

Detection of Cosmic Microwave Background Structure in a Second Field with the Cosmic Anisotropy Telescope

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ABSTRACT

We describe observations at frequencies near 15 GHz of the second $2^\circ \times 2^\circ$ field imaged with the Cambridge Cosmic Anisotropy Telescope (CAT). After the removal of discrete radio sources, structure is detected in the images on characteristic scales of about half a degree, corresponding to spherical harmonic multipoles in the range $\ell \approx 330$ –680. A Bayesian analysis confirms that the signal arises predominantly from the cosmic microwave background (CMB) radiation for multipoles in the lower half of this range; the average broad-band power in a bin with centroid $\ell = 422$ ($\theta \approx 51'$) is estimated to be $\Delta T/T = 2.1_{-0.5}^{+0.4} \times 10^{-5}$. For multipoles centred on $\ell = 615$ ($\theta \approx 35'$), we find contamination from Galactic emission is significant, and constrain the CMB contribution to the measured power in this bin to be $\Delta T/T < 2.0 \times 10^{-5}$ (1σ upper limit). These new results are consistent with the first detection made by CAT in a completely different area of sky. Together with data from other experiments, this new CAT detection adds weight to earlier evidence from CAT for a downturn in the CMB power spectrum on scales smaller than 1° . Improved limits on the values of H_0 and Ω are determined using the new CAT data.

Key words: Cosmic microwave background — Cosmology: observations

1 INTRODUCTION

Observations of spatial fluctuations in the cosmic microwave background (CMB) radiation are fundamental to our understanding of structure formation in the universe as they mark the earliest observable imprints of massive gravitational structures (see e.g. review by White, Scott & Silk 1994). The distribution and amplitude of anisotropies in the CMB sky over scales from degrees to arcminutes can be used to discriminate between competing cosmological theories. On scales of 0.2° – 2° , inflationary models predict that increased power should be seen in the CMB sky due to scattering of photons during acoustic oscillations of the photon-baryon fluid at recombination. Detection and study of these acoustic or ‘Doppler’ peaks in the power spectrum is one of the primary goals of CMB astronomy. Furthermore, the

amplitudes and angular scales of the acoustic peaks provide powerful constraints on basic cosmological parameters including H_0 and Ω .

The first clear indication of a downturn in the power spectrum on sub-degree scales was provided by the detection of CMB power by the Cambridge Cosmic Anisotropy Telescope (CAT) on scales of about half a degree (Scott et al. 1996; Paper I). The CAT is a three-element interferometer operating at frequencies between 13 and 17 GHz (Robson et al. 1993). It is sensitive to structure on angular scales of about $10'$ to $30'$ over a field of view covering $2^\circ \times 2^\circ$ (primary beam FWHM). This paper describes observations of a second field observed with CAT and the detection of CMB anisotropies within it, at levels consistent with measurements in the first field.

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2 OBSERVATIONS AND DATA REDUCTION

Observations have been made with the CAT of a blank field centred at the position 17 00 00 +64 30 00 (B1950), which we call ‘CAT2’. The field was chosen to be relatively free from strong radio sources at frequencies up to 5 GHz (Condon, Broderick & Seielstad 1989), lie at high Galactic latitude ($b > 30^\circ$) and away from known Galactic features (e.g. the North Polar spur).

In periods during the interval 1995 March – 1997 June, CAT observed the CAT2 field at three frequencies, 13.5, 15.5 and 16.5 GHz. The three baselines of the array were scaled with frequency to achieve the same resolution at each frequency. The resulting synthesised beams measured $20'$ FWHM in right ascension and $24'$ in declination. The primary beam of the telescope, due to the symmetric nearly-Gaussian envelope beams of the three horn-reflector antennas, has a FWHM of 1.96° at 15.5 GHz, scaling inversely with frequency. The telescope observes in two orthogonal linear polarisations (which rotate on the sky as it tracks), and has a system noise temperature of 50 K. An observing bandwidth of 500 MHz was used. Amplitude and phase calibrations were carried out daily with observations of Cas A (using the flux scale of Baars et al. 1977), and cross checked periodically by observations of other 15-GHz calibrators from the VLA list (Perley 1982). Typical uncertainties in flux scaling are less than 10%. Observations were generally carried out at night (about 80% of the data) or pointing $> 90^\circ$ away from the sun to avoid possible solar interference; no extra emission from the moon was detected at this declination.

The CAT2 data were reduced using the same method as for the first field, CAT1, as described in detail by O’Sullivan et al. (1995). Phase rotation and flux calibration were applied first, and the data were then edited and analysed using standard tasks in AIPS. Excessively noisy data (reflecting periods of poor weather) were excised — the visibility amplitudes were all checked by eye for periods where they regularly exceeded the mean value by more than 3σ and then these data (± 1 hour) were removed from all baselines. Across the remaining dataset, individual visibilities with amplitudes exceeding the 3σ threshold were also excluded. In total, about 40% of the data were excluded by this process leaving 370, 310 and 1340 hours of good data at 13.5, 15.5 and 16.5 GHz respectively. Since the atmospheric coherence time is very short (10s) compared with the total integration time, any remaining atmospheric signals will be distributed uniformly across the synthesised map as noise, unlike true sky signals which will be modulated by the envelope beam pattern. The efficacy of atmospheric filtering for the CAT interferometer has already been demonstrated (Robson et al. 1994). CAT’s sidelobe response and lack of crosstalk and correlator offsets are discussed in O’Sullivan et al. (1995). No radio interference was seen.

3 SOURCE SUBTRACTION

Radio sources contributing significantly to the CAT2 image were identified and monitored at 15 GHz using the Ryle Telescope (RT). Five RT antennas were used in a configuration giving a synthesised beam of $30''$ FWHM. The RT has an instantaneous field of view of $6'$ FWHM, but for these observations is used in a rastering mode which covers $30' \times 30'$

in 12 hours to a typical flux sensitivity of 1.5 mJy/beam. To detect sources within the the CAT2 field, the central $2^\circ \times 2^\circ$ area was scanned with the RT in raster mode in sixteen days. A source list was then compiled, including sources listed in the Green Bank 4.85-GHz survey (Condon et al. 1989). Pointed observations with the RT were then made, and repeated regularly to check for variability over the whole period of the CAT observations. In all, twenty-nine sources were detected, the faintest having a flux density of 4.5 mJy at 15 GHz. Flux densities at 13.5 and 16.5 GHz were extrapolated using spectral information obtained from lower frequency surveys (i.e. 4.85 GHz, Condon et al. 1989, and 1.4 GHz, Condon et al. 1998) where available. A flat spectrum between 13.5 and 16.5 GHz was assumed for three sources without other data. After correcting for CAT primary beam attenuation, the corresponding flux densities were subtracted as point sources from the visibility data. Totals of 33 mJy at 13.5, 27 mJy at 15.5 and 20 mJy at 16.5 GHz were subtracted. The robustness of the source-subtraction procedure is illustrated in O’Sullivan et al. The strongest source in the field, at position 16 45 32 +63 35 29 (B1950), was highly variable (by factors of up to two over periods of a few days) and so was monitored regularly with the RT; no residuals at the source position remain after subtraction of the variable source. The successful subtraction of this source, 1° away from the pointing centre and clearly visible at the same position in all three maps, shows that CAT phase calibration and pointing are accurate.

4 THE IMAGES

The resulting source-subtracted images each show excess signal in the central $2^\circ \times 2^\circ$ falling away at larger radii as expected from the antenna envelope beam. These are displayed in Figure 1. The instrumental noise levels (measured directly from the visibilities) for each source-subtracted image are 6.1, 6.5 and 3.5 mJy/beam rms for 13.5, 15.5 and 16.5 GHz respectively. At the three frequencies, excess powers above the intrinsic noise level in the central $2^\circ \times 2^\circ$ area of 7.8 ± 1.0 , 8.2 ± 1.0 and 8.3 ± 0.5 mJy/beam rms were found for the source-subtracted 13.5, 15.5 and 16.5 GHz images respectively. Checks were made by splitting the data in time (consistent excesses were seen), polarisation (no excess power was visible on polarisation difference maps) and cross-correlating the source-subtracted image with a reconstructed map of the radio sources as in O’Sullivan et al. (no correlation was found); most importantly, maps were made by correlating orthogonal polarisations and these gave the *same* noise levels as those above.

To attempt to remove the instrumental response and thereby illustrate the distribution of features on the sky, we have co-added the data from the three frequencies weighted as ν^2 and CLEANed the final image. This is shown in Figure 2 and shows the presence of significant features in the central region as well as the diminution of the telescope sensitivity in accordance with the envelope beam.

The strongest feature in the CAT2 images is a negative one centred at position 17 05 29 +64 47 37 (B1950) reaching -39 mJy at 16.5 GHz (i.e. 5σ , relative to the rms excess power in the sky). For comparison, the strongest positive feature in the 16.5-GHz dirty map has a peak flux density of 26

mJy at position 16 55 55 +63 49 47 (B1950). The negative feature can be seen at all three frequencies (most clearly in the 13.5 and 16.5-GHz images in Figure 1), both before and after source subtraction and in different time cuts, and its spectrum is consistent with that of CMB radiation. For example, even before source subtraction the hole reaches -30 mJy in the 16.5-GHz image, and only three weak sources ($S_{16.5} < 10$ mJy) lie within $40'$ of it. No obvious Galactic structures at the position of the negative feature were visible in IRAS $100\mu\text{m}$ (Wheelock et al. 1994) or H I 21-cm sky survey images (Lockman & Dickey 1995) or the $100\mu\text{m}$ map of Schlegel, Finkbeiner & Davis 1998. Indeed, there is no resemblance at all between any of these images of the CAT2 region and the CAT2 image itself.

On the scales sampled by CAT, the negative feature is unlikely to have been caused by a Sunyaev-Zel'dovich (S-Z) effect (Sunyaev & Zel'dovich 1972; Rephaeli 1995) towards a single massive cluster. Any cluster which might produce such an effect would have to be nearby (subtending a large angle on the sky, filling the CAT beam) and/or very massive to produce such a strong signature. The strongest S-Z decrements measured towards nearby clusters at 15 GHz with the RT (Grainge et al. 1996; Jones et al. 1993) are about -0.5 mJy on arcminute scales. Observing a similar cluster at $z \sim 0.2$ (e.g. gas mass $10^{14} M_{\odot}$, with a King profile of core radius ~ 300 kpc, truncated at about ten core radii) with the larger CAT beam of $30'$ would produce a similar decrement amplitude, due to the balance between the effects of beam dilution and sampling cluster gas out to a larger radius. In order to maximise the S-Z signal in a $30'$ beam with the minimum gas mass, a nearby cluster ($z \approx 0.05$) with $10^{15} M_{\odot}$ of gas would be required, which is patently not observed. A system at any higher redshift would require an even higher mass because of beam dilution.

A central portion of the CAT2 field has been observed serendipitously with ROSAT. The direction of the negative CMB feature lies close to the edge of the PSPC field ($45'$ off axis) and is partially shadowed by the support structure of the PSPC detector. An X-ray source (heavily distorted by the PSPC point spread function) is found nearby (at the position 17 05 49 +64 45 50, B1950) but its X-ray spectrum does not fit a thermal model for any reasonable temperature, and is fit much better by a power law, implying it is not a cluster (but perhaps an AGN or Galactic source). Four clusters (Abell 2246 and two others at $z = 0.25$ plus one at $z = 0.44$) — and an optically luminous QSO (HS 1700+6416) — have been detected by ROSAT and lie within the central $10'$ of the CAT2 field (Reimers et al. 1997; Vikhlinin et al. 1998). All four clusters are fainter than 10^{44} erg s $^{-1}$ at X-ray energies 0.4–2.0 keV and none is apparent in the CAT images.

Finally, we emphasise that the presence of a 5σ feature in a single CAT field should not be construed as evidence for non-Gaussianity of the CMB fluctuations: the side-lobe structure of the synthesised beam of the three-element CAT is significant, and analysis should be carried out in the aperture plane — see Section 5. As a check, we have simulated CAT images given standard CDM-based realisations of CMB structure (using the actual CMB and Galactic mean power measured by CAT), and find that features which appear as strong as 5σ occur in about 10% of cases. We return to this point in Section 5.

5 DETERMINATION OF THE CMB COMPONENT

Due to the limited range of baselines and resulting sparse sampling of the $u-v$ plane by CAT, a statistical likelihood analysis was employed to estimate the relative contributions of CMB and Galactic components given the three-frequency CAT data. A Bayesian likelihood method was used, as in Paper I, as described by Hobson, Lasenby & Jones (1995). This method uses the complex visibility data directly in the calculation of the likelihood function to avoid the problem of the long-range correlations present between different resolution elements in the image plane.

As described in Paper I, power was estimated in two independent annular bins centred on spherical harmonic multipole values of $\ell = 410$ and $\ell = 590$ and with widths equivalent to the diameter of the antenna function, thus together spanning the range $\ell \approx 330 - 680$. The noise-weighted centroid positions for data in each bin are $\ell = 422$ and $\ell = 615$. CMB and Galactic signals were modelled as independent Gaussian distributions with a power-law spectrum ($S \propto \nu^{\alpha}$), the CMB with a fixed spectral index of +2 in flux density and the Galactic spectral index variable between 0 and -1 (as expected for Galactic free-free and synchrotron emission).

After marginalising over the Galactic parameters, this analysis confirmed that the bulk of the power in the 16.5 GHz map (Fig. 1) arises from CMB fluctuations. The CMB component was clearly distinguished from possible Galactic contamination in the $\ell = 422$ bin; $\Delta T/T = 2.1_{-0.5}^{+0.4} \times 10^{-5}$ was estimated for the CMB signal, compared with only $\Delta T/T = 0.8_{-0.8}^{+0.5} \times 10^{-5}$ for any Galactic component. The uncertainties quoted are 1σ values. The CMB-Galaxy separation was less certain in the $\ell = 615$ bin — a Galactic contribution of $\Delta T/T = 1.0_{-1.0}^{+0.7} \times 10^{-5}$ was given by the likelihood analysis, which is equivalent to an upper limit for the marginalised CMB power of $\Delta T/T < 2.0 \times 10^{-5}$ (1σ). These values are plotted in Figure 3. The average values of $\Delta T/T$ in the CAT2 field agree with the CAT1 result (Paper I) within 1σ ; for comparison the measured CMB powers in the CAT1 field were $\Delta T/T = 1.9_{-0.5}^{+0.5} \times 10^{-5}$ ($\ell = 420$) and $\Delta T/T = 1.8_{-0.5}^{+0.7} \times 10^{-5}$ ($\ell = 590$).

We have also investigated how much of the CMB power is not associated with the strong negative feature discussed in Section 4. We removed the dip as a point source from the visibilities and repeated the above analysis. Significant power remained, at around half of the level with the negative feature included.

6 ESTIMATION OF COSMOLOGICAL PARAMETERS USING NEW CAT RESULTS

The CAT2 points, taken in conjunction with the results from the Saskatoon experiment (Netterfield et al. 1997), provide further evidence for a downturn in the CMB power spectrum for $\ell \gtrsim 300$. To assess the implications for cosmological parameters using current CMB data sets, we have extended the analysis presented previously by Hancock et al. (1998). This analysis used a statistically independent subset of the current data and carried out χ^2 fitting for a range of cosmological models and parameters. The extensions carried

Model		Best Fit	Marginalised ranges	
		value	(1 σ)	(2 σ)
Flat models	h	0.3	0.3 – 0.55	0.3 – 0.8
	n	0.88	0.8 – 1.15	0.65 – 1.3
Lambda models	Ω_Λ	0.3	0.4 – 0.7	0.3 – 0.7
	h	0.35	0.3 – 0.55	0.3 – 0.8
	n	0.9	0.8 – 1.1	0.7 – 1.2
Open models	Ω_m	0.7	0.5 – 1.0	0.3 – 1.0
	h	0.6	0.3 – 0.7	0.3 – 0.8

Table 1. Results of the fitting analysis. Non-stated parameters were marginalised over to estimate the 1 σ and 2 σ ranges.

out for the present work were (a) the inclusion of the CAT2 point at $\ell = 422$; (b) the inclusion of new points from experiments Python (Python III, Platt et al. 1997), MSAM (the 2nd and 3rd flights, Cheng et al. 1996, 1997, Ratra et al. 1997), ARGO (Aries+Taurus region, Masi et al. 1996), FIRS (Ganga et al. 1994) and BAM (Tucker et al. 1997), and with the latest calibration correction to the Saskatoon data (i.e. increased by 5%, Leitch, private communication); (c) consideration of a wider class of cosmological models, all treated using exact power spectra rather than the generic forms assumed in Hancock et al. (see also Rocha 1997; Rocha et al. in preparation). The formalism and approach are otherwise the same as in Hancock et al. (1998), to which the reader is referred. The cosmological models considered were:

- (i) Flat models with $\Lambda = 0$, and with a range of spectral tilts (i.e. $n \neq 1$);
- (ii) Flat models with $\Lambda \neq 0$, and a range of spectral tilts;
- (iii) Open models with $\Lambda = 0$ and open-bubble inflation spectrum (Hu & Sugiyama 1995; Ratra & Peebles 1994; Kamionkowski et al. 1994).

In cases (i) and (ii), nucleosynthesis constraints, with $0.009 \leq \Omega_b h^2 \leq 0.02$ (Copi, Schramm & Turner 1995) were assumed. Theoretical power spectra from Seljak & Zaldarriaga (1996) were used in cases (i) and (ii), and kindly provided by N. Sugiyama for case (iii). The parameters fitted for (unless fixed) were the Hubble constant h (in units of $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$), the spectral tilt n , the cosmological constant Ω_Λ and the matter density Ω_m in units of the critical density. The flat models are defined by $\Omega_m + \Omega_\Lambda = 1$. Note the ranges of h and Ω_Λ considered were 0.3 – 0.8 and 0.3 – 0.7 respectively.

The results are displayed in Table 1. In each case the best fit values of the parameters are shown, together with marginalised error ranges. These marginalised errors are $\pm 1\sigma$ confidence limits formed by integrating over all the other parameters with a uniform prior.

In common with other recent work on fitting to current CMB data (e.g. Lineweaver & Barbosa 1998) a tendency to low H_0 values (except in the case of open models) is found, although it is clear from the marginalised ranges that the statistical significance of this is not yet high. For comparison with the results of Webster et al. (1998), who worked jointly with recent CMB and IRAS large-scale structure results, we note that a flat Λ model with normalization fixed to the COBE results and $n = 1$ yielded a best fit of $\Omega_\Lambda = 0.7$

and $h = 0.6$. In conjunction with the CAT points, new results forthcoming from the Python, Viper and QMAP[†] experiments may soon be very significant in ruling out open models and in further delimiting the Doppler peak, sharpening up these parameter estimates. Recent OVRO results at $\ell \sim 590$ (Leitch, private communication) agree well with the values found by CAT. The joint CAT and OVRO results will clearly be very significant in constraining the latest cosmic string power spectrum predictions, which now include a cosmological constant (Battye et al. 1998). These predictions succeed in recovering a significant ‘Doppler peak’ in the power spectrum, but have peak power for ℓ in the range 500 to 600, at variance with the trend of the current experimental results.

7 CONCLUSIONS

- (1) We have imaged a $2^\circ \times 2^\circ$ patch of sky at 13-17 GHz with the CAT; this is the second field observed by CAT.
- (2) Significant CMB anisotropy is detected in the CAT2 field with an average power of $\Delta T/T = 2.1_{-0.5}^{+0.4} \times 10^{-5}$ for the $\ell = 422$ bin, and with an upper limit of $\Delta T/T < 2.0 \times 10^{-5}$ for $\ell = 615$ (due to Galactic contamination).
- (3) This new result is consistent with the first detection made by CAT in a different area of sky.
- (4) Together with other CMB data over a range of angular scales, the inclusion of the new CAT2 detection restricts the likely values of cosmological parameters.

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[†] Results from QMAP published after this paper was submitted show a rise in the power spectrum from $\ell \sim 40$ to $\ell \sim 200$ consistent with the Saskatoon results (de Oliveira Costa et al. 1998).

Figure 1. Images of source-subtracted CAT2 data at a) 13.5, b) 15.5 and c) 16.5 GHz. RA and Dec (B1950) and grey scale flux ranges (mJy/beam) are indicated. Instrumental noise levels are 6.1, 6.5 and 3.5 mJy/beam rms for a), b), c) respectively, reflecting the total integration times.

Figure 2. CLEANed image of co-added CAT2 data (three frequencies weighted as ν^2 .)

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Figure 3. Plot of average marginalised power ($\ell^2 C_\ell / 2\pi$ against ℓ) in CMB fluctuations (solid lines) and Galactic emission (dotted lines) in the CAT2 field as estimated by the Bayesian method for the two ($\ell = 422$ and $\ell = 615$) bins. Error bars (1σ) are shown. The prediction of a standard CDM model ($\Omega_m = 1$, $\Omega_\Lambda = 0$, $\Omega_b = 0.05$; $h = 0.5, n = 1$, no tensors) is shown (solid curve) for comparison.

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