Title
Polarization of the CMB Anisotropy

Author
White, Martin

Publication Date
1998-10-30

Proceedings: Evolution of Large Scale Structure – Garching, August 1998

POLARIZATION OF THE CMB ANISOTROPY

Martin White
Departments of Astronomy and Physics, University of Illinois
at Urbana-Champaign, Urbana, IL 61801-3080, U.S.A.

ABSTRACT. I review why we expect the CMB anisotropy to be polarized, what we can learn from studying polarization and the level of the experimental challenge it presents. A discussion of current and future polarization sensitive experiments will focus on the expected sensitivity of PLANCK.

1 Introduction

In this contribution I discuss the theoretical predictions, and experimental prospects for detection of polarization in the anisotropy of the cosmic microwave background (CMB) radiation. While there is every reason to believe that the anisotropy is polarized, there is no experimental verification of this prediction yet. This is not too surprising, since the level of the polarization is but a small fraction of the already extremely small anisotropy itself.

The degree of (linear) polarization is directly related to the quadrupole anisotropy in the photons when they last scatter, at $z \sim 10^3$. While the exact properties of the polarization depend on the mechanism for producing the anisotropy, several general properties arise. The polarization peaks at angular scales smaller than the horizon at last scattering due to causality. Furthermore, the polarized fraction of the temperature anisotropy is small since only those photons that last scattered in an optically thin region could have possessed a quadrupole anisotropy. The fraction depends on the duration of last scattering. For the standard thermal history, it is 10 per cent on a characteristic scale of tens of arc minutes. Since temperature anisotropies are at the 10^{-5} level, the polarized signal is at (or below) the 10^{-6} level, or several μK, representing a significant experimental challenge. However, as I shall describe below, there are many things that a study of the polarization can teach us, so the experimental investment is well worth while.

The outline is as follows. In the next section I discuss why we expect the CMB anisotropy to be (linearly) polarized. I follow this with some reasons why we should attempt to study this polarization, and end with a discussion of the experimental prospects, focusing specifically on the Planck Surveyor satellite mission. The goal here is to provide a simple picture of the various issues involved. For the mathematical formalism, and much more detail, the reader is referred to (Bond & Efstathiou 1984, Polnarev 1985, Zaldarriaga & Seljak 1997, Kamionkowski, Kosowsky & Stebbins 1997, Hu & White 1997ab).

2 Why is the CMB supposed to be polarized?

The Thomson scattering cross section depends on polarization as

$$\frac{d\sigma_T}{d\Omega} \propto |\hat{\epsilon}\cdot\hat{\epsilon}'|^2 \,, \tag{1}$$

where $\hat{\epsilon}$ ($\hat{\epsilon}'$) are the incident (scattered) polarization directions. Heuristically, the incident light sets up oscillations of the target electron in the direction of the electric field vector $\vec{E}$, i.e. the polarization. The scattered radiation intensity thus peaks in the direction normal to, with polarization parallel to, the incident polarization. More formally, the polarization dependence of the cross section is dictated by electromagnetic gauge invariance and thus follows from very basic principles of fundamental physics.

If the incoming radiation field were isotropic, orthogonal polarization states from incident directions separated by 90° would balance so that the outgoing radiation would re-

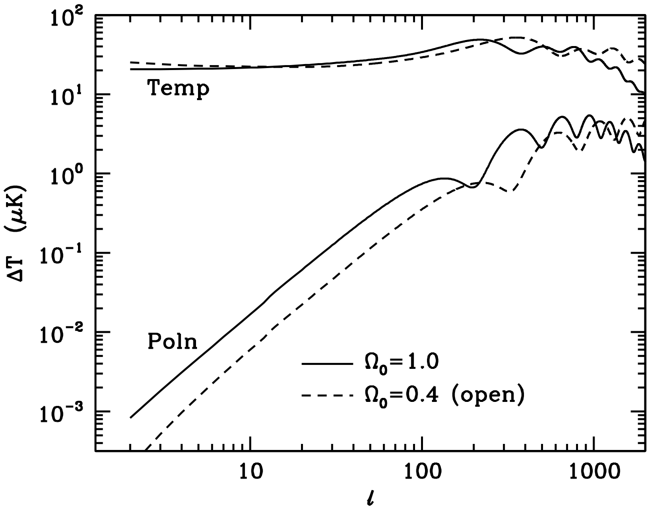

Figure 2. *The temperature and polarization angular power spectra predicted in two cold dark matter models, one with critical density and one open. The model contains only density perturbations, so only the E-mode polarization is non-zero. This model assumes no late reionization of the universe, so the large-angle polarization is purely a projection of smaller scale polarization generated during last scattering.*

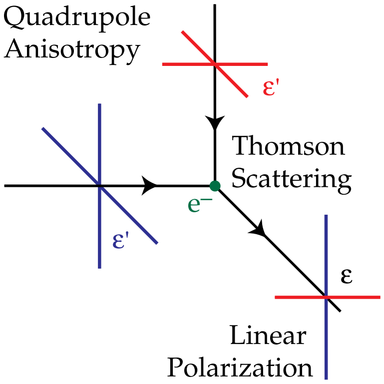

Figure 1. *Thomson scattering of radiation with a quadrupole anisotropy generates linear polarization. Thick lines represent hot and thin lines cold radiation.*

main unpolarized. Conversely, if the incident radiation field possesses a *quadrupolar* variation in intensity or temperature (which possess intensity peaks at $90^\circ = \pi/2$ separations), the result is a *linear* polarization of the scattered radiation (see Figure 1). A reversal in sign of the temperature fluctuation corresponds to a 90° rotation of the polarization, which reflects the spin-2 nature of polarization.

The radiative transfer of polarized light in the expanding universe can be solved numerically by following the Boltzmann equation for brightness and polarization perturbations. Such machinery is not necessary in order to understand the main physical points however. We describe polarized light by the Stokes parameters: I, Q, U and V. The latter, describing circular polarization, is expected to be absent in the cosmological context due to parity conservation. This leaves us with 3 observables. The intensity fluctuations are seen by us as temperature perturbations. It is convenient to construct a linear combination of the Q and U stokes parameters. The new basis vectors are called E- and B-mode polarization (not to be confused with the electric and magnetic fields of the e-m radiation itself). The E-mode polarization is correlated with the temperature, while the B-mode polarization is not. Again for reasons of parity, the density perturbations which give rise to large-scale structure in the universe generate purely

E-mode polarization (in the absence of gravitational lensing effects – see Zaldarriaga & Seljak 1998).

The temperature and E-mode polarization predicted in cold dark matter models of structure formation are shown in Figure 2. The vertical axis is the rms fluctuation as a function of angular scale, where the horizontal axis is the multipole number $\ell \sim \theta^{-1}$ with 1° corresponding to $\ell \sim 10^2$. Note that the polarization peaks at smaller angular scales, higher ℓ, than the anisotropy and at about 10 per cent of the amplitude. A closer examination will reveal that the peaks in the polarization spectrum are out of phase with those in the temperature spectrum, and slightly "sharper".

Of critical importance is the somewhat obvious fact that polarization is only generated by *scattering*. Gravitational interactions do not generate any polarization. Thus the generation of polarization is localized in time, at the last scattering epoch and perhaps at low-z when the universe reionized.

3 Why should we care?

Why should we be concerned with the polarization of CMB anisotropies? There are 3 main reasons. First, that the CMB anisotropies are polarized is a fundamental prediction of the gravitational instability paradigm. Under this paradigm, small fluctuations in the early universe grow into the large scale structure we see today. If the temperature anisotropies we observe are indeed the result of primordial fluctuations, their presence at last scattering would polarize the CMB anisotropies themselves. The verification of the (partial) polarization of the CMB on small scales would thus represent a fundamental check on our basic assumptions about the behavior of fluctuations in the universe, in much the same way that the redshift dependence of the CMB temperature is a test of our assumptions about the background cosmology.

Furthermore, observations of polarization provide an important tool for reconstructing the model of the fluctuations from the observed power spectrum (as distinct from fitting an *a priori* model prediction to the observations). The polarization probes the epoch of last scattering *directly* as opposed to the temperature fluctuations which may evolve between last scattering and the present. This localization in time is a very powerful constraint for reconstructing the sources of anisotropy. Moreover, different sources of temperature anisotropies (scalar, vector and tensor) give different patterns in the polarization: both in its intrinsic structure and in its correlation with the temperature fluctuations themselves. For example, the relative prominence of the B- and E-modes of the polarization and the slope of the spectra at low-ℓ distinguish the different types of fluctuations (Hu & White 1997ab). A large B/E ratio indicates the presence of vector modes. Since vector modes decay with the expansion of the universe, this tells us that whatever forms them (e.g. cosmological defects) must be acting now. In an inflationary model the perturbations were laid down at early times, and the vector modes will have decayed away by the present. The structure of the polarization spectrum around $\ell \sim 10^2$ also allows us to unambiguously distinguish adiabatic models (e.g. inflation) from isocurvature models (Hu, Spergel & White 1997, Spergel & Zaldarriaga 1997). Thus by including polarization information, one can distinguish the ingredients which go to make up the temperature power spectrum and so the cosmological model (for a detailed discussion see Hu & White 1997b).

Finally, the polarization power spectrum provides information complementary to the temperature power spectrum even for ordinary (scalar or density) perturbations. This can be of use in breaking parameter degeneracies and thus constraining cosmological parameters more accurately. The prime example of this is the degeneracy, within the limitations of cosmic variance, between a change in the normalization and an epoch of "late" reionization.

A period of late reionization recouples the CMB photons to the matter. The scattering that occurs erases anisotropy on scales smaller than the horizon at that epoch, but also produces more (large-angle) pol-

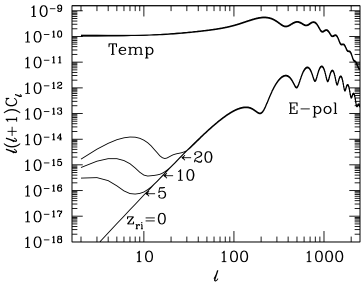

Figure 3. *Late reionization generates large-angle polarization, allowing the degeneracy between a change in amplitude and reionization to be broken.*

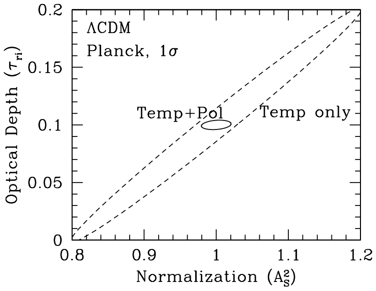

Figure 4. *The inclusion of polarization information breaks the degeneracy between a change in the normalization and a change in the optical depth to Compton scattering (i.e. the redshift of reionization). The contours denote* 1σ *error ellipses in the normalization–reionization plane, that would be determined by Planck using only temperature information (dashed) or temperature and polarization information (solid). All other parameters have been marginalized over.*

arization. This is shown in Figure 3. If the reionization occurs late enough the suppression of anisotropy is uniform for almost all multipoles, and looks much like a change in the amplitude of the spectrum. The differences are constrained to large angles, small ℓ, where cosmic variances limits the precision to which the spectrum can be measured. This makes these two parameters highly degenerate: an increase in the normalization can be counteracted by an increase in the redshift of reionization. Because the large-angle polarization is so sensitive to reionization, it can break this degeneracy as shown in Figure 4.

Perhaps more important than breaking degeneracies in parameterized models, polarization holds the key to reconstructing the underlying model for the fluctuations directly from the observed anisotropy spectra.

4 Experimental Prospects

Theoretically therefore, the case for observing the polarization is very strong. Unfortunately the experimental challenge is daunting. Existing upper limits are nearly an order of magnitude above the theoretical predictions (Hu & White 1997b). In addition to the challenge in raw sensitivity, the foregrounds are not well understood at any CMB frequency (Keating et al. 1998). Free-free emission from Thomson scattering in HII regions leads to polarization of the order of 10 per cent. Extrapolations of dust emission from higher frequencies suggest a polarization of a few to 10 per cent. Radio point sources can be 20 per cent polarized. Synchrotron radiation is perhaps the largest worry, since it can be up to 75 per cent polarized.

The answer to all of these concerns is of course the same as for the temperature anisotropies themselves. One observes as much of the sky as possible, in as many wavebands as possible at the highest angular resolution and with the highest sensitivity one can achieve. These are the design drivers for the Planck Surveyor satellite.

In the *absence* of foregrounds the sensitivity that *MAP*[1], the Planck[2] LFI and HFI will achieve is shown in Figure 5. This figure assumes uniform coverage of the sky. In reality Planck will go a factor of 2 deeper in the polar caps, increasing the signal to noise in those regions over the mean value shown in the Figure. The signal-to-noise ratio is interpreted in a more familiar form in Figure 6.

---

[1] http://map.gsfc.nasa.gov

[2] http://astro.estec.esa.nl/Planck

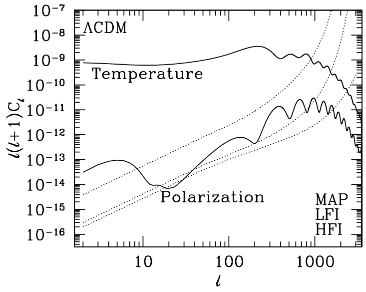

Figure 5. *The predicted signal (solid) and noise (dashed) levels for cosmological polarization in a* Λ*CDM model. The signal level for the temperature anisotropy is shown for reference. The noise power spectra are for MAP, the Planck LFI and HFI respectively (top to bottom) and assume averaging into 5 per cent bands in* ℓ*.*

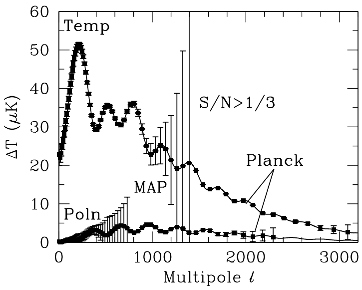

Figure 6. *The* 1σ *errors on a series of uncorrelated band powers, as would be measured with MAP and Planck. For clarity, only points with* $S/N > 1/3$ *are plotted.*

5 Conclusions

I have argued that if the structure we see did grow from initially small perturbations, the CMB anisotropy should be polarized. Detection of this polarization represents a fundamental test of our theories of structure formation. If the CMB is polarized, then we gain two additional observables, in addition to the temperature fluctuations themselves. Since the temperature and E-mode polarization are predicted to be correlated, this takes us from one power spectrum (TT) to 4: TT, TE, EE and BB. The polarization power spectra have a different dependence on the cosmological parameters than does the temperature spectrum, allowing us to break some parameter degeneracies.

The angular spectrum of the polarization is predicted to be "sharper" than the temperature spectrum, to peak at smaller angular scales than the temperature, and be ~ 10 per cent of its amplitude. Measurements of the polarization spectra provide an important cross check on our modeling assumptions. In principle, observations of the polarization could allow us to decompose the model of structure formation into its building blocks, allowing full reconstruction rather than simple model fitting.

Acknowledgments

I would like to thank Wayne Hu for a long and productive collaboration upon which this work is based. Thanks also to the organizers for making the conference the success it was.

References

Bond J.R., Efstathiou G., 1984, ApJ Lett, 285, L45.

Hu W., Spergel D.N., White M., 1997, Phys. Rev. D 55, 3288 [astro-ph/9605193]

Hu W., White M., 1997a, Phys. Rev. D56, 596 [astro-ph/9702170]

Hu W., White M., 1997b, New Astronomy, 2, 323 [astro-ph/9706147]

Kamionkowski M., Kosowsky A., Stebbins A., 1997, Phys. Rev. D55, 7368 [astro-ph/9611125]

Keating B., Timbie P., Polnarev A., Steinberger J., 1998, ApJ, 495, 580 [astro-ph/9710087]

Polnarev A.G., 1985, Sov. Astron., 29, 607.

Spergel D.N., Zaldarriaga M., 1997, Phys. Rev. Lett., 79, 2180 [astro-ph/9705182]

Zaldarriaga M., Seljak U. 1997, Phys. Rev. D 55, 1830 [astro-ph/9609170]

Zaldarriaga M., Seljak U. 1998, Phys. Rev. D 58, 023003 [astro-ph/9803150]