NEW RESULTS ON CMB STRUCTURE FROM THE TENERIFE EXPERIMENTS

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Abstract. Temperature fluctuations in the CMB (Cosmic Microwave Background) are a key prediction of cosmological models of structure formation in the early Universe. Observations at the Teide Observatory, Tenerife using radiometers operating at 10, 15 and 33 GHz have revealed individual hot and cold features in the microwave sky at high Galactic latitudes. These well-defined features are not atmospheric or Galactic in origin; they represent the first detection of individual primordial fluctuations in the CMB. Their intensity is defined by an intrinsic *rms* amplitude of 54^{+14}_{-10} μK for a model with a coherence angle of 4°. The expected quadrupole term for a Harrison-Zel'dovich spectrum is $Q_{RMS-PS} = 26 \pm 6$ μK. When our data at Dec=+40° are compared with the COBE DMR two-year data, the presence of individual features is confirmed. New experiments to detect structure on smaller scales are described.

1. Introduction

The study of the CMB radiation gives a unique insight into physical conditions in the early Universe, providing direct access to the epoch $\sim 300,000$ years after the initial singularity. By observing different angular scales, we investigate different linear and mass scales; for example on the 5° scale of

M. Kafatos and Y. Kondo (eds.), Examining the Big Bang and Diffuse Background Radiations, 453–460.

our Tenerife beamswitching experiments, we are probing the equivalent of 300−500 Mpc structure in our contemporary Universe, which corresponds to the largest scales identified in the distribution of galaxies.

Much attention is being directed both observationally and theoretically, towards a comparison of the amplitude of CMB structure as a function of angular scale. The standard picture envisages two components of the structure on scales $\gtrsim 2^\circ$. The first is scalar fluctuations arising from the Sachs-Wolfe effect, while the second is a tensor component due to gravitational wave radiation coming from the inflationary era. A detailed measurement of the spectrum of fluctuation amplitude on such scales will then establish the tensor contribution. A second feature of the angular spectrum of fluctuation amplitudes is the "Doppler peak" centred on scales of $1^\circ - 2^\circ$. These fluctuations are due to the motion of massive structures in the epoch of recombination, and are expected to have an amplitude of $2 - 3$ times that on large angular scales.

Now that the *rms* amplitude of CMB fluctuations is established to be at least 30 μK over a large angular range (Smoot *et al.* 1992, Strukov *et al.* 1993, Hancock *et al.* 1994, Ganga *et al.* 1993, Clapp *et al.* 1994, Schuster *et al.* 1993, Wollack *et al.* 1993, Cheng *et al.* 1994, De Bernardis *et al.* 1994), it is possible to undertake observations with adequate sensitivity to obtain detailed maps on a reasonable timescale. We describe here a programme of actual and planned observations covering the angular range from a few arcminutes to $\sim 15^\circ$. Our beamswitching observations on an angular scale of 5° have now detected structure, with the unambigous identification of hot and cold features on the Dec=+40° scan (Hancock *et al.* 1994), while scanning observations at adjacent declinations are now reaching the sensitivity required to make maps.

2. The experimental arrangement

The choice of radio frequency for observation is a critical parameter in the design of a system capable of detecting intrinsic CMB structure. A ground-based system is limited by the atmosphere to operate at frequencies below 40 GHz, and the presence of Galactic emission requires that observations should be made over a substantial range of frequencies to correct for that contribution. In our experiments the lowest frequency was chosen to be 10.45 GHz where the dominant Galactic emission is likely to be synchrotron or free-free with spectral indices ~ -3.0 (Lawson *et al.* 1987, Watson *et al.* 1992) and -2.1 respectively. An intermediate frequency was chosen at 15 GHz, and the highest at 33 GHz where the synchrotron and free-free contributions are respectively 10 and 30 times less than at 10.45 GHz. At 33 GHz the variability of atmospheric water vapour limits the amount of time for which good data can be obtained. Our experience at the Teide Observatory at 2400 m altitude showed that the atmospheric conditions allow us to operate for a significant amount of time at this frequency (Davies *et al.* in preparation).

Central to the design of our radiometers is the triple beam switching technique (Davies *et al.* 1992). This is achieved by fast switching (61 Hz) between two adjacent beam horns combined with a slow (~ 8 sec) wagging of the double-beam response. The resulting beam response has the form (-0.5, $+1.0$, -0.5) with the central beam (FWHM$\sim 5°$) lying in the meridian and the negative beams displaced $\sim \pm 8°$ in azimuth. The fast switching removes receiver instabilities on timescales $\lesssim 0.1$ sec, while the beam wagging greatly reduces the long-term atmospheric and radiometer drifts. Systematic effects arising from the environment of the equipment are reduced to a minimum by keeping the system fixed and scanning the sky using Earth-rotation.

The sensitive amplifier element in each receiver is a high electron mobility transistor (HEMT) amplifier. Each system has a bandwidth of $\sim 10\%$ and operates at an equivalent system brightness temperature in the range 70 – 100 K; this latter figure includes the effects of circulator and feed losses as well as atmospheric emission. Each instrument consists of two independent channels giving further confidence in identifying atmospheric and systematic effects. The resulting theoretical sensitivities, including both channels, are 5.6, 3.4 and 2.2 mK$\times$Hz$^{-1/2}$ at 10, 15 and 33 GHz respectively.

3. Observations and analysis of the results

Our objective is to construct a map of the sky covering declinations 30° to 45° by observations in strips separated $2\overset{\circ}{.}5$ in declination. By observing N times at each declination we obtain a very sensitive scan with a reduction in noise by a factor $\sqrt{N}$ compared with an individual scan. Figure 1 shows these stacked scans at 15 GHz covering the declination range 30° to 45°. The strong emission at RA$\sim 300°$ is the most intense crossing of the Galactic plane; the weak crossing which contains several components is also evident in the RA range 60° to 80°. A clear correlation exists between the Galactic signals on adjacent declinations at $2\overset{\circ}{.}5$ separation. The most intense signal comes from the Cygnus X H II region at Dec$\sim 41°$, RA$=305°$. No structures other than the Galactic crossings are seen on this intensity scale. The search for CMB fluctuations must be made at high Galactic latitudes. Table 1 presents the sensitivity per beam area reached at each declination and frequency in the section of our data in the range RA$=161°-250°$ corresponding to high Galactic latitude. On the basis of the *rms* of the CMB

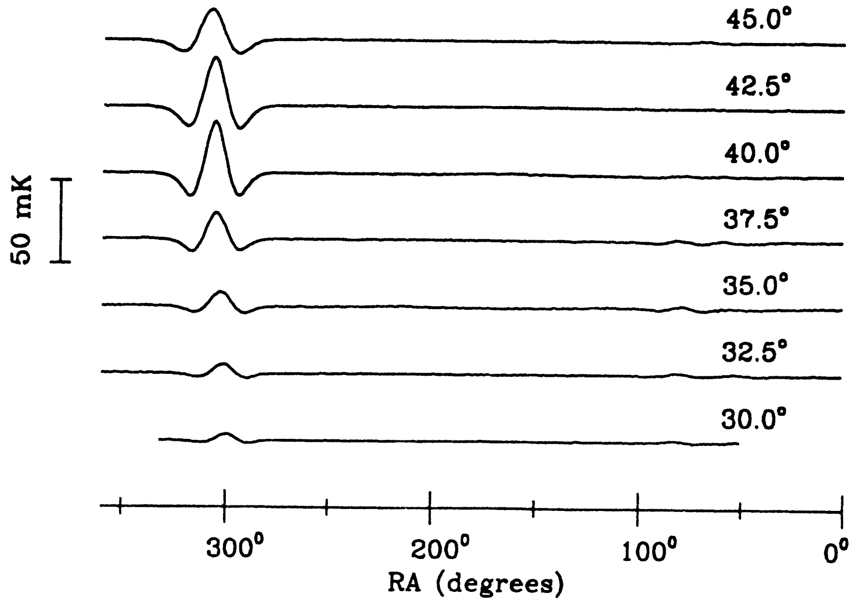

Figure 1. Stacked scans for each declination at 15 GHz, showing the strong (RA~ 300°) and the weak (RA ~ 60° – 90°) crossings of the Galactic plane.

fluctuations claimed by several experiments (see Section 1), we can see that the sensitivity reached at some declinations and frequencies is enough to detect and map features in the CMB. In particular, at Dec=+40° we have reached a good sensitivity in our scans at 15 and 33 GHz; these are shown in an expanded scale in Figures 2*a* and 2*b* respectively. Common features are clearly seen in both scans with the most intense centred at RA~ 185° having a similar amplitude at both frequencies. Our scan at 10 GHz has not reached enough sensitivity to clearly delineate the CMB features; at this low frequency some degree of Galactic contamination is expected. Nevertheless the results at 10 GHz are important in that they can be used to put limits on the possible Galactic contribution at the higher frequencies. We have computed a maximum Galactic *rms* contribution at 33 GHz of 4 μK which is a small fraction of the detected signals at this frequency. Our conclusion is that most of the signal present in these scans at 15 and 33 GHz is cosmological in origin. Assuming that all signals present at both frequencies are real CMB fluctuations, we can add them to obtain the very sensitive scan shown in Figure 2*c*. Using a likelihood analysis we have estimated the amplitude of the signals present in our data. For a model of Gaussian fluctuations with a coherence angle of 4°, we obtain an

TABLE 1. Standard error (in μK) per beam-sized area over the RA range 161°–250°.

	Declination						
Experiment	30°0	32°5	35°0	37°5	40°0	42°5	45°0
10 GHz	–	69	97	62	57	75	77
15 GHz	22	27	30	19	30	25	24
33 GHz	–	38	54	47	21	–	–

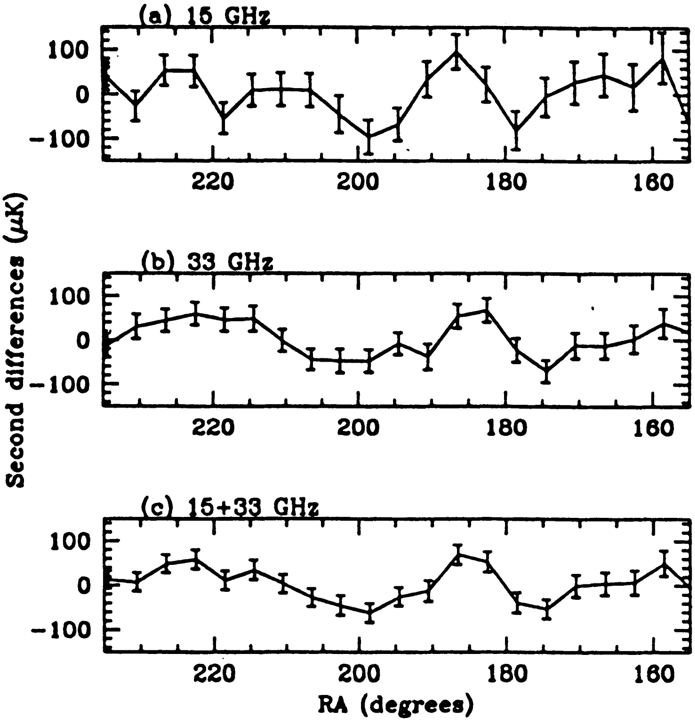

Figure 2. The stacked data scans at Dec=+40° and their one-sigma error-bars in a 4° bin in RA at (a) 15 GHz, (b) 33 GHz and (c) (15+33) GHz.

intrinsic *rms* signal of 54^{+14}_{-10} μK. Assuming a Harrison-Zel'dovich spectrum for the primordial fluctuations we infer an expected quadrupole amplitude $Q_{RMS-PS} = 26 \pm 6$ μK (Hancock *et al.* 1994).

4. Comparison with COBE

A most important outcome of a comparison between the CMB amplitudes on the angular scales represented by the Tenerife and COBE measurements is the determination of the spectrum of primordial fluctuations. The statistic most suitable for this comparison is the equivalent quadrupole component of the power spectrum Q_{RMS-PS}. The COBE first-year data gave the value of 16.3 ± 4.6 μK for a model with an spectral index $n = 1.15$ (Smoot *et al.* 1992), which may be compared with our value of 26 ± 6 μK at $n = 1$. Both these results are affected by random error, as well as cosmic variance and sample errors. All these factors can be taken into account using Monte Carlo techniques to produce a large number of sky realizations described by a power law spectrum with a range of power law indices n. By combining the Tenerife and COBE detections it is possible to restrict the range of n to $0.87 \leq n \leq 1.6$ as compared with either experiment alone. This lower limit is particularly significant in the context of inflationary theories of galaxy formation, since $n \approx 0.8$ is the value where the tensor mode contribution to the CMB fluctuations is equal to the scalar contribution. For $n \gtrsim 0.8$ the tensor contribution declines rapidly. Clearly further observations with COBE using the full 4 years of data along with Tenerife observations at adjacent declinations, will restrict the range of n even further and provide one useful test of inflationary models of structure formation in the early Universe.

Our Tenerife experiments have unequivocally detected hot and cold features in the CMB field, whereas COBE DMR first year of data did not have enough sensitivity to identify particular spots and consequently gave only a statistical result representative of the whole sky. Certain areas of the DMR sky survey have more sensitivity than the average point; it is fortunate that such an area near the North ecliptic pole coincides with the high Galactic latitude section of the Tenerife Dec=+40° scan. That makes possible a direct comparison of features in the COBE DMR two-year data (Bennett *et al.* 1994) and in the Tenerife data.

The RA=160° to 230° part of the Dec=+40° scan was used to investigate the presence of structures in both data sets which had the properties of CMB fluctuations. The most prominent feature in the Tenerife data (at RA$\sim$ 185°) is evident in the 53 and 90 GHz maps (the 31 GHz has lower sensitivity) and has the Planckian spectrum expected for CMB anisotropy. Futhermore, the correlation function between the Tenerife and COBE DMR scans is also indicative of common structure across the range RA=160°–230°. The combination of the spatial and spectral information from the two data sets is consistent with the statistical level of fluctuations claimed by each experiment and strongly supports the cosmological origin of this structure. The detection covers a range of 10 to 90 GHz. This is the first confirmation of actual CMB structural features detected in two independent experiments.

5. The future programme

The present situation in the beamswitching radiometer programme operated by NRAL Jodrell Bank and IAC at Teide Observatory, Tenerife, is summarized in Table 1. Data collection will continue in order to give a coverage of Dec=+30° to 45° at the full sampling separation of $2\overset{\circ}{.}5$ (half the FWHM). We plan to reach *rms* sensitivities in a 5° beam of 20 μK at 15 and 33 GHz, and 50 μK at 10 GHz. This combination of sensitivities will enable us to detect CMB fluctuations, and at the same time to determine the Galactic contribution to better than 5 μK at the highest frequency.

A 33 GHz two-element interferometer is being constructed at Jodrell Bank in preparation for installation at Teide Observatory in collaboration with IAC. This interferometer will have a resolution of $2\overset{\circ}{.}5$ with full sine and cosine correlation in a 3 GHz bandwidth. The low noise amplifiers used are cryogenically cooled HEMTs, and the anticipated sensitivity is 0.7 $\mathrm{mK}\times\mathrm{Hz}^{-1/2}$. A 5 GHz interferometer of similar correlator design but using a beamwidth of 8° has been operating at Jodrell Bank for several years. Observations have been taken over the declination range 30° to 50° at separations of 11λ and 33λ. These data are being used to estimate the contribution of Galactic emission and extragalactic sources at 5 GHz.

The Cosmic Anisotropy Telescope (CAT) has been developed by the MRAO group. It is operating at Cambridge making synthesis maps of CMB structure over the angular range $10'$ to $2\overset{\circ}{.}5$. The frequency range is 12 to 18 GHz, and the sensitivity achieved per resolution element is approaching 20 μK. Point source contribution is removed by making observations with the Ryle telescope array at the same frequency. CAT is promising to have a significant contribution to CMB structure studies in the next few years.

The collaboration between MRAO, NRAL and IAC continues with a proposal to build the Very Small Array (VSA) for CMB structure studies. Operating at 33 GHz on the Tenerife site, the VSA will have the capability of imaging primordial CMB structure to a sensitivity of 5 μK over the angular range $10'$ to $2\overset{\circ}{.}5$. Funding is being sought for this project.

Acknowledgements

The Tenerife experiments are supported by the UK PPARC, the European Community "Science" programme SC1-CT92-830, and the Spanish DGICYT science programmes.

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