The Atacama Cosmology Telescope Project: A Progress Report

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Abstract

The Atacama Cosmology Telescope is a project to map the microwave background radiation at arcminute angular resolution and high sensitivity in three frequency bands over substantial sky areas. Cosmological signals driving such an experiment are reviewed, and current progress in hardware construction is summarized. Complementary astronomical observations in other wavebands are also discussed.

Key words: cosmic microwave background, cosmology: observations, cosmology: theory, telescopes, instrumentation: detectors

1 Science Motivation and Sky Signals

The full-sky microwave maps from the WMAP satellite have provided a definitive measurement of the microwave background temperature on angular scales down to around 15 arcminutes, in five frequency bands from 23 to 90 GHz (1). These measurements determine the primordial power spectrum of fluctuations in the baryon-photon plasma of the early universe, resulting in tight constraints on the basic cosmological model of the universe (2) and bringing to fruition a decade of anticipation (3). While additional measurements will provide refined constraints on some cosmological parameters, they are unlikely to alter qualitatively our fundamental picture of the universe which has emerged.

Significant experimental attention has now turned to microwave background temperature measurements at smaller angular scales. At scales smaller than...
10 arcminutes, the power in primary fluctuations produced at the surface of last scattering begins to drop precipitously, due to diffusion damping on length scales smaller than the thickness of the last scattering surface. But secondary fluctuations in microwave temperature at arcminute angular scales are induced by interaction of the microwaves with large-scale structure at redshifts between zero and a few. In contrast with large-angle temperature measurements, which image fluctuations in the early universe, high-resolution temperature measurements mainly probe the subsequent development of structure in the universe. The Atacama Cosmology Telescope (ACT) project (4; 5; 6) is one effort to map the microwave background at angular resolutions better than two arcminutes, at sensitivities sufficient to detect all major effects contributing to the temperature fluctuations at these scales. The rest of this introductory section will review the specific signals of interest; then an overview of the ACT experiment and its current status will be given, along with plans for complementary astronomical observations in other wave bands.

1.1 Power Spectrum

The power spectrum of primordial perturbations, usually characterized by the power law index $n$, has been measured by WMAP over a range of multipole moments from $l = 2$ to $l = 700$ (2). Further constraints on $n$ come from combining WMAP data with other measures of power at smaller scales (e.g., (7)), but these heterogeneous approaches are susceptible to systematic errors; the microwave background provides the cleanest way to measure the power spectrum. ACT will extend the range of precision multipole measurements out to the point where the primary fluctuations cease being the dominant contribution to the temperature fluctuations, around $l = 3500$. In principle, ACT will be able to measure $n$ over nearly an additional decade in scale, significantly increasing the precision with which $n$ can be constrained. Measurements over a larger range of angular scales also increase sensitivity to any departure from a perfect power law, often characterized by the “running” of the spectral index $dn/d\ln k$ (8). Determination of $n$ and its running are the most powerful current sources of information about inflation or other fundamental processes producing fluctuations in the very early universe. In practice, the precision in $n$ will be determined by the accuracy of the relative calibration of ACT maps at 145 GHz with WMAP maps at 90 GHz and much lower resolution. We are currently studying the issue of relative calibration using sky and instrument simulations outlined below.
1.2 Gravitational Lensing

Mass density variations along the path of microwave photon propagation result in the photon experiencing a varying gravitational potential, and thus deflections in the direction of the potential gradient. This gravitational lensing effect is always small in cosmological contexts; the propagation direction of an average microwave photon will be deflected by an angle of tens of arc-seconds over its journey of 13 billion light years. These deflections are also coherent over larger scales up to a degree, so that detecting them requires more work than simply having angular resolution better than the detection angle. The original temperature fluctuations are a gaussian random field to a good approximation; gravitational lensing will induce a particular additional four-point correlation function into the temperature map \(9\). Detecting these characteristic correlations requires comparing temperature fluctuations in the maps at small scales of a few arcminutes with larger scales around a degree \((10; 11; 12)\). The overall amplitude of the temperature signal is on the order of the mean temperature difference on the deflection scale, which is on the order of five \(\mu\)K.

In addition to lensing from large-scale structure distributed evenly across the sky, galaxy clusters also give localized gravitational lensing signals. If the cluster is in front of a background microwave temperature gradient, the lensing produces a dipole-like pattern aligned with the temperature gradient \((13)\). The separation of the hot and cold peaks is on the order of one arcminute and the peak-to-peak amplitude can be of order 10 \(\mu\)K for a large cluster in front of a substantial gradient \((14; 15; 16)\). Such signals are in principle observable with ACT’s sensitivity and resolution, but other signals associated with clusters will make reliable lensing mass estimates difficult.

1.3 Thermal Sunyaev-Zeldovich Effect

The thermal Sunyaev-Zeldovich (SZ) Effect describes the energy boost received by low-energy microwave background photons Compton scattering from high-energy electrons in hot, ionized gases \((17)\). The SZ effect has so far been detected towards a number of galaxy clusters through pointed observations in the direction of known clusters \((see (18) for a review); ACT and similar experiments aim to detect thousands of clusters via blind surveys of large sky areas. The effective temperature shift of the microwave background black-body spectrum has the characteristic form of a Compton y-distortion; below the “null” at a frequency of around 217 GHz the radiation flux is decreased, while above 217 GHz the flux is increased, and the amplitude is proportional to the pressure of the ionized gas integrated along the path of photon propa-
The largest galaxy clusters have SZ effective temperature distortions as large as 100 $\mu$K, making them the largest amplitude signals expected at ACT frequencies.

Unlike clusters selected via X-ray or optical observations, the cluster SZ signal is essentially independent of cluster redshift for a cluster of a given mass and gas distribution. The SZ signal, which depends linearly on the electron density, is less sensitive to internal gas structure than the X-ray emission, which is quadratic in the electron density. Selecting clusters via their SZ distortion is also physically much simpler than selecting clusters optically via the light from their resident galaxies, since the SZ signal is directly related to the majority of the baryonic cluster mass, while the optical light comes from galaxies which represent only a small fraction of the baryonic mass, and whose light emission is due to complex, highly nonlinear processes which are not entirely understood. These considerations make thermal SZ distortions an ideal method for selecting galaxy cluster samples of cosmological interest.

The overall number density of clusters in the universe at a given redshift and mass limit is a sensitive function of cosmological expansion history, making this a potentially powerful probe of dark energy; combining an SZ catalog with optical cluster redshifts provides a probe of cluster growth through time. The difficulty in this approach is that cluster number counts also depend sensitively on systematic errors, particularly in understanding the cluster mass selection function. Over the coming few years, significant numbers of clusters with SZ, X-ray, and optical observations, including weak-lensing mass estimates, will reveal whether clusters are regular enough to understand systematics in their selection functions and exploit them as probes of cosmology.

Outside of clusters, small diffuse SZ signals may also come from from hot gas in numerous individual galaxies heated by star formation or active galactic nuclei or from the first generation of stars. These signals will be at amplitudes of a few $\mu$K, and the extent to which they can be exploited for useful scientific information, as opposed to serving only as a noise source, is not yet clear.

### 1.4 Kinematic Sunyaev-Zeldovich Effect

The kinematic Sunyaev-Zeldovich Effect also arises from photon-electron scattering; it is essentially a Doppler distortion coming from bulk velocity of the electrons along the line of sight, and is proportional to the cluster ionized gas mass times its radial peculiar velocity. For large galaxy clusters with characteristic radial velocities of a few hundred km/s, the kSZ blackbody distortion will be between a few and 10 $\mu$K. Simulated clusters show that the
internal gas motions in a cluster give an intrinsic scatter of around 50 km/s to cluster velocities inferred from kSZ observations (27). In principle, galaxy cluster radial peculiar velocities can be measured directly from kSZ observations, if cluster velocities and gas masses can be disentangled using thermal SZ or X-ray observations (28). The cluster velocity field then provides a direct and clean probe of the cosmic velocity field and an independent test of the hierarchical structure formation picture. Such velocity catalogs would be a significant improvement over current velocity catalogs based on galaxy velocities, which are inferred from their redshifts combined with a distance estimate.

1.5 Other Sky Signals

These sky signals – thermal and kinematic SZ effect, gravitational lensing, and primary microwave background blackbody fluctuations, can be separated through their frequency and spatial dependences. Detecting them will be complicated, however, by other astrophysical “noise” sources (which, however, are interesting in their own right!). Galactic dust can contribute substantial signal at these wavelengths; to minimize this signal, the cosmologically useful portions of the sky are likely to be well away from the galactic plane. Infrared point sources, which are thought to be high-redshift galaxies with significant dust emission from massive star formation, will likely give a confusion noise limit in the range of a few µK at ACT frequencies (29, 30); removing the brightest infrared point sources through complementary observations at higher redshift will certainly be helpful. Likewise, bright radio point sources, generally emission from active galactic nuclei, can contribute, though these will probably have significantly less overall signal than the infrared sources, judging from naive extrapolations of microwave and SCUBA observations (29), unless the radio sources are strongly correlated with clusters.

2 Telescope

Observing the signals outlined in the preceding section requires mapping the microwave sky in several frequency bands with an angular resolution of around an arcminute and noise of a few µK per resolution element. These science requirements drive a number of design decisions evident in the ACT telescope. To observe the frequency dependence of the thermal SZ effect requires frequencies in the neighborhood of 200 GHz; ACT has three frequency bands with central frequencies (bandwidths) of 147 (23) GHz, 215 (23) GHz, and 279 (32) GHz. These bands take advantage of atmospheric windows, significantly reducing atmospheric noise. At these frequencies, the resolution requirements dictate a primary mirror of at least 6 meter diameter; ACT’s 6-meter primary
is constructed from aluminum panels. The need for control of systematic errors to detect temperature anisotropies which are tiny fractions of the total signal lead to an off-axis Gregorian optical design with a clear aperture, a large 2-meter secondary mirror, and an optical path which has no moving elements, including ground screens which reflect into sidelobes. The focal plane is a square with side 22' on the sky, with a plate scale of approximately 0.7' / mm.

The telescope is designed to make observations at a fixed elevation while scanning in azimuth, so that the air mass the microwave photons propagate through is as nearly constant in time as possible: an elevation change of one degree changes the atmospheric signal by tens of mK, thousands of times larger than the few μK sky signals we aim to detect. Scanning in azimuth allows repeated imaging of the same patch of sky on time scales short enough to overcome detector 1/f noise; the telescope is designed to complete a scan with an amplitude of a few degrees in azimuth in 5 seconds. To obtain uniform sky coverage, the scan should be as close to a constant angular velocity as possible; the acceleration at the scan turnaround points compared to the optical tolerance determines the necessary structural stiffness of the telescope structure and the specifications of the hydraulic azimuthal drive motor. The telescope also has an elevation drive for checking calibration sources or to accommodate observations at different central elevations. The telescope is being built by AMEC Dynamic Systems in Port Coquitlam, British Columbia.

The radiation from the secondary mirror is imaged onto the focal plane via three separate optical tubes, one for each frequency band; each tube contains an independent system of cold silicon lenses, a cold Lyot stop, and frequency filters (Fig. 2). ACT collaborators have developed high-performance anti-reflection coatings for the silicon lenses [31] to reduce internal reflections to an acceptable level. Three separate bolometer arrays, described below, lie in the focal plane to detect the radiation. Detecting three frequency bands simultaneously has the advantages of eliminating different time-dependent systematic effects between the bands, especially atmosphere, and increasing the efficiency of observations; the price is a larger receiver. The three detector arrays are arranged so that approximately 75% of the sky area covered by at least one detector array will be covered at all three frequencies.

The bolometers operate at superconducting temperatures below 1 K; the entire optical assembly, focal plane, and detector assembly is contained in a large cylindrical dewar approximately 1 meter in diameter and 2 meters in length. Two stages of pulse-tube coolers maintain the outer optics at 40 K and an inner region at 3 K; helium-4 and helium-3 sorption refrigerators bring the temperature of the detectors down to under 300 mK. The entire refrigeration system contains no consumable liquid cryogens.
Fig. 1. The ACT telescope, during construction in Port Coquitlam, British Columbia. The 6-meter primary is contained in the right part of the structure; the 2-meter secondary is at left, and the detectors are contained in a large cryogenic dewar behind the housing in the center. The large azimuth bearing on which the entire structure rotates is visible at the bottom. Additional ground screens attach to the outside of the structure shown here. The top of the primary housing is 13.5 meters from the ground. It is clear that Port Coquitlam is not an ideal observing site!

As of mid-2006, telescope construction is nearly complete, and the instrument is undergoing engineering tests. During the second half of 2006, the telescope will be partially disassembled and shipped to Chile. It will then be reassembled and installed at its observing site on Cerro Toco, at an elevation of 5100 meters. The telescope will have the capability of remote operation from a base in San Pedro, Chile.

3 Detectors

Large detector arrays are necessary to reach the sensitivity goals for ACT and similar experiments: photon shot noise sets a fundamental noise limit for any single detector of microwave background radiation flux. The heart of the ACT experiment are the bolometer arrays and related electronics, called the Millimeter Bolometric Array Camera (MBAC). This detector design has been
Fig. 2. The ACT optical design, showing the optical elements in the three optics tubes. Radiation from the secondary mirror is coming from the top left; three independent sets of cold filters and lenses image the three frequency bands onto the focal plane. Mean Strehl ratios for point sources are greater than 0.985 in all three frequencies, and 95% of the focal plane has Strehl ratios higher than 0.96 in all three frequencies.

presented in some detail elsewhere ([32](#) [33](#)) and will only be summarized here. When the MBAC is complete, it will use three $32 \times 32$ arrays of popup bolometers, developed at NASA Goddard Space Flight Center. The arrays are divided into columns of 32 bolometers; each column is modular and is fabricated as a single unit. The bolometers are each squares with side length 1 mm, and each array is closely packed. Each column of bolometers and associated leads and support structures are etched onto silicon using lithographic techniques (pictured in Fig. 3). The silicon sheets are then folded in a custom-designed jig so that all of the visible structures above and below the bolometers themselves are perpendicular to the bolometer row. The bolometers lie in the focal plane; the perpendicular structures physically support the bolometers and contain electrical leads.

The MBAC uses transition edge-sensing (TES) bolometers ([34](#) [35](#)). To increase sensitivity, the bolometers are cooled to their superconducting transition temperature, and a fixed bias voltage is applied across them. When the amount of radiation falling on the detector changes, its temperature changes...
slightly; since it is at its superconducting transition, a tiny temperature change translates into a large change in resistance. This results in a changing current through the bolometer, which is detected with a superconducting quantum interference device (SQUID) via magnetic inductance. Multiplexed arrays of these readout SQUIDs have been developed at the National Institute of Standards and Technology (36), reducing the required number of connections from the cold detectors to the room-temperature data acquisition electronics by a factor of ten. The detectors must have extensive magnetic shielding since the SQUIDs are highly sensitive to changing magnetic fields.

4 Observations

A prototype detector consisting of a single column of 32 multiplexed TES bolometers was coupled to the sky using a spare mirror for the WMAP satellite and used to observe the sky from the physics building at Princeton University in late 2005. A resulting image of Saturn at microwave frequencies is shown in Fig. 4. This follows the first multiplexed TES bolometer sky measurements made several years ago (37). The first MBAC array is currently being constructed; a partial array will be used for the first observations with ACT from Chile.

The Atacama site on Cerro Toco is at the location of the MAT/TOCO experiment (38), and is near the ALMA, APEX, and CBI experiments. The atmosphere is very dry, minimizing water vapor absorption; extensive atmospheric data at millimeter wavelengths has been taken in preparation for ALMA. The site is at a latitude of -23°. Azimuthal scans at a constant elevation near 45° will map the sky around a strip centered on a particular declination, with scans taken to the east and west of the South pole crossing at a nearly perpendicular angle. The initial ACT survey region will be a strip roughly two
Fig. 4. This image of Saturn at 145 GHz was made with a multiplexed TES-bolometer MBAC prototype detector. The outputs of 22 detectors have been coadded. A cryogenic neutral density filter attenuates the input to enable these observations from Princeton, New Jersey. A Lee spatial filter has been applied. These data were taken in November, 2005.

degrees wide centered at declination -55.2°, covering the entire 24 hours in right ascension. This particular declination was chosen to maximize the strip area with very low galactic dust emission. The strip also contains a number of known X-ray clusters, including the heavily studied “hot bullet cluster” 1E0657-56 (39, 40), the Marano Field which has been imaged deeply at a range of frequencies (41; 42; 43; 44), and three radio point sources detected by WMAP (45). The galactic plane intersects our strip in two locations, and this region of the strip will be unsuitable for cosmological observations due to excessive dust emission. The best region of the strip is from RA 22 hr to 7 hr.

When ACT observations begin from Chile, the telescope will be run continuously, mostly doing the same two constant-elevation scans, centered on each side of the South celestial pole. The bolometer signals will be sampled
at around 100 Hz, resulting of a data rate on the order of one MB per second, or on the order of 100 GB per day. The time stream data will include the constant sky signal, time-varying instrument noise, and time-varying but largely coherent atmospheric signal. With thousands of detectors, ACT will have highly redundant information, and the various cosmic and instrumental signals can be reliably separated through their different temporal and spatial dependences. A given point on the sky will be sampled on a range of time scales: the pixel transit time during a scan, the array transit time, the scan rate, the pixel sky drift time, the array sky drift time, the time between east and west scans of the same point, and the day time scale for observing the entire region. This hierarchy of observation time scales allows detection and elimination of numerous systematic effects. Techniques for inverting the time stream into sky maps are well known, but making maps of reasonable accuracy in close to real time as the data is obtained is computationally non-trivial, especially if the noise correlations between different detectors are significant.

Our baseline plan is to make engineering observations starting at the end of 2006, then perform science observations for two to three months in each of years 2007 and 2008. The total amount of data collected during these runs will be in the range of 15 to 20 terabytes.

5 Sky and Instrument Simulations

We have constructed instrument and sky simulations for testing analysis pipeline code. The instrument simulator includes an accurate model of the MBAC focal plane, detector thermal and $1/f$ noise and noise correlations between detectors, detector time constants, model beam shapes, a pointing model, an atmosphere model, a microwave sky model, and routines to produce a model data time stream. The atmosphere model is currently a simple frozen turbulence model (46) which is blown across the field of view with a constant velocity; more sophisticated models are simple to incorporate.

The sky model includes primary blackbody microwave background fluctuations, thermal and kinematic SZ effects taken from a large cosmological $N$-body simulation with a gas physics prescription (47), relativistic corrections to the thermal SZ effect (48), galactic dust (49), and a random distribution of radio (29) and infrared (50) point sources with varying spectral indices based on observations. Further map iterations will also include gravitational lensing by large-scale structure and the Rees-Sciama Effect. Additional signals which are not yet modeled but can be added are the SZ signal from individual galaxies and Ostriker-Vishniac fluctuations induced during reionization. The sky maps are constructed for a strip several degrees wide and at constant declination, mirroring the ACT sky region. We have produced simulated maps at
the three ACT frequency bands, plus a map at 90 GHz which is useful for studying relative calibration with WMAP; all of these maps are at resolutions of 0.25 arcminutes. These maps can be used for evaluating the impact of various experimental noise sources on sky maps reconstructed from the data, determining how well small map signals can be extracted from noisy data, and modelling the ACT galaxy cluster selection function. The simulated sky maps are available upon request; a cluster catalog from the large-scale structure simulations used to make the maps is also available.

6 Complementary Observations

Exploiting fully the cosmological information in high-resolution microwave background observations requires complementary information from other wave bands. In particular, galaxy clusters which are efficiently imaged via their thermal Sunyaev-Zeldovich signature, independent of their distance, require optical follow-up imaging to establish redshifts. This galaxy cluster redshift catalog, complete down to a given SZ distortion, forms the basis for cosmological tests and probes of cluster evolution. For standard cosmological models, ACT will detect over one thousand galaxy clusters above a mass limit of $2 \times 10^{14} M_\odot$ over a sky area of 200 square degrees. Thus followup at other wavelengths requires significant telescope resources and data analysis.

Several ACT collaborators are part of the Blanco Cosmology Survey (BCS) project, led by Joe Mohr [51]. This effort is imaging 100 square degrees of sky in four optical bands (SDSS g, r, i, z) using the Blanco Telescope at CTIO. The first season of data has yielded approximately 30 square degrees of imaged sky, most in four bands. The survey covers two fields, one centered around RA 23 hr and the other around RA 5.5 hr; the former field will cover less range in declination and more in RA, compared to the roughly square 5.5 hour field. Both extend to a southern declination of around $-56.5^\circ$, so that the ACT strip runs along their southern edges. Four-band imaging will provide moderately good photometric redshifts for galaxies, and provide imaging for planning spectroscopic follow-up observations of galaxy clusters. BCS collaborators are also working on extracting shear maps from the galaxy images, making use of the Deep Lens Survey pipeline which was constructed for the same telescope and detector. Two further blocks of observing time will occur at the end of 2006 and the end of 2007. The Blanco Cosmology Survey is a joint project involving three leading groups working on making high-resolution microwave temperature maps (ACT, the South Pole Telescope, and the Atacama Pathfinder Experiment).

ACT also plans to use the new Southern African Large Telescope (SALT) for extensive optical observations [52]. ACT collaborators at Rutgers and
University of KwaZulu-Natal (South Africa) have committed 20 nights per year on this 11-meter telescope to support ACT. SALT has an imaging camera with an 8 arcminute field of view, and a spectrograph with imaging Fabry-Perot and multi-slit modes of operation. We plan to do multi-band imaging of the ACT region which is not covered by the Blanco Cosmology Survey, but SALT’s primary advantage will be in obtaining spectroscopy of galaxies in clusters. The multi-object mode of the spectrograph will be able to obtain 50 to 100 galaxy spectra simultaneously, and the 11-meter aperture of the telescope makes spectroscopy of faint high-redshift galaxies efficient. Spectroscopy will provide dynamical galaxy cluster mass estimates and constraints on stellar populations, along with accurate cluster redshifts. SALT had its official first light in November 2005, but is still in an engineering observation mode.

ACT collaborators are involved with the Astronomical Thermal Emission Camera (AzTEC), a 144-bolometer detector optimized for infrared observations. AzTEC successfully observed the sky from the James Clerk Maxwell Telescope in 2005; it is scheduled to be placed on the Large Millimeter Telescope in Mexico, which can observe the ACT region, in 2007. High redshift galaxies with large amounts of dust emission are common and are a significant foreground in the ACT frequency bands. Further observations are necessary to gain a better understanding of this population and its possible impact on cluster Sunyaev-Zeldovich measurements.

Radio point sources, some of which appear in the WMAP data, are another possible complication for ACT. We are pursuing cluster observations with the Very Large Array to investigate the extent to which radio sources are correlated with galaxy clusters. We are investigating possibilities for a radio survey of the ACT region to identify and remove the brightest radio sources from the ACT maps.

7 Institutions and Support

The Atacama Cosmology Telescope project has drawn together collaborators with wide-ranging skills from many US and international institutions. Around 30 faculty-level scientists are actively involved, with about 20 postdocs and graduate students. Princeton University is the lead institution and Lyman Page of Princeton is the Principal Investigator. The collaboration also includes members from Cardiff University (UK), Catolica University (Chile), Columbia University, Haverford College, Lawrence Livermore National Lab, NASA Goddard Space Flight Center, National Institute for Astrophysics, Optics, and Electronics (INAOE, Mexico), National Institute of Standards and Technology, Rutgers University, University of British Columbia (Canada), University of KwaZulu-Natal (South Africa), University of Massachusetts, University of
Pennsylvania, University of Pittsburgh, University of Toronto (Canada), and York College of the City University of New York.

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