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MICROWAVE BACKGROUND INTERFEROMETRY IN CAMBRIDGE

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ABSTRACT Interferometric methods of studying the Cosmic Microwave Background (CMB) have some distinct advantages over the switched-beam techniques which have mostly been used. However, most existing interferometers are not well suited to CMB observations, for a variety of reasons. These include poor temperature sensitivity due to a low filling factor, and systematic effects which limit the maximum possible integration time. A new instrument, the Ryle Telescope, has been developed in Cambridge which has a high temperature sensitivity (120 μK in 12 h) and the ability to integrate for several hundred hours on the same field. It will be used to study the CMB on angular scales of a few arcminutes, with particular emphasis on the Sunyaev-Zel'dovich effect. A second instrument to study the CMB on angular scales of tens of arcminutes, the Cosmic Anisotropy Telescope (CAT), is also being developed.

INTRODUCTION

Observations of the Cosmic Microwave Background (CMB) radiation have many possible astrophysical uses, including measuring H_0, studying the early evolution of clusters and constraining the initial density fluctuations which gave rise to galaxy formation. In the study of temperature fluctuations in the CMB, two main lines of investigation have so far been followed: the search for intrinsic fluctuations on all angular scales, and the Sunyaev-Zel'dovich (S-Z) effect (Sunyaev & Zel'dovich 1972) toward galaxy clusters. The size of the fluctuations expected is of the order of 1 part in 10^4 for the S-Z effect, and 1 part in 10^5 for the intrinsic fluctuations. Most of these observations have been made using switched-beam techniques, for example the observations of the S-Z effect by Birkinshaw (1989) and Uson (1986), and the intrinsic fluctuation studies by Readhead *et al.* (1988) and Davies *et al.* (1987).

This type of observation suffers from several intrinsic problems. For example, the differencing techniques needed to remove the effects of atmospheric emission and groundspill also reduce the measured signal, and the difficulty of completely removing atmospheric effects limits observations to the best weather at very good sites. Also, source confusion is difficult to deal with: you need information on source positions at a higher resolution than the experiment you are doing, which requires using a different telescope.

WHAT SORT OF TELESCOPE WOULD WE LIKE?

Interferometers overcome many of the systematic effects which plague switched-beam observations. Groundspill and atmospheric emission are in general uncorrelated between different aerials, and only add to the overall noise level. The components which are correlated have, in general, a fringe rate which puts them far from the point of interest on the synthesised map. Also, an interferometer with many baselines is sensitive to a range of angular scales simultaneously. As well as giving information about the CMB on a range of scales, this allows you to remove the effect of compact sources from the baselines corresponding to the larger angular scales.

Unfortunately, most interferometers are not well suited to CMB observations. The sensitivity of an interferometer to temperature fluctuations depends on the filling factor of the array (see e.g. Saunders 1986), and telescopes designed for high resolution observations do not have a high enough filling factor to be useful. For example, Birkinshaw (1989) gives the example of an interferometer with 25-m antennae observing the S-Z effect in a cluster with a diameter of ~ 2 arcmin, at $\lambda = 6$ cm. If the shortest baseline were 45 m, more than 80% of the flux would be resolved out, and the longer baselines would be even less efficient.

A dedicated CMB interferometer must therefore have many short baselines; the antennae must be small enough to allow baselines corresponding to the angular scales of interest. For the S-Z effect, this means several arcminutes. Longer baselines must also be present to resolve confusing sources. Also, in the interest of sensitivity the bandwidth must be high and the system temperature low. Finally, to allow long integration times, it must be free from systematic effects such as crosstalk between the antennae and imperfections in the correlator and other backend systems.

THE RYLE TELESCOPE – A SEMI-CUSTOM INTERFEROMETER

The Five Kilometre Telescope in Cambridge (Ryle 1972) satisfied some of the above requirements, namely small antennae with the possibility of a high filling factor and also some long baselines. However, its sensitivity was quite inadequate for CMB observations. It has therefore been rebuilt as a dedicated CMB instrument, and renamed the Ryle Telescope (RT). The important parameters of the telescope are listed in Table 1.

In order to meet the requirement for low systematics, great care has been taken in the design of the analogue and digital receiver systems to minimise crosstalk, pickup, and any effect which could give rise to spurious correlation or reduce the dynamic range. For example, three levels of phase switching are used to eliminate crosstalk and offsets in the whole system from the first mixer to the post-correlation integration. The analogue IF system is extensively shielded and the power supply and grounding arrangements designed to minimise earth loops and coupling via the power supplies. To reduce crosstalk between the antennae, the original feed arrrangement of the 5-km telescope has been retained: on-axis fixed feeds at the Cassegrain focus. Although this makes changing frequency or polarization a difficult and cumbersome process, there is a significant improvement in crosstalk performance compared with off-axis designs, and the absence of rotating joints improves the system temperature.

TABLE I Ryle Telescope Parameters

Antennae	8 x 13 m Cassegrain focus paraboloids, 4 fixed, 4 moveable on 1.2 km track.
Baselines	18 m – 4.6 km
Observing frequencies	5 GHz & 15 GHz
Observing bandwidth	350 MHz
Polarizations	I+Q, I-Q, Q, U
Correlator	Hybrid XF: 5-band analogue filter-mixers; 5 x 78 MHz, 7-channel digital XF correlators
Point-source Sensitivity	100 μJy in 12 h
Temperature sensitivity in most compact array	120 μK in 12 h

Test observations have been made using about half of the total bandwidth at 5 GHz, and the results so far show that the expected noise performance has been achieved, and no systematic effects have been discovered. Figure 1 shows a map resulting from 144 hours (12 x 12 hour observations) integration using 5 antennae with a bandwidth of 160 MHz. The noise level goes down as $\sqrt{t}$ as the observations are accumulated, and no artefacts are visible at the phase centre. With this performance we expect to be able to make maps of the S-Z effect in clusters with a temperature sensitivity at the most favourable angular scale (2 arcmin at 15 GHz, 6 arcmin at 5 GHz) of 120 μK in 12 h, or 20μK in one month.

THE COSMIC ANISOTROPY TELESCOPE (CAT)

There are theoretical reasons for regarding angular scales of 20 arcmin – 1 degree as particularly interesting for CMB observations (e.g. Bond & Efstathiou 1987). These are too large to be observed with the RT, requiring baselines of $\sim 50 - 150\ \lambda$, i.e. 1 – 3 m at 15 GHz. We are designing a new instrument, the Cosmic Anisotropy Telescope (CAT), to operate at these scales, due to begin observing in 1992. The CAT will have three elements with apertures of $\lesssim 1$ m, and will therefore produce maps only 3 or 4 pixels square. The RT will be essential to the operation of the CAT, providing data on compact sources to remove from CAT observations. Because of the high filling factor over the range of baselines covered, the CAT will have very good temperature sensitivity; simultaneous or near-simultaneous coverage of three 500 MHz bands in the 12 – 18 GHz range will allow removal of both galactic and atmospheric emission, giving a sensitivity of 6 μK in 1 month.

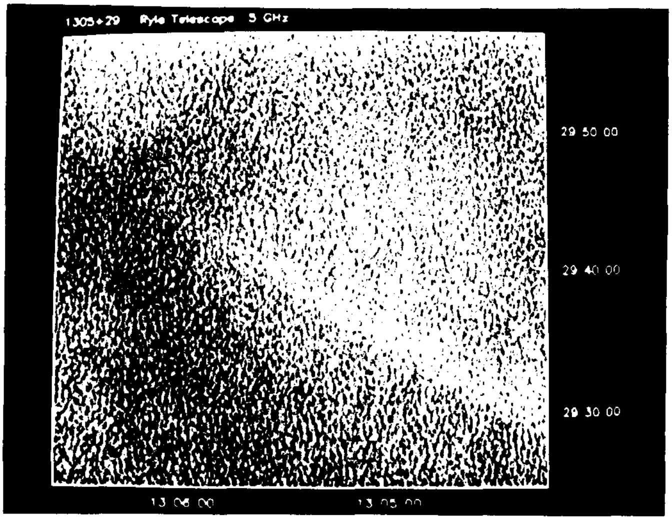

Fig. 1. A 144 hour observation of a 'blank' field. The rms noise level is 80 μJy; the grey-scale runs from -1 to 1 mJy. The brightest source is 980 μJy.

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Tom Landecker: Have you considered the possibility that the atmospheric emission and ground emission might be correlated when the antennas are close together?
M. E. Jones: We have done some studies with a short baseline interferometer at 15 GHz (S. Church, thesis 1990) which show that atmospheric emission is rejected by a factor of 10^4 on baselines as short as 3 meters. Residual atmospheric and ground emission that is correlated will be attenuated by fringe rotation and will appear far from the phase center of the map.

P. Napier: For the deep integration map that you showed, did you have to take any special measures to remove artifacts at the phase center.
M. E. Jones: The map was made simply by clipping the visibilities to remove gross interference and mapping on a standard way. Note that the map is 'dirty', not deconvolved in any way.