by sidereal time into bins of 2 hr width. In 2 hr the sky rotates about the NCP by approximately 1/3 of the beamwidth in elevation of the central interference lobe; therefore the sky is slightly oversampled. The mean and standard deviation in $T_w - T_E$ are computed for each bin. Each of the 12 bins contains between 6 and 15 hr of data.

II. SYSTEMATIC EFFECTS

Because of the symmetry of the observing scheme, the mean of the 12 binned points should be zero; the extent to which this is true is a test of the effectiveness of the wobble procedure.
Astronomical sources appearing at one time will reappear 12 hr later and will produce an output of opposite polarity. However, signals from persistent spurious sources which are not completely subtracted out by wobbling, such as nonuniform ground emission into antenna sidelobes, can give rise to a nonzero mean ("offset"). Initially, we had such a source due to radar pulses from the Saskatoon airport. Careful screening removed most of the interference, but a small effect may have remained. A diffraction calculation of the beam pattern, which agrees well with measurements of the beam pattern, shows that the total power radiated from the ground and horizon into each antenna is 10 mK. If the ground temperature is spatially uniform the interference pattern and wobbling procedure will subtract out this radiation. The weighted mean of the 12 points is 190 ± 50 μK and is consistent with pickup of nonuniform radiation from the ground. Such a source would be expected to vary by <10% over 24 hr from changes in the temperature of the Earth's surface. The mean (i.e., offset) is too small for us to see such a temporal effect; in fact, there is no evidence that the offset varies with time. The fact that this mean is so small (<1 part in 10^5 of the power entering in each antenna) indicates that the observing procedure rejects nonastronomical contamination to a high level. The mean is subtracted from each of the 12 binned points; Figure 2 shows the resulting data points. The errors are statistical only and are consistent with the measured system noise divided by the square root of the integration time for each bin; there is no evidence for significant excess noise arising from atmospheric fluctuations. The 10% calibration error is negligible in comparison to the statistical errors and is not included.

The contributions of normal astronomical radio sources in the main antenna beams are negligible at the frequency, beam size, and sensitivity of this experiment. Also, the Sun and Moon appeared in the antenna sidelobes at least 100° and 84°, respectively, from the forward beam. Based upon beam pattern measurements, we estimate that they contribute less than 20 μK and 8 μK to the radiometer output. Galactic synchrotron emission is estimated by extrapolating a 408 MHz map (Haslam et al. 1982) to 43 GHz using the usual ν^{-2.8} scaling law. The Galactic synchrotron signal in the polar region should contribute less than 10 μK to our signal. Galactic bremsstrahlung sources could be glowing faintly, and we would not yet know about them; if anisotropy is seen, its spectrum will have to be checked. Extrapolating recent measurements of Galactic dust emission (Matsumoto et al. 1988) we expect less than 30 μK contribution at 43 GHz. No corrections for foreground sources are made to the data of Figure 2.

V. RESULTS

Figure 2 shows that no large temperature fluctuations in the CMR have been found on the angular scale of our antenna beams, ~1°. A CMR signal would appear as a statistically significant deviation from the mean that recurs with opposite sign after 12 hr. All the data points lie within 2 standard deviations of the mean. The χ² for a fit to (Tw - Tg) = constant is 16.5 for 11 degrees of freedom; roughly speaking, the data are consistent with temperature fluctuations in the sky (with the pattern of Fig. 1b) having a ΔTrms of 180 μK, or less.

In order to set more meaningful limits on CMR anisotropy we employ statistical tests to compare the data to several models of CMR fluctuations. Comparison to a given model allows one to account for the shape of the beam pattern and its sensitivity to anisotropy over a range of angular scales.

The statistics of Gaussian fluctuations in the CMR anisotropy are completely specified by their two-point correlation function, which depends only upon the magnitude of the separation angle, θ (Bond and Efstathiou 1987):

\[ C(θ) = \frac{ΔT(θ)}{T} \frac{ΔT(θ_2)}{T}, \]

\[ θ = |θ_1 - θ_2|, \]

(1)

and

\[ C(θ)^{1/2} = \frac{ΔT_{\text{rms}}}{T}, \]

(2)

where T = 2.76 K (Johnson and Wilkinson 1987). We first compare our results (Fig. 2) to two "generic" correlation functions. Several more specific models are examined in § VI. The first general model tested is for the correlation function \[ C(θ) = C_0 e^{-θ^2/2σ^2}, \]

which corresponds to temperature fluctuations with a Gaussian-shaped power spectrum and with an angular correlation length = θc. The second model is for "monochromatic" temperature fluctuations in which the power spectrum is a delta function. Here the correlation function is a Bessel function, \[ C(θ) = C_0 J_0(2πθ/θ_0), \]

where θ0 is the angular wavelength of the fluctuations; the correlation length is \[ θ_0 = θ_0(2)^{1/2}. \]

For each model we employ a likelihood ratio test (Martin 1971; Lawrence et al. 1988) to distinguish between two hypotheses: \[ H_0 \] (null hypothesis), that the data are described by a combination of instrument noise and true CMR fluctuations given by the model, or \[ H_a \] (alternative hypothesis), that the data arise from instrument noise alone.

The likelihood ratio, \( λ \), is defined to be the ratio of the probability density functions under test:

\[ λ = \frac{f_0}{f_a}. \]

(3)

We determine a value, k, such that when \( λ < k \) we chose \( H_a \) as the correct hypothesis. When \( λ > k \) we choose \( H_0 \) over \( H_a \). The value of k selected determines the confidence level of the test; we choose a confidence level of 95%. The Neyman-Pearson
lemma ensures that this test is a most powerful test for selecting between two simple hypotheses at a given significance level (Martin 1971). The parameters $f_0$ and $f_a$ are multivariate normal probability density functions with zero mean:

$$f_0 = \frac{e^{-iR_0 - 1/2}}{(2\pi)^{N/2} |R_0|^{1/2}},$$  \hspace{1cm} (4)

and

$$f_a = \frac{e^{-iR_a - 1/2}}{(2\pi)^{N/2} |R_a|^{1/2}},$$  \hspace{1cm} (5)

where the $N$ observed data points shown in Figure 2 are the components of the vector $t$ and $R_s$ and $R_o$ are correlation matrices that depend on the hypotheses as shown below.

Let $T = T(\theta)$ be the CMR temperature at a position, $\theta$, in the sky. Let $h(\theta)$ be the beam pattern of the interferometer, including wobble, for a particular orientation of the sky with respect to the beam. The index "i" is a function of hour angle and is a discrete variable since we have divided the sky into $N = 12$ sectors. Each sector is 2 hr wide and is observed twice a day. Then the CMR temperature measured by the instrument at a particular hour angle is

$$\langle T_W - T_E \rangle \equiv \tau_i = \int T(\theta)h(\theta)d\theta.$$  \hspace{1cm} (6)

If the correlation function under test is $C(\theta)$, then the effective correlation function measured by the instrument is

$$\frac{\langle \tau_i \tau_j \rangle}{T^2} = \int \int \int \int C(\theta' - \theta')|h(\theta')h(\theta')|d\theta'd\theta''.$$  \hspace{1cm} (7)

The correlation matrices corresponding to our two hypotheses can now be expressed.

For $H_o$, the data, $t$, include both CMR anisotropy, $\tau_a$, and instrument noise, $n_i$: $t_i = \tau_i + n_i$. The correlation matrix is

$$R_o = \frac{\langle t_i + n_i t_j + n_j \rangle}{T^2} = \frac{\langle t_i t_j \rangle}{T^2} + \frac{\sigma_i^2 \delta_{ij}}{T^2},$$  \hspace{1cm} (8)

where $\sigma_i^2$ is the measured variance of the data from sector $i$. Noise is not correlated between one beam position and another so it adds only diagonal terms to $R_o$. For $H_a$, $t$ includes only instrument noise, so $t_i = n_i$ and

$$R_a = \frac{\langle n_i n_j \rangle}{T^2} = \frac{\sigma_i^2 \delta_{ij}}{T^2}.$$  \hspace{1cm} (9)

For each $C(\theta)$ to be tested a Monte-Carlo simulation of the experiment is used to determine the expected distribution of the statistic, $\lambda$. That is, simulated data belonging to the probability density $f_0$ are generated and used to compute the probability distribution of $\lambda$ corresponding to $C(\theta)$. The value $k$ is determined by evaluating the likelihood ratio using the actually measured data. The area under the $\lambda$ curve for $\lambda > k$ is the confidence level of the test. The amplitude, $C_0$, of the correlation function under test is varied until a 95% confidence level is obtained and that value of $C_0$ is the anisotropy limit. The power of the test is then determined in a similar way, by computing a new $\lambda$ distribution based on simulated data belonging to $f_a$.

The test is repeated over a range of characteristic angles, $\theta_c$. Figure 3 shows the 95% confidence level upper limits for CMR anisotropy as a function of $\theta_c$ for the two generic correlation functions. We conclude that the hypothesis that $C(0)^{1/2}$ is greater than the limits plotted in Figure 3 can be rejected at the 95% level. That is, there is only a 5% chance that data obtained in a universe correctly described by the correlation function under test could exhibit as low a value of $\lambda$ as the actual data had. In addition, the power of the test indicates that in 53%–62% of repeated experiments the data arising from instrument noise alone could be correctly distinguished from data including the CMR anisotropy signal at the given limit level.

VI. DISCUSSION

Limits on anisotropy for more specific models of CMR anisotropy can be obtained using the above statistical procedure. Adiabatic and isothermal models of structure formation in a universe dominated by baryonic matter predict correlation lengths of $\sim 10'$. The best limits on these scales have been obtained by Uson and Wilkinson (1984a, b) and Readhead et al. (1989). The present experiment is optimized for a larger angular scale ($\sim 2'$) and hence is not as sensitive as previous experiments to these models. It does, however, confirm some results. We use correlation functions given by Wilson and Silk (1981) and Wilson (1983) and assume no reionization, a process that can alter medium and small-scale anisotropy (Vishniac 1987). For adiabatic initial density perturbations with a spectrum $|\delta_\nu|^2 \sim k^\lambda$, this experiment rules out a universe with $\Omega = 0.1$ and $n \geq 2$. For $\Omega \geq 1$, only $n = 0$ is rejected. For the isothermal case, $\Omega = 0.1$ and $n = -1$ can be eliminated.

For cold dark matter (CDM) scenarios we use correlation functions presented by Bond and Efstathiou (1987). These models have correlation lengths more appropriate to our experiment ($\sim 1'$), but their predicted amplitudes are well below our sensitivity. For example, for a CDM universe with $\Omega = 1$, $\Omega_{\text{baryonic}} = 0.03$, and $h = 0.75$, Bond and Efstathiou predict adiabatic fluctuations with $C(0)^{1/2} = 1.8 \times 10^{-5}$. Our 95% upper limit for this model is $C(0)^{1/2} \leq 2.1 \times 10^{-4}$; we are a factor of 12 away from seeing this level of anisotropy. Another way to put it is to compute the contribution made by the predicted CDM temperature fluctuations to the signal.
plotted in Figure 2. The convolution of our beam pattern with the given CDM correlation function predicts signals of \( \sim 25 \) \( \mu K \). Since the uncertainty in each point is \( \sim 150 \mu K \), at least an order of magnitude improvement in sensitivity is required.

However, for this correlation function the wobbled interferometer’s beam pattern is quite effective. Even an “ideal” experiment with a single narrow beam chopped between two spots 20° apart (much larger than the coherence length of the model) would have to measure a temperature difference of 48 \( \mu K \) to detect the predicted fluctuations; we lose less than a factor of 2 in sensitivity because of our beam geometry, which is optimized to eliminate atmospheric noise and ground pickup.

Peebles (1987) has computed the CMB anisotropy due to prameval isocurvature perturbations in a universe dominated by barions and radiation. The natural coherence scale of this model is \( \theta_i \), \( \sim 2° \) to \( 4° \), well matched to the angular size of our beams. For a Gaussian-shaped correlation function \( \Delta T_{\text{rms}}/T \) is estimated to be \( \sim 10^{-3} \), too small for detection with our current sensitivity. Also, Juszkiewicz et al. have shown that if large-scale streaming exists and is driven by the gravity of mass inhomogeneities, CMB anisotropy on a scale of \( \sim 2° \) is expected, since those same mass inhomogeneities generate anisotropy via the Sachs-Wolfe effect (Sachs and Wolfe 1967).

In this model predictions of \( \Delta T_{\text{rms}}/T \) range from \( 10^{-6} \) to a few times \( 10^{-5} \), still below our limits but having the appropriate angular scale. In particular, their model predicts that for an rms streaming velocity of 500 km s\(^{-1}\) and a flow scale of 50 Mpc, our experiment would see anisotropy at the \( \Delta T/T \sim 1.5 \times 10^{-10} \) level. We set an upper limit of \( \Delta T/T \leq 1.3 \times 10^{-4} \) (with 57% power) for their model.

In comparing our results to models and to other experiments, it is important to stress that we have quoted limits on intrinsic CMB correlation functions \( C_{TT}^{(0.4)2} \), rather than the measured correlation function \( [C_{TT}(0.4)]^{1/2} \) as defined in Davies et al. which contains the “dilution” effects of a particular experiment’s beam pattern and observing scheme. Limits placed on the intrinsic correlation functions will generally be poorer than those placed on the measured correlation function. Also, this experiment, like all the most sensitive ground-based searches for CMB anisotropy covered a small fraction of the sky. However, the likelihood ratio analysis performed here accounts for limited sky coverage as well as the details of the complicated beam pattern. A more complete sky survey at a comparable level of sensitivity per observed spot would be more capable of discovering any “hot spots” (Vittorio and Juszkiewicz 1987) that might exist and would set lower limits on \( C(0) \) if none were found.

Davies et al. (1987) reported a detection of a signal that corresponds to \( C(0)^{1/2} = \Delta T_{\text{rms}}/T = 5.7 \times 10^{-5} \) for a Gaussian-shaped correlation function with \( \theta_i \sim 4° \). This level is \( \sim 4 \times \) lower than our sensitivity to such correlation functions at \( \theta_i = 4° \) and \( 2 \times \) lower than our optimum sensitivity, which occurs at \( \theta_i = 1° \).

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REFERENCES

Environment Canada. 1983, Principal Station Data: Saskatoon A (Ottawa: Canadian Government Publishing Center).

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