Measuring the polarization of the CMB

Michael Peel

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Lecturer: Ian Browne

Department of Physics and Astronomy
The University of Manchester

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Abstract

The polarization in the Cosmic Microwave Background (CMB) radiation presents a useful cosmological probe that is complementary to the well-known CMB anisotropies. In this essay, we summarize its origins and the types of amplified radio detectors that can be used to quantify it. Instrumental noise and foreground removal are discussed. Finally, optimal design choices are suggested for a ground-based CMB polarization experiment.

1 Introduction

The temperature anisotropies of the Cosmic Microwave Background (CMB) have provided impressive constraints on theories of the early universe. However, it is not the only probe of the early universe; the polarization of the CMB provides a direct probe of the epoch of last scattering. As the polarization is not directly connected to the temperature anisotropies, it provides a complementary source of cosmological information (Hu and White, 1997; Abidin, 2005). Limits on the polarization were first set by Penzias and Wilson (1965); it was first detected by DASI in 2002 (Kovac et al., 2002).

In §2, we summarize the effects that generate the CMB polarization. §3 provides the Stokes parameters, and discusses their use in observations of the CMB. §3 also summarizes the types of receivers that can be used, and gives example sensitivities for the detection of the polarization. §4 deals with instrumental noise, while §5 looks at foreground removal. §6 summarizes the author's opinions of the optimal design choices for a ground-based experiment and concludes this essay.

2 Origin of CMB polarization

The CMB photons are linearly polarized by Thomson scattering within quadrupole density perturbations at the time of last scattering. These density perturbations have several causes. Scalar perturbations are caused by the gravitational potential and temperature fluctuations. Vortical motions of matter induce vector perturbations, while tensor perturbations are caused by gravitational waves (Abidin, 2005).

The resulting polarization from the scalar potentials are characterized by E modes, which consist of perpendicular or parallel alignment of polarization; they have no curl component. They result from all of the linear, vector and tensor perturbations. The cross correlation between these and the total intensity is denoted TE; this provides information on whether the density mode amplitude was decreasing or increasing at the time of decoupling (Kovac et al., 2002). The E-modes can also be correlated with themselves, giving EE.

B modes result from the vector and tensor perturbations. They represent the curl component of the polarization. They are not typically correlated with the total intensity; they can be correlated with themselves to give BB.

It is possible that the CMB photons were scattered by free electrons during the epoch of reionization, where the electrons were ionized by UV light from an early generation stars or from quasars. The optical depth to Thomson scattering would provide constraints on the redshift at which reionization happened (Seljak, 1997). This is given by first peak in spectrum, which is near $l \sim 20$ (Keating et al., 1998).

An important parameter for constraining inflation is the tensor-to-scalar relationship, r, which is the ratio of the tensor and scalar power spectrum amplitudes at a pivot wave number $k_0 = 0.05\mathrm{Mpc}^{-1}$. Values for this can be found from polarization measurements (see Bowden et al., 2004).

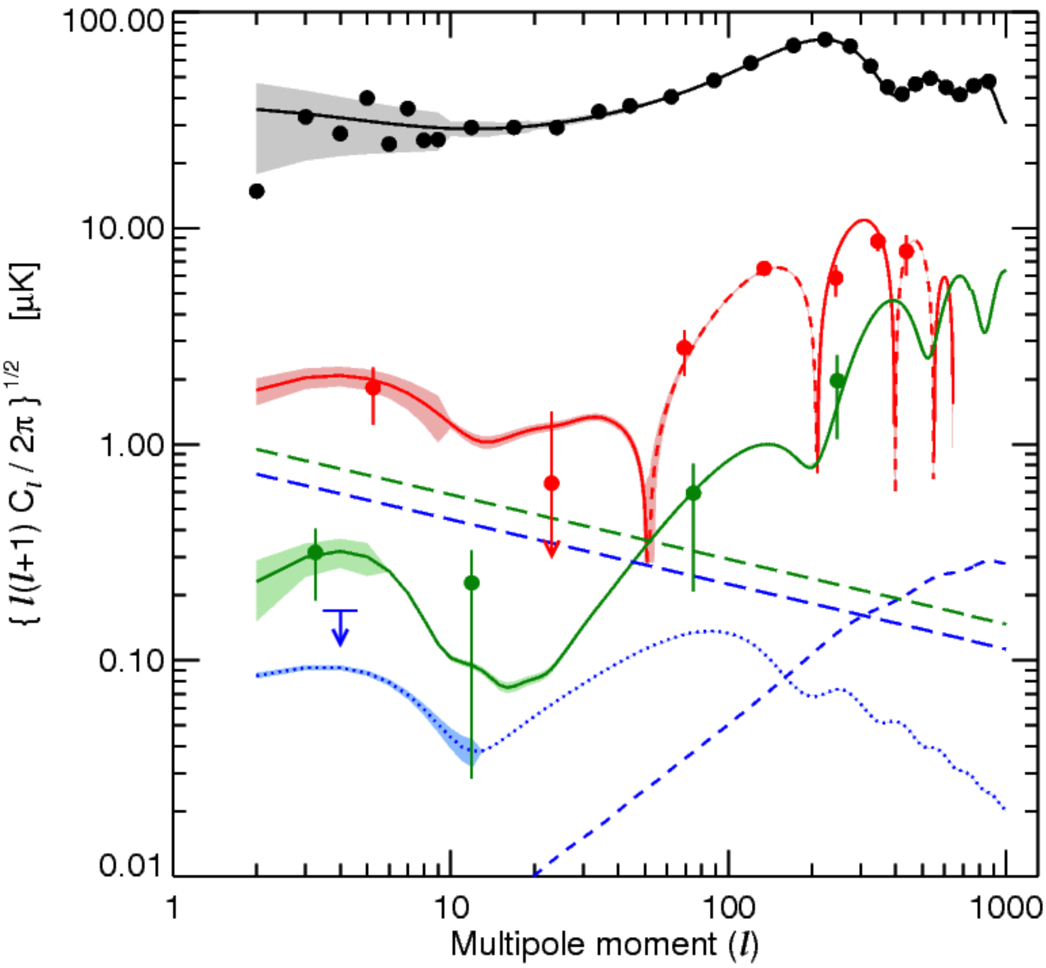

Figure 1: Theoretical TT (black), TE (red), EE (green) and BB (blue) spectrums. Cosmic variance is shown by shading around the lines. The dashed lines are expected foreground levels; the green and dark blue lines represent synchrotron and dust foregrounds for EE and BB respectively at 65GHz; the light blue line represents the expected BB lensing signal. Data points are measurements from WMAP. From Page et al. (2006).

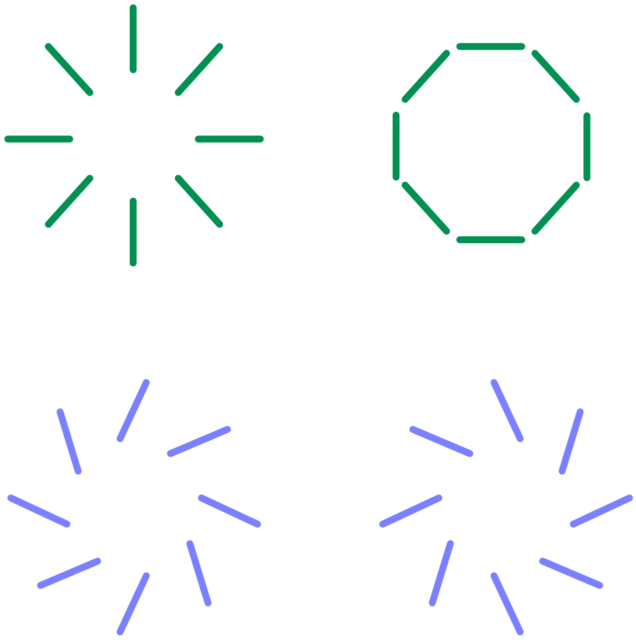

Figure 2: Example of E- and B-type polarization patterns. Green represents E-modes, blue represents B-modes.

3 Measuring the polarization

3.1 Polarization parameters

Setting the components of the EM field of a photon to be $E_x = a_\mathrm{x}\cos(\omega t - \phi_\mathrm{x})$ and $E_\mathrm{y} = a_\mathrm{y}\cos(\omega t - \phi_\mathrm{y})$, the Stokes parameters are (Abidin, 2005):

$$I = \langle |E_\mathrm{x}|^2\rangle + \langle |E_\mathrm{y}|^2\rangle = a_\mathrm{x}^2 + a_\mathrm{y}^2, \quad (1)$$

$$Q = \langle |E_\mathrm{x}|^2\rangle - \langle |E_\mathrm{y}|^2\rangle = a_\mathrm{x}^2 - a_\mathrm{y}^2, \quad (2)$$

$$U = \langle E_\mathrm{x}E_\mathrm{y}^\dagger\rangle + \langle E_\mathrm{y}E_\mathrm{x}^\dagger\rangle = 2a_\mathrm{x}a_\mathrm{y}^2\cos(\phi_\mathrm{x} - \phi_\mathrm{y}), \quad (3)$$

$$V = i(\langle E_\mathrm{x}E_\mathrm{y}^\dagger\rangle - \langle E_\mathrm{y}E_\mathrm{x}^\dagger\rangle) = 2a_\mathrm{x}a_\mathrm{y}^2\sin(\phi_\mathrm{x} - \phi_\mathrm{y}). \quad (4)$$

I measures the total intensity; this is the most commonly measured component in CMB experiments. Q and U measure the linear polarization; these are of cosmological interest as they result from the Thomson scattering in the early universe, and are measured in observations of the CMB polarization. V measures the circular polarization; this cannot be produced by Thomson scattering (Seljak, 1997), hence this parameter is not usually measured (but see Readhead et al., 2004).

Individual polarization experiments measure the amount of polarization in terms of the Stokes parameters; however, these depend on the choice of coordinate system. They are normally subsequently converted into E and B modes, in which the orientation is defined relative to itself (Seljak, 1997). These are rotationally invariant parity fields (see Zaldarriaga and Seljak, 1997; Zaldarriaga, 2004); E remains unchanged when acted upon by a parity operator, while B changes sign.

3.2 Receivers

There are several types of receiver that can be used for amplified systems using High Electron-Mobility Transistors (HEMPs) (bolometers are neglected here).

The first are correlation polarimeters, which split the signal into two circularly polarized components by using a polarizer and an orthomode transducer (OMT). These components are then filtered and amplified before they are correlated and I, Q and U are subsequently derived (Abidin, 2005). Example experiments that used this type of detector are DASI (Kovac et al., 2002) and POLAR (Keating et al., 2003).

The second type of receiver are differencing polarimeters. In these, the signal from the OMT is split into two linear components that are then amplified and detected. The sum of the two components provides I, while the difference is either Q or U depending on the orientation of the system. The two signals can be Dicke-switched to reduce $1/f$ noise. The Planck LFI will use this type of receiver (Leahy et al., 2001).

A third type would consist of a normal, amplified receiver with a rotating polarizer in front of it. This would mean that the receiver would measure one Stokes parameter (either Q or U), then after the polarizer has rotated by $\pi/2$ it would measure the other one, and so on (see Siringo et al., 2005, which discusses bolometers, but the process could be adapted for radiometers).

The receivers can be mounted on a single dish, or multiple receivers can be used to construct an interferometer. Interferometers have the advantages that they measures the Fourier modes of the anisotropies directly, atmospheric emission is largely rejected and in correlated interferometers the $1/f$ noise is not significant as the interferometer elements don't make total intensity measurements (Padin et al., 2002). The disadvantages are that it requires increased instrumentation and a more complicated system (and hence is more expensive). To date, interferometer polarization detectors have used small dishes, so they do not have the collecting area available to single, large dish experiments.

4 Instrumental noise

The sensitivity required to detect the polarization depends on the type of polarization being observed and the multipole that is being measured (see Figure 1). It is typically $\sim 1\mu$K for E modes; the B modes are expected to be an order of magnitude below this.

The minimum signal temperature that a detector can measure is given by (Burke and Graham-Smith, 2002)

$$\Delta T = \frac{T_{\rm sys}}{\sqrt{B\tau}}, \tag{5}$$

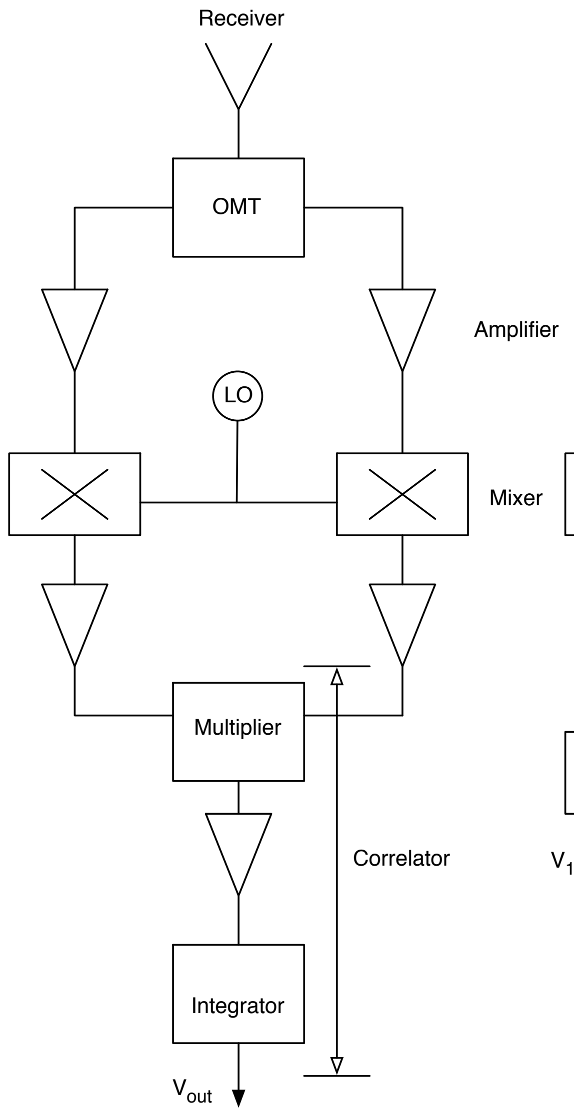

Figure 3: Block diagrams of a correlation receiver (left) and a differencing receiver (right). OMT denotes OrthoMode Transducer; LO denotes Local Oscillator.

where $T_{\rm sys}$ is a measure of how noisy the system is (in Kelvin), B is the bandwidth available and τ is the integration time. For two amplifier chains (numbered 1 and 2), $T_{\rm sys} \equiv \sqrt{T^1_{\rm sys} T^2_{\rm sys}}$, and a factor of $(\cos^2(\phi)_\nu)^{-1/2}$ is added to the equation to account for the phase shift ϕ between the signals. Note that this equation is only valid when there are no RF gains or offset fluctuations (Keating et al., 2003). This sensitivity needs to be at least ~ 5 sigma below the detected strength of the signal for a definite detection.

As a result, the instrument design needs to have low noise temperatures, which means cryogenically cooled detectors and amplifiers. The noise levels should also be stable, and there should be low cross-talk between amplifier channels. Also, wide bandwidths should be used to increase the sensitivity.

The siting and design of the telescope needs careful consideration; detectors require low ground spill-over (this can also be significant, see e.g. Readhead et al., 2004), and care needs to be taken with antenna sidelobes. Polarized emission from the Sun and Moon can also cause interference (Keating et al., 2003).

In addition, very accurate noise accounting needs to be done (see e.g. Padin et al., 2002), and when the experiment is being run, long integration times will likely be needed, as dictated by equation (5).

Calibration of polarization detectors using real astronomical signals is difficult and time-consuming; POLAR, for example, would have required a source of $\sim$ 1700Jy to calibrate the system in one second; the brightest radio source in the sky is Cas A, and the polarized part of this would only have provided a signal of $\leq$ 20Jy. Instead, the experiment used both wire grid and dielectric sheet calibrators. The former provides a large polarization source with a limited dynamic range, while the latter mimics the polarization of the sky with a large dynamic range. The former was used in initial tests, while the latter was used during observing runs (Keating et al., 2003). PIQUE used a nutating aluminium plate as a calibrator, as radiation reflected from the plate is weakly polarized due to the finite conductivity of the aluminium (Staggs et al., 2002).

5 Foreground removal

A variety of sources will provide foregrounds to the intrinsic CMB polarization; the importance of them will depend on the frequencies and angular sizes that are being observed. On small angular scales, polarized emission from extragalactic radio sources will present a foreground. The main foreground at large angular scales is dust (10% polarized) and synchrotron (70% polarized) emission from our galaxy (Seljak, 1997).

On average, foreground polarization contributes equally to both E and B modes. However, lensing can turn E-modes into B-modes; this happens at $l \sim 1000$ (see Figure 1).

The foregrounds can be removed in a similar way to the removal of temperature foregrounds in the CMB (Seljak, 1997). Many frequencies can be observed, and the frequency dependence of the different sources can be utilized to remove them. Individual experiments do not necessarily need to observe at multiple frequencies, however, as results from other surveys at different frequencies in the same parts of the sky can be used (see e.g. Readhead et al., 2004).

Careful selection of the observing frequencies can also reduce the amount of foreground that is present. For example, the Cosmic Background Imager used frequencies that were in the minima between foregrounds. Point sources, galactic synchrotron and free-free emission mainly dominate at low frequencies, while interstellar dust and atmospheric noise dominate at high frequencies. The frequency dependence of receiver noise temperatures also needs to be taken into consideration; it is greater at higher frequencies (Padin et al., 2002).

6 Optimal design and Conclusion

The amount of the sky that needs to be observed depends on the multipole that is being measured; at low multipoles, the whole sky must be observed, while at high multipoles only small parts of the sky need to be measured (although it is best to sample large regions of sky and average the multipole across them; see Bowden et al., 2004). Observations of the whole sky would need multiple ground-based experiments or a space-based experiment, while observations at higher multipoles ($l \geq 20$) would only need a single ground-based experiment. Observations at $l \sim 100 - 1000$ would also coincide with the peaks in the expected power of both E and B modes.

To reach the necessary sensitivity in a reasonable amount of time, a large collecting surface and a wide bandwidth are required. The receiver must be significantly cooled, and have low noise characteristics. A correlation polarimeter would be the best choice of receiver system, as it also measures I, so TE measurements can be made without requiring separate observations of the total intensity. Also, the output from differencing polarimeters is highly sensitive to both physical temperature and amplifier gain changes (Leahy et al., 2001).

Having multiple receivers, i.e. a focal plane array, would also increase the amount of sky that could be observed within a set time period. Observations at multiple frequencies would provide good foreground removal, although this could be achieved using results from other experiments.

Obviously, multiple experiments using different polarimeters and detection mechanisms will cumulatively provide the best scientific results.

To conclude, the future of CMB polarization observations is bright. Many experiments are either currently online, or will be started in the near future. Two of the main objectives of near-future experiments will be to refine measurements of the E modes, and obtain first measurements of the B-modes.

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