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Cosmic Microwave Background Observations in the Era of Precision Cosmology

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Abstract. The cosmic microwave background (CMB) radiation is a major arena for testing cosmological theories. Its discovery confirmed the hot-big-bang origin of the universe and ruled out the steady-state theory. Since that time the impact on cosmology of CMB studies has grown steadily, indicating the prevalence of non-baryonic matter and the existence of a negative pressure component in the 1980's; the discovery of anisotropy in the 1990's spurred a new generation of experiments and the entry into the era of precision cosmology in 2000 with the demonstration that the geometry is close to flat. The new "holy grail" of the field is the large-scale B-mode polarization component, which would reveal the energy scale of inflation. The sensitivity needed is $\sim 10^{-8}$ Kelvin, and at this level foreground polarized emission is likely to dominate over most of the sky. New radio-frequency cameras consisting of ~1,000-element MMIC arrays will be deployed over the next few years on a wide variety of instruments and should bring about a revolution in radio astronomy with enormous consequences, not only for cosmology, but also for a wide variety of astrophysical studies.

1. Introduction

It is fair to say that amongst the impressive arsenal of observational techniques that astrophysicists and cosmologists have brought to bear on the study of the large-scale structure and evolution of the universe, the Cosmic Microwave Background (CMB) has provided the most direct and easily interpretable approach to cosmological studies, with minimal concerns regarding systematic errors because the physics is simple linear perturbation theory and the observations have been remarkably clear-cut. There has been an almost unprecedented agreement among a wide range of experimental approaches, demonstrating that systematic errors have thus far been controlled. This may be about to change dramatically for reasons I will come to later. As enumerated in a classic paper by Kamionkowski, Kosowsky, & Stebbins (1997), the CMB signals that we have detected, or can hope to detect, consist of total-intensity fluctuations—the so-called "T"-mode signal, which is caused by scalar perturbations—and fluctuations in polarized intensity—the so-called "E" or "G"-mode (gradient of a scalar field) signal caused by scalar perturbations, and the so-called "B" or "C"-mode (curl of a vector field) signals, which are caused by weak lensing, by gravitational waves, or by foregrounds. The only non-zero spectra are the power spectra "TT","EE", "BB", and the cross spectrum "TE".

2. The Pre-Precision Era

In the late 1960's and throughout the 1970's, CMB theories, which at that time assumed that the dominant energy constituent of the universe was baryonic matter, predicted temperature anisotropies in the range $\delta T/T \sim 10^{-3} - 10^{-4}$. As the observed fractional limits on temperature anisotropy were pushed first below 10^{-3} and then below 10^{-4}, it was recognized that simple cosmological models based on baryonic matter alone were being challenged. By the 1980's the "holy grail" of CMB observations had become the search for intrinsic anisotropy in the CMB, whilst theorists—motivated by the increasingly stringent observed upper limits on temperature anisotropy—were developing cosmological models based on a mixture of baryonic matter and cold dark matter, or hot dark matter, and on adiabatic and isocurvature fluctuations, and also on cosmological models with a non-zero cosmological constant.

For this discussion I have selected only some of the key observations prior to the era of precision cosmology in order to set the stage for the later discussion, so the reader should understand that these results are in every case backed up by a number of other vitally important results that provide essential confirmation, or data complementary to the key results that I have focused on here. Only a thorough review could do justice to the enormous amount of creative work that has brought the field to where it stands today. In their 1992 review of anisotropies of the CMB, which predated the COsmic Background Explorer (COBE) discovery of CMB anisotropies, Readhead & Lawrence (1992) divided the history of observations of CMB anisotropies into phases. The first lasted until the early 1980's and culminated in the discovery of the dipole anisotropy. In the second phase, which spanned the 1980's, the limits on intrinsic anisotropy were pushed down to fractional temperature variations $\delta T/T \sim 10^{-5}$. Evidence for a negative-pressure component to the universe mounted steadily from the mid-1980's via the lack of small-scale structure in the CMB, plus indications of low matter density from large-scale-structure studies. The observations on arcminute scales reported by Readhead et al. (1989) used a traveling-wave maser receiver designed by Craig Moore at NRAO and Bob Clauss at JPL (Moore & Clauss 1978). These observations yielded a 95% confidence upper limit of $\delta T/T < 1.7 \times 10^{-5}$, which was sufficiently stringent to rule out theories of galaxy formation based only on baryonic matter, but which was consistent with models including non-baryonic matter and models invoking non-zero cosmological constants (Readhead et al. 1989, Table 6). Thus by the end of the 1980's it had been established from the CMB upper limits alone that non-baryonic dark matter dominates the universal matter budget and also that dark energy is possibly the dominant constituent of the universal energy budget.

The third phase began with the COBE discovery of intrinsic anisotropy and the demonstration of the exquisitely good fit of the CMB spectrum to that of a black body. This phase lasted until 2000. The spectacular COBE anisotropy and CMB spectrum results (Smoot et al. 1992; Mather et al. 1994) are recognized as a critical watershed in cosmological observations. The discovery of the CMB anisotropy demonstrated convincingly that primordial fluctuations exist in the CMB on angular scales larger than 7 degrees (corresponding to mass scales larger than $10^{20}\mathrm{M}_\odot$) and that these anisotropies therefore provide a critical new window on the early universe, and the exquisitely precise agreement of the spectrum with that of a black body provides compelling evidence for the cosmological origin of this signal.

The COBE results provided a further impetus to this active field, and observers who had been pushing the limits on anisotropy redoubled their efforts, while a number of new groups joined the quest to determine the intrinsic anisotropy spectrum. There followed many detections of the anisotropy on angular scales down to one degree. Of particular note were the anisotropy observations (Hancock et al. 1994; Gutierrez de La Cruz et al. 1995) by Davies, Lasenby, and their collaborators; the anisotropy observations of the CAT experiment (Scott et al. 1996) and the discovery of anomalous Galactic emission on large angular scales (Kogut et al. 1996) and on small angular scales (Leitch et al. 1997).

After the groundbreaking COBE results mentioned above, the most important observational results in phase 3 were those coming from the Saskatoon and TOCO experiments by the group led by Page (Netterfield et al. 1997; Miller et al. 1999). Netterfield et al. (1997) provided a spectrum of the anisotropy that showed a clear rise in power towards the first peak from the angular scales probed by COBE, and Miller et al. (1999) provided tantalizing evidence for a drop in power at multipole $l \sim 300$, localizing the first peak at $l \sim 200$. The complementary observations of Leitch et al. (2000), when combined with those of Readhead et al. (1989), strengthened the conclusion that we live in an $\Omega \sim 1$ universe.

While some of the scientific community was convinced by this localization of the first acoustic peak, these results were by no means universally accepted, because of discrepant results that had been published around the same time. This was where things stood in early 2000.

3. The Era of Precision Cosmology

It would be hard to exaggerate the impact of the Boomerang results on the field of CMB observations. With Boomerang we entered a new era, and the earlier results were swept aside by the far greater sensitivity and multipole range of Boomerang (de Bernardis et al. 2000; Lange et al. 2001). Boomerang was the first of a new generation of instruments to bear fruit, and those of us working in this field were completely stunned by the beautiful Boomerang CMB anisotropy spectrum, with seven measurements delineating the first acoustic peak alone, and by the precision of the determinations of the geometry of the universe, the slope of the primordial fluctuation spectrum, the baryonic and cold-dark-matter components, and the dark-energy component. It was clear that the era of precision cosmology had arrived. Other outstanding complementary results followed, e.g., MAXIMA (Hanany et al. 2000) and, most notably, the DASI results (Halverson et al. 2002) that gave a clear detection of both the first and second acoustic peaks, thereby providing another set of precise measurements of the above key cosmological parameters (Pryke et al. 2002), while the Cosmic Background Imager (CBI) provided an entirely independent determination of the key cosmological parameters based on observations on smaller angular scales (see below). In addition, the Archeops and Very Small Array (VSA) experiments provided important confirmation of the key features of the Boomerang+DASI spectrum (Benoit et al. 2003; Scott et al. 2003).

Of course, a key contribution to precision cosmology has been the exquisite Wilkinson Microwave Anisotropy Probe (WMAP) and WMAP3 results (Spergel et al. 2003; Hinshaw et al. 2007; Spergel et al. 2007) which superseded the above low-resolution anisotropy experiments, i.e. up to multipoles $l \sim 500$, providing yet more accurate estimates of the key cosmological parameters. While significantly refining the estimates of cosmological parameters, and presenting tantalizing evidence for a non-scale-invariant anisotropy spectrum or tensor modes, one of the most significant WMAP results has been the beautiful TE spectrum, which demonstrated convincingly that these fluctuations are indeed acoustic waves with the expected phase relationship between the total-intensity fluctuations and the E-mode polarization fluctuations.

The WMAP 3-year CMB anisotropy spectrum is shown in Figure 1.

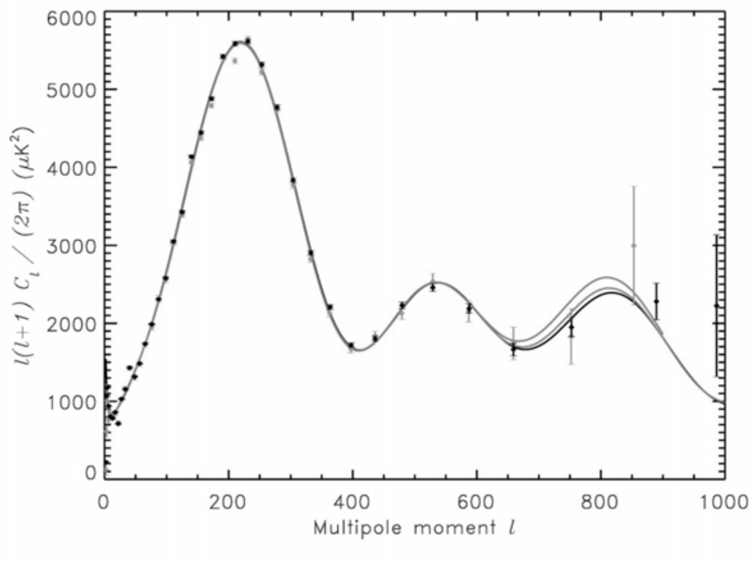

Figure 1. The grey points are the WMAP 1-yr data and the black points are the WMAP 3-yr data (see text). The black (lowest) curve shows the best fit to the WMAP-only ΛCDM 3-yr data. The middle curve shows the best fit to the combination of the 1-yr WMAP, CBI, and Arcminute Cosmology Bolometer Array Receiver—ACBAR—data (this demonstrates the power and importance of the high-resolution CBI and ACBAR data). The upper curve shows the best fit to the WMAP-only 1-yr data.

The NRAO has played an absolutely crucial role in this field, a fact that appears not to be well understood by the scientific community. The low-noise amplifiers (LNAs) of the CBI, DASI, VSA, Berkeley-Illinois-Maryland Association (BIMA), and WMAP were all either built at the NRAO or they were built by people who were taught the art of building low-noise High Electron Mobility Transistor (HEMT) amplifiers at the NRAO Central Development Laboratory under the guidance of Marian Pospieszalski. The TT results based on NRAO LNAs are shown in Figure 2.

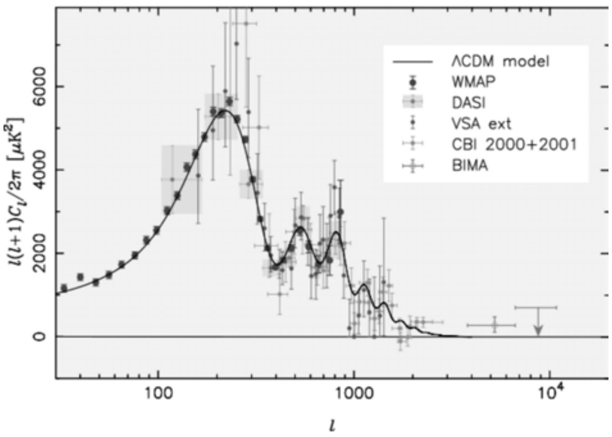

Figure 2. Demonstrating the enormous impact that the NRAO has had on CMB observations. Every observation shown here was made with an "NRAO" low-noise amplifier (LNA). The NRAO Central Development Laboratory built all of the LNAs for WMAP and BIMA, and they instructed visitors from Pasadena, Chicago, and Jodrell Bank on how to build the amplifiers for the CBI, DASI, and the VSA.

With the CBI we deliberately chose to build a higher-resolution instrument in order to study the multipole range $l \sim 300 - 4,000$. From November 1999 to July 2001 the CBI had this field entirely to itself. Unlike the lower-resolution experiments, which address mass scales larger than superclusters of galaxies, the range of angular scales addressed by the CBI corresponds to mass scales that range from a few times the mass of the local group up the largest superclusters. The first two key results of the CBI were, therefore, (i) the measurement of anisotropies on angular scales corresponding to the masses of clusters of galaxies (this was the first time that the primordial seeds of galaxy clusters had been detected) and (ii) the first detection of one of the pillars of the cosmological models: the damping tail caused by photon diffusion and the finite thickness of the last-scattering region (Padin et al. 2001), the so-called "Silk damping". Another significant advantage of observing in a multipole range not covered by other experiments was that it was possible, using the CBI, to derive precise values of the cosmological parameters independent of the first acoustic peak (Mason et al. 2003; Pearson et al. 2003; Sievers et al. 2003) and hence to derive the cosmological parameters independently from the values obtained by other experiments, which relied heavily on the position and shape of the first acoustic peak, thereby providing a crucial completely independent check of the interpretation of all of these other experiments.

The other notable experiment that has concentrated on high-resolution CMB observations is ACBAR (Kuo et al. 2004), which came into operation about 18 months after the CBI. Its impressively high-sensitivity observations have complemented those of the CBI, leading to even more precise determinations of the key cosmological parameters.

Table 1. Cosmic parameter values for the flat tilted adiabatic ΛCDM model

Parameter (1)	Prior Range (2)	WMAP1+CBI+ DASI+B03 TT+EE+TE (best-fit) (3)	WMAP1+CBI+ DASI+B03 TT+EE+TE (4)	CBI+ DASI+B03 EE+TE (5)
θ/θ_0	0.5 to 10	1	1.001 ± 0.0042	0.987 ± 0.017
$\Omega_b h^2$	0.005 to 0.1	0.0226	0.0232 ± 0.0013	0.018 ± 0.005
$\Omega_c h^2$	0.01 to 0.99	0.117	0.114 ± 0.011	0.119 ± 0.034
τ	0.01 to 0.8	0.105	0.149 ± 0.086	0.33 ± 0.18
$n_{\rm s}$	0.5 - 1.5	0.960	0.978 ± 0.039	0.92 ± 0.23
$\ln[10^{10} A_{\rm s}]$	2.7 to 4.0	3.09	3.18 ± 0.16	3.37 ± 0.35
$q_s = A_s e^{-2\tau} / A_{s0} e^{-2\tau_0}$	-	1	0.992 ± 0.037	0.86 ± 0.14
Ω_Λ	-	0.714	0.733 ± 0.054	0.58 ± 0.25
Age(Gyr)	-	13.6	13.5 ± 0.26	14.4 ± 0.80
Ω_m	-	0.286	0.267 ± 0.054	0.42 ± 0.25
σ_8	-	0.83	0.848 ± 0.063	0.94 ± 0.21
z_{re}	-	12.5	15.1 ± 5.3	32 ± 15
H_0	40 to 100	70.0	72.6 ± 5.6	64 ± 15

The first group shows the six independent (fitted) parameters; the second group shows parameters derived from them. Mean values and standard deviations are given for TT+EE+TE data in column 4 and for EE+TE in column 5. The ranges for the uniform weak priors imposed for the MCMC runs are given in column 2. The best-fit model parameters defining the "fiducial model" of Sievers et al. (2007) are shown in column 3. For this model $\theta_0 = 1.0437$ and $A_{s0} e^{-2\tau_0} = 17.9 \times 10^{-10}$. These are slightly different than the parameters defining the WMAP team's best-fit (Spergel et al. 2003) using WMAP1 TT+TE + ACBAR TT + an earlier version of the CBI TT data (Pearson et al. 2003) and different priors: $\Omega_b h^2 = 0.0224$, $\Omega_c h^2 = 0.111$, $n_{\rm s}(k = 0.05) = 0.958$, $\tau = 0.11$, $H_0 = 72$. This was the fiducial model used in Readhead et al. (2004a).

Because the CBI and ACBAR results extend to high multipoles, they have been heavily used to supplement WMAP (Spergel et al. 2003) and, more recently, as they too have pushed to higher multipoles, the Boomerang03 (Jones et al. 2006) and VSA (Rebolo et al. 2004) results have been added to those of the CBI (Readhead et al. 2004) and ACBAR to supplement WMAP3 (Spergel et al. 2007; Sievers et al. 2007) to provide the most precise measurements yet of the key cosmological parameters, as shown in Table 1, which is taken from Sievers et al. (2007).

3.1. Anisotropies in the Polarization Intensity of the CMB

A critical prediction of the ΛCDM cosmological model is the existence of E-mode polarization anisotropy. The detection of E-mode polarized anisotropy by the DASI project (Kovac et al. 2002) was therefore an important milestone. A difficulty in making observations of the polarized CMB anisotropy is that the maximum signal is at higher multipoles than is the case for the anisotropy in total intensity. For this reason the CBI is particularly well-suited to polarized CMB observations, and it is therefore not surprising that the most significant detection of E-mode polarization and the first measurement of the actual spectrum, as opposed to a detection via a shaped fit, was made with the CBI (Readhead et al. 2004a; Sievers et al. 2007). The spectra of all published EE detections to

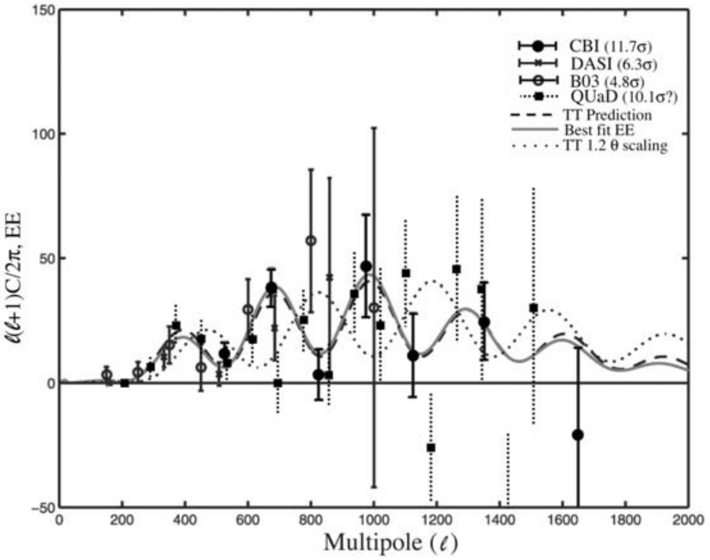

Figure 3. Significant detections of the EE polarization have now been made by the DASI team, who were the first to observe it, by the CBI, who have the most significant detection thus far (11.7σ, see text), and by Boomerang and QUaD. The fits above antedate the QUaD observations, and so are for CBI+DASI+B03 only. The black dashed curve shows the predicted EE spectrum based on the best fit to the TT data only; there are no free parameters here. The grey dotted curve shows the same thing shifted by 20% in θ. The grey solid curve shows the best fit to CBI+DASI+B03 data alone. The good agreement between the TT-only derived (dashed) curve and the EE-only (solid) best-fit curve indicates the power of the EE observations alone and is a powerful demonstration of the fact that we are dealing with acoustic waves.

date are shown in Figure 3. The CBI produced the first image of CMB E-mode polarization, and the CBI polarization results, with significance in the detection of E-mode polarization at 11.7σ, still remain unsurpassed over three years after the CBI was declined NSF funding a second time. Had funding continued the CBI would have demonstrated even more powerfully the fact that interferometers are ideal instruments for eliminating systematic errors and posed an even greater challenge to subsequent experiments.

As with the CBI total-intensity first detections on these angular scales, the significance of the CBI polarization results is that they address the mass scales of clusters of galaxies. The phase of the spectrum, which is clearly out of phase with the total-intensity spectrum, as is expected for acoustic waves, provides a crucial demonstration on these critical mass scales that the acoustic-wave interpretation of the anisotropies is correct. The Boomerang03 polarization (Piacentini et al. 2006) cross power spectrum provides an important independent confirmation of this critical point over the relevant multipole range.

4. The Future of CMB Observations in the Era of Precision Cosmology

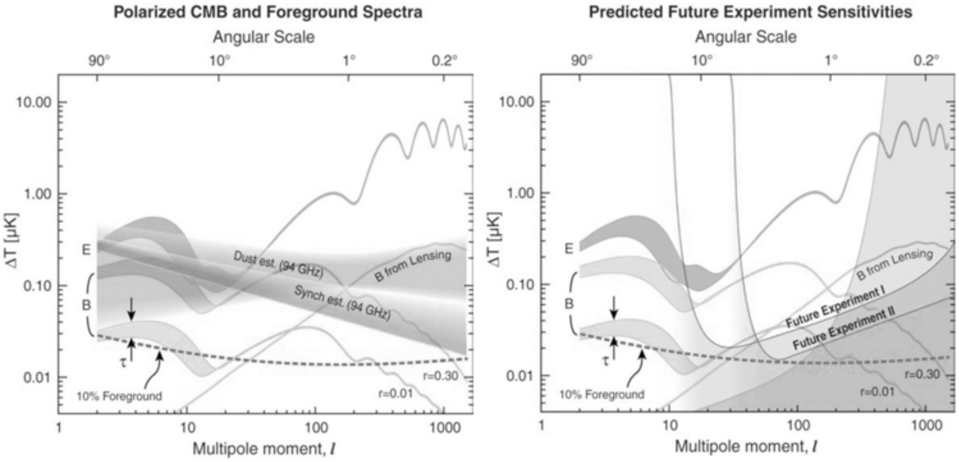

Figure 4. Left: The predicted EE and BB power spectra (marked "E" and "B") are shown. Note that the E spectrum and the B spectrum from lensing are secure predictions since they are based on existing observations (E spectrum) or the distribution of dark matter in galaxy clusters (B spectrum). However the B spectrum caused by primordial gravitational waves depends on the tensor-to-scalar ratio, which is completely unknown. Also shown are the predicted levels of synchrotron and dust foregrounds. The dotted curve shows the sensitivity level that might be achieved if these polarized foregrounds can be removed leaving only 10% residuals. There may well be other polarized foregrounds caused by, e.g., magnetized spinning dust; this is unknown at present. Right: Predicted levels of sensitivity for two future ground-based experiments using 1,000-element receivers operating for one year: (I) observing 4% of the sky with 6 arc minute resolution and (II) observing 0.4% of the sky with 1 arc minute resolution. The shaded grey region on the right shows a possible future experiment from space. [Weiss Task Force on Cosmic Microwave Background Research (`arXiv:astro-ph/0604101`)].

The next important goal in CMB observations of intrinsic anisotropy is the detection of B-mode polarization. Some predictions of the expected levels of the signal are given in Figure 4, together with estimates of the likely level of the polarized foregrounds. The strongest B-mode signal is expected on small angular scales, where it is dominated by weak gravitational lensing by dark matter in clusters of galaxies. The level of the expected signal is an order of magnitude smaller than the E-mode polarization, providing a formidable challenge to observers. The level of this signal can be predicted with confidence since we know a good deal about the fluctuations in dark matter on these mass scales. On larger angular scales the level of the B-mode signal might be dominated by the effects of long-wavelength gravitational waves produced in an inflationary epoch, and the detection of this signal has become the new "holy grail" of the field since it would provide direct evidence of inflation and reveal the energy scale of inflation. However, on these scales even the most optimistic predictions place the level of the signal fully two orders of magnitude below the EE signal we have detected. We now, therefore, have to detect a signal of one hundredth of a microkelvin, and furthermore, this must almost certainly be done in the presence of larger polarized foregrounds.

4.1. The QU Imaging ExperimenT (QUIET)

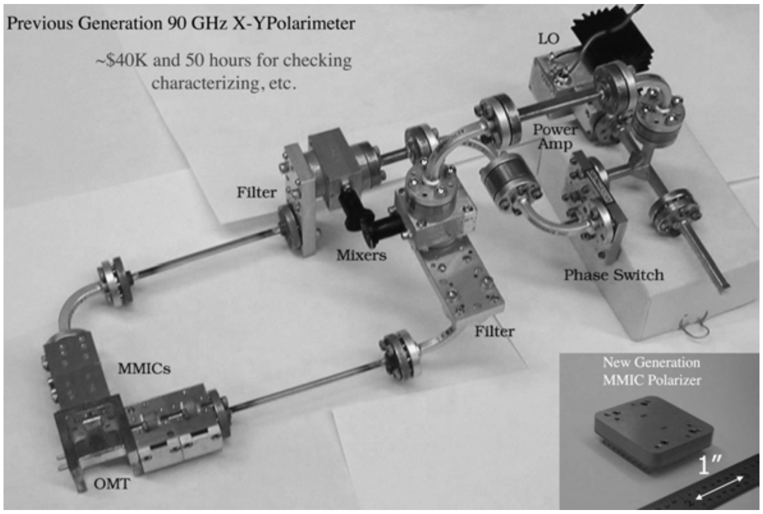

Figure 5. The JPL-NGST collaboration has led to modularized correlation differential radiometers in which the functionality of the discrete component receiver shown at the top, which was state-of-the-art a few years ago, has been replaced by the module at the lower right. This development makes possible arrays of MMIC-based modules for applications to single-dish and interferometric observations both in continuum and spectral-line mode.

At present the only way to achieve the required sensitivity is by using arrays of ∼1,000 detectors. This has forced us to abandon the interferometric approach that has been so successful and powerful in eliminating systematic errors, in order to achieve the necessary two orders of magnitude improvement in sensitivity. This is, however, only a temporary obstacle because digital processing power will within a few years reach the level at which one can correlate the signals from ∼1,000-element interferometers over ∼30 GHz bandwidths. But for the present this is not possible, so we concentrate here on the next generation of experiments, which are not interferometric. We give a brief discussion of one particular experiment that aims to detect the small- and large-scale B-mode signal in the CMB: the QU Imaging ExperimenT (QUIET). There are several such experiments underway, all of which have comparable sensitivity in the thermal noise alone, and each of which will have its own particular limiting sources of systematic error, which are unknown at this stage.

QUIET takes advantage of a remarkable development from a productive collaboration between Northrup Grumman Space Technologies and JPL, in which Monolithic Microwave Integrated Circuits (MMICs) using HEMTs have been

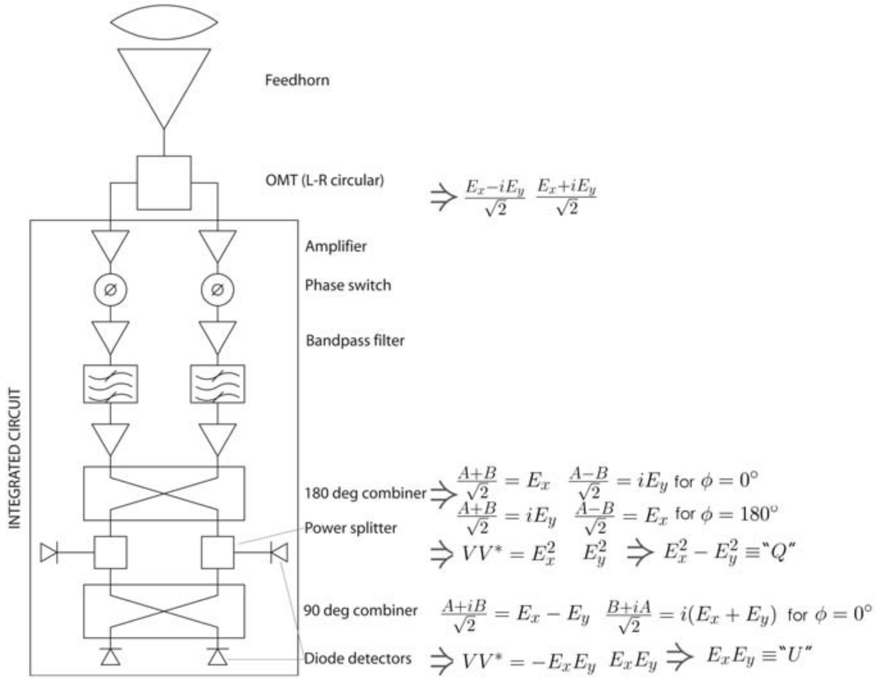

Figure 6. Block diagram of a MMIC module designed at JPL for the QUIET experiment. This is a pseudo-correlation differential radiometer that can measure both the Q and the U Stokes parameters using the same horn. This design doubles the efficiency of detectors in the focal plane and also eliminates a number of sources of systematic errors. (Courtesy Todd Gaier.)

incorporated in a module to produce a "plug-in" differential radiometer module. The volume of the receiver has been reduced by four orders of magnitude, as shown in Figure 5. In addition, when the technique has been perfected, it is expected to lead to a reduction in cost of almost two orders of magnitude for a state-of-the-art differential radiometer, from ∼\$40,000 to ∼\$500. The modules are pseudo-correlation differential radiometers that can measure both the Q and U Stokes parameters through the same feed. A block diagram of a module is shown in Figure 6. In QUIET, MMIC arrays will provide the first radio-frequency cameras consisting of ∼1,000 detectors. The sensitivity will be such that it will be possible to measure the small-scale B-mode signal, and, if the foregrounds can be constrained, it will also be possible to measure, or place interesting limits on, the large-angular-scale B-mode polarization signal produced by gravitational waves from the epoch of inflation, as shown in Figure 7.

A number of telescopes are already planning to use MMIC arrays, including the GBT, the Combined Array for Research in Millimeter-wave Astronomy (CARMA), the Effelsberg 100 m and IRAM 30 m telescopes, the Sardinia 64 m telescope, and the Cornell Caltech Atacama Telescope (CCAT), all shown in Figure 8.

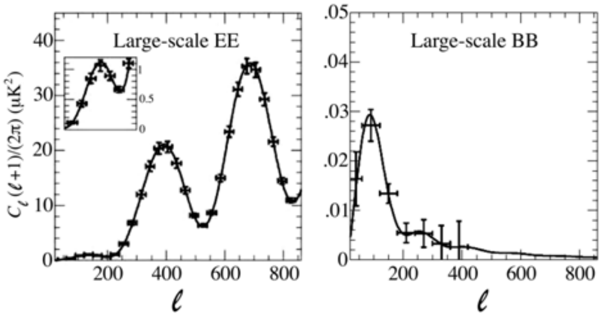

Figure 7. Predicted sensitivities in EE and BB of the QUIET experiment, which will deploy ∼1,000 detectors at 44 GHz and 90 GHz. In these simulations the effects of the known foregrounds have been taken into account. (Courtesy the QUIET Collaboration,)

Figure 8. Focal Plane Arrays of MMIC modules are currently being considered for CARMA, CCAT, the GBT, the IRAM 30 m telescope, the Effelsberg 100 m telescope, and the Sardinia 64 m telescope.

5. The Future of Large MMIC Arrays

The power of coherent detectors is that, once one has paid the "quantum tax" of detection that limits the sensitivity of the detector to hν/k, the signal can be divided and cross-multiplied with signals from other antennas in a multiplying interferometer. In addition, the stability provided by the incorporation of a mixer and stable local-oscillator signal on the module makes possible extremely versatile spectrometers. Thus these remarkable devices enable us to employ the whole arsenal of coherent radio-frequency techniques, developed over the last six decades, to arrays of high-frequency detectors.

Two important developments have shown that these techniques should be applicable at frequencies up to at least 300 GHz and to large interferometers in space. The latest MMICs from Northrup Grumman, using short gate (35 nm) indium-phosphide HEMTs, have noise figures at room temperature which, if extrapolated to cryotemperatures using the usual model, which is thought to be a reliable extrapolation, imply noise temperatures of only twice the quantum limit at frequencies up to 180 GHz and very good performance all the way up to 300 GHz. The other development is a breakthrough in digital correlators under development at JPL, for a 300-element antenna array with 400 MHz bandwidth that requires only 4W of power. Such systems would be ideal for space applications.

These two developments point the way to a suite of very large interferometers on the ground and in space, with thousands of feeds, bandwidths of 30 GHz, and operating in as many wavelength bands as necessary to delineate and remove the foregrounds. Such a suite of instruments would enable us to mount the ultimate experiment to measure the gravitational B-mode signal from our position in the Galaxy.

Acknowledgments. The NRAO has provided dynamic leadership to the world radio-astronomy community for the last five decades, for which we in the university community should be most grateful, and at this 50th anniversary, on the eve of ALMA, it is fitting to acknowledge this and to recognise the fact that the symbiotic practice of radio astronomy at universities and national laboratories worldwide is both an extraordinary accomplishment and essential to our future success. I thank Alan Bridle for his patience and assistance in preparing this manuscript.

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