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Overview of Cosmic Microwave Background Polarization Experiments

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Abstract. We give an overview of experiments now underway to measure the faint polarization that is expected in the 2.7 K Cosmic Microwave Background Radiation. In addition, we review design details of two particular experiments, called POLAR and COMPASS, and speculate on the future of measurements in this rapidly-growing field.

1. Introduction

Investigations of the 2.7 K Cosmic Microwave Background Radiation (CMB) have begun a new era of 'Cosmological Precision', which was unimaginable only two decades ago. Recent measurements of the temperature anisotropy of the CMB from BOOMERanG (Lange et al. 2001), MAXIMA (Lee et al. 2001), and DASI (Pryke et al. 2001) have measured the baryon content and curvature of the universe to 10 % accuracy. Remarkably, future experiments are poised to determine nearly all of the parameters of the standard Big Bang cosmological model to sub-percent accuracy (Jungman et al. 1996). However, a complete characterization of the CMB requires specification of its polarization state. This is true of any electromagnetic radiation, but particularly, for the CMB, detection of its polarization is essential for understanding the fundamental properties of the Big Bang model. Polarization at large (degree) scales can arise from the rescattering of the CMB during the epoch of reionization of the universe when the first compact objects formed after the "cosmic dark ages." At slightly smaller scales, polarization signals from gravitational waves in the Inflationary epoch may be our only probe of physics at the GUT scale of particle physics. Finally, at sub-degree scales CMB polarization complements the measurements of temperature anisotropy. For a review of CMB physics, see Hu & White (1997), Hu, Sugiyama, & Silk (1997), Kamionkowski & Kosowsky (1999).

The predicted CMB polarization signals are extremely faint, ranging from a few μK at small scales to $\leq 0.5\mu K$ at larger scales. So far only upper limits have been reported (see Figure 1 as well as the review of experiments by Staggs, Gundersen, & Church (1999)).

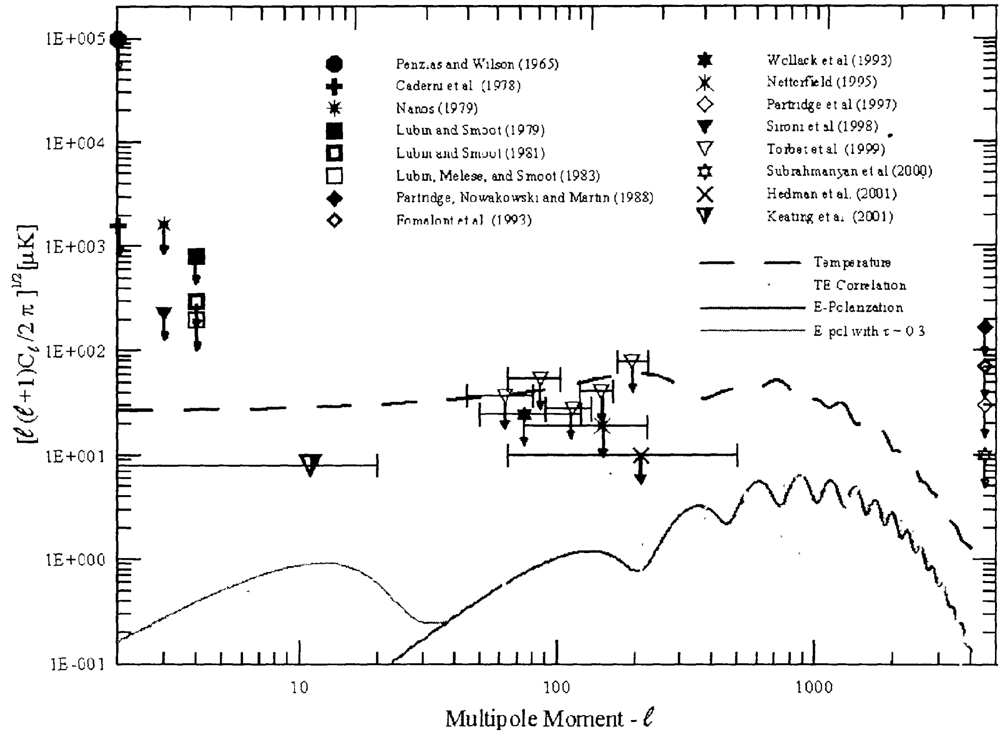

Figure 1. A summary of all existing CMB polarization upper limits (with the exception of the original Penzias and Wilson 1965 point at 0.1 K). All the upper limits, with the exception of the two most recent, should be interpreted as estimated upper limits based on quoted limits on Q, U or $|Tx - Ty|$ rather than limits on the E-mode angular power spectrum. These can be compared to the theoretical angular power spectra for temperature anisotropy (long dash), the E-mode polarization (solid), and the temperature-polarization correlation (short dash). The theoretical angular power spectra are calculated using CMBFAST (Seljak & Zaldarriaga 1996) assuming $\Omega = 1$ and the parameters from Pryke et al. (2001). The thin solid line at low multipoles represents the modified E-mode polarization with $\tau = 0.3$. This is an updated version of a figure that appeared in the review by Staggs et al. (1999)

2. Overview of Experiments

The expected level of the CMB polarization signal is roughly a few μK rms across the sky, while the rms noise of the detector systems are roughly two orders of magnitude larger than this signal. Therefore, these measurements require long integration times, and control of systematic effects at the μK level. Because the signal is smaller (by approximately a factor of 10) than the temperature anisotropy, experiments must be more sensitive and "cleaner" than comparable temperature-anisotropy experiments.

Table 1 lists parameters of some current and future CMB polarization experiments of which we are aware. If CMB polarization exists at the expected levels, all of these instruments should be able to detect the signal. Full exploitation of the polarization signal requires a measurement of the polarization power spectrum and many of these measurements should be able to do so. Because foreground radiation is not well understood (see next section), most of these instruments operate at a variety of different frequencies.

Table 1. Current and Pending CMB Polarization Experiments

Experiment	Frequencies in GHz(# of pixels)	Beamsize	Site	Technique
CAPMAP	40 (4). 90 (10)	13', 6'	NJ	Correl. rad. array
DASI	30 (13)	20'	S. Pole	Interferometer
CBI	30 (13)	3'	Atacama	Interferometer
ATCA	8.7 (5)	2'	Australia	Interferometer
AMiBA	90 (19)	2'	M. Loa	Interferometer
Polatron	90 (1)	2'	OVRO	Bolo. halfwave plate
QUEST	100, 150 ($\approx$ 30)	6'	M. Kea	Bolo array, halfwave plate
POLARBEAR	150 (3000 dt'rs)	10'	TBD	Bolo array
Boom2K1	150(4). 240(40), 340(4)	10'	Antarctic LDB	Bolo array
MAXIPOL	150 (12), 420 (4)	10'	US-Balloon	Bolo array, cold halfwave plate
BaR-SPOrt	32, 90	30', 12'	Antarctic LDB	Correl. rad. array
MAP	22, 30, 40(2), 60(2), 90(4)	13'	L2, full-sky	Correl. rad. array
SPOrt	22, 32, 60, 90	7°	ISS, full-sky	Correl. rad. array
PLANCK-LFI	30(4), 44(6), 70(12),100(34)	33',23',13',10'	L2, full-sky	Correl. rad. array
PLANCK-HFI	143(12), 217(12), 353(6)	8', 6', 5'	L2, full-sky	Bolo array

The wide range of techniques used by these various experiments shows that there is no one "best" way to perform the measurements. The observing sites range from the ground all the way to space-based platforms. While there is general agreement that systematic effects are best minimized in a space mission, there is lots of room for improved measurements from the ground. All of the measurements in Figure 1 are ground-based. The detectors used in these measurements fall into two main classes: coherent receivers based on cooled amplifiers (using high electron mobility transistors, or "HEMTs") and incoherent detectors, bolometers cooled to below $300\mu K$. Coherent receivers have the advantage that they only require cooling to $\approx 20K$, a feat easily achieved with closed-cycle refrigerators or passive cooling in space. They can also be formed into correlation radiometers (see section on POLAR and COMPASS below) which demonstrate excellent rejection of low-frequency amplifier noise. An even more powerful technique with coherent amplifiers is interferometry, which combines the advantages of correlation radiometry with image-formation. Bolometers have two advantages of their own. When used in low-background environments, such as high ground-based sites, balloons, or space, bolometers can have extremely high sensitivity, $\approx 10\times$ better than the best HEMT amplifier. Philhour et al. (2001) describes a ground-based bolometric polarization instrument called the Polatron. In addition, techniques are being developed for building large arrays of bolometers. The table entry for "Polarbear" indicates that arrays of $\approx$ 1000 bolometers may soon be realized.

3. Foregrounds

The search for polarization of the CMB is an extremely challenging task. Any proposed measurements must pay extremely careful attention to systematic effects. Here we discuss the issue of foreground contamination of polarization maps.

The contribution of astrophysical foregrounds to CMB polarization measurements is poorly known. However, the spectral characteristics of these contaminants can be separated from the (known) spectrum of CMB polarization if measurements are made at multiple frequencies. Figure 2 gives an overview of current knowledge of polarized galactic radiation at microwave and millimeter wavelengths. The region near 90 GHz (W-band) may be the cleanest. The amplitude of foreground sources depends sensitively on the exact region of sky one observes. For example, scaling of the polarization map made by Brouw & Spoelstra (1976) indicates that foregrounds will probably not be a problem for the NCP region at the level of $\approx 1\mu$K.

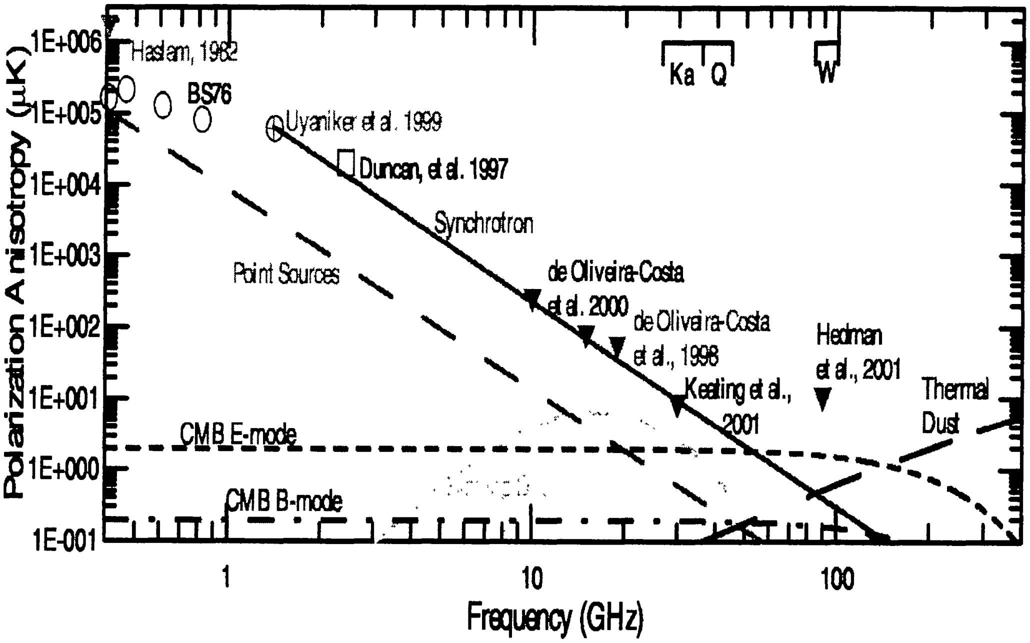

Figure 2. Estimated brightness spectra of foreground contaminants and CMB signal as well as measured upper limits (upside-down triangles) and polarization detections (other symbols). These foreground and CMB signal estimates are relevant to angular scales of $0.2° - 0.5°$ and regions within galactic latitudes $20° \leq |b| \leq 30°$. The various foreground contaminants change as a function of galactic latitude (de Oliveira-Costa et al. 2000) and are expected to vary as a function of angular scale (Tegmark et al. 2000). The frequency bands of some ground-based experiments are shown on the top.

CMB polarization can also be distinguished from foreground sources by the difference in their angular power spectra. While neither the foreground nor the CMB power spectra are known exactly, they can be constrained as shown in Tegmark et al. (2000). In that paper the foreground models are characterized as "optmistic", "middle-of-the-road", and "pessimistic" scenarios. Even in the pessimistic model it appears possible to remove these foregrounds based on their spectral and spatial differences compared to the CMB. So far, none of these foregrounds have affected the measurements of CMB polarization upper limits. The bottom line on foregrounds will only be known after more measurements.

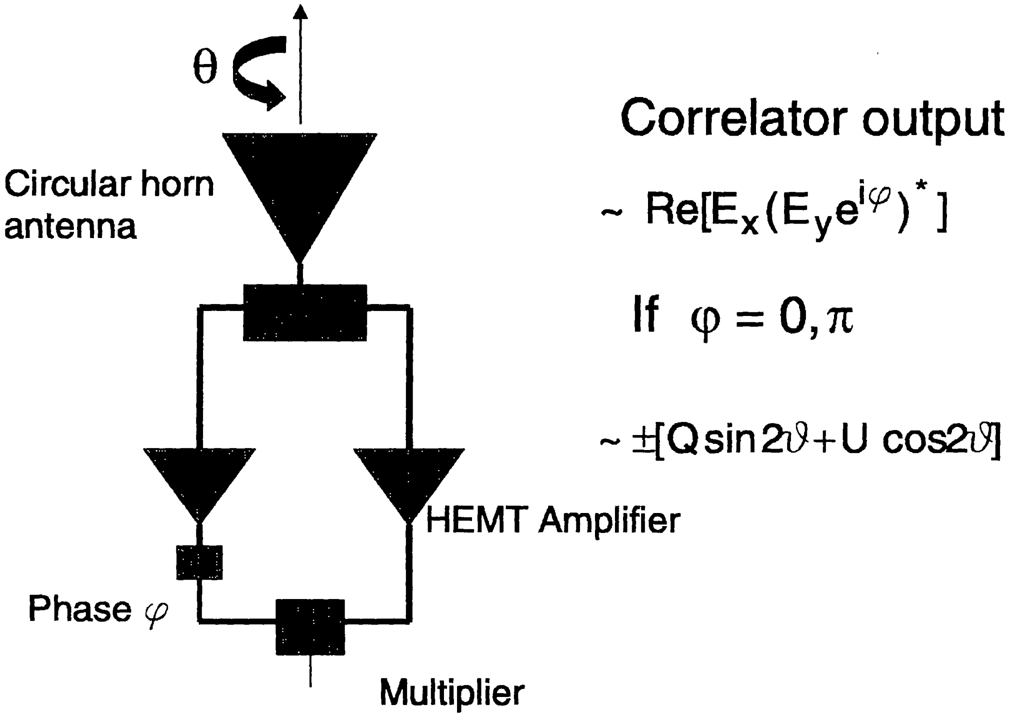

Figure 3. Cartoon of a correlation radiometer, similar to the one used for POLAR and COMPASS. Electromagnetic radiation enters the cylindrical feedhorn either directly from the sky (as in POLAR) or from a telescope (as in COMPASS). The two linear polarization components are split by an orthomode transducer (OMT) and then amplified by separate HEMT amplifier chains. The signals are then multiplied (correlated), producing a signal proportional to the Stokes U parameter. Under instrument rotation, the output alternates between Stokes U and Q. This technique has been used by several instruments, e.g. Hedman et al. (2000).

4. POLAR and COMPASS

The authors have been involved with two measurements to attempt to detect these signals. The POLAR (Polarization of Large Angular Regions) experiment

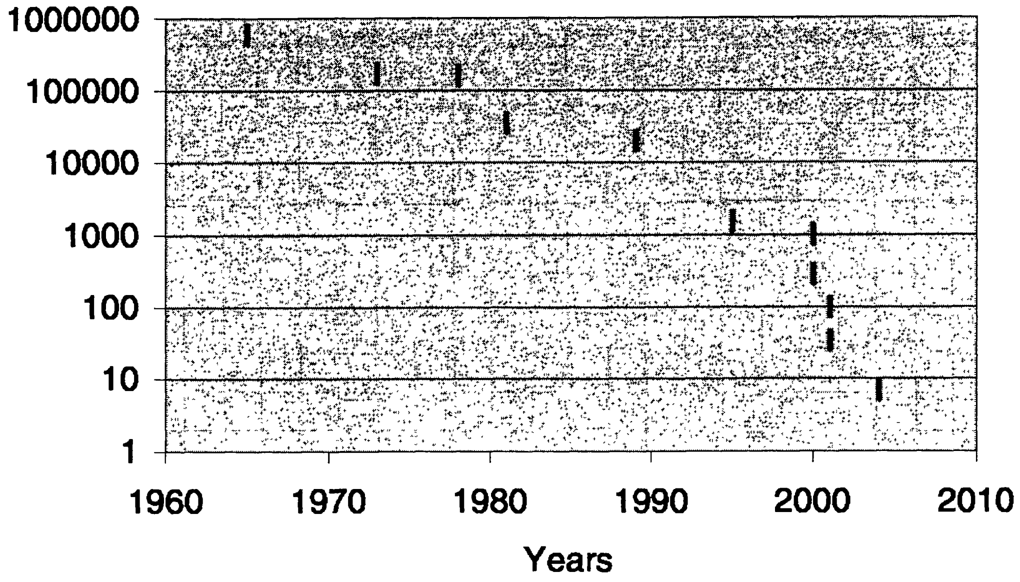

Figure 4. Improvement of detector technology vs time. The raw sensitivity of detector systems used to measure CMB anisotropy and/or polarization has improved dramatically over time. The vertical axis is in microKelvin. Each point represents the sensitivity of a particular instrument; the figure of merit plotted is the noise (ΔT_{RMS}) in one second of integration time for each detector in the instrument divided by the square root of the number of detectors. The leftmost point is from Penzias & Wilson (1965). The steepening of the curve for future instruments (post-2001) occurs because of the introduction of detector arrays and a healthy dose of optimism.

used a 7° FWHM beam during the spring of 2000 to set an upper limit of $10\mu K$ on polarization (Keating et al. 2001a) at large angular scales. COMPASS (COsmic Microwave Polarization At Small Scales) focused on a 1° diameter patch near the NCP with a 20' beam in 2000-2001; when analysis is complete we hope to reach a similar level of sensitivity (Piccirillo et al. 2001) as POLAR. These instruments shared the same single-pixel polarimeter, using cooled HEMT amplifiers in a correlation polarimeter (Figure 3) configuration (Keating et al. 2001b and 2001c), and observed from our observatory near Madison, WI in the atmospheric window near 30 GHz (1 cm). We will begin observing this year with a single-pixel polarimeter in the 90 GHz (0.3 cm) window with a 7' beam.

5. Future

It seems likely that a detection of CMB "E" mode polarization will occur in the next few years. Characterization of the polarization power spectrum at small scales may follow fairly quickly, depending upon our understanding of the foregrounds. As we have heard at this conference, there is considerable interest in measuring the "B" modes that are expected to arise from gravitational waves during inflation. These modes could produce a polarization signature at $\leq 100nK$, at least another order of magnitude below the small-scale "E" modes, and probably belong to a future generation of measurements beyond those listed in Table 1. However, based on the strong record of technological innovation that has marked CMB measurements in the past, this goal is well worth striving for (Figure 4).

References

Brouw, W. N., & Spoelstra, T. A. T. 1976, A&AS, 26, 129

Caderni, N., Fabbri, R., Melchiorri, B., Melchiorri, F., & Natale, V. 1978, Phys.Rev.D, 17, 1901

de Bernardis, P. et al. 2000, Nature, 404, 955

de Oliveira-Costa, A., Tegmark, M. Page, L. A., & Boughn, S. P. 1998, ApJ, 509, L9

de Oliveira-Costa, A., Tegmark, M., Finkbeiner, D. P., Davies, R. D., Gutierrez, C. M., Haffner, L. M., Jones, A. W., Lasenby, A. N., Rebolo, R., Reynolds, R. J., Tufte, S. L., & Watson, R. A. 2000, astro-ph/0010527

Duncan, A. R., Haynes, R. F., Jones, K. L., & Stewart, R. T. 1997, MNRAS, 291, 279

Fomalont, E. B., Partridge, R. B., Lowenthal, J. D., & Windhorst, R. A. 1993, ApJ, 404, 8

Haslam, C. G. T., Salter, C. J., Stoffel, H., & Wilson, W. E. 1982, A&AS, 47, 1

Hedman M. M., Barkats, D., Gundersen, J. O., Staggs, S. T., & Winstein, B. 2000, ApJ, 548, L111

Hu, W., & White, M. 1997, New Astron. 2, 323

Hu, W., Sugiyama, N., & Silk, J. 1997, Nature, 386, 37

Jungman, G., Kamionkowski, M., Kosowsky, A., & Spergel, D.N. 1996, Phys.Rev.D, 52,1332

Kamionkowski, M., Kosowsky, A., & Stebbins, A. 1997, Phys.Rev.D, 55, 7368

Kamionkowski, M., & Kosowsky, A. 1999, Ann. Rev. Nucl. Part. Sci., 49, 77

Keating, B. G. 1999, Ph.D. Thesis, Brown University

Keating, B., Steinberger, J., Timbie, P., & Polnarev, A. 1998, ApJ, 495, 580

Keating, B. G., O'Dell, C. W., de Oliveira-Costa, A., Piccirillo, L., Stebor, N., Tegmark, M., & Timbie, P. T. 2001c, in the Proceedings of the 2K1BC Workshop, Experimental Cosmology at mm-waves, Breuil-Cervinia (AO) Italy

Keating, B. G., O'Dell, C. W., de Oliveira-Costa, A., Klawikowski, S., Stebor, N., Piccirillo L., Tegmark, M., & Timbie, P. T. 2001a, ApJ, 560, L1.

Keating, B. G., O'Dell, C. W., Gundersen, J. O., Stebor, N., Piccirillo, L., & Timbie, P. T. 2001c, submitted to ApJ, astro-ph/0111276

Lange, A. E. et al. 2001, Phys.Rev. D, 63, 042001

Lee, A. T. et al. 2001, ApJ, 561, L1

Lubin, P., Melese, P., & Smoot, G. 1983, ApJ, 273, L51

Lubin, P. M. & Smoot, G. F. 1981, ApJ, 245, L1

Nanos, G. P. Jr. 1979, ApJ, 232, 341

Netterfield, B. C., Jarosik, N., Page, L., Wilkinson, D., & Wollack, E. 1995, ApJ, 445, L69

Padin, S. et al. 2001, ApJ, 549, L1

Partridge, R. B., Nowakowski, J., & Martin, H. M. 1988, Nature, 331, 146

Partridge, R. B., Richards, E. A., Fomalont, E. B., Kellermann, K. I., & Windhorst, R. A. 1997, ApJ, 483, 38

Penzias, A. A. & Wilson, R. W. 1965, ApJ, 142, 419

Philhour, B. J., Keating, B. G., Ade, P. A. R., Bhatia, R. S., Bock, J. J., Church, S. E., Glenn, J., Hinderks, J. R., Hristov, V. V., Jones, W. C., Kamionkowski, M., Kumar, D. E., Lange, A. E., Leong, J. R., Marrone, D. P., Mason, B. S., Mason, P. V. , Shuman, M. M., & Sirbi G. I. 2001, astro-ph/0106543

Piccirillo, L., Dall'Oglio, G., Farese, P., Gundersen, J., Keating, B., Klawikowski, S., Knox, L., Levy, A., Lubin, P., O'Dell, C., Timbie, P., & Ruhl, J. 2001, in the Proceedings of the 2K1BC Workshop, Experimental Cosmology at mm-waves, Breuil-Cervinia (AO) Italy

Pryke, C., Halverson, N. W., Leitch, E. M., Kovac, J., Carlstrom, J. E., Holzapfel, W. L., & Dragovan, M. 2001, astro-ph 0104490

Sironi, G. et al. 1998, New Astron., 3, 1

Smoot, G. F. & Lubin, P. M. 1979, ApJ, 234, L83

Staggs, S.T., Gundersen, J. O., & Church, S. 1999, in ASP Conference Proceedings Vol. 181, Microwave Foregrounds, ed. A. de Oliveira-Costa & M. Tegmark, 299

Subrahmanyan, R., Kesteven, M. J., Ekers, R. D., Sinclair, M., & Silk, J., 2000, MNRAS, 315(4), 808

Tegmark, M., Eisenstein, D. J., Hu, W., & de Oliveira-Costa, A. 2000, ApJ, 530, 133

Uyaniker, B., Furst, E., Reich, W., Reich, P., & Wielebinski, R. 1998, A&AS, 132, 401

Wheelock, S. L., McCallon, H., Boulanger, F., Gautier, T.N., Oken, C., Good, J., Chillemi, J., White, J., Chester, T., Kester, D., & Gregorich, D. 1994, IRAS Sky Survey Atlas: Explanatory Supplement, Pasadena: JPL 94-11

Wollack, E. J., Jarosik, N. C., Netterfield, C. B., Page, L. A., & Wilkinson, D. 1993, ApJ, 419, L49

Zaldarriaga, M. 1998, Ph.D. Dissertation, M.I.T.

Zaldarriaga, M. & Seljak, U. 1997, Phys.Rev.D, 55, 1830