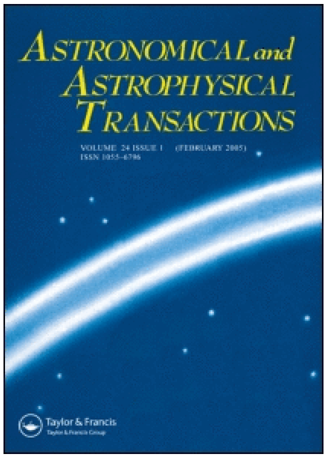

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THE STATUS OF THE TENERIFE EXPERIMENTS CMB ANISOTROPY MEASUREMENTS – A PRACTITIONER'S VIEW

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I describe here the evolution of the Tenerife group of experiments from the first beamswitch experiments with the MkII telescope at Jodrell Bank, through the large angular scale beamswitch and interferometer experiments on Tenerife to the construction of the Very Small Array. Lessons learned from these experiments are applicable to the modern generation of CMB anisotropy observations. Our experience shows that high quality data can be obtained up to frequencies of 30–40 GHz on high dry ground sites; the prospects for the VSA, and CBI are excellent. Galactic foregrounds at these frequencies have rms values less than 10 percent of the anisotropy level in the coolest few steradians of the intermediate and high Galactic latitude sky. With modern receiver sensitivities it is possible to cover many hundreds, if not thousands, of beam areas to bring down the sky sample variance – a limitation in the majority of experiments performed up to the present.

KEY WORDS Cosmic microwave background, CMB anisotropy, Tenrife experiments

1 INTRODUCTION

The cosmological significance of the detection and measurement of structure in the cosmic microwave background is profound. A determination of the spatial spectrum of the fluctuations over an angular scale extending down to several arcminutes will provide an indication of the cosmological model of galaxy formation and estimates of the basic cosmological parameters such as H_0, Ω_0, Λ_b, Λ_0, n etc. Any observational programme should aim at obtaining sensitive data over as wide a range of angular scales as possible. An integral part of this campaign is the determination of the foreground contribution to confusion of Galactic emission and extragalactic point sources.

The CMB programme began at Jodrell Bank in 1980 using a switched 5 GHz receiver on the Az-El 125 ft ×85 ft MkII telescope. By fast switching between two horns offset in azimuth and slowly wagging the telescope in azimuth by the same offset a triple beam response was achieved with a beamwidth of 8 arcmin and an offset of ±30 arcmin. When a suitable region of the sky, known to be free of point sources, is tracked throughout the day, the brightness temperature of a circular annulus 8 arcmin wide and 30 arcmin radius is measured relative to a beam located at the centre of the annulus. This experiment achieved the sensitivity sufficient to detect fluctuation levels predicted by popular theories at the time ($\Delta T/T \sim 10^{-3}$) but of course detected no CMB signals. Upper limits of $\Delta T/T < 3 \times 10^{-4}$ at 8 arcmin scales and $< 4.6 \times 10^{-4}$ at 30 arcmin scales were set (Lasenby and Davies, 1983). This approach was abandoned for two reasons, both related to the much lower levels predicted by theory soon after these observations were completed. One was the unusually cold dry winter and the resulting low atmospheric noise when this experiment was conducted – the next winter was not so kind! The second was the realization that the Galactic foreground contamination was likely to be a problem at the sensitivity required. As a consequence of these factors it was decided to completely redesign the experiment and move it to Teide Observatory, Izana, Tenerife as a collaboration with the Instituto de Astrofisica de Canarias.

I will describe the experience with the Tenerife experiments in the following sections, illustrating their evolution from a single 10 GHz beamswitching radiometer, to a multifrequency suite of beamswitch instruments and interferometers and to a description of the 14 element VSA CMB array being built in collaboration between Manchester and Cambridge Universities and the IAC.

At this point I should reiterate the obvious within our CMB community, but not so easily argued in the funding agencies as I know by refereeing grant applications in Europe and North America; it is essential that multiple groups conduct these fundamental cosmological observations with a variety of observing strategies and detector systems because of constraints from systematics, foregrounds and reduction techniques. One only has to look at the current compilations of 'best results' to see the scatter between them which is far outside the quoted errors. The subject is on the threshold of a major breakthrough in the quality of the data and the science that can be obtained.

2 CHOICE OF SITE

CMB fluctuation measurements are undertaken on the ground and in space, each presenting their own opportunities. Observations from the ground give ready access to the experiment and allow upgrading to take advantage of continually developing technology; a diverse range of observing techniques and strategies is available to a wide community. The atmosphere provides the limitation – the higher and drier one goes, the greater are the opportunities. Balloons reach altitudes where atmospheric contributions are negligible; but campaigns are of restricted duration – lasting typically one week. Space observations give long observing periods and no atmospheric problems; because of their costs they are less frequent. Following the successful COBE DMR flight in 1990–1994 the next CMB space missions are MAP planned for launch in 2001 and the more ambitious Planck satellite in 2007.

I will describe our experience on Tenerife with relation to water vapour effects. The Teide Observatory is at a height of 2400 m and is above the inversion layer for 70-80% of the year. Using data from our own 33 GHz beamswitching radiometer and from 12 hourly meteorological balloon flights we estimate that the precipitable water vapour (pwv) content lies between 1–3 mm for 50 percent of the year. There is an increase around mid-day which is largely removed from our records because at this time the Sun transits the outer side lobes of the beam.

Our 10, 15 and 33 GHz beamswitching experiments can be used to measure the relative strengths of water vapour fluctuations at these frequencies which are in the ratio 1:2:10; this is an agreement with models of the atmospheric water spectrum. The current design of the 33 GHz beamswitch geometry gives satisfactory operation for 30 percent of the time, compared with 80 percent at 10 GHz; these refer to fluctuations between positions $\sim 8^\circ$ apart.

In our programme to extend the spatial spectrum to angular scales below those used in the beamswitching experiments, we constructed a 33 GHz interferometer to investigate structure on a scale of 2°, and subsequently at 1°. The interferometer response, with its simultaneous detection of positive and negative lobes within the $5^\circ \times 2^\circ$ primary beam, was markedly less affected by water vapour. Our experience over several years shows that the amplitude of the water vapour effects at 2° scales is a factor of 100 less than in the 5°–15° beamswitch data. A significant part of this reduction (a factor of ~ 10 possibly) is due to reduced atmospheric structure level on smaller angular scales. On 1° scales the interferometer further reduces atmospheric contributions by a factor of 2–4.

Our experience with the 33 GHz interferometer, where less than 10 percent of the data is lost due to weather conditions, has provided the justification for erecting the Very Small Array (VSA) on the site of the current Tenerife experiments at Teide Observatory, Izana. The angular scales to be covered by the VSA range downwards from those of the current 33 GHz interferometer where atmospheric effects will be even smaller. Technical support for this instrument on this site is readily accessible at IAC, Manchester and Cambridge.

3 FOREGROUNDS

The principal foregrounds at frequencies up to 30–50 GHz arise from synchrotron and free-free emission. The synchrotron emission comes from relativistic electrons originating in supernovae or interstellar shocks and subsequently spiralling in the interstellar magnetic field. The free-free emission is the thermal bremsstrahlung from hot (10^4K) electrons produced in the interstellar medium by the Galactic optical and UV radiation field. At frequencies above ~ 30 GHz a significant foreground contribution will come from spinning and vibrating dust grains. In addition to these Galactic contributions there will be a component of emission from faint unresolved extragalactic sources which is significant on scales smaller than 1°. Below I will describe the main properties of each of these foregrounds. The review by De Zotti *et al.* (1999) gives quantitative estimates of the foregrounds. In section 4 their contributions as measured in the Tenerife experiments will be evaluated.

3.1 Synchrotron Emission

The emissivity per unit volume of synchrotron radiation is a function of the relativistic electron energy and spectral index as well as the local magnetic field strength. These properties all vary from point to point in the Galactic disk and give rise to structures seen on all scales. With an interstellar field of 2–5 microgauss, emission at GHz frequencies is characteristically from relativistic electrons with an energy of 1–10 GeV. The spectral index of the emission will vary with position in the Galaxy for two reasons. Firstly the relativistic electron spectral index varies from one (originating) supernova to another and secondly, the spectral index of the emission steepens by up to 0.5 with time due to radiation energy loss thus giving an age-dependent spectral index. For these reasons it is unwise to use low frequency surveys (for example those at 408 and 1420 MHz) to predict synchrotron structure at tens of GHz.

At low and intermediate Galactic latitudes, supernova remnants (SNRs) with a wide range of ages can be identified. Objects like Cas A and Tau A are 500 to 1000 years old and are in the free expansion stage, while other remnants such as IC442 and the Cygnus Loop, 10,000 to 20,000 years old, are losing energy in multiple shocks. At an age of 10^5 to 10^6 years the expansion velocity will have slowed to the local sound velocity so that the remnant is not clearly recognizable as a single entity; this may be the origin of the many spurs extending from the Galactic plane to higher latitudes. The Cygnus Loop (the Veil Nebula) provides an excellent case study of an SNR in a later phase of evolution. It lies 100 pc below the Galactic plane and has dimensions of $3.^\circ5 \times 2.^\circ5$ (30 pc × 20 pc). The 1.4 GHz synthesis map of Leahy, Roger and Ballantyne (1997) with 1×1 arcmin^2 resolution shows diffuse structure as well as filaments up to 90 arcmin long and a few arcmin in width. By comparing maps of the Cygnus Loop at 0.408 and 2.7 GHz, Green (1990) found significant variations in spectral index of 0.3 between major features of the remnant.

Large-area surveys at low frequencies, such as those at 0.408 GHz by Haslam *et al.* (1982), at 1.42 GHz by Reich and Reich (1988) and at 2.3 GHz by Jonas, Baart and Nicolson (1998), show many large features of synchrotron emission extending far from the Galactic plane. The most prominent of these are the spurs and loops first shown by Berkhuijsen, Haslam and Salter (1971) to describe small circles in the sky with diameters ranging from 60° to 120°. They are believed to be the larger diameter and lower surface brightness counterparts of SNRs seen at lower latitudes. Other more diffuse structures at high latitudes may be even older remnants. Clear variations in the emission spectral index of at least 0.3 are found across the northern sky in these surveys; the loops appear to have the steepest spectral indices.

3.2 Free-free Emissions

Free-free emission has a brightness temperature spectral index of -2.15 which distinguishes it from synchrotron emission in the Galaxy with values in the range -2.6 to -3.2. Free-free emission is likely to be the dominant foreground at frequencies in the range 20–70 GHz. It is generally inextricably mixed with synchrotron emission and is not easily separated at intermediate and higher latitudes. Hα emission is thought to be a good tracer of Galactic diffuse thermal electrons giving free-free emission. The major Hα structures in the sky lie in the well-known Local (Gould Belt) System which extends 30° to 40° from the plane to positive latitudes above the Galactic centre ($l = 0°$) and to negative latitudes in the anticentre ($l = 180°$). Other Hα features are also found extending 15°–20° from the plane (Sivan, 1974).

Quantitative measurements of the Hα emission at intermediate and higher latitudes are now becoming available from accurate spectroscopy such as that of Reynolds (1992) which distinguishes it from the confusing geocoronal emission. Reynolds' work suggests that the rms variation on 1° scales at intermediate latitudes is ~ 0.6 Rayleighs (= an emission measure of 1.2 cm^{-6} pc) which corresponds to 6μK of brightness temperature at 45 GHz.

3.3 Dust Emission

That dust is wide-spread in the Galaxy has been well-demonstrated by the IRAS 60 and 100μ surveys and the more recent COBE DIRBE maps at 140 and 240μ. Dust grains absorb UV and optical photons and re-emit the energy through vibrational oscillations in the far infrared. The larger dust grains attain an equilibrium temperature in the range 15–30K to give a grey-body spectrum with a peak at 150μ. The dust emission will produce the dominant Galactic foreground at frequencies of 100 GHz and above. The level of its contribution at lower frequencies depends on the power law emissivity term which modifies the blackbody spectrum; this term is not yet well-determined at frequencies below 100 GHz.

The bulk of the dust detected in the far infrared has a temperature in the range 16–21K and a power law term $\alpha = -2.0$ to -1.5. Reach *et al.* (1995) also detected a widespread component at a temperature of 4–7K. Rowan-Robinson (1993) explains this emission in terms of amorphous carbon grains 30μ in diameter.

An entirely different emission mechanism of dust emission has been proposed by Draine and Lazarian (1997). They envisage small grains of 10^2 to 10^3 atoms being heated by single photons in the interstellar radiation field and producing rotational emission at frequencies up to ~ 50 GHz with a peak between 10 and 30 GHz. Such emission is likely to be correlated with the 100μ IRAS dust emission. Evidence already exists that this emission has been detected in the 10–100 GHz region at intermediate Galactic latitudes (Kogut *et al.*, 1996; de Oliveira-Costa *et al.*, 1997; Leitch *et al.*, 1997).

3.4 Extragalactic Sources

The stronger extragalactic point sources have well-known flux densities and can be removed from the CMB maps. This statement is less true at higher frequencies where the population of flat-spectrum variable radio sources increases. This requires contemporary data on these sources if reliable source subtraction is required. In addition, various algorithms have been proposed which will effectively allow the removal of any point source stronger than 5 times the rms of the map. Even though the stronger sources may be removed in these ways, there still remains the contribution of the weaker sources in the beam area of the survey. This Poisson contribution is significant (Franceschini *et al.*, 1989). A Poisson distribution of extragalactic point sources produces a simple white-noise power spectrum with the same power at all multipoles and accordingly the point source fluctuations become increasingly important with decreasing angular scale (Toffolatti *et al.*, 1998). Thus at angular scales of 30 arcmin and less the point source contribution is greater than the Galactic contribution at frequencies up to 100 GHz in surveys at intermediate and high galactic latitudes.

3.5 Polarization of the Foregrounds

Polarization of the CMB provides information about the Universe not contained in the temperature data. The CMB is 1–10 percent polarized, its actual value depending on the angular scale and the cosmological model. With the higher sensitivities now being achieved in CMB surveys, increasing interest is being shown in CMB polarization searches and the first experiments are being mounted. Galactic foreground polarization may be more of a problem for CMB polarization than for temperature studies. I will mention the likely contributions.

Synchrotron radiation is by its very nature strongly polarized; some features in the Galactic synchrotron emission have polarization approaching the theoretical value of 70% expected in a well-aligned magnetic field. Synchrotron emission is likely to provide the dominant polarized foreground up to 50 GHz. Structure is found on all scales investigated from degrees to several arcminutes.

The alignment of dust grains in the Galactic magnetic field has been well-studied for 50 years. This alignment will produce polarized emission in the blackbody emission from the dust. The polarization percentage of the far infrared emission has been measured at levels of 5–10 percent (Hildebrand, 1988). Theoretical models of the emission from the small spinning dust grains predict ~ 10 percent polarization.

The scattering of free-free emission in the thermal plasma on the way from its point of emission to the observer is also likely to produce ~ 10 percent polarization. This effect has not yet been detected.

4 RESULTS FROM THE TENERIFE EXPERIMENTS

The Tenerife experiments have been based on 24 hr right ascension scans in the declination range 30° to 50°. This 1.5 steradian area of sky contains the region of lowest Galactic foregrounds in the northern hemisphere.

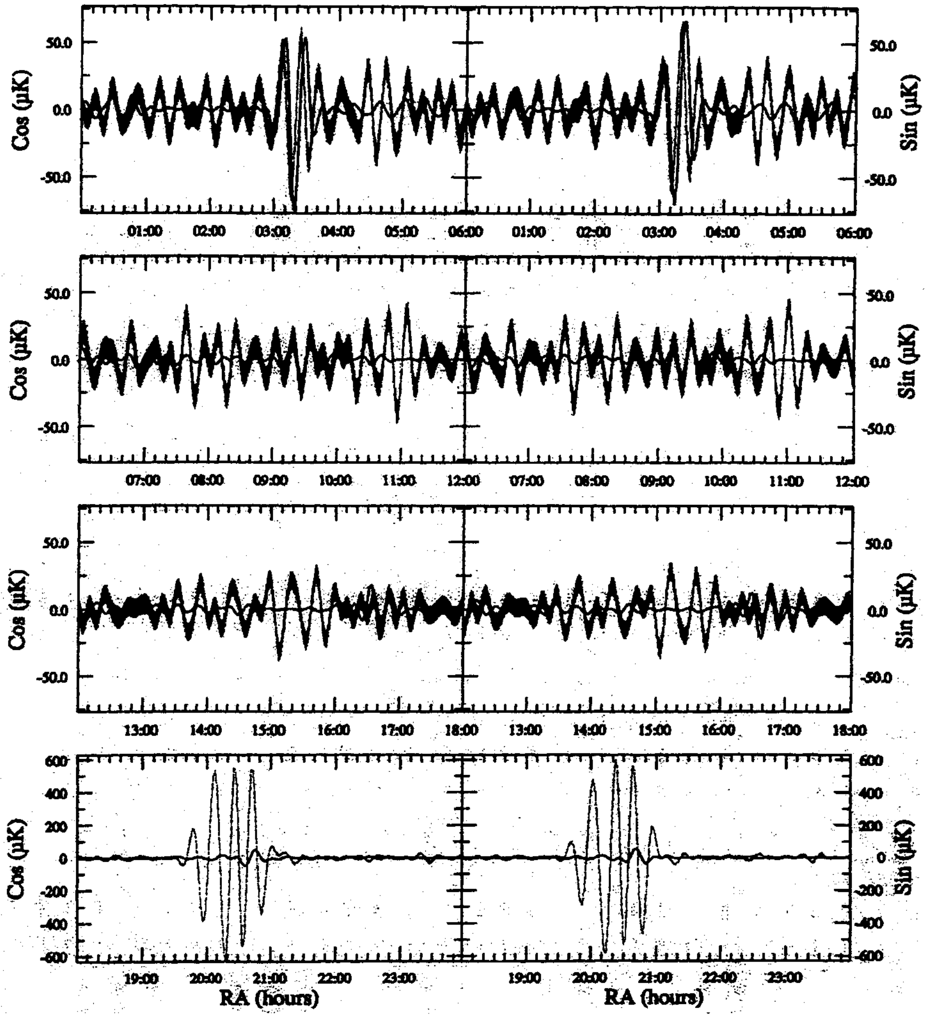

Figure 1 The data stack at Dec = 41° from the 33 GHz interferometer at Tenerife obtained with 2° lobe spacing. The grey lines are the MEM-fitted data with their 1σ errors. The black lines represent the contribution from known point sources. The strong Galactic plane crossing at RA = 20^h30^m is clearly evident. 3C84 is at RA = 03^h20^m.

4.1 CMB Fluctuation Amplitudes

A deep survey at Dec = 40° was made with beamswitching radiometers having the same beam geometry at 10, 15 and 33 GHz. The three-frequency data set enabled the Galactic contribution to be separated from the CMB structure. The rms (CMB amplitude was estimated to be $\Delta T = 48\ (+21, -15)\ \mu$K in the angular range 5°–15° corresponding to multipoles l = 10–30 (Hancock *et al.*, 1997). The declination range 32.°5 to 42.°5 has now been covered to a sensitivity of 31 μK and 12 μK per 5° × 5° beam area at 10 and 15 GHz respectively. The rms CMB fluctuation level was $\Delta T = 30\ (+10, -8)$ μK (Gutierrez *et al.*, 1999).

A sensitive 33 GHz interferometer has been operating at Tenerife for the last 3 years, giving data with 2° fringe-width in a 5° × 2° beam size. Point sources are corrected for by using the monitoring data from the Metsahovi observatory in Finland. The MEM reconstruction of the observations at Dec = 41° is shown in Figure 1. CMB features are clearly seen; the strongest have a signal-to-noise ratio of more than 5. The rms CMB fluctuation temperature is $\Delta T = 45\ (+13, -12)$ μK at $l = 109 \pm 19$. The contamination by the Galaxy is negligible. The main contribution to the error is in the sky sample variance: a greater sky coverage will reduce this error.

4.2 Galactic Emission

By using high sensitivity data taken over a large frequency range, the Galactic contribution can be identified. By combining the Tenerife and COBE data covering 10 to 90 GHz, Jones *et al.* (1999a) in a multi-MEM analysis showed that the Galactic contribution to both the 15 and 33 GHz Tenerife data is small enough to be ignored in comparison with the magnitude of the CMB signal. Between 10 and 15 GHz the Galactic contribution is free-free emission. At 10 GHz the Galactic and CMB fluctuations are comparable in magnitude.

The short baseline interferometer operating at 5 GHz at Jodrell Bank has made surveys at 2° and 1° resolution. Comparison with low frequency (408 and 1420 MHz) maps, synchrotron emission is found to be the dominant contribution at high galactic latitudes at frequencies below 5 GHz (Jones *et al.*, 1999b). The temperature spectral index over this range is 3.0 ± 0.4. The fluctuation level at 5 GHz is 100 ± 32 μK.

The 10 and 15 GHz Tenerife data have been used to assess the spinning dust contribution. A preliminary study (de Oliveira-Costa *et al.*, 1999) shows a significant detection of diffuse microwave emission correlated with IRAS dust emission. This dust emission would contribute less than 5 μK at 33 GHz however.

4.3 Cosmology

The rms fluctuation observations when taken together indicate the presence of a Doppler peak. Assuming $H_0 = 50$ km s^{-1} Mpc^{-1} the data indicate a primordial spectral index of 1.1 ± 0.1 in close agreement with the inflationary prediction of 1.0 (Hancock *et al.*, 1998).

By combining the current observational data on CMB anisotropies with gravitational lensing statistics it is possible to place significant constraints on both Λ_0 and Ω_0. The main result is that $\lambda_0 = 0$ for any value of Ω_0 is ruled out at better than 99 percent confidence. The best-fit model has $\lambda_0 = 0.6$ and $\Omega_0 = 0.34$ at 95 percent confidence and the lower limit on $\lambda_0 + \Omega_0$ is 0.8 (Macias-Perez *et al.*, 1999).

5 FUTURE PROGRAMME

The Tenerife project will continue with the 10, 15 and 33 GHz beamswitch radiometers and the 33 GHz interferometer to cover the declination range 30° to 50°. It is expected to achieve a sensitivity of 10 μK per beam area at 15 and 33 GHz and 15 μK at 10 GHz. It is planned to cover at least 1000 beam areas at 2° and 1° resolution with the 33 GHz interferometer. These large area surveys will reduce the sample variance which is the limitation of the current results.

The Very Small Array (VSA), a collaboration between the Universities of Manchester and Cambridge and the IAC, is at present under construction on Tenerife. The instrument will cover angular scales of 0°.2 to 4° (l = 130–1800) which will encompass the first three Doppler peaks. The VSA consists of 14 antennas, with a minimum spacing of 18 cm, operating in the 26–36 GHz band. It incorporates the best front end amplifiers and will have an observing bandwidth of 1.5 GHz at any one time. In 300 hours of observation, the sensitivity will be 7 μK in a 30 arcmin pixel over a 4°.5 field or in a 12 arcmin pixel over a 2° field. Observations will begin in summer 2000.

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