The Astrophysical Journal, 553:L1–L4, 2001 May 20

A PRELIMINARY DETECTION OF ARCMINUTE-SCALE COSMIC MICROWAVE BACKGROUND ANISOTROPY WITH THE BIMA ARRAY

K. S. Dawson,[1] W. L. Holzapfel,[1] J. E. Carlstrom,[2] M. Joy,[3] S. J. LaRoque,[2] and E. D. Reese[2]
Received 2000 December 7; accepted 2001 April 18; published 2001 May 10

ABSTRACT

We have used the Berkeley-Illinois-Maryland Association (BIMA) array outfitted with low-noise millimeter-wave receivers to expand our search for arcminute-scale anisotropy of the cosmic microwave background (CMB). The interferometer was placed in a compact configuration for sensitivity on arcminute scales over its 6′.6 FWHM field of view. This experiment is most sensitive to flat band power described by an average multipole of $l = 5530$, corresponding to an angular scale of ∼2′. We present the analysis of 11 independent fields that were selected based on their low contrast in infrared dust emission and lack of bright radio sources. Applying a Bayesian analysis to the visibility data, we find CMB anisotropy flat band power $Q_{\rm flat} = 6.1^{+2.8}_{-4.8}$ μK at 68% confidence. The measured signal exceeds that expected from instrument noise with 76% confidence, and we find an upper limit of $Q_{\rm flat} < 12.4$ μK at 95% confidence. We have supplemented our BIMA observations with concurrent observations at 4.8 GHz with the Very Large Array to search for and remove point sources. We find that point sources make an insignificant contribution to the observed anisotropy.

Subject headings: cosmic microwave background — cosmology: observations

1. INTRODUCTION

The cosmic microwave background (CMB) radiation carries a wealth of information about the early universe. In the standard inflationary model, the distribution of matter at the epoch of recombination leads to small temperature anisotropy of the CMB. Measurement of this anisotropy on the largest angular scales reveals the primordial distribution of matter (Smoot et al. 1992). Structures that came into the horizon and were able to collapse near the epoch of recombination lead to anisotropy at degree angular scales. The resulting CMB anisotropy angular power spectrum on these scales is highly sensitive to the parameters of the cosmological model. Recent measurements of degree-scale anisotropy have been used to constrain the curvature of the universe (Miller et al. 1999; de Bernardis et al. 2000; Hanany et al. 2000). The anisotropy on smaller angular scales, less than a few arcminutes, will be exponentially damped to vanishingly small levels because of photon diffusion and from the finite thickness of the "surface" of last scattering (Hu & White 1997). At arcminute scales, so-called secondary anisotropy generated by the reionization of the universe and the Sunyaev-Zeldovich (SZ) effect from galaxy clusters should dominate the primary signal (for a review see Haiman & Knox 1999).

In this Letter, we report results from our ongoing program using the Berkeley-Illinois-Maryland Association (BIMA)[4] array to search for arcminute-scale CMB anisotropy. Discussion of the instrument, data reduction, Bayesian maximum likelihood analysis, expected signals (from primary anisotropies, secondary anisotropies, and foreground emission), and comparison with previous experiments is included in the release of our earlier results (Holzapfel et al. 2000, hereafter H2000). The selection and observations of the fields are reviewed in § 2. The results of the Bayesian analysis are presented in § 3, including a discussion of the effects of point-source subtraction. Finally, in § 4, we summarize the results and compare them with predicted levels of anisotropy.

2. OBSERVATIONS

We used the BIMA array at 28.5 GHz during the summers of 1997, 1998, and 2000 to search for arcminute-scale CMB anisotropy. We observed seven independent fields over the course of the first two summers. In two of these fields we found significant detections of excess power (H2000). We extended our observations of those two fields in the summer of 2000 and added four new fields to the survey.

2.1. *Field Selection*

For the summer of 2000 observations, we selected four new fields, each located within 2° of one of the fields selected in 1998. This strategy was employed to make efficient use of observing time, allowing a 6 hr separation between fields as in the 1998 survey, and to search for systematic errors related to sky position, which could have resulted in false detections in our previous observations (see § 3.2). The new fields were chosen to lie in regions of low dust emission and contrast as determined from examination of *IRAS* 100 μm maps. The NRAO VLA Sky Survey (Condon et al. 1998) and Faint Images of the Radio Sky at 20 cm survey (White et al. 1997) were then used to select regions free of bright point sources at 1.4 GHz. In addition, we used the SkyView digitized sky survey and *ROSAT* images to check for bright optical or X-ray emission, which could complicate follow-up observations. The pointing centers for each of the six fields observed in the summer of 2000 are given in Table 1.

2.2. *BIMA Observations*

All anisotropy observations were made using the BIMA array at Hat Creek. For the CMB observations, nine of the 10 6.1 m telescopes of the array were equipped for operation at 28.5 GHz, providing a 6′.6 FWHM field of view. In order to track phase and gain fluctuations, each 25 minute field obser-

[1] Department of Physics, University of California, Berkeley, Berkeley, CA 94720.
[2] Department of Astronomy and Astrophysics, University of Chicago, 5640 South Ellis Avenue, Chicago, IL 60637.
[3] Space Science Laboratory, SD50, NASA Marshall Space Flight Center, Huntsville, AL 35812.
[4] The BIMA array is operated by the Berkeley-Illinois-Maryland Association under funding from the National Science Foundation.

TABLE 1
Field Positions and Observation Times

Field	R. A. (J2000)	Decl. (J2000)	Observation Year	Time (hr)
BDF6	18 21 00.0	59 15 00	1998, 2000	81.2
BDF7	06 58 45.0	55 17 00	1998, 2000	68.2
BDF8	00 17 30.0	29 00 00	2000	34.6
BDF9	12 50 15.0	56 52 30	2000	24.5
BDF10	18 12 37.21	58 32 00	2000	14.3
BDF11	06 58 00.0	54 24 00	2000	22.1

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

TABLE 2
Image Statistics for u-v Range 0.63–1.2 kλ

Field	Beam Size (arcsec)	rms (μJy beam^{-1}) Estimated	rms (μJy beam^{-1}) Measured	rms (μK) Estimated	rms (μK) Measured
BDF6	106.7 × 118.9	113	166	13.4	19.6
BDF7	108.0 × 120.3	130	166	15.0	19.2
BDF8	102.6 × 116.1	166	133	20.9	16.7
BDF9	101.6 × 118.9	209	196	26.0	24.3
BDF10	105.3 × 115.5	275	276	33.9	34.0
BDF11	104.4 × 115.1	208	279	26.0	34.8

vation was bracketed by a 5 minute observation of a bright radio point source (see H2000). The fluxes of these calibration sources are all referenced to the flux of Mars, which is uncertain by approximately 4% at 90% confidence (see discussion in Grego et al. 2001). This uncertainty is small compared with the uncertainty in the anisotropy amplitude we report here and therefore makes a negligible contribution to the error in the reported values. Of the total time spent observing, ∼60% was spent on a blank field. The cumulative integration times for each of the six fields observed in 2000 are listed in Table 1. Combined with the observations described in H2000, a total of 470 hr of on-field integration have been dedicated to the 11 fields included in this project.

2.3. *VLA Observations and Point-Source Results*

Observations of the CMB power spectrum can be contaminated by foreground emission. Contributions at 28.5 GHz arising from Galactic sources such as dust, synchrotron, and free-free emission are expected to be below the microkelvin level at arcminute angular scales (Tegmark et al. 2000). Emission from radio point sources is expected to be the dominant form of foreground contamination for the observations presented here.

The compact configuration used for the 2000 summer BIMA anisotropy observations produced high sensitivity to extended sources but lacked the spatial dynamic range to distinguish point sources from CMB fluctuations. To help constrain the contribution from point sources to our anisotropy measurements, we used the Very Large Array (VLA)[5] at a frequency of 4.8 GHz to survey each of the new fields as well as two of the 1998 fields that lacked point-source observations. With 1.5 hr of observing time per field, we reached an rms flux of ∼25–30 μJy at the center of a 9′ FWHM region centered on each of the blank fields observed with BIMA. In the six fields examined with the VLA, we found 18 point sources with fluxes adjusted for the attenuation of the primary beam ranging from 157 to 2000 μJy.

[5] The VLA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

The point-source fluxes at 28.5 GHz are extrapolated from the lower frequency VLA data by assuming a spectral index of $\alpha = 0.71$, where $S_\nu \propto \nu^{-\alpha}$ (Cooray et al. 1998). After accounting for attenuation due to the BIMA primary beam, all of the point sources detected with the VLA are estimated to be near or below the measured rms flux density achieved in the BIMA blank-field data.

3. RESULTS

We have produced and analyzed images for each of the observed fields. The statistics of the images produced with only short baselines are listed in Table 2. The observed rms values are compared with those expected from the noise properties of the visibilities. We also express our results in terms of the rms Rayleigh-Jeans temperature fluctuations. The short baselines used to produce Table 2 nearly match the baselines used to determine the CMB anisotropy. The window function produced from the noise-weighted sum of the window functions of the individual visibilities peaks at a multipole $l = 5906$ and has an FWHM of $l = 2470$, with an average value of $l = 5530$. The window function is similar to those shown in Figure 5 of H2000.

3.1. *Anisotropy Analysis*

We use the method described in H2000 to determine the relative likelihoods that the observed fields are described by a model for the CMB fluctuations with flat band power $Q_{\rm flat}$. We present the results of the analysis of the BIMA data both with and without the subtraction of the point-source fluxes extrapolated from the VLA observations. In Table 3, we show the most likely $Q_{\rm flat}$ for each of the fields observed in the summer of 2000. Results for the individual fields BDF1–BDF5 are reported in H2000. Figure 1 shows the relative likelihoods as a function of assumed $Q_{\rm flat}$ for each of the fields observed in the summer of 2000 when no point sources are subtracted. The results are normalized to unity likelihood for the case of no anisotropy signal. Note that the results for fields BDF6 and BDF7, as displayed in both Table 3 and Figure 1, include the data collected in the summer of 1998.

TABLE 3
Most Likely $Q_{\rm flat}$ and Confidence Intervals for Individual Fields

Field	$Q_{\rm flat}$ (no point sources) (μK) Most Likely	68%	95%	$Q_{\rm flat}$ (flat spectral index) (μK) Most Likely	68%	95%
BDF6	15.0	8.2–22.4	0.8–28.6	15.2	8.2–22.6	0.0–29.2
BDF7	13.2	3.2–21.2	0.0–31.8	18.6	8.4–28.8	0.0–37.0
BDF8	0.0	0.0–10.4	0.0–21.2	0.0	0.0–10.2	0.0–20.6
BDF9	0.0	0.0–15.0	0.0–30.6	0.0	0.0–14.2	0.0–28.8
BDF10	0.0	0.0–23.2	0.0–47.6	0.0	0.0–25.6	0.0–50.6
BDF11	23.2	10.8–35.6	0.0–46.2	22.4	10.0–34.8	0.0–45.6

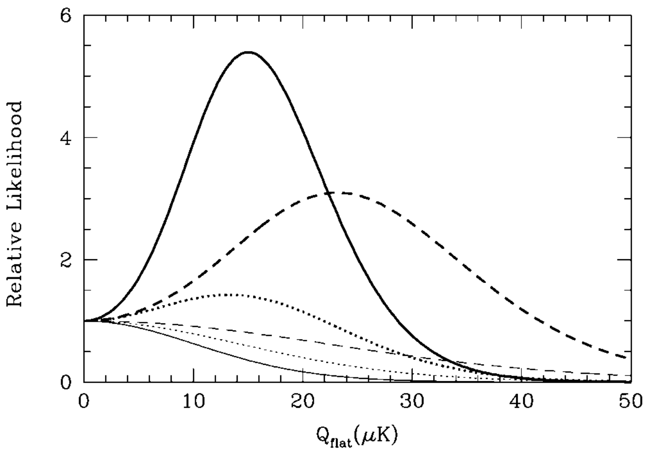

FIG. 1.—Relative likelihood that the observed signal in each field is described by flat band power with amplitude $Q_{\rm flat}$, ignoring possible point sources. Fields BDF08 (*light solid line*), BDF09 (*light dotted line*), BDF10 (*light dashed line*), BDF06 (*heavy solid line*), BDF07 (*heavy dotted line*), and BDF11 (*heavy dashed line*) are shown.

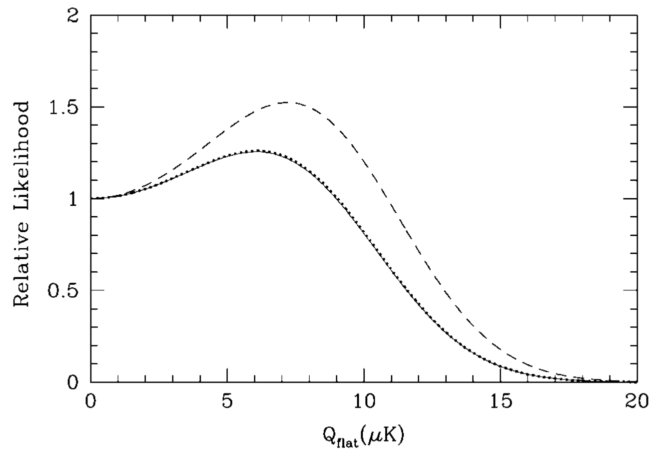

FIG. 2.—Relative likelihood that the observed signal in the 11 combined fields is described by flat band power with amplitude $Q_{\rm flat}$. The solid line corresponds to an analysis ignoring the measured point sources, the dotted line is the result of subtracting point sources assuming a spectral index of -0.71, and the dashed line is the result of subtracting measured point sources assuming a flat spectrum.

We estimate the point-source contribution to the BIMA results by extrapolating the flux of point sources detected with the VLA at 4.8 GHz to the 28.5 GHz BIMA observation frequency assuming a spectral index α. These sources are then removed from the data by taking the Fourier transform of the point-source model modulated by the primary beam response and subtracting it directly from the raw visibility data. Table 3 compares results for individual fields with no point-source subtraction to results using a model for the point sources that assumes a flat spectral index ($\alpha = 0$), which is considered to be a worst case scenario. In Figure 2, we plot the combined likelihood for all 11 of the fields under three assumptions for subtracted point-source model: no point sources, extrapolated fluxes assuming $\alpha = 0.71$, and extrapolated fluxes assuming a flat spectral index. In Table 4, we list the 68% and 95% confidence intervals in $Q_{\rm flat}$ for each of the three point-source extrapolations considered. The results are essentially identical before and after the subtraction of the extrapolated source fluxes assuming $\alpha = 0.71$. Assuming a flat spectrum, the most likely $Q_{\rm flat}$ increases slightly, indicating that we have overestimated the flux of the point sources and by subtracting these sources we are adding excess power to the BIMA data. It is clear that the point sources observed with the VLA cannot account for the detected excess power.

Again, as found in H2000, the joint likelihood for all the data, shown in Figure 2, peaks at $Q_{\rm flat} > 0$. While the most likely $Q_{\rm flat}$ remains essentially unchanged from the H2000 results, the addition of the new observations has increased the significance of the detection. Regardless of the spectral index assumed in the extrapolation of the point-source fluxes, the confidence that the data is described by a model with a nonzero $Q_{\rm flat}$ for the joint likelihood is greater than 76%, which can be compared with 44% for the total of all data collected prior to the summer 2000 observations.

3.2. *Systematics Check*

Much of the motivation for the new BIMA observations described here was to perform tests for systematic errors that could have been responsible for the previously reported detections in fields BDF6 and BDF7. This involved choosing new fields located within 2° of the original fields. This relatively small offset should allow us to test whether the data suffer from a false correlation because of a time- or position-dependent source of interference. We note that both the 1998 and 2000 observations were obtained in the same four weeks (mid-August to early September), and therefore fields with similar coordinates were observed at the same time of the day and with similar offsets from the Sun. As in 1998, no significant excess power was detected in either the $13^{\rm h}$ fields or the $00^{\rm h}$ fields; no further systematic checks on these fields are included in this section.

We first investigated whether the observed excess power might somehow depend on the position of the source on the sky. The results for the two $18^{\rm h}$ right ascension fields, BDF6 and BDF10, were compared. The observations in 2000 repeated the detection of excess power in BDF6, but none was found in BDF10, suggesting that the observed excess power in BDF6 is not due to a systematic associated with sky position (at least on the 2° scale). For the two $7^{\rm h}$ right ascension fields, BDF7 and BDF11, the results are not as conclusive; excess power was detected in both fields. To check for the possibility of a coherent signal between the fields, e.g., possibly from a local source of interference, we combined the data from the two fields as if they were from the same position on the sky. The process of combining the two fields dropped the most likely value to $Q_{\rm flat} = 6\ \mu$K, effectively eliminating the excess power found in either field. This result leads us to believe that there is no correlation of anomalous power due to sky position.

We have performed several additional tests of the data to search for systematic errors in the fields in which we find excess power. Since the data on each field were collected over an extended period of time, we divided the data into blocks of several days and analyzed each block independently. If a spurious signal were injected over a short period of time, we might

TABLE 4
ANALYSIS OF COMBINED FIELDS INCLUDING CONFIDENCE OF $Q_{\rm flat} > 0$

Point-Source Model	$Q_{\rm flat}$ (μK) Most Likely	68%	95%	Confidence $Q_{\rm flat} > 0$
None	6.1	1.3–8.9	0.0–12.4	76%
$\alpha = -0.71$	6.1	1.4–8.9	0.0–12.4	76%
$\alpha = 0$	7.2	2.4–10.5	0.0–13.2	85%

expect to find a significantly larger detection in one of the blocks of data. The analysis of individual data blocks did not result in any significant detection, and we can conclude that any source of interference must be constant over several days. We next checked for the presence of systematic errors as a function of time of day. For each field, we divided the data into three blocks spanning equal intervals in hour angle. Again, there was no evidence for the excess power that would be expected if one block of data were responsible for the signal. We see no convincing evidence that our determination of excess power is the result of a systematic error. In order to eliminate this possibility, it will be necessary to identify the astrophysical sources of the extra power.

4. CONCLUSION

Over the course of three summers, we have used the BIMA array in a compact configuration at 28.5 GHz to search for CMB anisotropy in 11 independent 6.′6 FWHM fields. With these observations, we have made a preliminary detection of arcminute-scale CMB anisotropy. In the context of an assumed flat band power model for the CMB power spectrum, we find $Q_{\rm flat} = 6.1^{+2.8}_{-4.8}$ μK at 68.3% confidence with sensitivity on scales that correspond to an average harmonic multipole $l_{\rm eff} = 5530$. The confidence of a nonzero signal is 76%, and we find an upper limit of $Q_{\rm flat} < 12.4$ μK at 95% confidence. When extrapolated to 28.5 GHz, the fluxes of the point sources located with the VLA are near or below the noise level in the BIMA images and make no significant contribution when included in the likelihood analysis. A recent search for CMB anisotropy on arcminute angular scales with the Australia Telescope Compact Array at 8.7 GHz (Subrahmanyan et al. 2000) was able to place an upper limit of $Q_{\rm flat} < 25$ μK at 95% confidence, but this work was believed to be confusion-limited by unresolved point sources. Using the method described in H2000, we can use the VLA 5 σ flux limit of ∼150 μJy at 4.8 GHz to estimate the contribution of unresolved point sources to the excess power. Assuming a universal spectral index of $\alpha = -0.71$, we expect a contribution of $Q_{\rm flat} \sim 1.1$ μK due to unresolved point sources in the BIMA data at 28.5 GHz. Assuming a flat spectral index of $\alpha = 0$, we expect a contribution of $Q_{\rm flat} \sim 3$ μK as a conservative upper limit.

This work may represent the first detection of secondary CMB anisotropy in a region of the sky not selected for the presence of known galaxy clusters. A detection of excess power is not surprising when one considers the level of anisotropy expected from the SZ effect in distant clusters of galaxies. Recent hydrodynamic simulations of cluster formation predict $Q_{\rm flat}$ values that range from 5.0 to 9.7 μK at the angular scales on which this experiment is sensitive (Springel, White, & Hernquist 2001; Refregier & Teyssier 2000; Seljak, Burwell, & Pen 2001). Our results agree with these simulations to 95% confidence. However, we should keep in mind that our method of choosing fields in regions free of bright point sources could result in a lower $Q_{\rm flat}$ than would be found in a survey of fields selected at random to the extent that radio sources are correlated to galaxy clusters. If the excess power we have detected is indeed due to the SZ effect in distant clusters of galaxies, deeper observations planned for summer 2001 will be capable of resolving the individual clusters and begin the study of their structure and distribution.

This Letter is dedicated to the memory of Mark Warnock, an electronics engineer at the BIMA observatory. His expertise and experience helped ensure the success of the centimeter-wave imaging program at BIMA. We thank the entire staff of the BIMA observatory for their many contributions to this project. We also thank Rick Forster, Laura Grego, Daisuke Nagai, and Dick Plambeck for their assistance with both the instrumentation and observations. This work is supported in part by NASA LTSA grant NAG5-7986. The BIMA millimeter array is supported by NSF grant AST 96-13998. We are grateful for the scheduling of Target of Opportunity time at the VLA in support of this project.

REFERENCES

Condon, J. J., Cotton, W. D., Greisen, E. W., Yin, Q. F., Perley, R. A., Taylor, G. B., & Broderick, J. J. 1998, AJ, 115, 1693
Cooray, A. R., Grego, L., Holzapfel, W. L., Joy, M., & Carlstrom, J. E. 1998, AJ, 115, 1388
de Bernardis, P., et al. 2000, Nature, 404, 955
Grego, L., Carlstrom, J. E., Reese, E. D., Holder, G. P., Holzapfel, W. L., Joy, M., Mohr, J. J., & Patel, S. 2001, ApJ, 552, 2
Haiman, Z., & Knox, L. 1999, in ASP Conf. Ser. 818, Microwave Foregrounds, ed. A. De Oliveira-Costa & M. Tegmark (San Francisco: ASP), 227
Hanany, S., et al. 2000, ApJ, 545, L5
Holzapfel, W. L., Carlstrom, J. E., Grego, L., Holder, G., Joy, M., & Reese, E. D. 2000, ApJ, 539, 57 (H2000)
Hu, W., & White, M. 1997, ApJ, 479, 568
Miller, A. D., et al. 1999, ApJ, 524, L1
Refregier, A., & Teyssier, R. 2000, Phys. Rev. D, submitted (astro-ph/0012086)
Seljak, U., Burwell, J., & Pen, U. 2001, Phys. Rev. D, 63, 063001
Smoot, G. F., et al. 1992, ApJ, 396, L1
Springel, V., White, M., & Hernquist, L. 2001, ApJ, 549, 681
Subrahmanyan, R., Kesteven, M. J., Ekers, R. D., Sinclair, M., & Silk, J. 2000, MNRAS, 315, 808
Tegmark, M., Eisenstein, D. J., Hu, W., & de Oliveira-Costa, A. 2000, ApJ, 530, 133
White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479