Overview of Secondary Anisotropies of the CMB

A. Refregier

Department of Astrophysical Sciences, Peyton Hall, Princeton, NJ 08544

Abstract. While the major contribution to the Cosmic Microwave Background (CMB) anisotropies are the sought-after primordial fluctuations produced at the surface of last scattering, other effects produce secondary fluctuations at lower redshifts. These secondary fluctuations must be carefully accounted for, in order to isolate primordial fluctuations. In addition, they are interesting in their own right, since they provide a wealth of information on the geometry and local properties of the universe. Here, I survey the different sources of secondary anisotropies and extragalactic foregrounds of the CMB. I show their relative importance on the multipole-frequency plane. I discuss in particular their impact in the future CMB missions MAP and Planck Surveyor.

1. Introduction

The Cosmic Microwave Background (CMB) provides a unique probe of the early universe (see White, Scott, & Silk 1994 for a review). If CMB fluctuations are consistent with inflationary models, future ground-based and satellite experiments will yield accurate measurements of most cosmological parameters (see Zaldarriaga, Spergel, & Seljak 1997; Bond, Efstathiou, & Tegmark 1997 and reference therein). These measurements rely on the detection of primordial anisotropies produced at the surface of last scattering. However, various secondary effects produce fluctuations at lower redshifts. The study of these secondary fluctuations (or extragalactic foregrounds) is important in order to isolate primordial fluctuations. In addition, secondary fluctuations are interesting in their own right since they provide a wealth of information on the local universe.

In this contribution, I present an overview of the different extragalactic foregrounds of the CMB. The foregrounds produced by discrete sources, the thermal Sunyaev-Zel’dovich (SZ) effect, the Ostriker-Vishniac (OV) effect, the Integrated Sachs-Wolfe (ISW) effect, gravitational lensing, and other effects, are briefly described. I show their relative importance on the multipole-frequency plane, and pay particular attention to their impact on the future CMB missions MAP (Bennett et al. 1995) and Planck Surveyor (Bersanelli et al. 1996). A more detailed account of each extragalactic foreground can be found in the other contributions to this volume. In this article, I have focused on the latest literature, and have not aimed for bibliographical completeness. This overview...
is based on a more detailed study of extragalactic foregrounds in the context of the MAP mission (Refregier et al. 1998).

2. Comparison of Extragalactic Foregrounds

To assess the relative importance of the extragalactic foregrounds, I decompose the temperature fluctuations of the CMB into the usual spherical harmonic basis, $\delta T(\theta) = \sum_{\ell,m} a_{\ell m} Y_{\ell m}(\theta)$, and form the averaged multipole moments $C_\ell \equiv \langle |a_{\ell m}|^2 \rangle$. Following Tegmark & Efstathiou (1996), I consider the quantity $\Delta T_\ell \equiv [\ell (2\ell + 1) C_\ell / 4\pi]^{1/2} T_0$, which gives the rms temperature fluctuations per ln $\ell$ interval centered at $\ell$. Another useful quantity that they considered is the value of $\ell = \ell_{eq}$ for which foreground fluctuations are equal to the CMB fluctuations, i.e. for which $C_\ell^{\text{foreground}} \simeq C_\ell^{\text{CMB}}$. Note that, since the foregrounds do not necessarily have a thermal spectrum, $\Delta T_\ell$ and $\ell_{eq}$ generally depend on frequency.

The comparison is summarized in table 1 and in figure 1. Table 1 shows $\Delta T_\ell$ and $\ell_{eq}$ for each of the major extragalactic foregrounds at $\nu = 94$ GHz and $\ell = 450$, which corresponds to a FWHM angular scale of about $\theta \sim 0.3$ deg. These values were chosen to be relevant to the MAP W-band ($\nu \simeq 94$ GHz and $\theta_{\text{beam}} \simeq 0.21$). I also indicate whether each foreground component has a thermal spectrum.

Figure 1 summarizes the importance of each of the extragalactic foregrounds in the multipole-frequency plane. It should be compared to the analogous plot for galactic foregrounds (and discrete sources) shown in Tegmark & Efstathiou (1996; see also Tegmark 1997 for an updated version). These figures show regions on the $\ell$-$\nu$ plane in which the foreground fluctuations exceed the CMB fluctuations, i.e. in which $C_\ell^{\text{foreground}} > C_\ell^{\text{CMB}}$. As a reference for $C_\ell^{\text{CMB}}$, a COBE normalized CDM model with $\Omega_b = 0.05$ and $h = 0.5$ was used. Also shown in figure 1 is the region in which MAP and Planck Surveyor are sensitive, i.e. in which $\Delta C_\ell^{\text{noise}} < C_\ell^{\text{CMB}}$, where $\Delta C_\ell^{\text{noise}}$ is the rms uncertainty for the instrument. Note that this figure is only intended to illustrate the domains of importance of the different foregrounds qualitatively.

In the following, I briefly describe each extragalactic foreground and comment on its respective entries in table 1 and figure 1.

2.1. Discrete Sources

Discrete sources produce positive, point-like, non-thermal fluctuations. While not much is known about discrete source counts around $\nu \sim 100$ GHz, several models have been constructed by interpolating between radio and IR observations (Toffolatti et al. 1998; Gawiser & Smoot 1997; Gawiser et al. 1998; Sokasian et al. 1998). Here, I adopt the model of Toffolatti et al. and consider the two flux limits $S < 1$ and 0.1 Jy for the source removal in table 1. The sparsely dotted region figure 1 shows the discrete source region for $S < 1$ Jy. In the context of CMB experiments, the Poisson shot noise dominates over clustering for discrete sources (see Toffolatti et al.). As a result, the discrete source power spectrum, $C_\ell^{\text{discrete}}$, is essentially independent of $\ell$. 
Table 1. Summary of Extragalactic Foregrounds for $\nu = 94$ GHz and $\ell = 450$.

| Source  | $\Delta T_\ell$ ($\mu$K)$^a$ | $\ell_{\text{eq}}$$^b$ | Thermal$^c$ | Note | Ref.$^d$ |
|---------|-------------------------------|-----------------|--------------|------|---------|
| CMB$^e$ | 50                            | yes             | S < 1.0 Jy   | 2    | 1       |
| Discrete$^f$ | 5 1800                     | no              | S < 0.1 Jy   | 2    | 2       |
|          | 2 3100                      | no              | S < 0.1 Jy   | 2    | 2       |
| SZ$^g$  | 10 1900                     | no              | C            | 3    | 3       |
|          | 7 2300                      | no              | NC           | 3    | 3       |
| OV$^h$  | 2 2900                      | yes             | $z_r = 50$   | 4    | 4       |
|          | 1 3100                      | yes             | $z_r = 10$   | 4    | 4       |
| ISW     | 1 5000                      | yes             | $\Omega h = 0.25$ | 5   | 5       |
|          | 0.9 5800                    | yes             | $\Omega h = 0.50$ | 5   | 5       |
| Lensing | 5 2400                      | yes             |               | 6    | 6       |

$^a$ $\Delta T_\ell \equiv [\ell(2\ell + 1)C_\ell/4\pi]^{1/2}$ centered at $\ell = 450$ and $\nu = 94$ GHz.

$^b$ Value of $\ell$ for which $\Delta T_\ell = \Delta T_{\ell,\text{CMB}}$.

$^c$ Thermal (yes) or nonthermal (no) spectral dependence.

$^d$ 1: Seljak & Zaldarriaga 1996; 2: Toffolatti et al. 1998; 3: Persi et al. 1995; 4: Hu & White 1996; 5: Seljak 1996a; 6: Zaldarriaga & Seljak 1998a.

$^e$ Primordial CMB fluctuations for a CDM model with $\Omega_m = 1$, $\Omega_b = 0.05$, and $h = 0.5$.

$^f$ Discrete sources with 94 GHz removal threshold of 0.1, 1 Jy, respectively.

$^g$ SZ effect with (C) and without (NC) cluster cores respectively.

$^h$ OV effect with two different reionization redshifts $z_r$. 
Figure 1. Summary of the importance of extragalactic foregrounds of the CMB. Each filled area on the multipole-frequency plane corresponds to regions where the foreground fluctuations exceed those of the CMB. The sparse and dense dotted regions correspond to discrete sources (with $S < 1$ Jy) and the Sunyaev-Zel’dovich effect (with cluster cores), respectively. The horizontal, descending and ascending hashed regions correspond to the Ostriker-Vishniac effect (with $z_r = 50$), gravitational lensing, and the integrated Sachs-Wolfe effect (with $\Omega h = 0.25$), respectively. The areas marked MAP (thick line) and Planck (thin line) show the regions of sensitivity for each of the future missions, i.e. regions where the CMB fluctuations exceed the noise for each of the instruments (see text).
2.2. Thermal Sunyaev-Zel’dovich Effect

The hot gas in clusters and superclusters of galaxies affects the spectrum of the CMB through inverse Compton scattering. This effect, known as the Sunyaev-Zel’dovich effect (for reviews see Sunyaev & Zel’dovich 1980; Rephaeli 1995), results from both the thermal and bulk motion of the gas. We first consider the thermal SZ effect, which typically has a larger amplitude and has a non-thermal spectrum (see the §2.3 below for a discussion of the kinetic SZ effect). The CMB fluctuations produced by the thermal SZ effect have been studied using the Press-Schechter formalism (see Bartlett 1997 for a review), and on large scales using numerical simulations (Cen & Ostriker 1992; Scaramella, Cen, & Ostriker 1993) and semi-analytical methods (Persi et al. 1995). Here, I consider the SZ power spectrum, $C_{\ell}^{\text{SZ}}$, calculated by Persi et al. (see their figure 5). In table 1, I consider their calculation both with and without bright cluster removal. In figure 1, only the spectrum without cluster removal is shown.

2.3. Ostriker-Vishniac Effect

In addition to the thermal SZ effect described above, the hot intergalactic medium can produce thermal CMB fluctuations as a result of its bulk motion. While this effect essentially vanishes to first order, the second order term in perturbation theory, the Ostriker-Vishniac effect (Ostriker & Vishniac 1986; Vishniac 1987), can be significant on small angular scales. The power spectrum of the OV effect depends on the ionization history of the universe, and has been calculated by Hu & White (1996), and Jaffe & Kamionkowski (1998; see also Persi et al. 1995). We use the results of Hu & White (see their figure 5) who assumed that the universe was fully reionized beyond a redshift $z_r$. In table 1, I consider the two values $z_r = 10$ and 50, while in figure 1, I only plot the region corresponding to $z_r = 50$. For consistency, the standard CDM power spectrum is still used as a reference, even though the primordial power spectrum would be damped in the event of early reionization. (Using the damped primordial spectrum makes, at any rate, only small corrections to both table 1 and figure 1.)

2.4. Integrated Sachs-Wolfe Effect

The Integrated Sachs-Wolfe Effect (ISW) describes thermal CMB fluctuations produced by time variations of the gravitational potential along the photon path (Sachs & Wolfe 1967). Linear density perturbations produce non-zero ISW fluctuations in a $\Omega_m \neq 1$ universe only. Non-linear perturbations produce fluctuations for any geometry, an effect often called the Rees-Sciama effect (Rees & Sciama 1968). Tuluie & Laguna (1995) have shown that anisotropies due to intrinsic changes in the gravitational potentials of the inhomogeneities and anisotropies generated by the bulk motion of the structures across the sky generate CMB anisotropies in the range of $10^{-7} \lesssim \frac{\Delta T}{T} \lesssim 10^{-6}$ on scales of about 1° (see also Tuluie et al. 1996). The power spectrum of the ISW effect in a CDM universe was computed by Seljak (1996a; see also references therein). In table 1, I consider values of the density parameter, namely $\Omega h = 0.25$ and 0.5. In figure 1, only the $\Omega h = 0.25$ case is shown. As above, the standard CDM ($\Omega = 1, h = 0.5$) spectrum is still used as a reference.
2.5. Gravitational Lensing
Gravitational lensing is produced by spatial perturbations in the gravitational potential along the line of sight (see Schneider, Ehlers, & Falco 1992; Narayan & Bartelmann 1996). This effect does not directly generate CMB fluctuations, but modifies existing background fluctuations. The effect of lensing on the CMB power spectrum was calculated by Seljak (1996b) and Metcalf & Silk (1997). Recently, Zaldarriaga & Seljak (1998a) included the lensing effect in their CMB spectrum code (CMBFAST; Seljak & Zaldarriaga 1996). This code was used to compute the absolute lensing correction $|\Delta C^{lens}_\ell|$ to the standard CDM spectrum, including nonlinear evolution. The results are shown in table 1 and figure 1.

2.6. Other Extragalactic Foregrounds
In addition to the effects discussed above, other extragalactic foregrounds can cause secondary anisotropies. For instance, patchy reionization produced by the first generation of stars or quasars can cause second order CMB fluctuations through the doppler effect (Aghanim et al. 1996a,b; Gruzinov & Hu 1998; Knox, Scoccimaro, & Dodelson 1998; Peebles & Juzkiewicz 1998). Calculations of the spectrum of this effect are highly uncertain, but show that the resulting CMB fluctuations could be of the order of 1 $\mu$K on 10 arcminute scales, for extreme patchiness. More likely patchiness parameters make the effect negligible on these scales, but potentially important on arcminute scales. Another potential extragalactic foreground is that produced by the kinetic SZ effect from Ly$\alpha$ absorption systems, as was recently proposed by Loeb (1996). The resulting CMB fluctuations are of the order of a few $\mu$K on arcminute scales, and about one order of magnitude lower on 10 arcminute scales. Because of the uncertainties in the models for these two foregrounds and because they are small on 10 arcminute scales, they are not included in table 1 and figure 1.

3. Discussion and Conclusion
An inspection of table 1 shows that, at 94 GHz and $\ell = 450$, the power spectra of the largest extragalactic foregrounds considered are a factor of 5 below the primordial CDM spectrum. As can be seen in figure 1, the dominant foregrounds for MAP and Planck Surveyor are discrete sources, the thermal SZ effect and gravitational lensing. Note that, for Planck surveyor, these three effects produce fluctuations which are close to the sensitivity of the instrument. The spectra of the OV and ISW effects will produce fluctuations of the order of 1$\mu$K, and are thus less important for a measurement of the power spectrum. The effect of gravitational lensing is now incorporated in CMB codes such as CMBFAST, and can thus be taken into account in the estimation of cosmological parameters. The other two dominant extragalactic contributions, discrete sources and the thermal SZ effect, must also be accounted for, but are more difficult to model. Note that, on large angular scales, extragalactic foregrounds produce relatively small fluctuations, and are thus not detectable in the COBE maps (Boughn & Jahoda 1993; Bennett et al. 1993; Banday et al. 1996; Kneissl et al. 1997)

While I have concentrated above on the power spectrum, secondary anisotropies are also a source of non-gaussianity in CMB maps. Discrete sources and the
SZ effect from clusters of galaxies mainly produce Poisson fluctuations and are thus clearly non-gaussian. The other extragalactic foregrounds (SZ, OV, ISW, and lensing) are also non-gaussian and trace large-scale structures in the local universe. As a consequence of the latter fact, extragalactic foregrounds can be probed by cross-correlating CMB maps with galaxy catalogs, which act as tracers of the large scale structure. Such technique can be used to detect the ISW effect (Boughn et al. 1998, and reference therein), gravitational lensing (Suginohara et al. 1998) and the SZ effect by superclusters (Refregier et al. 1998). Gravitational lensing is particularly interesting since it produces a specific non-gaussian signature (Bernardeau 1998). This signature can be used to reconstruct the gravitational potential projected along the line of sight (Zaldarriaga & Seljak 1998b). Further non-gaussian signatures result from the fact that the different extragalactic foregrounds are spatially correlated. For instance, a detection of the cross-correlation signal between gravitational lensing and the ISW and SZ effects would allow us to determine the fraction of the ionized gas and the time evolution of gravitational potential (Goldberg & spergel, 1998; Seljak & Zaldarriaga 1998). A detection of secondary anisotropies would help break the degeneracy between cosmological parameters measured from primary anisotropies alone.

Acknowledgments. I thank David Spergel and Thomas Herbig for active collaboration and discussions on this project. This work was supported by the MAP MIDEX program.

References

Aghanim, N., Desert, F.-X., Puget, J. L., & Gispert, R. 1996a, A&A, 311, 1; see also erratum to appear in A&A, preprint astro-ph/9811054
Aghanim, N., Puget, J. L., & Gispert, R. 1996b, in Microwave Background Anisotropies, proceedings des XVIèmes Rencontres de Moriond, p. 407, eds. Bouchet, F.R., Gispert, R., Guiderdoni, B., & Trân Thanh Ván, J.
Bartlett, J. G. 1997, course given at From Quantum Fluctuations to Cosmological Structures, Casablanca, Dec. 1996, preprint astro-ph/9703091
Banday, A. J., Górski, K. M., Bennett, C. L., Hinshaw, G., Kogut, A., & Smoot, G. F. 1996, ApJ, 468, L85
Bennett, C. L., Hinshaw, W. G., Banday, A., Kogut, A., Wright, E. L., Loewenstein, K., & Cheng, E. S. 1993, ApJ, 414, L77
Bennett, C.L. et al. 1995, BAAS 187.7109; see also http://map.gsfc.nasa.gov
Bernardeau, F. 1998, A&A, 338, 767
Bersanelli, M. et al. 1996, COBRAS/SAMBA, Report on Phase A Study, ESA Report D/SCI(96)3; see also http://astro.estec.esa.nl/Planck/
Bond, J.R., Efstathiou, G., & Tegmark, M. 1997, MNRAS, 291, L33
Boughn, S. P., & Jahoda, K. 1993, ApJ, 412, L1
Boughn, S. P., Crittenden, R.G., & Turok, N.G. 1998, NewA, 3, 275
Cen, R., & Ostriker, J. P. 1992, ApJ, 393, 22
Gawiser, E., & Smoot, G. 1997, ApJ, 480, L1
Zaldarriaga, M., Spergel, D. N., & Seljak, U. 1997, ApJ, 488, 1
Zaldarriaga, M. & Seljak, U. 1998a, preprint astro-ph/9803150
Zaldarriaga, M. & Seljak, U. 1998b, preprint astro-ph/9810257