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The Cosmic Microwave Background as a Cosmological Probe

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Abstract. Observations of the Cosmic Microwave Background (CMB) have already proven to be a powerful probe of physical conditions in the early universe ($z \sim 10^3$). These observations have made precision tests of the standard cosmological model and appear to confirm that we live in a bizarre universe mostly composed of dark matter and dark energy. Over the next several years, new experiments will make high resolution measurements of the microwave background. These measurements use the microwave background as a "backlight" for studying the universe at low redshift. The scientific value of these high resolution CMB observations will be significantly enhanced by cross-correlating these observations with optical, radio and X-ray observations.

1. Standard Cosmology Model: Answers and Questions

Recent observations have established a new standard model of cosmology. With only five basic parameters (the age of the universe, the density of matter, the density of atoms, the amplitude of primordial fluctuations and their scale dependence), this model fits both microwave background observations of the physical conditions in the early universe and observations of the large-scale distribution of galaxies (Spergel et al. 2003).

While remarkably simple, the new standard cosmological model is also rather bizarre. It implies that protons, neutrons and electrons compose only 5% of the energy density of the universe. Cosmologists believe that most of the mass in the universe is composed of weakly interacting subatomic particles, the so called "dark matter", which has never been directly detected. We also believe that all of the matter comprises only 25% of the total energy density of the universe, with the balance comprised of some kind of "dark energy" associated with empty space. We do not even understand the distribution of the ordinary matter. In the local universe, observed stars, gas and dust appear to account for only a small fraction of the total density in baryons (Fukugita et al. 1998; Fukugita & Peebles 2004).

As is often true in science, answering old questions such as: "What is the shape of the universe?" "What is the age of the universe?" and "What seeds galaxy formation?" has led to new questions: "What is the dark energy?" "What is the dark matter?" and "How do galaxies emerge from fluctuations in the early universe?" This talk will focus on the role of microwave background experiments to address these questions. My talk will both describe recent results from WMAP and look forward to the next generation of small scale experiments that will probe the CMB sky with higher angular resolution.

2. WMAP and the Standard Model

A few hundred thousand years after the big bang, the universe was a very simple place: the universe was composed of ionized hydrogen and helium, dark matter and photons with only tiny fluctuations in density and temperature. Because of this simplicity, we can easily interpret CMB observations: the position of the CMB acoustic peaks depend primarily on the geometry of the universe, while the peak heights depend primarily on the density of the universe. CMB measurements alone can place significant constraints on basic cosmological parameters.

While CMB measurements probe density fluctuations at $z = 1000$, observations of large scale structure probe density fluctuations in the nearby universe. By combining these two measurements, we can probe the growth rate of structure and further constrain basic cosmological parameters. Table 1 lists the best fit parameters for different combinations of CMB and large scale structure data: WMAP + CBI + ACBAR (Spergel et al. 2003), WMAP + CBI+ ACBAR + BOOMERANG + MAXIMA (ALL CMB) (Bond et al. 2003), WMAP + CBI + ACBAR + 2dfGRS (Spergel et al. 2003) and WMAP + SDSS (Tegmark et al. 2004). The remarkable agreement between the different measurements suggests that there are minimal systematics in the different experiments and that the current cosmological model appears to be a good description of the basic properties of the universe.

Table 1. Cosmological Parameters

Parameter	WMAP+CBI +ACBAR	All CMB	CMB+2dFGRS	WMAP+SDSS
$\Omega_b h^2$	0.023 ± 0.001	0.023 ± 0.001	0.023 ± 0.001	0.0232 ± 0.010
$\Omega_x h^2$	0.117 ± 0.011	0.117 ± 0.010	0.121 ± 0.009	0.122 ± 0.009
h	0.73 ± 0.05	0.72 ± 0.05	0.73 ± 0.03	0.70 ± 0.03
n_s	0.97 ± 0.03	0.967 ± 0.029	0.97 ± 0.03	0.977 ± 0.03
σ	0.83 ± 0.08	0.85 ± 0.06	0.84 ± 0.06	0.92 ± 0.08

3. Small Scale CMB Experiments

Over the next several years, there will be rapid advances in our ability to characterize small scale CMB fluctuations. Most microwave background experimental results and analyses have probed primordial physical conditions in the early universe, at a redshift $z \sim 1100$. While high-redshift physics is the dominant source of fluctuations on the large angular scales ($\theta > 10'$) probed by WMAP and most existing ground-based and balloon-based surveys, low-redshift physics dominates fluctuations on the small angular scales probed by these small scale experiments. This key difference means that they represent a fundamentally different kind of science project from most previous microwave experiments, relying more heavily on astronomical observations and astrophysical theory to extract the science from the high-resolution maps. These experiments will not only be able to detect CMB fluctuations generated at $z \sim 1000$, but also to probe low-redshift physics.

There are several exciting new projects that are expected to report results in the next five years:

- Planck (http://planck.esa.int) is scheduled to launch in 2007 and will measure CMB fluctuations across the entire sky with better than twice the angular resolution of WMAP and over a wider range in frequency. Planck's higher angular resolution will make it much more sensitive to many of the small scale effects that we discuss in this section.

- The Cosmic Background Imager (http://www.astro.caltech.edu/ tjp/CBI), based in Chile, has already reported small scale CMB results (Mason et al. 2003; Pearson et al. 2003; Readhead et al. 2004) that not only lead to improved cosmological parameters (Sievers et al. 2003; Spergel et al. 2003), but also show evidence for the signature of low-redshift effects such as the Sunyaev-Zel'dovich (SZ) effect (Bond et al. 2002).

- ACBAR (http://cosmology.berkeley.edu/group/swlh/acbar) not only has the resolution to detect the small scale fluctuations but also has the frequency range needed to separate the thermal SZ effect from primordial CMB fluctuations. ACBAR has already reported measurements that probe the CMB fluctuation spectrum to $l = 3000$ (Kuo et al. 2002).

- APEX (http://www.mpifr-bonn.mpg.de/div/mm/apex/) is a 12 meter telescope situated at the ALMA site. It is focused primarily on detecting SZ fluctuations.

- SPT (http://spt.uchicago.edu) is an 8 meter telescope based at the South Pole that will survey a large swath of the southern sky at 200-450 μm and is optimized for detecting large numbers of SZ clusters (Ruhl et al. 2004).

- ACT (http://www.hep.upenn.edu/act/) is an Atacama-based 6 meter telescope that will survey a 100 square degree region of the southern sky in three millimeter bands at resolutions ranging from 0.9 to 1.7 arcminutes, with a target sensitivity of 2 μK per pixel. This high sensitivity will enable it to detect not only SZ clusters but also other low redshift physical effects. ACT funding began in January 2004; it is currently on schedule for engineering observations in the second half of 2006, with full science observations in 2007 and 2008.

3.1. Low Redshift Physics

Gas and matter at low redshift also leave their imprint on the microwave background through a number of physical effects:

- Photons scattering off hot gas gain energy (thermal Sunyaev-Zel'dovich effect - tSZ). Since the photon number is conserved, the tSZ effect produces cold spots at low frequency and hot spots at high frequency (Sunyaev & Zeldovich 1980a,b)

- Photons scattering off moving gas are blueshifted or redshifted depending on the gas direction. The amplitude of the kinetic Sunyaev-Zeldovich (kSZ or Ostriker-Vishniac (Ostriker & Vishniac 1986)) effect is proportional to the gas velocity along the line-of-sight.

- Mass fluctuations along the line-of-sight from the surface of last scattering to our telescope deflect photon paths and distort the shape of CMB fluctuations (Seljak 1996). This gravitational lensing does not generate new fluctuations but distorts the shape of existing fluctuations. This distortion generates non-Gaussianities in the microwave sky. By measuring these non-Gaussianities, we can measure the amplitude of line-of-sight mass fluctuations (Seljak & Zaldarriaga 1999).

- The non-linear evolution of gravitational potentials produces new fluctuations through the Rees-Sciama effect. The same clusters that gravitationally lens the CMB and background galaxies also distort the CMB through the Rees-Sciama effect (Verde & Spergel 2002; Dore et al. 2004). Combined CMB and lensing observations can probe the properties of the dark energy.

All of these signals are detectable by ACT, and are potentially powerful ways of probing the low-redshift history of the universe. In contrast with the primordial fluctuations, however, the information contained in the microwave maps at these scales is not by itself sufficient to extract most of the interesting science. For example, CMB observations of clusters alone are difficult to interpret without measurements of cluster redshifts.

The microwave maps will also contain contributions that are difficult to characterize on their own, like lensing, but become much plainer when correlated with independent measurements of the matter distribution at low redshift, like weak lensing of background galaxies or galaxy counts in large redshift surveys. Astronomical surveys in optical and other wavebands will be essential for obtaining many of the most important results from ACT and other high-resolution microwave experiments.

The following section outlines the key science questions that a survey like ACT, combined with other observations, can address.

3.2. Addressing Key Science Questions

What is the dark energy? There are two main signatures of the gravitational effects of dark energy: the evolution of the scale factor, $a(t)$, and the growth rate of structure, $D(z)$. Observations that constrain the distance - redshift relationship (luminosity - distance observations, angular diameter - distance observations, and volume tests) measure $a(t)$ and probe the dark energy properties through the Friedmann equation, the homogeneous solution to the Einstein equations. Observations that measure the evolution of structure probe the dark energy properties through the evolution of linear perturbations.

We will have several independent approaches for measuring $a(t)$ and $D(z)$:

- Observations of gravitational lensing of the CMB and background galaxies measure the amplitude of mass fluctuations. By using photometric redshift data, we can measure the amplitude of the lensing signal as a function of redshift and infer $D(z)$ and $a(t)$. The number of clusters as a function of redshift is potentially a sensitive probe of dark energy properties. The challenge will be to understand the systematic effects of converting observables to mass. The number counts depend on both $D(z)$ and $a(t)$ (Haiman et al. 2001; Khoury et al. 2004). The SZ, weak lensing, and X-ray data can be combined to measure the angular diameter distance as a function of redshift (Pen 1997). These observations measure $a(t)$ through the angular diameter distance - redshift relation.

- The galaxy and CMB lensing observations will enable us to calibrate the *bias* of the galaxy population as a function of redshift (Seljak et al. 2004). When combined with SDSS measurements of galaxy fluctuations at low redshift and WMAP measurements, this measures $D(z)$.
- By cross-correlating lensing observations and galaxy counts with CMB measurements, we can separate out the Rees-Sciama signal and infer the evolution of the gravitational potential (Peiris & Spergel 2000).
- The differential ages of passively evolving galaxies as a function of redshift provide a direct measurement of $a(t)$. Using the spectra of galaxies in clusters discovered by ACT via the SZ effect, we will be able to measure $a(t)$ with another independent method (Simon et al. 2004).

The combination of small scale CMB and lensing observations provides many different independent methods of determining $w(z)$, the equation of state of dark energy. We will investigate how sensitive the determination of w is to systematic errors.

What is the mass of the neutrino? Solar neutrino observations and cosmic ray neutrino observations have shown that neutrinos have small, but non-zero, masses. These experiments measure the square mass difference between neutrino species and do not measure the absolute mass of the neutrino. Massive neutrinos affect the growth rate of large-scale structure; thus, the combination of CMB observations, which measure the amplitude of density fluctuations at $z \sim 1000$, and measurements of the amplitude of density fluctuations in the nearby universe constrain the neutrino mass (Spergel et al. 2003; Pierpaoli 2003). Current constraints are limited by uncertainties in the scattering optical depth for the CMB and uncertainties in σ_8, the amplitude of density fluctuations today. ACT will measure the optical scattering depth through the Ostriker-Vishniac effect. The combination of optical lensing data, photometric redshifts and ACT data will measure the evolution of density fluctuations as a function of redshift. This will enable an order-of-magnitude improvement in neutrino mass bounds.

Where are the missing baryons? Most of the baryons at low redshift ($z < 2$) are thought to be in the hot intergalactic medium. This hot diffuse ionized gas is very difficult to observe through its emission. X-ray and ultraviolet absorption line studies (Richer et al. 2004) have detected highly ionized oxygen in the intergalactic medium; however, because of uncertainties in gas metallicity and ionization state, we cannot directly infer the gas density in the intergalactic medium.

Since the amplitude of the kinetic Sunyaev-Zeldovich (kSZ) signal is directly proportional to the gas density (rather than its square), it is, potentially, a powerful tracer of low-density gas (Dedeo & Spergel 2005). While only hot cluster gas produces detectable X-ray signals and thermal SZ signals, any ionized gas will produce a kSZ signal proportional to its mass and velocity. By cross-correlating the variance in the CMB signal with the number density of galaxies, we will be able to measure the evolution of the mass in the intergalactic medium as a function of redshift. Combined CMB/optical observations should be able to detect the missing baryons.

3.3. How Do Galaxies Affect the Cluster Environment? How Does the Environment Affect Galaxies?

Active galactic nuclei, jets and supernova explosions deposit large amounts of energy and entropy into the intercluster medium (ICM). Simulating their effect in the computer is extremely complex and needs to be aided by observations. One of the main effects of this *feedback* is to create density enhancements in the ICM. This in turn will affect the CMB photons that will be received by ACT (Oh 2004; Scannapieco & Oh 2004). Additional observations in the X-ray and millimeter (ALMA) will trace where these density enhancements are radiating their energy. By having a mass limited catalog of SZ clusters, we will be able to address some of the following questions: "Is feedback responsible for cold fronts in clusters of galaxies?" (Jimenez et al. 2005), "Do galaxies stir the ICM to supersonic velocities?" (Faltenbacher et al. 2004), and "Is feedback from active galactic nuclei the main culprit of heating the ICM?"

Numerical simulations (Motl et al. 2005) show that supernova explosions significantly alter the integrated X-ray flux of the ICM, but do not alter the thermal SZ flux. Analyses of X-ray data alone can yield erroneous estimates of cluster mass. However, the combination of X-ray and SZ data yields an improved mass estimate and a direct measure of supernova feedback. Our UV and optical measurements of the SZ-selected clusters will yield measures of star formation rates. An ambitious optical/UV follow-up program could provide these measurements for thousands of clusters over a wide range of mass and redshift. SZ identified clusters will be an important sample for understanding the physics of galaxy formation.

4. Conclusions

The combination of large-scale CMB observations, observations of the large-scale structure and supernova observations have helped establish a new standard model of cosmology. While this model answers many of the old questions of cosmology, it raises new questions. Over the next several years, the rapid pace of improvement in CMB data will continue as new experiments probe fluctuations on smaller angular scales. The combination of these small scale experiments and optical observations will probe the growth rate of structure, the distribution of baryons and the emergence of galaxies.

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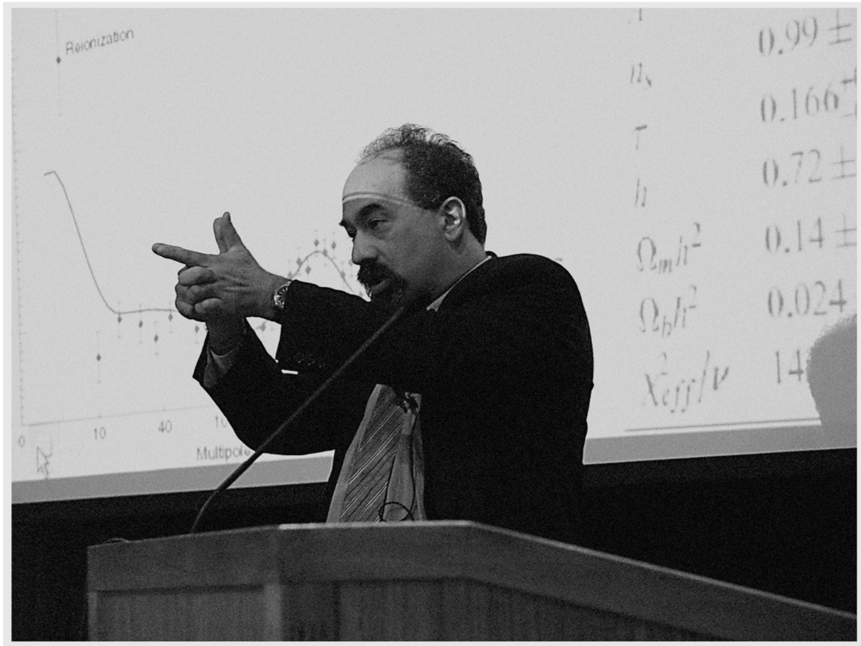
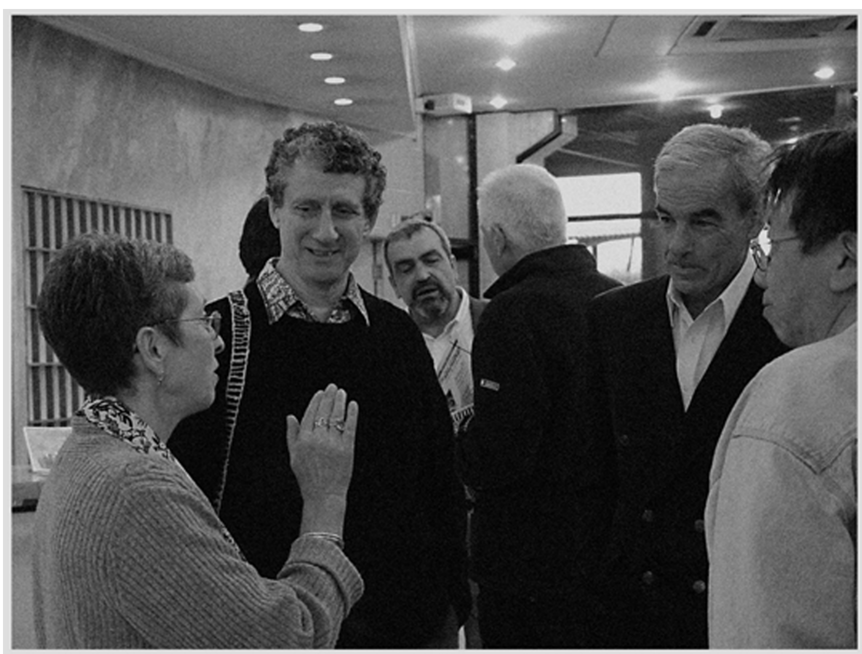


D. Spergel illustrates a point during his talk.



From left to right, **D. Alloin**, **T. Geballe**, **J. Cernicharo**, **A. Castets**, **F. Mirabel** and **P. Ho** in the hotel lobby.