PROCEEDINGS OF SCIENCE

CMB Power Spectrum Results from the South Pole Telescope

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The South Pole Telescope (SPT) is a 10-meter telescope designed to survey the millimeter-wave sky. The telescope and its 960-element bolometric camera were successfully installed at the South Pole in 2007. Since then, the SPT has imaged 2200 square degrees of the sky with low noise and arcminute resolution. We report on the CMB power spectrum results from SPT. In conjunction with data from the WMAP satellite, the new SPT data leads to a 6 sigma detection of gravitational lensing in the CMB. The SPT+WMAP data also improve constraints on the shape of the primordial power spectrum with implications for inflationary models. Finally, the SPT+WMAP data yield measurements of the primordial helium abundance and the number of relativistic particle species in the early Universe.

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1. Introduction

Measurements of temperature anisotropy in the cosmic microwave background (CMB) are among the most informative and robust probes of cosmology. The acoustic oscillations of the primordial plasma have been measured on degree scales ($\ell \lesssim 500$) with cosmic-variance-limited precision by the WMAP [1], yielding a wealth of cosmological information [1]. The CMB temperature anisotropy power falls exponentially to smaller scales. The reduction in CMB power is due to the diffusion of photons in the primordial plasma and is often referred to as Silk damping [2]. This "damping tail" of the primary CMB anisotropy has been measured by a number of experiments, notably ACBAR [3], QUaD [4], and ACT [5].

Measurements of the CMB damping tail, in conjunction with WMAP's measurements of the degree-scale CMB anisotropy, provide a powerful probe of early-universe physics. The damping tail measurements significantly increase the angular dynamic range of CMB measurements and thereby improve the constraints on inflationary parameters such as the scalar spectral index and the amplitude of tensor fluctuations. Measurements of the angular scale of the damping can constrain the primordial helium abundance and the effective number of relativistic particle species during the radiation-dominated era. Finally, the damping tail is altered at the few-percent level by gravitational lensing of the CMB, and is therefore sensitive to matter fluctuations at intermediate redshifts.

In this conference, we have presented a measurement of the CMB damping tail using data from the SPT [6, hereafter K11]. The data were taken at 150 GHz during 2008 and 2009 and cover approximately 790 square degrees of sky. The K11 power spectrum is the best measurement of the CMB temperature anisotropy across a multipole range $650 < \ell < 3000$ (angular scales of $4' < \theta < 16'$).

We describe the SPT survey in §2. The observations, analysis and resulting bandpowers are presented in §3. We examine the cosmological implications in §4, and conclude in §5.

2. The SPT Survey

The SPT is a 10-meter diameter off-axis Gregorian telescope located at the South Pole (left panel of Figure 1). The current receiver is equipped with 960 horn-coupled spiderweb bolometers with superconducting transition-edge sensors. The sensors are read out using frequency multiplexing. The receiver included science-quality detectors at frequency bands centered at approximately 150 and 220 GHz in 2008, and at 95, 150, and 220 GHz from 2009 onwards.

The SPT will finish a survey of 6% of the sky (2500 square degrees) in the winter of 2011 (middle panel of Figure 1). This region was selected for its extremely low level of galactic dust emission and visibility from the South Pole. The SPT dataset will yield a large catalog of SZ-discovered galaxy clusters, measurements of the small-scale Sunyaev-Zel'dovich (SZ) and CMB temperature power spectra, and a high-S/N detection of CMB lensing.

3. Observations to Bandpowers

The power spectrum analysis presented here uses data at 150 GHz taken during the 2008 and 2009 austral winters. This includes five fields whose total area is 790 square degrees. Each field

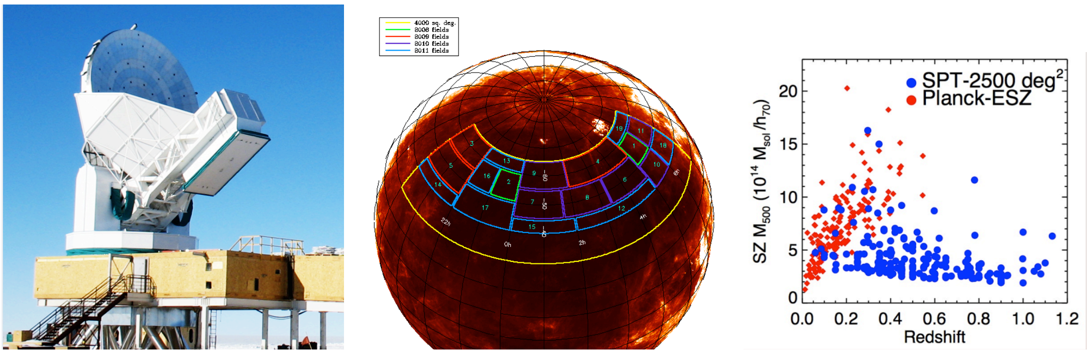

Figure 1: ***Left panel:*** The SPT is a 10-m telescope located at the South Pole and optimized for a large SZ galaxy cluster survey. ***Middle panel:*** The SPT survey overlaid on the IRAS dust map. The survey region was chosen for its exceptionally low galactic dust emission. The survey will finish observing 2500 deg^2 at 95, 150, and 220 GHz by the end of 2011. The power spectrum discussed in this work is based on a third of the survey. ***Right panel:*** Galaxy cluster mass versus redshift for clusters in the Planck ESZ catalog or SPT catalog. Due to its smaller beam, the SPT survey is more sensitive to high redshift galaxy clusters.

was observed to an approximate depth of 18 μK-arcmin at 150 GHz. Details of the calibration, beam, and bandpower estimation can be found in K11; we outline the basics here.

We use a pseudo-C_ℓ method to estimate the bandpowers. In pseudo-C_ℓ methods, bandpowers are estimated directly from the spherical harmonic transform of the map after correcting for effects such as TOD filtering, beams, and finite sky coverage. We process the data using a cross spectrum based analysis to eliminate noise bias. Our scan strategy produces of order 100 complete but noisy maps of each field, and so is ideally suited to a cross-spectrum analysis. Before Fourier transforming, each map is apodized by a window designed to mask out > 50 mJy point sources and to avoid sharp edges at the map borders. Beam and filtering effects are corrected for using simulations. We report the bandpowers in terms of $\mathscr{D}_\ell$, where

$$\mathscr{D}_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell \,. \tag{3.1}$$

The data is also subjected to a stringent set of jackknife tests to search for systematic errors. We find no significant evidence for systematic contamination of the SPT bandpowers.

The resulting bandpowers[1] are shown in Fig. 2, along with other published data for comparison. The K11 bandpowers map out the damping tail of the CMB temperature power spectrum, and are the best measurement of the CMB power spectrum from the third to ninth acoustic peaks.

4. Cosmological Implications

We fit the SPT data using Monte Carlo Markov chain (MCMC) methods (see K11 for details). We include the seven-year WMAP (WMAP7, [1]) bandpowers in all MCMCs. Low redshift measurements of the Hubble constant H_0 using the Hubble Space Telescope [8] and the baryon acoustic oscillation (BAO) feature using SDSS and 2dFGRS data [9] are included in some results.

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[1] http://lambda.gsfc.nasa.gov/product/spt

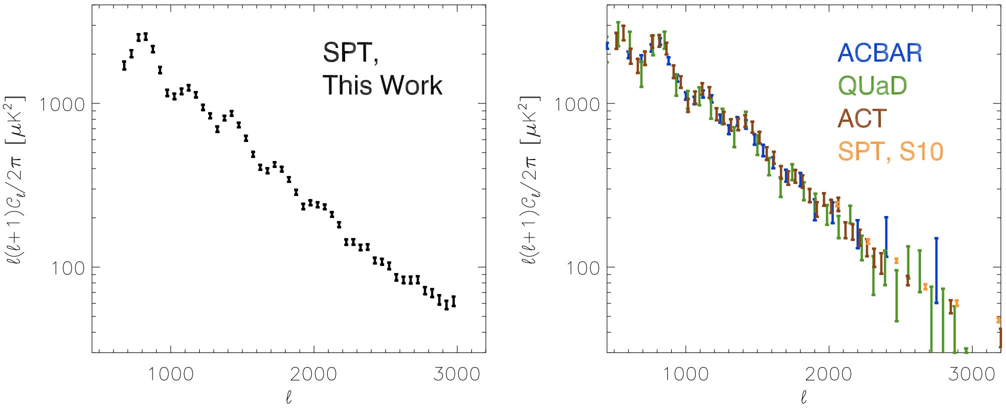

Figure 2: The SPT power spectrum from K11. The peak at $\ell \sim 800$ is the third acoustic peak. For comparison we show in the right panel other recent measurements of the CMB damping tail from ACBAR [3], QUaD [4], ACT [5], and SPT [7].

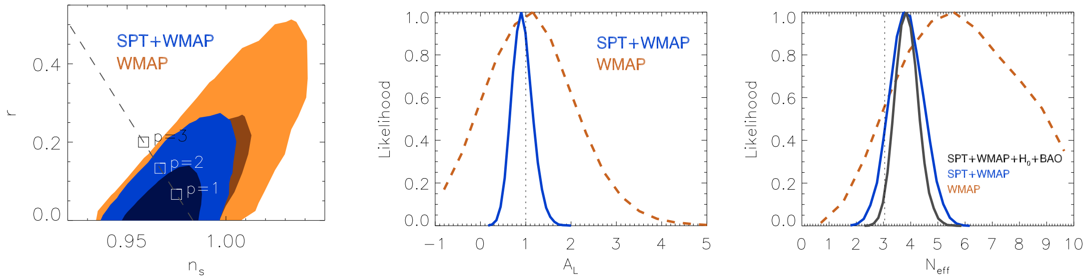

Figure 3: ***Left panel:*** Likelihood surfaces for r and n_s for the WMAP7 and WMAP7+SPT power spectra. The SPT data significant improve the limits on inflation. The line marks the prediction for chaotic inflationary models. ***Middle panel:*** Likelihood function for the magnitude of gravitational lensing potential. ***Right panel:*** Likelihood function for the number of relativistic species (e.g. neutrinos) with different data sets.

Our baseline cosmological model is a spatially flat, gravitationally lensed ΛCDM cosmology. In this model, the addition of the SPT data improves the constraints on $\Omega_b h^2$ and n_s by ∼25%, and the constraint on θ_s by nearly a factor of two.

The SPT small-scale power spectrum measurement significantly improves our ability to investigate extensions to the ΛCDM model. K11 explore a number of extensions, here we summarize the results on the tensor-to-scalar ratio, gravitational lensing, and neutrinos.

4.1 Tensor-to-Scalar Ratio

Inflation is expected to produce primordial tensor perturbations (i.e. gravitational waves). These perturbations imprint potentially detectable effects onto the CMB temperature and polarization spectra. The amplitude of the tensor spectrum is often given in terms of the tensor-to-scalar ratio, $r = \Delta_h^2(k_0)/\Delta_\mathcal{R}^2(k_0)$ with pivot scale $k_0 = 0.002$ Mpc^{-1}. A detection of r would provide an extremely interesting window onto the energy scale of inflation.

In the long run, the best measurement of r will come from B-mode CMB polarization. However at the present, the strongest constraints come from the CMB temperature anisotropy. There is a degeneracy between r and n_s as shown in the left panel of Fig. 3. The CMB power at low multipoles increases as r increases, but this effect can be partially cancelled by increasing n_s and decreasing Δ_R^2. The small-scale CMB measurements help to break this degeneracy. The SPT data together with WMAP7, BAO, and H_0 constrain $r < 0.17$ (95% CL), a factor of two improvement over WMAP7 alone. We also show the predictions for r and n_s from chaotic inflationary models with inflaton potential $V(\phi) \propto \phi^p$ and $N = 60$, where N is the number of e-folds between the epoch when modes that are measured by SPT and WMAP exited the horizon during inflation and the end of inflation. These models predict $r = 4p/N$ and $n_s = 1-(p+2)/2N$. Models with $p \geq 3$ are disfavored at more than 95% confidence for $N \leq 60$.

4.2 Gravitational Lensing

The paths of CMB photons are distorted by the gravity of intervening matter as they travel from the surface of last scattering to us, a process referred to as gravitational lensing. Lensing alters the CMB temperature power spectrum at the few percent level. The acoustic peak structure is smoothed, and power is preferentially added to smaller angular scales. K11 parameterize the lensing amplitude by a factor A_L which rescales the lensing potential power spectrum in a ΛCDM cosmology. Since lensing encodes information on the distribution of matter at intermediate redshifts, the magnitude of lensing informs us about the neutrino mass, curvature, dark energy and modified gravity theories.

The SPT bandpowers accurately measure the acoustic peaks in the damping tail and are therefore sensitive to the lensing magnitude (middle panel of Fig. 3). The SPT + WMAP7 data measure $A_L^{0.65} = 0.94 \pm 0.15$ (K11). The exponent of 0.65 is chosen to gaussianize the posterior likelihood. No lensing is rejected at $6\,\sigma$. This is the best detection measurement of CMB lensing.

4.3 Neutrinos

In the standard theory of the early universe, there are three neutrino species that contribute ∼10% of the energy density at recombination. The effective number of particle species that are relativistic prior to and during recombination, $N_{\rm eff}$,[2] is slightly higher (3.046) due to energy injection from electron-positron annihilation at the end of neutrino freeze-out. A significant detection of $N_{\rm eff} \neq 3.046$ would point to the presence of extra relativistic species in the early universe.

The addition of extra relativistic species increases the expansion rate during the radiation-dominated era. After fixing the quantities that are the robustly measured by WMAP, the main effect of this increased expansion rate is to increase the angular scale of photon diffusion and thereby lower power in the damping tail [10]. Hence measurements of the CMB damping tail in conjunction with WMAP constrain the number of relativistic species.

We extend the ΛCDM model by introducing $N_{\rm eff}$ as a free parameter (right panel of Fig. 3). K11 find a preference $N_{\rm eff}$=3.046 over no relativistic species at $7.5\,\sigma$. [1] find $N_{\rm eff} > 2.7$ (95% CL) using WMAP7 alone, while the SPT+WMAP7 data constrain $N_{\rm eff}$ to be $N_{\rm eff} = 3.85 \pm 0.62$ (K11). This constraint is $1.3\,\sigma$ higher than the standard $N_{\rm eff} = 3.046$. When the H_0 and BAO data are added, the constraint tightens to $N_{\rm eff} = 3.86 \pm 0.42$, $1.9\,\sigma$ higher than the standard value. For

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[2] $N_{\rm eff}$ is defined such that $\rho_\nu = N_{\rm eff} 7/8 (4/11)^{4/3} \rho_\gamma$

massless neutrinos, these high values of $N_{\rm eff}$ are in tension with the observed number counts of low-redshift galaxy clusters — high $N_{\rm eff}$ would underpredict the observed number counts. However, this tension vanishes when neutrinos are allowed to have mass. With massive neutrinos, the preferred $N_{\rm eff}$ is similar at 3.97 ± 0.43.

5. Conclusion

We have reported on recent measurements of the damping tail of the CMB power spectrum using data from the SPT by K11. The SPT power spectrum uses 150 GHz data and spans the multipole range $650 < \ell < 3000$, where it is dominated by primary CMB anisotropy. K11 combine this spectrum with data from WMAP7, H_0, and BAO to constrain extensions to the ΛCDM cosmological model. Here we have presented the salient results on the tensor-to-scalar ratio, gravitational lensing, and the number of neutrinos.

The SPT data presented here account for only a third of the full SPT-SZ survey. The full SPT-SZ survey, which is expected to be completed by the end of 2011, will cover approximately 2500 square degrees. With 150 GHz data of the quality used here and with additional data at 95 and 220 GHz, a power spectrum analysis of the full SPT survey will be twice as sensitive as that presented here.

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