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Observing the Evolution of the Universe

Cover page for a white paper in support of fine angular scale CMB probes.[1]

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Executive summary

How did the universe evolve? The fine angular scale ($\ell > 1000$) temperature and polarization anisotropies in the CMB are a Rosetta stone for understanding the evolution of the universe. Through detailed measurements one may address everything from the physics of the birth of the universe to the history of star formation and the process by which galaxies formed. One may in addition track the evolution of the dark energy and discover the net neutrino mass.

We are at the dawn of a new era in which hundreds of square degrees of sky can be mapped with arcminute resolution and sensitivities measured in microKelvin. Acquiring these data requires the use of special purpose telescopes such as the Atacama Cosmology Telescope (ACT), located in Chile, and the South Pole Telescope (SPT). These new telescopes are outfitted with a new generation of custom mm-wave kilo-pixel arrays. Additional instruments are in the planning stages.

1 Introduction

The primary CMB has been a gold mine for understanding the cosmos. Through the study of the CMB we have determined the geometry, age, and contents of the universe at the few percent level. Observations have reached the point where we now have a "standard model of cosmology." Yet there is much more to learn from the CMB. In the standard model there are new unanswered questions and more traditional questions are more sharply focused. The following are within our reach in the next decade:

1. What is the dark energy and what are its characteristics? Did the dark energy act differently before $z = 1$?
2. Did neutrinos leave an identifiable imprint on the cosmos and if so what is the sum of their masses? Measurements of neutrino oscillations show that the difference in the square of the masses is ~ 0.002 (eV)^2, indicating that at least one species must have a mass near 0.05 eV. This value can be determined with fine scale anisotropy measurements.
3. Where are the missing baryons? Big Bang nucleosynthesis and CMB derived baryon densities are not in accord with the observational census.
4. How did the first stars turn on and what is their ionization history?
5. Did the early universe have only Gaussian fluctuations or were there phase transitions that perhaps produced cosmic strings? The discovery of primordial non-Gaussianity would revolutionize cosmology.
6. Are the fluctuations solely adiabatic or is there an admixture of isocurvature modes?

All of these questions may be addressed with measurements of the fine angular scale anisotropy in the CMB. The answers to a number of the questions come both from the CMB itself and from the CMB in correlation with radio, infrared, visible, and X-ray observations of galaxies and clusters of galaxies. Thus there are built in consistency relations.

Our knowledge to date has been based primarily on the anisotropy at angular scales larger than a quarter degree ($\ell \sim 1000$) and with the successful launch of the Planck satellite this will be pushed to a tenth degree ($\ell \sim 2500$) . *The fine angular scale measurements* ($1000 \lesssim \ell \lesssim 10000$) *described here are a critical complement to Planck.*

At angular scales larger than $\sim 0.1^\circ$, the anisotropy may be thought of as a direct probe of the response of the CMB to perturbations laid down in the early universe as seen at a redshift of $z = 1090$. The fluctuations are a part in 10^5 of the background and with linear perturbation theory the properties of the CMB may be computed with exquisite accuracy.

At smaller angular scales, new phenomena become apparent. Objects such as galaxies and clusters of galaxies emerge from the primordial plasma and leave their imprint on the CMB. These objects and their environments can in turn be used as beacons with which to interrogate the evolution of spacetime. They can be used to probe components of the standard model such as the neutrino mass to new depths. And through a rich set of cross correlations with radio, infrared, optical, and X-ray surveys, the fine scale anisotropy may be used to pin down the process of cosmic structure formation.

At small angular scales, one may think of the CMB as a backlight with precisely known statistical properties at a precisely known distance. This light illuminates all that is between us and the surface of decoupling. Different phenomena leave different imprints on the light. For example, the hot electrons in galactic clusters reveal their presence by scattering the CMB with a characteristic frequency signature. This is called the Sunyaev-Zel'dovich (SZ) effect. In another mechanism, mass concentrations throughout the universe gravitationally lens the CMB. This lensing can be measured through the correlations it imposes on the CMB.

A new generation of instruments is poised to increase the angular resolution of CMB-frequency maps by a factor of five and to increase the sensitivity by an order of magnitude. Because of the vast scientific possibilities, an even more advanced generation of instruments is already in the design phase.

2 The Science

The fine-scale anisotropy, both temperature and polarization, provide four distinct avenues for scientific investigation. There has been considerable theoretical work on all the general areas mentioned below and there are more research topics than there is space to mention. Because there are thousands of papers, we limit references to review articles. One should also keep in mind that the fine angular scale anisotropy is relatively unexplored. With the recent advances in sensitivity, there is significant potential for discovering new phenomena.

1. **Measure the intrinsic anisotropy to determine the high-ℓ tail of the primary anisotropy and to search for intrinsic non-Gaussianity.** Our most direct probe

of the infant universe is the scalar spectral index, n_s, and its change with scale. The formal accuracy on n_s from the Planck satellite is 0.5%. However, our confidence in the result will depend on detailed knowledge of the transition from the linear regime (primary CMB) to the non linear regime (secondary CMB). This transition can only be measured through the fine scale anisotropy. In addition, we will want to be certain that n_s is not being affected by foreground emission, point sources, or low levels of secondary anisotropies. This is best done through fine scale anisotropy measurements.

In the standard model, the fluctuations are Gaussian. It is widely believed that if the model is incomplete or incorrect the first hints will come through the detection of non-Gaussianity. Alternative models of the early universe and remnants of primordial phase transitions predict measurable levels of non-Gaussianity. For example, cosmic strings would be directly detectable through their imprint on the CMB. Fine scale measurements will provide the crucial results that will build on those from Planck.

2. **Measure the gravitational lensing of the CMB [1].** The CMB lensing field can be described by the deflection field as $T_{obs}(\hat{n}) = T_{int}(\hat{n} + \vec{d})$ where T_{int} is the unlensed temperature field, $\hat{n}$ is the direction, and $\vec{d}$ is the deflection field. The deflection field may be reconstructed from the four-point distribution of the temperature anisotropy and from the polarization B-modes. *Thus the measurement of both the fine scale temperature and polarization anisotropy is important.* The lensing B-modes are distinct from the ones associated with inflation and must exist.

   The deflection field is a measure of the effects of the spacetime between us and the decoupling surface and thus probes different physical processes than does the primary anisotropy. The deflection field is sensitive to the volume between us and the decoupling surface. As a consequence, it breaks the "geometric degeneracy" associated with the primary anisotropy. With the primary anisotropy in hand, the power spectrum of the deflection field can give an excellent measure of the neutrino mass, spatial curvature, and "early dark energy." For example, a measurement of the polarization to a level of 5 $\mu\mathrm{K}-\mathrm{arcmin}$ with a $\theta_{FWHM} = 2$ arcmin beam over a quarter of the sky has an uncertainty on the sum of neutrino masses of 0.05 eV and on the curvature of 0.2%. CMB lensing provides the best way to study the nature of dark energy at early times because the lensing kernel probes a wide range of redshifts that peaks at $z \sim 3$ to 4, while low-redshift cosmological probes, including galaxy lensing, are sensitive to cosmology at $z < 2$. These measurements are well within our reach in the coming decade.

   The deflection field may also be correlated with the SZ effect, galaxy shear, the LRGs and a host of other phenomena to find the growth rate of structure. The growth rate in turn is another probe of dark energy and the mass of the neutrino [2].

3. **Find clusters of galaxies through their SZ effect, determine the cluster redshifts with optical follow up, understand the mass selection function with a combination of SZ, optical, and X-ray measurements, and from the cluster catalog determine dN/dz or $dN(> M)/dM$** [3]. The number distribution is exponentially sensitive to the dark matter and dark energy densities. Depending on

the visibility of clusters, the equation of state may be determined to $\sim 10\%$ accuracy. Multi-frequency observations to separate the thermal SZ from the kinetic SZ and primordial fluctuations will be an important component of this research. This program will evolve throughout the decade and is anticipated to be an important complement to other methods based on weak lensing, supernovae, and baryon acoustic oscillations.

There are a host of other phenomena one may pursue. A key attribute of a survey of SZ clusters is a well defined selection function that is almost redshift independent. The sample may be used to constrain the neutrino mass and is especially sensitive to σ_8. Ultimately, it may even be possible to measure large scale structure through the cluster polarization.

4. **Correlate and compare the CMB with lower redshift cosmological measurements.** In the most straightforward application, one uses the interaction of the CMB with lower redshift phenomena and from that determines the growth rate of structure. The growth rate is then directly related to cosmology. However, it is also possible to examine other phenomena. For example, many believe that the "missing baryons" are in the outskirts of clusters. If this is the case, they should be visible by stacking clusters and identifying the SZ effects. In another example, the correlations are a probe of the process of reionization. And in yet another, the cross-correlation with massive galaxies has the potential to measure the energy feedback from supermassive black holes, which heats the surrounding intergalactic medium and creates a small-scale SZ distortion. The various phenomena are distinguishable through their specific correlations and spatial distributions.

3 Scientific Instrumentation

The quest to understand the cosmos through measurements of the CMB has led to rapid advances in scientific instrumentation and experimental technique. A decade ago, researchers were talking about arrays of hundreds of detectors and observing with a handful. Today observations are made with kilo-pixel arrays, and larger and more sophisticated arrays are in the works. The field has been an incubator for multiple new and diverse technologies.

In the past two years two telescopes dedicated to measuring the fine scale anisotropy have been commissioned and have begun taking data. One is the Atacama Cosmology Telescope (ACT) located in northern Chile near ALMA and the other is the South Pole Telescope (SPT) located at the Amundsen-Scott South Pole station. The telescopes complement each other in their sky coverage, technology, and observing techniques. They have also observed a common area of sky for cross calibration.

Table 1 gives a list of instruments that are anticipated to be measuring the fine angular scale anisotropy and the SZ effect in the next decade. It is not exhaustive. It omits some efforts early in the proposal phase. For example, a balloon borne arcminute CMB measurement has been discussed. It also omits a good number of CMB experiments targeted at measuring the polarization in the $\ell < 2000$ range. These experiments are discussed in a separate report authored by Stephan Meyer.

Table 1: Telescopes for measuring the $\ell > 1000$ CMB anisotropy.

Name	Location	Diameter/Separation (m)	Wavelength (mm)	ℓ_{max}
ACT	Atacama	6	1-2	7800[1]
PolarBear	Atacama	3.5	1-3	3000[1]
SPT	South Pole	10	0.3 - 3	9000[1]
AMI[2]	MRAO, UK	3.7-13	18	10000
AMiBA [2]	Hawaii	1	3	>2000
APEX-SZ[3]	Atacama	12	1-3	12000[1]
AzTEX on the LMT	Sierra Negra, MX	50	0.7-3	60000
CCAT[4]	Atacama	25	0.7-3	40000
MUSTANG on the GBT[3]	West Virginia	100	3	80000
SZA/CARMA[5]	California	3.5-10.4	3-10	>10000

The lower entries are anticipated to focus on SZ and source measurements in the 2010 decade. One should also keep in mind that observation wavelength is flexible.

[1] Taken as $\pi/\theta_{\mathrm{FWHM}}$ at 150 GHz.

[2] Interferometer with resolution dependent on baseline.

[3] General purpose. Observes the CMB/SZ only part of the time.

[4] Proposed for SZ cluster and other studies.

[5] Heterogenous interferometer array for SZ imaging.

New detector arrays have been developed to operate with the new telescopes. Superconducting transition edge bolometers operating near 0.3 K are currently the detectors of choice. Figure 2 shows two examples. Other arrays based on microwave kinetic induction detectors, MKIDs, and planar phased array antennas are also under development. Examples are shown in Figure 3. The large number of detectors has required new readout and multiplexing electronics. Both time domain multiplexing, developed at NIST, and frequency domain multiplexing, developed at Berkeley, are being employed.

4 References

[1] "CMBPol Mission Concept Study: Gravitational Lensing," K. Smith et al., arXive:0811.3916v1, Nov 2008.

[2] "Findings of the Joint Dark Energy Mission Figure of Merit Science Working Group," Albrecht et al. 2009, eprint arXiv:0901.0721.

[3] "Cosmology with the Sunyaev-Zel'dovich Effect," Carlstrom, J., Holder, G., & Reese, E., Annual Review of Astronomy and Astrophysics, Vol. 40, p. 643-680, 2002.

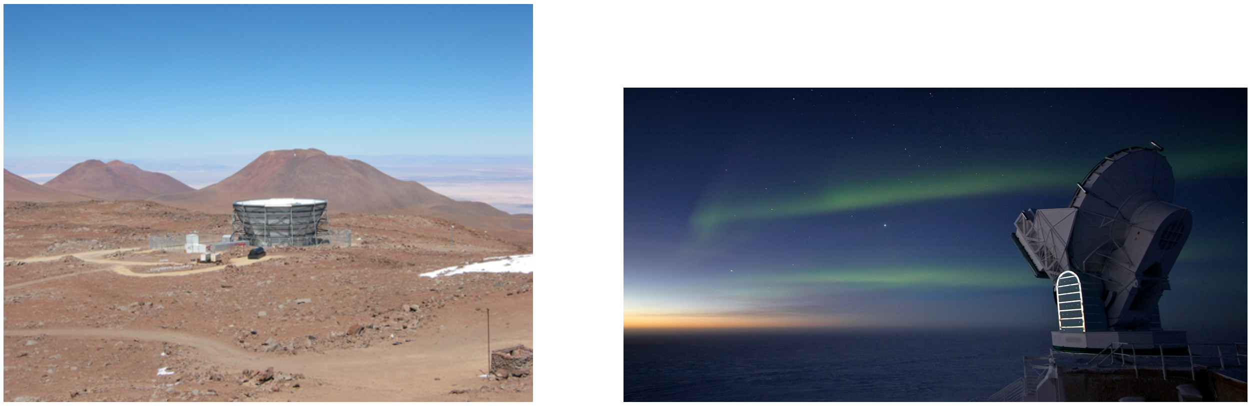

Figure 1: On the left is the Atacama Cosmology Telescope which is situated in the Chajnantor Science Preserve in northern Chile, adjacent to the ALMA site. The entire telescope is inside a three story high ground screen. ACT is at 5200 m. It takes advantage of the high dry site. On the right is the South Pole Telescope with the aurora in the background. SPT is at 2800 m, with an equivalent pressure altitude of 3500-4000 m. It takes advantage of the flat and exceptionally dry polar cap. Photo credits Adam Hincks (ACT) and Keith Vanderlinde (SPT).

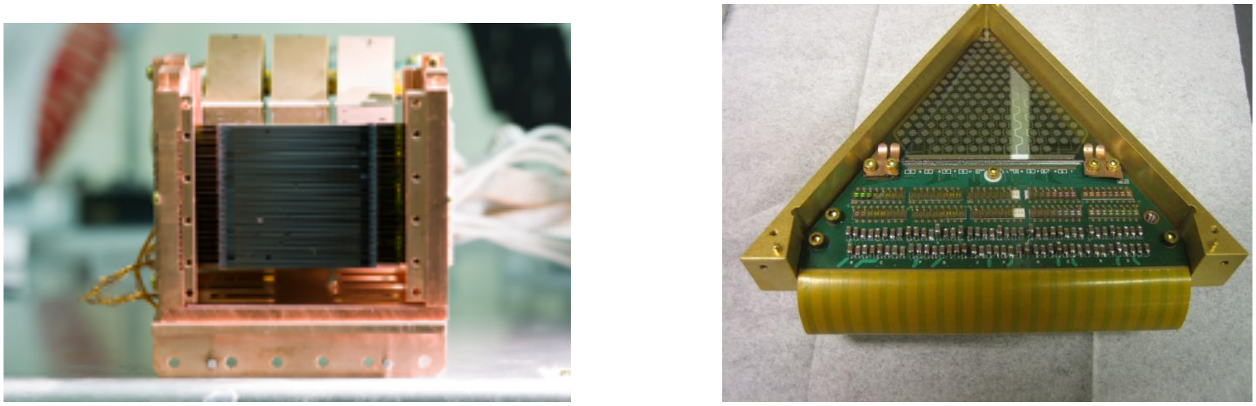

Figure 2: Detector arrays for ACT and SPT. On the left is one of the ACT arrays. It contains 32 by 32 detectors that were fabricated at NASA/GSFC. Cryogenic optics images the sky onto the 32 by 33 mm active area. Each strip of 32 detectors is built onto a silicon card. On the right is an image of a SPT sub array developed at Berkeley. The TES detectors are at the top. Feed horns (not shown) couple the radiation onto the detectors. The circuit board at the bottom contains multiplexing circuitry.

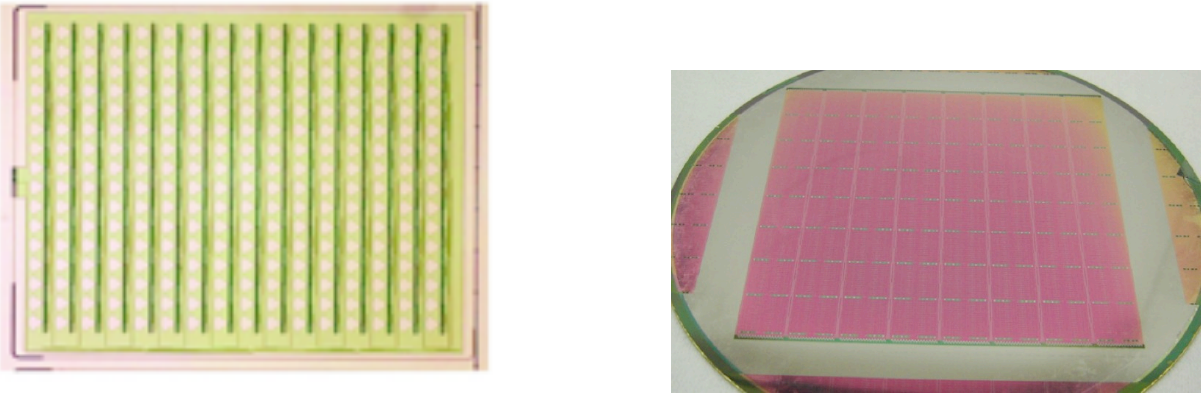

Figure 3: On the left is a MKID demonstration array. On the right is a planar phased array of antennas coupled to detectors. Each of the 64 elements measures both polarizations. Multiple sub arrays may be combined. Both of these examples are from Caltech/JPL.