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Ongoing and future ground-based and balloon-borne CMB temperature and polarization experiments

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Although *Planck* will be the dominant CMB experiment of the next few years, ground and balloon-based experiments are increasing dramatically in both number and capability. Taking advantage of the fact that the atmosphere is nearly unpolarized, suborbital experiments will achieve extremely low noise levels, test new technologies, measure polarized foregrounds with high precision, and significantly advance high-ℓ and polarization science.

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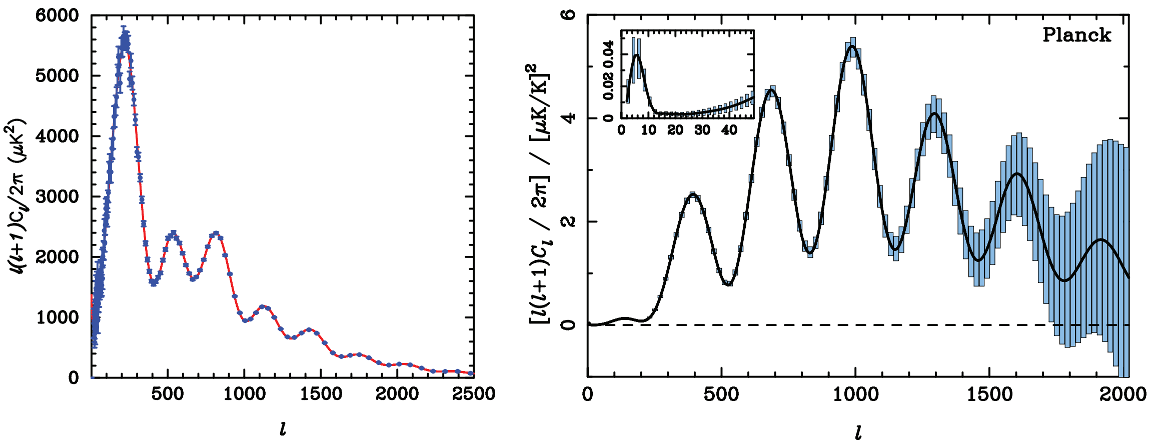

Figure 1: Temperature and polarization power spectrum expected from one year of *Planck* data, with concordance ΛCDM model (red line). From *Planck: The Scientific Programme 2005*.

1. Introduction

If all goes as planned, the dominant CMB experiment of the foreseeable future will be *Planck*, which is designed to extract essentially all information in the primary temperature anisotropies of the cosmic microwave background (CMB) down to an angular scale of $5'$(Planck 2006; Fig. 1 left). It will also achieve a major advance in polarization measurement of the CMB (Fig. 1 right).

To frame a discussion of current and future sub-orbital CMB experiments, it is useful to ask the question "What won't *Planck* do?" There are two things. *Planck* won't measure temperature anisotropies on angular scales below $5'$ (corresponding to $\ell \gtrsim 2500$), and it will leave lots of polarization science to be done. Current and future sub-orbital experiments, therefore, fall into two categories, namely those aimed at high resolution observations of (mostly) secondary anisotropies (e.g., SZ effect) at high resolution, and polarization experiments.

The high-ℓ science requires either large telescopes of 5–10 m or so, or interferometers. In the foreseeable future, such experiments will be done from the ground, where telescopes of this size do not require major technology development. The high-ℓ science also requires significant sky coverage, which in turn requires either large detector arrays or many interferometer elements.

It is more complicated to specify what is needed in the case of polarization, for two reasons. First, CMB polarization, produced by Thompson scattering of quadrupole anisotropies in the surface of last scattering, comes in several flavors (see figures elsewhere in this volume showing TT, EE, and BB spectra).

E-mode polarization of the CMB results from density perturbations. E-mode anisotropies are 1–2 orders of magnitude smaller than temperature anisotropies, and contain information about the Universe not available in temperature anisotropies. B-mode polarization of the CMB can be produced by two quite distinct causes. Neither has been detected as yet. At medium and small angular scales, weak lensing of CMB anisotropies by intervening matter turns E-modes into B-modes. At large angular scales, B-mode polarization produced by gravitational waves provides, in principle, a direct measure of the energy scale of inflation. The level of these primordial B-modes is highly uncertain, but their non-detection by WMAP3 (Page et al. 2006) puts their level well below E-mode anisotropies, at best. Nevertheless, the possibility of measuring something fundamental at 10^{-35} s after the Big Bang is quite exciting.

The reason why this range of possibilities for CMB polarization science is a complication is no doubt obvious, but I'll state it anyway. Sub-orbital experiments optimized for one aspect of the science would not be as strong for the others. Even in space, it would not be easy, and it certainly would be expensive, to build an experiment that covered the whole range of science.

The second complication concerns foregrounds. As has been expected for a long time, and has been confirmed by the WMAP3 results (Page et al. 2006), polarized foreground emission and the separation of foregrounds from the CMB will play a critical and probably limiting role in the ultimate accuracy with which CMB polarization can be measured. Unfortunately, our knowledge of polarized foregrounds is poor. This makes it hard to design polarization experiments, and it also means that substantial effort must be devoted to simply measuring, characterizing, and understanding foregrounds themselves.

Because of the complications of polarization experiments, I will concentrate on them. First i'll discuss general characteristics of polarization experiments, including their ability to deal with foreground emission. Then I'll compare some current and planned experiments.

2. Polarization Experiments—General Characteristics

2.1 Science Goals

As shown in Figure 1, *Planck* will do quite a good job on the EE polarization, and 'nail' the optical depth from reionization (τ), and once the τ-n_s degeneracy is broken, the slope of the initial power spectrum (n_s). Unlike the case with temperature anisotropy, however, *Planck* will not be cosmic-variance-limited on polarization. To be cosmic-variance-limited on EE at $\ell < 1000$ (2000, 3000) requires noise 2 or 3 (10, 30) times lower than *Planck*. As will be seen, this is extremely demanding from a hardware point of view.

Lensing B modes will provide a good cross check, but are not the big scientific prize for at least three reasons: we can't move the lensing screen; potentially the most important arcminute scales are where the CMB signal disappears; and lensing measures the linear-theory power spectrum at $z \approx 3$, which *Planck* will do already from temperature anisotropies. However, we still need to measure lensing well enough to separate lensing B modes from gravitational wave B modes. This will require partial sky measurements for $\ell > 1000$, all-sky for $\ell < 1000$, and a noise level determined by how strong the gravitational wave B modes are.

Measurement of gravitational B modes would have a dramatic payoff, but the signal level is highly uncertain, and we don't know what the ultimate noise floor imposed by foreground signals will be. Still, we can say that we will need all sky measurements for the low ℓ values that must be measured, and noise levels as low as we can get them.

The key points to take away from this sketchy analysis are that polarization experiments must reach extremely low noise levels, and they must cover significant fractions of the sky.

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2.2 Sensitivity

For decades, increases in detector sensitivity have set the pace for better experiments. **Those days are over.** Individual detectors are approaching fundamental physical limits to noise, either the photon noise of the CMB itself, or the quantum limit for phase-preserving detector systems, or both.

The only way to achieve lower noise is to increase the product

$$\text{number of detectors} \times \text{integration time.}$$

To reduce noise by a factor of 30 over *Planck* (to reach the cosmic variance limit at $\ell \approx 3000$), this product must increase by 30^2. Integration times of hundreds of years are impossible, so *the number of detectors must be large*.

An important and sometimes underappreciated point is that the number of reasonably undistorted resolution elements in the focal plane of a CMB telescope of diamter $D = n\lambda$ is of order $(n/20)^2$. For visible light telescopes, with $n > 10^6$, detector arrays with a huge number of pixels fit easily in the focal plane. For CMB telescopes, however, where $D \approx \text{few} \times 10^2$, focal plane real estate is quite limited. As a result, *multiple-telescope experiments are becoming the norm*.

Almost all CMB experiments since Penzias and Wilson have been performed with either amplifiers or bolometers. Amplifier experiments dominate the list of CMB "firsts" (detection of the CMB itself; measurement of the dipole; SZ detection; measurement of anisotropy; and detection of CMB polarization), and have operational and systematic advantages as well. However, bolometers have a clear advantage in raw sensitivity above the atmosphere at high frequencies.

Which will be better for CMB polarization isn't clear. It depends on the frequency range necessary to deal with foregrounds, and it depends on the success of technology development efforts.

What is clear is that continued technology development is required in both areas to realize their full potential. For bolometers, this includes low frequencies, multiplexers and arraying technologies, coolers, and testing. For amplifiers, this includes antimonide-based monolithic microwave integrated circuits (MMICs) for lower noise and power dissipation, and testing. For both technologies, systematics, optics, and testing are key aspects that must be demonstrated at the sub-microkelvin level.

Raw sensitivity is only one of many characteristics of a detector system that is important for CMB polarization, and statements to the effect that only bolometers have the sensitivity required for polarization experiments are far too simple to be accepted at face value. Moreover, there is one aspect of detector sensitivity that seems not to be as widely known as it should be, but that is quite important especially in the context of sub-orbital experiments. That is that the sensitivity of amplifiers is pretty much the same on the ground as in space, but the sensitivity of bolometers is dramatically different on the ground from in space. The reason is that bolometers have very small dynamic range, and a bolometer designed to handle the higher photon background of a ground experiment must be different, and less sensitive, than a bolometer designed for the low background in space. Another difference between amplifiers and bolometers is that amplifiers are phase-preserving (or 'coherent') devices. This comes at a cost, the so-called quantum noise, which increases proportional to frequency, but has a benefit as well. In coherent systems, once the quantum tax is paid, signals can be reused multiple times without degradation. This allows coherent

TABLE 1

DETECTOR SENSITIVITY

Frequency [GHz]	From Ground (2005) Bolometer [μK s$^{1/2}$]	HEMT/$\sqrt{2}$ [μK s$^{1/2}$]	From Space (~2010) Bolometer [μK s$^{1/2}$]	HEMT/$\sqrt{2}$ [μK s$^{1/2}$]
30	...	93	57	48
40	...	115	51	51
60	...	175	44	60
90	250	224	40	75
120	250	...	40	93
150	250	...	43	...
220	250	...	64	...

[a] Bolometer values from A. Lange and J. Bock; HEMT values from T. Gaier.

[b] The $\sqrt{2}$ in the HEMT values comes from the fact that Q and U can be measured simultaneously behind one feed.

[c] The convention for polarization sensitivity used here is $(T_x - T_y)/2$.

systems to measure Stokes parameters Q and U simultaneously in a way that is not possible with non-phase-preserving detectors such as bolometers.

Table 1 shows predicted sensitivity numbers for amplifiers and bolometers, both now and in the future.

2.3 Location

To reach the cosmic variance limit, all sky observations are required. At low ℓ, we'll always want to reach the cosmic variance limit. All sky observations require space. (Some planned suborbital experiments will push sky coverage very hard, but it remains to be seen how successful they will be in stitching the sky together from several locations.)

However, much can be done from the ground, because **the atmosphere is almost completely unpolarized**. Even though almost everything about polarization is harder than temperature, all indications are that much better polarization experiments can be done from the ground than temperature experiments! But frequency coverage is limited. In particular, the oxygen lines near 60 GHz make the atmosphere completely opaque at this important frequency (see below), and much above 150 GHz the atmospheric windows are pretty opaque. For these reasons, balloon experiments still are important.

3. Foregrounds

I said above that separation of foregrounds from the CMB will almost certainly set the limit to how well CMB polarization can be measured. This has important implications for the design of experiments, as discussed below.

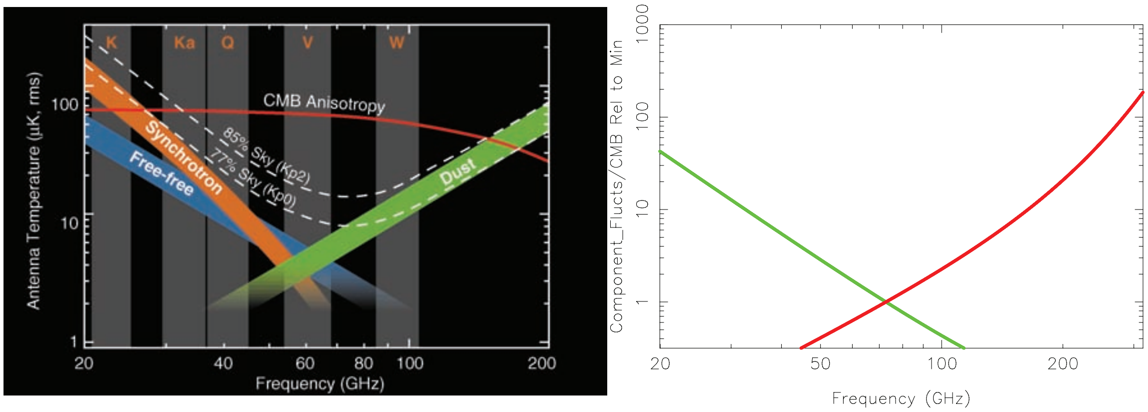

Figure 2: *Left panel:*—Diffuse temperature foregrounds as measured by WMAP1 on a 1° angular scale (Bennett et al. 2003). *Right panel:*—Level of synchrotron and dust fluctuations relative to CMB fluctuations from the left panel, normalized to the ratio at 70 GHz where the total diffuse foregrounds are a minimum.

3.1 Compact sources

Corrections to the WMAP3 power spectrum from discrete sources start to be important just beyond the first peak. This is a critically important topic for CMB experiments, but the methods for dealing with discrete sources will be quite different from those used to deal with diffuse foregrounds, and I won't say anything more about it here.

3.2 Diffuse foregrounds

WMAP1 found that the temperature foreground minimum on $\sim 1^\circ$ angular scales is around 70 GHz (Fig. 2 left; Bennett et al. 2003). Figure 2 right shows the level of synchrotron and dust fluctuations relative to their values at the foreground minimum. These are seriously steep functions of frequency. The dust side steepens at high frequencies as the CMB spectrum falls off on the Wien side. The synchrotron fluctuations increase relatively by a factor of four between 70 GHz and about 45 GHz, while the dust fluctuations increase by the same factor between 70 GHz and about 130 GHz. Note that by 30 GHz and 200 GHz the foreground fluctuations are up relatively by over an order of magnitude, and by 300 GHz are up by more than two orders of magnitude.

We don't know how well we can separate the CMB from foregrounds. Consider the problem. The simplest conceivable model of foregrounds would be something like the following:

- Synchrotron — a power law with amplitude and index varying with position (polarized)
- Free-free — a power law with fixed index $= -0.14$ (good over a wide temperature range) and amplitude varying with position (unpolarized)
- Dust — an emissivity law ($\propto \nu^{\beta} B_{\nu}$) with amplitude and emissivity varying with position (polarized)
- CMB — a temperature varying with position (polarized)

Even this simplest case has six parameters, requiring at least 7 constraints for separation. No experiment to date has had more than 5 frequencies. *Planck*, with 9, will be the first. Unfortunately, we already know that this simplest case is too simple. Simple power laws aren't right, and there is good evidence for another component.

Consider a more likely situation:

- Synchrotron — a power law with amplitude varying with position and index varying with position and frequency (polarized)
- Free-free — a power law with fixed index $= -0.14$ (good over a wide temperature range) and amplitude varying with position (unpolarized)
- Dust — an emissivity law ($\propto \nu^{\beta} B_{\nu}$) with amplitude and emissivity varying with position and frequency (polarized)
- "Anomalous dust" — something requiring at least two parameters to describe (polarized)
- CMB — a temperature varying with position (polarized)

This more realistic model requires at least 10 parameters, depending on how complicated the spatial and frequency dependence of the synchrotron and dust spectra are.

For temperature fluctuations, fortunately, foregrounds have modest impact on the power spectrum. As a result, foreground separation has not played a major role in CMB experiments with fairly high noise levels to date. For WMAP1, foreground "templates" provided additional constraints that were crude but better than nothing.

CMB polarization science requires sub-miocrokelvin noise levels, however. At these levels, there will be no escape from foregrounds, which will almost certainly set the ultimate limit on how well we can measure CMB polarization, as mentioned before twice and confirmed by WMAP3.

4. What Is Needed

Foregrounds will set the ultimate limit, but at the moment we know too little about polarized foregrounds to optimize experiments to deal with them. There are three critical needs. The first is sensitive measurements of polarized foregrounds over a wide range of frequencies, with good angular resolution. WMAP3 has made a small but important step in this direction. *Planck* will be a major advance. And new suborbital experiments just starting to observe, under construction, or being planned will make important progress in this area.

The second critical need is for simulations using realistic foregrounds that test both methods of separation and experimental design. Some initial simulations using the foreground models developed by the *Planck* team and the Eriksen et al. (2006) separation method suggest that:

- Frequency coverage centered on the foreground minimum, and not too wide, works best
- One-sided frequency coverage (e.g., "dust only" or "synchrotron only" experiments) does not work as well.

- Frequencies farther and farther from the minimum become less and less useful, because model errors acting on stronger foregrounds signals dominate.)

The third critical need is, of course, multifrequency experiments with enough frequencies to constrain the large (but currently unknown) number of parameters required to characterize the foregrounds.

5. Experiments

Rather than listing detailed characteristics of a long list of experiments underway or planned, I want to give an overall view of the experimental scene and capture a few key points. Comparing experiments is tricky. A useful comparison, if it were possible, would be to list the noise level per unit sky area including systematic errors for each frequency that will be achieved by the various experiments. Unfortunately, this can't be done. The level of systematic errors in the data is hard to determine in any case, but for experiments that haven't taken data, it is impossible.

What I have chosen to do instead is to compare the product highlighted in § 2.2 of the number of detectors built or planned for various experiments times the integration time, and the angular resolution. The integration time for various experiments is determined by a complicated mix of factors, but is quite different for ground and balloon experiments. Ground experiments generally take data for a couple of years, but only at night. Bad weather is a problem in mediocre sites, but most of the experiments being planned will go either at the South Pole, or at very high elevation in Chile. In both cases, a high nighttime duty cycle is expected. So one year of actual integration time is a reasonable value to use for ground based experiments. For balloon experiments, expected flight times of 20 days are typical. Most of this time is useful. For bolometers, as discussed in § 2.2, sensitivity in space and on balloons is better than on the ground. Accordingly, I've multiplied bolometer balloon experiments by a factor of 5, under the assumption that balloon experiments will realize sensitivities somewhere between the current ground values and the 2010 space values given in Table 1)

Table 2 lists experiments, frequencies, number of detectors, and angular resolution, and says whether the experiment is an interferometer. I've taken the most ambitious version of each experiment. Some are funded, some are partially funded (e.g., for an initial smaller version), and some are unfunded. The general hardware trend is seen quite well. Experiments are exploding in the number of detectors used, as they must. There is an increase in number of frequencies, in some experiments at least.

Figure 3 shows the information in Table 2 graphically. Interferometers are not included in the figure, because of a number of complications trying to compare heterodyne interferometers and direct detection interferometers such as MBI. Moreover, since the interferometer elements can be moved over a wide range of positions, whatever plot axes one chooses, interferometers would be plotted over ranges. In any case, although interferometry offers huge potential advantages in control of systematics, it will be some time before it is possible to build an interferometer with comparable raw sensitivity to experiments with huge focal plane arrays of detectors.

Three cautions are important. First, this is not a complete list of experiments. I took as my starting point the experiments described at the meeting *Fundamental Physics With Cosmic Mi-*

TABLE 2

EXPERIMENTS

NAME	ν [GHz]	N[a]	RESOLUTION [arcminutes]	COMMENT
ACBAR	150	8	4.8	
	219	4	3.9	
	274	4	3.9	
BICEP	100	50	60	
	150	48	42	
CAPMAP	40	8	6	
	90	24	4	
CBI	31	13	5	Interferometer
CℓOVER	97	320	8	
	150	512	8	
	225	512	8	
COFE	10	10	80	Balloon
	15	20	60	
	20	30	40	
EBEX	150	796	8	Balloon
	250	398	8	
	420	282	8	
KuPID	15	6	13.8	
MBI	90	16	60	Interferometer
PAPPA	100	240	30	Balloon
	200	240	30	
	300	240	30	
PolarBEAR	90	400	7	
	150	400	5	
	220	400	3	
QUAD	100	24	6	
	150	38	4	
QUIET	40	136	29	
	44	136	26	
	86	1588	14	
	95	1588	12	
	40	44	10	
	44	44	9	
	86	596	5	
	95	596	4	
Spider	45	64	145	Balloon
	75	256	69.1	
	85	256	60.4	
	108	256	52.4	
	144	512	36.0	
	162	512	32.0	
VSA	34	14	8	Interferometer
ACT	145	1024	1.7	SZ
	225	1024	1.1	
	265	1024	0.9	
APEX-SZ	150	324	1.0	SZ
SPT	90	320	1.7	SZ
	150	320	1.0	
	220	320	0.7	
SZA	30	8	0.5	SZ Interferometer
	90	8	0.5	

[a] N is number of detectors or number of interferometer elements.

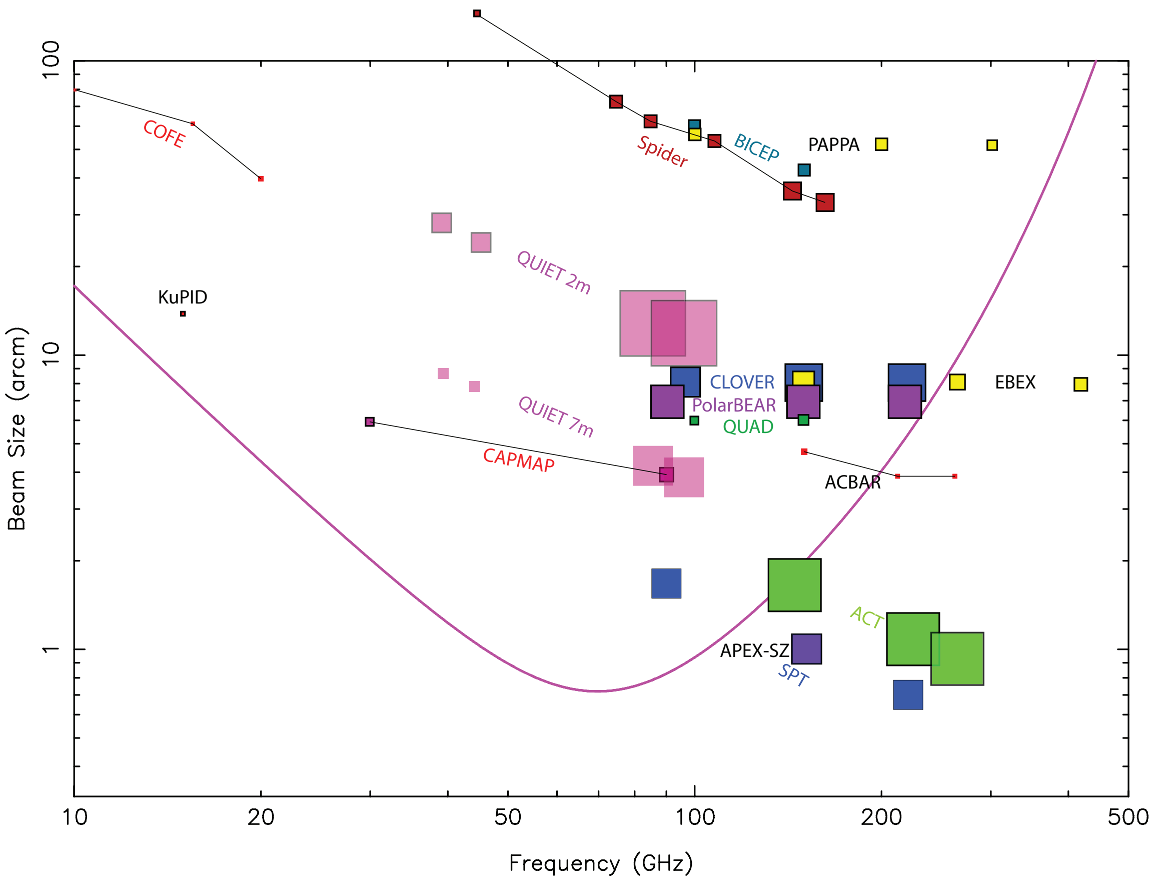

Figure 3: A sampling of suborbital experiments underway or planned. The area of the square is proportional to the number of detectors $\times$ integration time, where time = 1 year for ground experiments, and 20 days $\times$ 5 for balloon experiments. The factor of 5 for balloon experiments accounts roughly for the sensitivity advantage of bolometers above the atmosphere. No additional adjustments for sensitivity have been attempted, nor has any account been taken of planned sky coverage, etc. All frequency bands of the same experiment have the same color. To aid the eye, lines connect the multiple frequency squares of a some experiments. APEX-SZ and the middle SPT square overlap almost perfectly. The purple line shows the relative level of fluctuations in the diffuse foregrounds, from Fig. 2, on a logarithmic vertical scale not labeled spanning a factor of 100.

crowave Background Radiation, sponsored by UC Irvine and held at the Arnold and Mabel Beckman Center March 23–25, 2006 (see http://www.physics.uci.edu/CMB for details, and to download talks). A few additional experiments have been added.

Second, the information for the various experiments undoubtedly contains errors. There are several reasons for this, starting with the most important, namely, that I have not checked the information with the principals of the experiments for accuracy. Experiments change, sometimes dramatically, while they are being planned and built. Information on web sites is often out of date. I take full responsibility for the errors. However, I want to emphasize that the point of this exercise is not to provide an accurate compendium of experiments suitable for use in legal proceedings! Rather, it is to outline trends, and assess where suborbital experiments are heading.

Third, I emphasize again that I have not tried to assess sensitivity or noise levels that will be achieved. In my view, this can be done accurately only after the fact, with data in hand. For my purposes here, I think it more useful to show trends in hardware.

With these caveats in mind, then, let's take a look at the Table and Figure. What can we see?

5.1 Observations on Experiments

- SZ experiments are well segregated in the lower right hand corner of the plot (resolution below $2'$), quite similar to each other, and not polarized.

- There are no experiments covering the foreground minimum. Molecular oxygen lines make the atmosphere opaque around 60 GHz. Given the difficulties of separation of foregrounds discussed earlier, and given the likely importance of taking data where the foregrounds are a minimum, this is likely to be a significant limitation of suborbital experiments. Other frequency ranges of high atmospheric opacity and emission are avoided as well, as seen in the vertical bands where no experiments appear. If it turns out, as I expect, that continuous frequency coverage across some range of frequencies containing the foreground minimum is required for optimum separation of foregrounds, observations from space will be required.

- There is a significant asymmetry between the number of experiments above and below the foreground minimum. The disparity in the number of detectors is even greater. Partly this is explained by the fact that low frequency feeds are larger, leading to a lower density in the focal plane. But whatever the cause, it needs to be addressed. It is just as important to characterize and measure the synchrotron emission (and perhaps anomalous dust) at frequencies below the minimum as it is to measure the dust emission above the minimum.

- There is a shortage of high resolution experiments at low frequencies. This is no doubt driven by practicalities. High resolution at low frequencies requires larger telescopes than at high frequencies, and larger telescopes are more expensive and harder to move to remote sites. Although many large radio telescopes exist around the world, two special demands make it difficult to use them for CMB work. The first is that CMB work demands extremely clean beams with low sidelobe levels, usually achieved with severely under-illuminated unblocked-aperture optical systems that are quite different from standard radio telescopes. Second, and perhaps even more important, the long integration times and demands for continuous observing in CMB observations are impossible to achieve in the radio observatory context.

- The maximum number of frequencies in one experiment is six (Spider). Clearly, individual experiments will be unable to deal with foregrounds fully in a standalone fashion. Of course, all of the experiments will *learn* about foregrounds, and all frequencies measured will be valuable.

- Combinations of experiments are likely. E.g., QUIET and CℓOVER will both operate at the CBI site.

6. Assessment

I'll end by summarizing a few points on suborbital experiments.

- There is a tremendous amount of suborbital CMB activity
- Huge detector arrays are being developed, using both bolometers and amplifiers
- New technologies will be tested stringently
- Noise levels an order of magnitude or more lower than Planck will be achieved
- A huge amount will be learned about foregrounds. Limitations on the number of frequency bands and their spacing will affect how well foregrounds can be separated from the CMB. But observations will naturally concentrate on low-foreground patches of sky, and great progress will be made on CMB polarization. E-mode and B-mode lensing fluctuations will be well-measured for sure. It is conceivable that B-mode primordial fluctuations will be detected.
- With suborbital results and technological performance in hand, we will know how to design the "final word" space mission, and whether it is necessary.
- The combination of Planck and suborbital experiments will keep the CMB at the forefront of experimental cosmology for many years.

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