A New Millimeter-wave Camera for CMB Observations

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Abstract

Studies of the Cosmic Microwave Background (CMB), driven by advances in detector and telescope technology, have transformed cosmology into a precise science. In this thesis we present a means of observing the CMB with a new class of detectors.

Specifically, we present a description of the Column CAMera (CCAM), a prototype instrument for the Atacama Cosmology Telescope (ACT). ACT is designed to measure the CMB anisotropy up to $l \sim 10,000$ and perform a galaxy cluster survey using the Sunyaev-Zel’dovich effect. The CCAM instrument tests many of the technologies that will be used in the ACT receiver. We describe aspects of the design of CCAM’s cryogenic systems, optics, detector array, and housekeeping system.

CCAM observed the sky from Princeton in December, 2005. We measure the noise effective power (NEP) of the CCAM detectors on the sky to be $\sim 1.3 \times 10^{-17} - 3 \times 10^{-17}$ W/$\sqrt{\text{Hz}}$, comparable to what we expect from ACT. We measure the main beam profile using an astronomical point source using a simple model of the primary aperture intensity distribution. We investigate the sidelobes of the telescope response using the moon as a source and the same beam model as used for the main beam. Last, we examine the pixel-to-pixel covariance of the receiver at various steps during the mapmaking process and find that the cleaned data streams are not highly-correlated. The correlation properties of a point source map agree with the measured beam.
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Chapter 1

Introduction

1.1 The Cosmic Microwave Background

The early Universe was, apparently, a remarkably simple place. After expanding exponentially by roughly 60 e-foldings, producing baryons, and synthesizing the light nuclei in the first ∼100 seconds, the Universe was composed of relatively few elements: baryons (some bound in nuclei other than hydrogen), electrons, photons, and dark matter. Because the Universe was still hot (T ≥ 3000 K), the photons had enough energy to instantaneously ionize any neutral atom. This kept the interaction cross-section for photons and electrons high, which subsequently kept the photons in thermal equilibrium with the matter in the Universe for the next 380,000 years.

Once the temperature of the Universe dropped below approximately 3000 K (∼0.25 eV), there were no longer photons with energy sufficient to ionize hydrogen. Given the binding energy of hydrogen (13.6 eV), one might have expected this process to have occurred much earlier. However, if a proton captures an electron to the ground state of hydrogen, it will emit an energetic photon that will immediately ionize another atom, leading to no net change in the neutral atom fraction of the Universe. Only by capture to an excited state of hydrogen can the Universe crawl toward neutrality.

Once protons and electrons could combine to form neutral hydrogen, the photon scat-
tering cross-section dropped and the Universe transformed from an opaque plasma to a transparent space filled with neutral atoms. The photons previously strongly coupled to the electrons were “decoupled” and free to propagate without much further interaction through the Universe.

Because these photons were in thermal equilibrium with the matter in the Universe before decoupling, their energy spectrum at the time of decoupling followed the Planck distribution. In the billions of years following decoupling, the further expansion of the Universe redshifted these photons to ever lower energies. The thermal spectrum remained, though shifted to lower temperatures. Today, we see these redshifted thermal photons at $T_{\text{CMB}} = 2.725 \text{ K}[7]$ as the Cosmic Microwave Background (CMB), a 13.7-billion-year-old relic from the hot Big Bang[5].

Though it was predicted in 1948[4], the CMB went undetected for the next 17 years. Arno Penzias and Robert Wilson received the 1978 Nobel Prize in Physics for their 1965 detection of the CMB[8]. In the nearly 30 years after its initial detection, further experiments showed the CMB to be isotropic, unpolarized, and remarkably thermal (see Fig. 1.1).

1.2 Primary Anisotropies

The CMB contains fluctuations in its temperature as a function of position on the sky of approximately a part in $10^5$. The fluctuation in gravitational potential associated with these temperature fluctuations are the seeds of the structure we observe in the Universe today, such as galaxies, galaxy clusters, and large voids.

1.2.1 The Angular Power Spectrum

The information about fluctuations on various angular scales can be encoded in the CMB angular power spectrum. Like any well-behaved function, the temperature distribution of the CMB on the sky can be written using a suitably-chosen set of basis functions. In the case of a field on a 2D spherical surface such as the CMB, we choose the following representation
Figure 1.1: Spectrum of the CMB as measured by the FIRAS instrument on the COBE satellite indicating a blackbody at 2.728K from [9]. The error bars are smaller than the width of the line. A more recent analysis finds the temperature to be $T_{CMB} = 2.725 \pm 0.002$ K [7].

The CCAM observing band at $\sim 150$ GHz lies at $k \approx 5$ cm$^{-1}$.

of the intensity distribution $\Delta T(\theta, \phi)$ on the sky:

$$\Delta T(\theta, \phi) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\theta, \phi)$$

(1.1)

where the $Y_{lm}$ are the well-known spherical harmonics. Because $\Delta T$ is a real-valued function, the coefficients $a_{lm}$ must satisfy $a_{lm} = (-1)^m a_{l(-m)}^*$, where the asterisk denotes complex conjugation. Each spherical harmonic represents a mode with fluctuations of a characteristic angular size. The $l = 0$ component represents the overall mean of the temperature on the sky. Similarly, the dipole ($l = 1$), quadrupole ($l = 2$), octopole ($l = 3$), etc., terms represent fluctuations at ever smaller angular scales.

We average over the azimuthal coordinate $m$ to get the power in each multipole mode as $C_l = \sum_m |a_{lm}|^2/(2l + 1)$. By plotting the power in each mode as a function of multipole index $l$, we generate a curve that represents fluctuation power as a function of angular scale on the sky. We expect that the magnitudes $|a_{lm}|$ to be drawn randomly from a Gaussian distribution at each $l$ (the phases, in contrast, are drawn from a uniform distribution), and for such fluctuations the angular power spectrum contains a complete statistical description.
Figure 1.2: CMB anisotropy map as measured by the Wilkinson Microwave Anisotropy Probe (WMAP) satellite\[5\]. The fluctuation amplitude is approximately 1 part in $10^5$ of the temperature on the sky.

### 1.2.2 Sources of CMB Anisotropy

On large angular scales ($\theta \gtrsim 10^\circ$ or $l \lesssim 20$), the CMB anisotropy is due to the gravitational redshift of photons escaping from gravitational potential wells (the Sachs-Wolfe effect)\[10\]. In the case of an overdense region, the gravitational redshift of photons climbing out of the potential well is partially compensated by the intrinsic extra temperature of the dense region. The net result is that photons arriving from overdense regions appear slightly cooler than average while those from underdense regions are slightly warmer. The Sachs-Wolfe effect is summarized simply as

$$\frac{\Delta T}{T} \propto -\frac{1}{3} \Phi$$

where $\Phi$ is the gravitational potential. In 1992, anisotropies at these scales were detected by the COBE satellite\[11\]. At intermediate angular scales ($50 \lesssim l \lesssim 1000$), the temperature fluctuations give rise to oscillations in the primordial photon-baryon fluid. Overdense regions tend to pull matter in as photon pressure resists the infall into these potential wells.
These two opposing forces produce compression and rarefaction modes in the early Universe. At the time of recombination, these modes leave an imprint of their state in the CMB in the following way: if a given mode has had time, since the Big Bang, to compress just once, it will produce an excess of power at angular scales corresponding to the wavelength of that mode. If a mode has had time to compress and return to the average density of the Universe, it produces a dearth of power at that angular scale. In general, it is the modes that have had a half-integer (1/2, 2/2, 3/2, etc.) multiple of periods from the Big Bang to recombination (380,000 years later) that produce excess power. This process is shown schematically in Fig. 1.3.

Figure 1.3: A schematic of how certain modes produce excess fluctuation power. The solid line represents a mode that has only had time to compress during the period from the Big Bang to recombination. At recombination, the imprint of the overdense region is left in the CMB. The dashed line shows a mode that has had time to just return to the average and produces no anisotropy. The dash-dot line shows a mode that has compressed, passed through the average, and then reached a point of maximum rarefaction. Because the power spectrum is insensitive to the sign of the perturbation, underdense regions produce positive power just as overdense regions do. See [6] for more information.

At small angular scales \((l > 1000)\), the anisotropy spectrum of the CMB is dominated by exponential damping caused by photon diffusion (Silk damping)[12]. Fluctuations on scales smaller than the photon random-walk diffusion length are smoothed out, thus reducing the
anisotropy power on those scales. Together with the previous two effects, the major features of the CMB angular power spectrum can be explained.

The detailed features of CMB power spectra can be explained by models that take into account the geometry, baryon, dark matter, and dark energy content (among other parameters) of the Universe. Results from the recent WMAP 3-year dataset and the current best-fit model are shown in Fig. 1.4[13]. These results have been a dramatic confirmation of theories of the history of the early Universe. Now that the large scale features have been mapped out, the attention of the CMB community is now turning to high-resolution maps in order to measure the features of the CMB power spectrum at small angular scales. Doing so gives additional leverage on accurately determining parameters such as the primordial fluctuation scalar spectral index $n_s$. However, the CMB story doesn’t end there.

1.3 Secondary Anisotropies

Though the CMB is often colloquially referred to as the “surface of last scattering”, approximately 10% of CMB photons will scatter again from intervening ionized matter between us and the CMB.\(^1\) These effects include reionization (the ultraviolet radiation from the first stars dissociating neutral hydrogen), the Ostriker-Vishniac effect (scattering induced by the velocity of intervening gas clouds), the thermal Sunyaev-Zeldovich effect (scattering caused by the hot gas in galaxy clusters) and the kinetic Sunyaev-Zeldovich effect (analogous to the Ostriker-Vishniac effect in a cluster).

Of these, one of the most significant is the thermal Sunyaev-Zeldovich (SZ) effect. Most of the luminous (i.e. not dark matter) mass in a typical galaxy cluster comes from hot ($T > 10^6 - 10^7 K$) intra-cluster gas. At these temperatures, the gas is highly ionized, and a small fraction of CMB photons ($\sim 1\%$) will inverse-Compton-scatter off these hot, thermal electrons and gain energy. Because the number of photons is conserved, this energy gain results in a distortion of the CMB thermal spectrum towards higher frequencies. For a

\(^1\)In addition to photon-electron scattering processes, photons can also be gravitationally lensed by intervening matter, leading to a spatial distortion of the CMB anisotropies.
Figure 1.4: The CMB angular power spectrum. The points show the measurements from the WMAP 3-year dataset; the red line is the best-fit model to these results, indicating a Universe with 4% normal matter, 23% dark matter, and 73% dark energy. The grey region represents the inherent uncertainty in the model due to cosmic variance. Figure courtesy WMAP science team[13].

Cluster whose electron temperature and number density are described by $T_e$ and $n_e$, this distortion is given by

$$\frac{\Delta I_{SZ}}{I_0} = g(x) \int_{\text{LOS}} n_e \frac{k_B T_e}{m_e c^2} dl \quad (1.3)$$

where $x \equiv \frac{h \nu}{k_B T_{\text{CMB}}}$, $I_0 = 2(k_B T_{\text{CMB}})^3/(hc)^2$ and, in the limit of nonrelativistic electrons,

$$g(x) = \frac{x^4 e^x}{(e^x - 1)^2} \left( x \frac{e^x + 1}{e^x - 1} - 4 \right) \quad (1.4)$$

which is plotted in Fig. 1.5[14].

In terms of temperature, the distortion is given by

$$\frac{\Delta T_{SZ}}{T_{\text{CMB}}} = \left( x \frac{e^x + 1}{e^x - 1} - 4 \right) \int_{\text{LOS}} n_e \frac{k_B T_e}{m_e c^2} dl \quad (1.5)$$
Figure 1.5: The shape of the frequency-dependent distortion $g(x)$ (Eq. 1.4) on the specific intensity of the CMB due to the SZ effect. The dashed vertical line at 218 GHz indicates where the specific intensity is unchanged. The effects of relativistic electrons in the galaxy cluster will shift the frequency of this null higher as well as reduce the peak intensity of the effect.

The integrand in equations 1.3 and 1.5 is simply the gas pressure $n_e k_B T_e$. Integrating along the line of sight and then subsequently integrating $\Delta T_{SZ}$ over the solid angle of the cluster results in a measure of the total number of electrons in the cluster (and hence, the mass of the cluster) weighted by the electron temperature distribution:

$$\int \Delta T_{SZ} d\Omega \propto \frac{N_e(T_e)}{D_A^2}$$  \hspace{1cm} (1.6)

where $D_A$ is the angular diameter distance of the cluster.

It is important to note that the redshift $z$ appeared in none of the previous equations. One of the key features of the SZ effect is, in fact, that its strength is independent of the redshift of the cluster in the limit of nonrelativistic cluster electrons (and weakly dependent in the relativistic case). In addition, as can be seen from Fig. 1.5, the thermal SZ effect has a characteristic spectral shape that is readily distinguishable from the CMB. This has profound implications for the possibility of doing an SZ survey. Because the SZ effect does not suffer much cosmological dimming and because the angular diameter distance is...
Figure 1.6: The SZ effect in galaxy cluster CL 0016+16. Contours are SZ intensity from the OVRO and BIMA millimeter-wave interferometers; colors are X-ray intensity from ROSAT. Figure from [15]
relatively flat as a function of redshift at high redshift, galaxy clusters can be detected with the SZ effect at great distance. Therefore an SZ cluster survey is free of the typical biases such as Malmquist bias (preferentially detecting nearby objects because they suffer less $1/r^2$ dimming) that can affect surveys done using other techniques. An SZ survey is expected to find many clusters above a given mass threshold and, when combined with X-ray measurements of the cluster temperature and optical/infrared redshift data, will produce an unbiased catalogue of galaxy clusters at a wide range of redshifts to probe structure formation and the galaxy distribution in the Universe.

SZ observations to date have thus far largely focused on existing X-ray clusters (See, for example, Fig. 1.6). Undertaking an untargeted SZ survey requires the development of new telescopes with the capabilities to rapidly map large regions of the millimeter-wave sky in multiple bands to take advantage of the unique spectral signature. One of these telescopes is the Atacama Cosmology Telescope, described below.

1.4 ACT and CCAM

Though WMAP has and Planck no doubt will tell us much about the CMB anisotropy, their angular resolution limitations prevent them from measuring the features of the CMB angular power spectrum up to $l \sim 10,000$. Doing so requires experiments with both better angular resolution as well as improved sensitivity to detect the $\sim$few $\mu$K signals from secondary anisotropies as well as small-scale primary anisotropies.

The Atacama Cosmology Telescope (ACT)[16][17] will be an ideal tool for studying secondary CMB anisotropies. A 6-meter primary mirror coupled to the 3-color mm-wave Millimeter Bolometer Array Camera (MBAC) promise excellent angular resolution, high sensitivity, and fast mapping speed. The telescope is optimized for detecting the Sunyaev-Zeldovich effect with high signal-to-noise, allowing us to conduct an untargeted SZ survey of a strip in the southern sky. We have developed a receiver, CCAM, to test many of the technologies to be used in MBAC.
1.5 The Atacama Cosmology Telescope Project

ACT is a multi-institutional, multinational collaboration, with members from Princeton University, the University of Pennsylvania, NASA Goddard Space Flight Center, the National Institute of Standards and Technology at Boulder, Cardiff University, Columbia University, CUNY, Haverford College, INAOE, UBC, UMass, Rutgers University, University of Toronto, University of Pittsburgh, Universidad de Católica, and the University of KwaZulu-Natal. ACT is designed to make arcminute-scale three-color maps of the CMB. A six meter aperture results in an angular resolution of ∼2′ per pixel at 145 GHz. This resolution allows ACT to probe much smaller angular scales of the CMB power spectrum than have heretofore been studied (up to $l = 10,000$). At these scales, the CMB primary anisotropy power drops rapidly due to Silk damping, and even the strongest of the secondary anisotropies has a temperature of a few microKelvin. Detecting these miniscule signals requires not only sensitive detectors, but also a telescope that places a premium on control of systematic effects. ACT combats potential systematic effects in numerous ways.

First, ACT is an off-axis telescope with a clear aperture free from the scattering effects of a secondary mirror support structure. The reduction in sidelobe levels from this architecture helps ensure that spurious signals are not coupled into the camera system. In addition, ACT incorporates a “guard ring” around the periphery of the two mirrors to help control spillover to the ground. ACT will also be surrounded by a fixed ground screen so that any spillover that does exist will be reflected off the ground screen and to the sky. A drawing of ACT is shown in Fig. 1.7.

Perhaps just as important as the beam and sidelobe control is the choice of scan strategy. CMB experiments typically chop or scan between points on the sky in order to control the effects of $1/f$ drift in the instrument response. By modulating the sky signal at a known frequency, we move the signal band above the $1/f$ knee of the detectors. Many CMB experiments in the past have performed this chopping by moving one of the optical surfaces, either one of the mirrors or a dedicated flat chopping plate. However, this approach typically leads to modulating the instrument’s beam shapes on the sky and, worse, its sidelobe
response. To combat this, ACT is designed so that the entire telescope can scan back and forth in azimuth at 0.2 Hz. By moving the entire telescope, all of the optical surfaces stay fixed relative to one another producing consistent beams across the scan. In addition, using fixed optics prevents modulating resonant cavity modes between the detectors and reflecting surfaces.

Another significant contribution to systematic error is the atmosphere. Though the Atacama Desert is one of the best places in the world for mm-wave telescopes (see Sec. 1.5.2), the atmosphere above still emits substantially. A zenith sky temperature of 10 K gives a sky temperature gradient at 45° elevation of 236 mK per degree. Even a small
change in elevation will produce an atmospheric ‘signal’ many orders of magnitude larger than the cosmological anisotropies. Thus, in conjunction with the fixed optical surfaces, ACT is designed to make CMB observations while azimuth-scanning at a fixed elevation. Doing so ensures that the atmospheric contribution to the noise remains fixed for a given pixel as the telescope scans back and forth.

The final piece of the ACT scan strategy is the choice of observing positions on the sky. The ACT scan implements cross-linked scan by observing at two different central azimuth positions symmetric about the South Celestial Pole (SCP) while maintaining the same elevation. At one azimuth position, sky rotation coupled with the telescope scan motion sweeps out a ring at a central declination of -55°. At the other azimuth position, the same ring is covered; however, the direction of the scan on the sky is different than the scan direction from the first azimuth position. This produces a cross-linked map as shown in Fig. 1.8. Cross-linking is an essential element in producing a high-quality map that minimizes the effects of pointing-induced systematics and long-timescale $1/f$ detector drifts.

1.5.1 MBAC

The heart of ACT is the receiver, called the Millimeter Bolometer Array Camera (MBAC). MBAC consists of three independent cameras contained in a single cryostat, each pointing at a slightly different spots on the sky, in frequency ranges (145, 220, and 270 GHz) that neatly bracket the SZ null (see Fig. 1.9). Each camera will contain low-pass and band-defining filters, anti-reflection-coated silicon lenses, and a 32x32 array of transition-edge-sensor pop-up bolometers from Goddard Space Flight Center[18]. The detectors are cooled to ~280 mK using pulse-tube closed-cycle refrigerators[19] coupled to a $^4\text{He}/^3\text{He}$ sorption refrigerator[20], and are read out using time-domain SQUID (Superconducting Quantum Interference Device) multiplexors from NIST[21].
1.5.2 Location

ACT will operate from Cerro Toco, a mountain in the Chilean Andes. Previous CMB experiments (MAT/TOCO[23], CBI[24], and MINT[25]) as well as other projects (notably ALMA[26]) have chosen the Atacama as the ideal site for high-sensitivity measurements. The 17,000-foot altitude of the ACT site coupled with the dry air of the Chilean desert promise low sky temperatures and low noise. Fig. 1.9 shows the expected atmospheric emission temperature from Cerro Toco. ACT will observe only at night, when atmospheric conditions are most favorable.

1.5.3 Projected Performance

ACT will scan a region of sky centered around declination $\delta = -55^\circ$, mapping a total area of $\sim 240$ deg$^2$. Of the total sky coverage, roughly 100 deg$^2$ will be free from significant galactic foreground contributions and will be used for CMB and SZ survey analysis. The CMB sensitivity is estimated to be 300, 500, and 700 $\mu$K sec$^{1/2}$ per detector at 145, 220, and 270 GHz, respectively[22]. After one observing season we expect ACT to reach a sensitivity of a few microKelvin per 2' map pixel. In addition, this sensitivity gives an SZ galaxy cluster limiting mass of $M \gtrsim 2 \times 10^{14} M_{\odot}$, meaning all galaxy clusters above that mass limit can be detected. We expect ACT to detect 500-1000 galaxy clusters.

1.6 CCAM

CCAM (Column CAMera) was built to test many of the elements that will go into MBAC. A new cryostat was designed to house the two pulse tube refrigerators, closed-cycle helium sorption coolers, optics, TES detectors, and SQUID readouts, all of which are the same as or similar to those to be used in MBAC. The receiver was coupled an off-axis mirror system used by the WMAP group for initial sky observations from Princeton, NJ[27]. Each of these components will be described in detail in subsequent chapters. In addition, the results of our initial observations will be presented.
Figure 1.8: A schematic of how the ACT scan strategy produces cross-linked maps. Initially, ACT scans, at constant elevation, about the region indicated by the heavy red line. Sky rotation causes this scan to sweep out a ring. Some time later, ACT repoints to the region indicated by the heavy green line. This scan is similarly swept into the same ring on the sky, but the scan direction on the sky is different, thus producing a cross-linked dataset. Figure inspired by Jeff Klein at the University of Pennsylvania.
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Figure 1.9: Left: Plot of the atmospheric emission on Cerro Toco. The zenith optical depth is 0.04, which is achieved > 35% of the time in winter and ≈ 25% of the time in summer. Right: Plot of the fluctuation spectrum of the mm-wave sky with our spectral bands. The anisotropy is given as $\left(\frac{\partial B_\nu}{\partial T}\right) = \delta T$ with $\delta T = 100 \ \mu K$ and we use a Compton $y = 5 \times 10^{-5}$ for the S-Z effect, typical for a $z = 0.5$ cluster. Figure and caption from the ACT proposal[22].
Chapter 2

Cryogenics

2.1 Cryostat Overview

The CCAM cryostat was designed from the ground up with an entirely new approach to cryostat design. Instead of housing all of the components inside a single cylindrical vessel, CCAM is modular, with the refrigeration segregated from the detectors and optics. The primary motivation for this design was the space constraint imposed by the use of the WMAP Reflector Evaluation Unit (REU)[28] and to allow different people to work in parallel on different pieces.

2.2 Overall Design Considerations

The preferred orientation for a pulse tube refrigerator is with its axis vertical; however, the optics need to be aligned with the beam from the secondary mirror. This places the optical axis at 25.5° above horizontal when the telescope is observing at its nominal 45° elevation. Using separate enclosures for the optics/detectors and refrigerators allowed the refrigerators to operate at their nominal position during normal observations. The modular design also allowed us to build a compact cryostat, giving the telescope the elevation pointing range necessary to observe point sources high in the sky. An overall view of the cryostat is shown in Fig. 2.1.
Figure 2.1: The CCAM cryostat. The mounting plate is 26" wide and 42" long, and the optics tube axis is angled 25.5° above the horizontal. The dewar is made of aluminum.

2.3 Pulse Tube Refrigerators

The refrigeration system is built around two Cryomech\(^1\) PT407 Pulse Tube Refrigerators (PTR). PTR operation is well-documented elsewhere ([29][30][19]), so they will not be

\(^{1}\text{Cryomech, Inc: http://www.cryomech.com/} \)
Figure 2.2: Cryomech PT407 performance chart from [31]. CCAM pulse tubes operate at about 60K on the first stage and 3K on the 2nd stage.

described in detail here. For the end user, the PTR has several advantages over traditional Gifford-McMahon (GM) cryocoolers, stemming from the PTR’s lack of a reciprocating displacer. Because there are no reciprocating components, the vibration generated by a PTR is much lower than a GM, important in reducing spurious microphonic signals in the detector electronics. In addition, the lack of cold seals enhances reliability. Its primary disadvantage is that it must be operated with the cold end pointing down (within \( \sim 25^\circ \) of vertical) or the cooling performance degrades.

The PT407 refrigerators each provide 0.7 W and 25 W at 4.2 K and 55 K, respectively, with minimum (no load) temperatures of 2.2 K (2nd stage) and 30 K (1st stage). The performance chart of the PT407, provided by Cryomech, is shown in Fig. 2.2. Our refrigerators use Cryomech CP970 compressor units, one air-cooled and one water-cooled, and each consumes approximately 9 kW of input electrical power.
2.4 Sorption Refrigerators

In order to achieve temperatures below \( \sim 3 \) K, we use a closed-cycle \( ^4\text{He}/^3\text{He} \) adsorption refrigerator system. The system is described in detail in [20] and [32]. Each sorption refrigerator (one filled with \( ^4\text{He} \) and one with \( ^3\text{He} \)) consists of two “cans” connected by a thin stainless steel tube. The \( ^4\text{He} \) refrigerator has a copper disk (the “condensation plate”) soldered in place on the connecting tube that is thermally connected to the PTR baseplate. The \( ^3\text{He} \) fridge has two plates; the upper plate is connected to the PTR baseplate while the lower plate is thermally strapped to the \( ^4\text{He} \) lower can. The upper can (the “pump”) houses activated charcoal while the lower can (the “pot”) collects liquid helium as it condenses.

The pumps are normally thermally connected to the pulse tube baseplate via a gas-gap heatswitch. The gas-gap heatswitches consist of a thin-wall stainless-steel tube whose internal volume is filled with helium gas. Connected to this volume is a small, secondary volume holding a small amount of activated charcoal and a 10 kΩ heater resistor. When the heater is off, the helium gas is adsorbed onto the charcoal and the thermal conductivity from one end of the tube to the other is simply that of the thin-wall tube. When the heater is on, the helium desorbs and fills the stainless-steel tube, increasing the thermal conductivity from one end to the other. Thus, when the heater is off, the gas-gap heatswitch is “open”; “closing” the heatswitch corresponds to turning the heater on.

Each refrigerator is a sealed volume filled with 700 psi \( ^4\text{He} \) or 500 psi \( ^3\text{He} \) of gas at room temperature. A drawing of the system is shown in Fig. 2.3. The CCAM sorption refrigerators were built by Judy Lau.

With the entire system cooled to 3 K, the cycle is as follows (normal text indicates actions performed on the fridge and italics indicate the system’s response to those actions):

- Open both gas-gap heatswitches, heat \( ^4\text{He} \) pump to 45 K and \( ^3\text{He} \) pump to 35 K
- \textit{Helium-4 gas condenses at} \( ^4\text{He} \) \textit{condensation plate and drips down into pot}
- When \( T_{4\text{He \ pot}} \) < 3 K, shut off \( ^4\text{He} \) pump heat and close \( ^4\text{He} \) heatswitch.
Figure 2.3: Sorption refrigerator system. The lines represent thermal connections. The cycle process is described in the text.
• As the pump cools to $\sim 5\ K$, charcoal acts as vacuum pump, reducing vapor pressure over helium liquid, reducing its temperature to $0.7\ K$.

• $^3\text{He}$ condensation plate cools to $0.7\ K$ which causes $^3\text{He}$ to condense.

• Shut off $^3\text{He}$ pump heat and close $^3\text{He}$ heatswitch.

• Pump cools to $\sim 5\ K$, cold charcoal pumps on liquid $^3\text{He}$ dropping its temperature to $\sim 0.25\ K$.

2.5 Fridge Boxes

Each of the two “Fridge Boxes” was designed to contain a PTR and a helium sorption cooling system. The larger of the two, Fridge Box 1 (FB1), contains a $^4\text{He}/^3\text{He}$ system to cool the detectors while Fridge Box 2 (FB2) uses just a $^4\text{He}$ refrigerator to cool the last lens and the cavity around the detectors. What follows below is a description of the construction of FB1; FB2 was built and tested by Judy Lau following a design similar to that of FB1. Fig. 2.4 shows the layout of FB1.

2.5.1 Vacuum Shell

The vacuum shell of FB1 was cut from a solid block of aluminum\(^2\) in order to eliminate potential failure points at welded joints. Most of the interior volume was cut out using a bandsaw and machined to final shape.\(^3\) The outside dimensions of the FB1 vacuum shell are $22.00”\times 17.5”\times 6.25”$ with a $0.500”$ wall thickness. Many areas on the outside of the shell are milled out to $0.250”$ thickness to reduce weight; only the areas around vacuum seals and the handles were left at the full wall thickness. The vacuum lids are $0.375”$ thick and are secured by 10-32 socket-head cap screws that thread directly into tapped holes in the vacuum shell.

\(^2\)Unless otherwise specified, “aluminum” refers to 6061-T6 aluminum alloy, and “copper” refers to oxygen-free high-conductivity (OFHC) copper.

\(^3\)The “drop” material was subsequently used for the vacuum shell of FB2.
Figure 2.4: The layout of Fridge Box 1 as viewed with the lids removed. Not shown are various thermal interconnects.
O-ring glands for 3/32” (nominal) size O-ring material were cut into the large faces of the vacuum shell and o-rings were made by cutting Buna-N O-ring cord to length and gluing the ends together with cyanoacrylate. The remainder of the O-rings in the vacuum shell are standard AS568A-sized O-rings.

2.5.2 40K and 4K Shells

The 40K and 4K shells are similar in design. Each is built off of a large, vertically-oriented copper plate (0.250” for the 40K shell and 0.125” thick for the 4K shell), with four walls made of 0.250” aluminum and a 0.050” thick lid. The copper plates are necessary as they provide the thermal connection from the PTR to their corresponding shells inside the detector box. The bottom wall is left at 0.250” thick for strength while the remaining three walls have large regions milled to 0.050” thickness to reduce their heat capacity and weight. Some areas are left at full thickness to provide strength for mechanical support (see §2.5.3). Additionally, a pair of triangular gussets tie the copper plate rigidly to the bottom aluminum plate. The top wall of each shell has a large circular cutout for the PTR to pass through. The 40K shell has dimensions of 19.5”w×15.375”h×5.925”d and the 4K shell, which nests inside the 40K shell, is 17.5”w×14.3125”h×5.246”d.

Each shell is covered with Cryolam superinsulation, which has aluminized mylar laminated with a non-woven polymer fiber spacer layer. The 40K shell has ten layers and the 4K shell has seven. While it would have been advantageous to include more layers, especially on the 40K shell (as it sees the large radiative load from the 300 K dewar walls), space limitations precluded their use. The expected radiation load is given in Table 2.1.

2.5.3 Mechanical and Thermal Design Considerations

One disadvantage of the rectangular geometry is that it lacks the self-supporting qualities of a cylindrical shape when under vacuum. As such, the wall thicknesses need to be thicker than one might otherwise expect to control the deflection induced by vacuum inside the

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4Cryolam is made by MPI Products: http://www.mpirelease.com/.
dewar. The vacuum lid on FB1 has the largest area and as such is subject to the largest force and deflection. A calculation using a standard formula for the deflection of a fixed plate held at the edges with force (surface area × atmospheric pressure ≈ 5700 lbs) evenly applied over the entire surface produces a deflection of approximately 0.1”. The clearance from the vacuum lids to the 40K shell was then set to accomodate this deflection with some margin of safety to prevent a thermal short from 40K to room temperature. The remaining four walls, due to their much narrower width, have deflections less than 0.005” and thus their deflections were neglected in the design of the inner shells.

In more traditional designs, the cryostat is built around the cold head which provides a modicum of mechanical support to the different temperature cold plates. In CCAM, we wanted to mechanically decouple the PTR from the cryostat to reduce the risk of vibrations coupling microphonically into the detectors. Therefore we had to solve the problem of supporting the shells inside the dewar while keeping them thermally isolated.

The weight of each shell is supported by a pair of G10 tubes as shown in Fig. 2.5. The tubes supporting the 40K shell are 2.625”O.D.×5.00”lg×0.0625” wall thickness. Each tube has an aluminum mounting ring glued to each end using 3M Scotch-Weld 2216 epoxy. In order to ensure a good bond, the gluing surfaces on the tubes and rings were roughened with sandpaper and then cleaned with acetone, isopropyl alcohol, and trichloroethylene or methylethylketone. The room-temperature end of the each tube sits bolts to the bottom of “cup” that attaches to the bottom of the fridge box and the cold end bolts to the underside of the 40K shell’s 0.250”-thick bottom plate. The tubes are each wrapped with 20 layers of superinsulation. The G10 tubes are the dominant source of thermal load on the PTR’s second stage (at ∼3K), as discussed in §2.10.

The tubes supporting the 4K shell are slightly more complicated. They use a twin-tube re-entrant design to increase the thermal path length between the 40K and 4K shells. The outer tubes, 1.835”O.D.×4.40”lg×0.0425” wall, mount to the 40K shell and extend downward inside the 40K support tubes. Each end has an aluminum mounting flange epoxied to it; in addition, each flange is attached to the tube using six radially-oriented
Figure 2.5: Cross-section of the G10 tubes that support the shells inside FB1. The mounting flanges are made of aluminum and attached to the G10 with epoxy, and each tube is wrapped with 20 layers of superinsulation. The thermal load from the tubes is discussed in §2.10.

6-32 socket-head cap screws. The lower flanges also serve as the lower flanges for the inner tubes, at 1.085” O.D. × 5.00” lg × 0.0425” wall. These tubes extend upward and attach to the bottom plate of the 4K shell, again with an epoxied aluminum flange on the upper end.

The G10 tubes support the weight of the shells but do not constrain the side-to-side (i.e. along the smallest dimension) motion. As the entire telescope scans in the azimuth (side-to-side) direction, it is imperative that the components in the dewar not shift when subjected to these forces. We implemented a suspension system using titanium wire to hold the shells in place. For the 40K shell, each support consists of a titanium wire assembly, a pair of stainless steel brackets, and an aluminum clamp. Titanium was chosen for its low (for a metal) thermal conductivity and excellent strength.

Each titanium wire assembly consists of a piece of 0.050”-diameter, 5.125”-long 6Al4V titanium wire and ends made of 0.250” x 0.250” 6Al4V titanium bar. A 0.052” hole is drilled into the middle of one of the long faces of each bar, along with two 6-32 tapped
holes. A bar is then welded to each end, taking care to fully purge the weld area with argon shielding gas to avoid oxidation, which would reduce the strength of the welded joint. One of these assemblies was subjected to a pull test; with a load of 150 lbs applied overnight, the tension did not change, indicating that the material did not stretch over that time. The ultimate strength of the wire assembly was approximately 240 lbs, in rough agreement with the ultimate tensile strength of the titanium wire alone, indicating that the welding process did not compromise the strength of the finished assembly.

The stainless steel brackets are screwed to the inside wall of the vacuum shell and one end of the titanium wire is firmly attached to the inboard bracket. However, the titanium wire assembly is slightly shorter than the space between the brackets; thus, the screws at outboard end pull on the free end of the titanium wire to tension it. The wire is then clamped at its midpoint to the outside of the 40K shell. The aluminum clamp consists of a pair of 0.250”x0.250” bars with either two 6-32 clearance holes or two 6-32 tapped holes drilled through it. The block with clearance holes acts as a spacer between the 40K shell and the wire to avoid pulling radially on the wire. The tapped block is then clamped on top of the wire, secured by screws threaded from the inside of the shell.

The system for the 4K shell is similar, though it uses smaller diameter wire (0.040”) as well as shorter wire assemblies (4.375”) due to its smaller dimensions. Each shell uses six wire assemblies to hold it in place. To test the robustness of the suspension system, the 40K shell was mounted into the vacuum shell using only the titanium wires as support. The fridge box was placed on its side and a ∼175 lb force\(^5\) was applied repeatedly. The shell showed no signs of slippage.

The PTR is coupled to the shells using flexible couplings made from 1/4”-diameter OFHC copper rope.\(^6\) The wire rope has a thermal cross-sectional area and length of 50% and 110% of the actual area and length. The 40K stage uses two separate couplings, each with sixteen sections of 1” long rope, with ends made of OFHC copper welded on. Because the PTR sits inside the 4K shell, the 4K copper plate has large cutouts to allow the couplings

\(^5\)Roughly the weight of one grad student.
\(^6\)New England Wire Technologies; http://www.newenglandwire.com/
to attach to the 40K plate. The resulting gaps are then covered by superinsulation. They attach to the 40K stage of the PTR via a pair of copper fingers that extend downward off the cold stage. The 4K coupling uses sixteen 0.95”-long sections of copper rope with welded copper ends that bolt directly to the 4K stage of the PTR and to the 4K copper plate. All critical thermal connections utilize either flat sheets of indium or, in cases where precise dimensional tolerances must be kept, Apiezon N grease\textsuperscript{7} in order to reduce thermal contact resistance.

Because the 40K stage of the PTR sits entirely inside the 4K shell, it produces a significant radiation load ($\sim 50 \mu W$) to the sorption refrigerators in the fridge box. In addition, the concentric holes in the 40K and 4K shells provide a potential leak path for 300K radiation to enter the cold volume. In order to mitigate these effects, we first surround the 40K stage with a tight-fitting copper cylinder extending upward slightly past the 40K shell. The cylinder is held in place and thermally connected to the 40K stage using a stainless steel hose clamp. The gap between the can and the 40K shell is sealed with aluminized mylar tape. In addition, the entire section of the 40K stage inside the 4K shell is covered with 2 layers of superinsulation to further reduce the radiative load onto the sorption refrigerators.

\textbf{2.6 Detector Box}

The Detector Box (DB) houses the detectors and their associated cold electronics. Its shape is a right trapezoid in cross-section (see Fig. 2.6), with the angled upper lid removed for access to the inside and dimensions $18.00" \times 9.875" \times 17.51"$ (front) or $7.12"$ (rear). Due to the large dimensions, cutting the DB vacuum shell from a single piece of aluminum was deemed infeasible. Instead, it was constructed of six individual aluminum pieces – one $1/2"$-thick piece for each of the four vertical walls, and one $3/8"$-thick piece for each of the two large vacuum lid flanges – which were then dip-brazed to form a single unit.\textsuperscript{8} The vacuum flanges were made of separate pieces in order to avoid having to machine through

\textsuperscript{7}M&I Materials, Ltd.: http://www.apiezon.com/

\textsuperscript{8}The dip brazing operation was performed by Brazonics, Inc.: http://www.brazonics.com/
brazed joints while cutting the o-ring glands for the lids.

Figure 2.6: Cross-section of the shells in the Detector Box. The large open area to the left of the detectors houses the cold electronics for addressing and reading out the detectors.

The DB contains 40K and 4K radiation shells, each with a 1/4”-thick copper bottom plate and 1/4”-thick aluminum walls. The front plate of 4K shell is made of 1/4” copper and serves as a thermal link between the 4K baseplate and the optics tube. The lids are 1/8”-thick aluminum. Each shell is covered with 20 layers of superinsulation. The shells are supported by G10 tubes, of the same re-entrant design used in the fridge boxes, in three locations on each baseplate. Instead of using titanium wires, the lateral motion of the shells is suppressed with an X-shaped G10 brace that attaches to the inner walls of the warmer shell (300K,40K) at the ends of the “X” and to the lid of the colder shell (40K,4K) in the center.
2.7 Thermal Connections

The DB shells are thermally and mechanically connected to the FB1/2 40K and 4K plates via a pair of concentric copper tubes on each side. The outer 40K tube on each side has a 4.500” OD, 3.712” ID, and is 2.200” long. It bolts to the inboard side of its corresponding Fridge Box’s 40K plate using six 10-32 screws and passes through 5.000”-diameter holes in both the FB and DB vacuum shells. The end of the tube is held by a split clamp, and the clamp attaches to the 40K baseplate via a flexible coupling utilizing twelve 0.875” long copper rope segments. The tight tolerance of the tube-to-clamp fit requires the use of Apiezon N grease instead of indium. The 4K shell is connected in a similar fashion using a slightly smaller tube (3.250” OD × 2.750” ID × 3.340” long) and correspondingly smaller clamp and coupling with eight copper rope segments.

The sorption refrigerators are mounted to their corresponding Fridge Box baseplates via a right-angle copper “shelf” (Fig. 2.7) bolted to the condensation plate ($^4$He) or pre-cooling plate ($^3$He). In the case of the $^4$He fridges, the condensation plates are also connected directly to the PTR 2nd stage with braided copper straps.

![Figure 2.7: The $^4$He sorption fridge and its mounting shelf. The 4K baseplate is on the right and vertical in this figure. The $^3$He sorption fridge uses a similar mounting shelf.](image-url)
Cooling the detectors and baffling proved to be a significant challenge due to the geometry of the cryostat. The detectors in the Detector Box are cooled by the $^3$He refrigerator in FB1. In order to connect them thermally, a series of copper links winds through FB1, through the 4K tube connecting FB1 and the Detector Box, down toward the DB 4K baseplate, and then up to the detectors. The thermal link contains flexible sections to allow for stresses induced by cooling. The link is supported by a pair of kevlar “spiders” as it passes through the 4K connecting tube, and by a $4.500\text{"}lg \times 0.290\text{"} OD \times 0.020\text{"}$ wall Vespel tube inside the detector box. The entire link is constrained from moving laterally by clamping it to tensioned kevlar string in the Detector Box. The link from FB2’s $^4$He sorption fridge is similar in concept, though the details differ due to the slightly different geometry and because it uses a $0.010\text{"}$-wall G10 support tube instead of Vespel.

Parts of the 0.3 K thermal path are shown in Figs. 2.8 and 2.9.

2.8 Optics Tube

CCAM’s optics are contained in a cylindrical tube at the front of the Detector Box (see Fig.2.10). The Optics Tube (OT) vacuum can is made of aluminum with a $9.250\text{"} OD$, a $9.000\text{"} ID$, and an overall length of $15.375\text{"}$, and has $0.375\text{"}w \times 0.250\text{"}$-thick flanges at each end. The window end of the optics tube holds a machined piece that allows the mounting of the window holder previously used for the MAT/TOCO experiment. The window itself is a single piece of $0.022\text{"}$-thick polypropylene, sealed against vacuum with an o-ring. Alternatively, the window mount may be replaced with a vacuum can extension allowing the mounting of a heatable blackbody calibrator.

The 40K shell is made of $0.0625\text{"}$-thick aluminum with welded flanges on each end. It attaches to the DB 40K shell using 4-40 screws, and the first low-pass filter ($\S4.3.3$) is clamped to its lid. The 4K shell is made of $0.060\text{"}$-thick Cryoperm with flanges at each end. It attaches to the ring at the base of the 4K optics mounts which then attaches to the copper front panel of the DB 4K shell. Both shells are covered with 20 layers of superinsulation.

The 4K optics are held by a frame consisting of three $0.500\text{"}$-diameter copper rods held
Figure 2.8: Fridge Box 1, showing all thermal connections and wiring. The 0.3 K thermal link can be seen coming upward from the bottom of the $^3$He fridge and then disappearing behind it into the Detector Box.
Figure 2.9: The thermal links inside the Detector Box. The copper pieces on the right come from FB1 and route 0.3 K cooling power to the “upper” semicircular flange in the middle of the picture. The links on the left come from FB2 and are used for cooling the “lower” semicircular flange to 0.6 K. Also shown is the cryogenic breakout board (CBOB) and the cryogenic wiring from it to the rest of the dewar. The mechanical heat switch is used to thermally short the 0.3 K and 0.6 K stages to 4 K to speed their cooling from room temperature.
Figure 2.10: Cross-section of the Optics Tube. The rays reach their focus at the detector plane. Not shown is the neutral density filter (NDF) used for observations from Princeton. The NDF is placed between Filter 2 and Lens 1.
by copper rings at each end. The individual copper mounts for each optical component (lenses, filters, baffling) slide into the frame and clamp on to the rods to make solid thermal and mechanical connections. Each mount also bolts to the pieces adjacent to it, providing an additional thermal path for heat loads.

The third lens and baffling leading up to the detectors are held at 0.6 K. They are thermally isolated from the 4K optics tube section by three short G10 tubes, each of which has a 0.250” OD, 0.010” wall, and is 0.395” long. They are glued to aluminum mounting rings which are then bolted to the 4K and 0.6K sections on either side. The gap created by the tubes is covered with a few layers of superinsulation to minimize 4K radiation entering the detectors. The optics mounts and optical baffling were designed, built, and tested by Judy Lau. The lens mounts were designed to accommodate the differential thermal contraction between the copper mount (0.3% at 4 K) and silicon lens (0.02% at 4 K).

2.9 Cryogenic Wiring

For initial tests, FB1 and FB2 used flat cryogenic ribbon cables from Tayco Engineering.\textsuperscript{9} These cables use fine-gauge manganin twisted-pair wires encased in a polyimide sheath and a conductive ground shield on each side of the ribbon. The cables are terminated with MDM25 Micro-D connectors via a custom PCB and strain relief shell (designed by Glen Nixon). At the dewar wall, another PCB adapts the MDM25 to a standard 26-pin MIL-C hermetic feedthrough.

The connectors and cables pass through 1.375” × 0.500” slots in the bottom plate of each shell. The slots are covered by aluminum plates and/or superinsulation to prevent a radiation leak from warmer stages into colder stages. The cables were heatsunk to the 40K bottom plate with a flat clamp, and the connector shells were clamped on the 4K baseplate. In each Fridge Box, one ribbon cable was used for diode temperature sensors (Lakeshore\textsuperscript{10} DT470 and DT670) and heaters while the other was reserved for Ruthenium.

\textsuperscript{9}Tayco Engineering, Inc.: http://www.taycoeng.com/
\textsuperscript{10}Lakeshore Cryotronics, Inc: http://www.lakeshore.com/
Oxide (Lakeshore ROX-202A, 2 kΩ warm resistance) resistive temperature sensors. At the cold end, homemade wiring breaks the MDM25 out to the various sensors and heaters.

Once the Detector Box and Fridge Boxes were integrated, we migrated to a system developed by our colleagues at the University of Pennsylvania. This system is based around a cold printed circuit referred to as the Cryogenic Break-Out Board (CBOB). The CBOB connects to the outside world via two MDM51 (cold end)-to-DD50 (warm end) cables, one carrying temperature sensor signals and the other carrying heater signals. The CBOB routes each of these signals to one of six MDM25 connectors to which cables, going to various parts of the cryostat, are connected. These manganin cables are a mixture of Tekdata\(^{11}\) cables and ones made in-house, and they are terminated by Microtech\(^{12}\) GM-series 2-pin strip connectors.

The diode temperature sensors come on integrated bobbins and are ready for use simply by soldering the appropriate connector on the end. The ROX sensors are potted in custom-designed copper mounts using Stycast 2850FT Black epoxy. The ROX sensor on the detector array itself is a bare-chip ROX-102A (1 kΩ warm resistance) and is glued to the detector circuit board. The in-house wiring was made and debugged by Judy Lau.

### 2.10 Performance

The expected heat loads on FB1 are shown in Table 2.1. The radiation load numbers are calculated using a standard formula for radiative heat transfer between two surfaces at temperatures $T_{\text{hot}}$ and $T_{\text{cold}}$

\[
P_{\text{rad}} = \frac{\epsilon}{n+1}A\sigma(T_{\text{hot}}^4 - T_{\text{cold}}^4)
\]

(2.1)

where $\epsilon$ is the emissivity of aluminum, $n$ is the number of layers of superinsulation, $A$ is the total surface area, and $\sigma$ is the Stefan-Boltzmann constant. The conductive heat loads were calculated based on conductivity values from the NIST cryogenic material properties database [33].

\(^{11}\)Tekdata Interconnect Systems: http://www.tekdata-interconnect.com/

\(^{12}\)Microtech, Inc.: http://www.mmm-microtech.com/
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<th>Load at 4K (mW)</th>
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</table>

Table 2.1: Expected thermal loading on FB1 alone

When FB1 was tested alone, it reached final temperatures of 36 K on the first stage and 2.5 K on the second stage. These temperatures correspond to loading values of roughly 7 W and 50 mW, respectively. Though within a factor of two of the calculated numbers, they are both significantly higher than the loading we expect. For the 40 K stage, the discrepancy is likely due to not accounting for the seams in the superinsulation. At seams, all of the layers are thermally shorted to $T_{\text{cold}}$, reducing the effectiveness of the superinsulation in that region and increasing the loading. The excess power on the 4 K stage, 20 mW, is likely due to a slight radiation leak from the 300 K dewar walls. A 300 K radiation leak through an area of less than 0.5 cm$^2$ would be sufficient to produce the observed loading. We did not attempt to further track down the source of these power excesses.

Adding the Detector Box to FB1 resulted in a negligible increase in 2nd-stage PTR temperature but a significant increase in the 1st stage temperature (to 55 K). Though the Detector Box has more superinsulation and slightly less area than FB1, it also has more openings that require joints in the superinsulation. With the dewar completely assembled (both Fridge Boxes, the Detector Box, and Optics Tube), the PTR 2nd stage is approximately 3 K, and the Detector Box 40K plate temperature rises to 70 K. We have not been able to find any evidence of a direct thermal short between the 40K shell and the vacuum shell, leaving excessive radiation loading as the most likely cause for the high temperature.

The FB1 sorption fridge system works as designed, routinely cooling the detectors to 280 mK with a pot temperature of 250 mK, corresponding to $\sim 20 \mu W$ of loading, in line with our expectations from wiring and mechanical support conductive loads. However, the FB2 $^4$He fridge temperatures are significantly higher than we would expect. A pot temperature
of 0.7 K implies almost 4 mW of loading on the fridge. However, all the sources of loading add up to <0.3 mW. The source of this discrepancy is currently being investigated.
Chapter 3

Housekeeping

A robust and reliable housekeeping system is essential for any CMB experiment. Besides allowing us to monitor the health of the experiment in real time, accurate housekeeping records are essential during the analysis stage. The CCAM housekeeping system is built around a Data Acquisition System designed and built by Barth Netterfield’s group at the University of Toronto for the BLAST experiment ([34]). Auxiliary hardware from the University of Pennsylvania and built at Princeton allows us to use this system for reading out and recording cryogenic temperatures as well as controlling heaters inside the cryostat. A block diagram of the housekeeping system is shown in Fig. 3.1 and a picture is shown in Fig. 3.6.

3.1 Data Acquisition System

The BLAST Data Acquisition System (DAS) is a flexible electronics package housed in a 6U (10.5” tall) rackmount enclosure. The DAS is built around a common backplane which communicates with a dedicated computer via a custom-built PCI card. A custom software package called amcp, written by Adam Hincks and Eric Switzer, controls the DAS. The DAS can accept up to 18 analog-to-digital converter (ADC) cards; for CCAM we only use three. Each channel is configurable by setting jumpers on the circuit board for unipolar or bipolar inputs in multiple voltage ranges. We use the DAS ADC channels for reading
in the cryostat temperatures, heater current levels, ambient magnetic field levels, cryostat pressure, ambient pressure, and ambient temperature.

Each ADC card contains 25 analog-input channels which are digitized with 24 bits of resolution at 100 Hz. In addition, each ADC card provides 24 bits of optoisolated open-collector digital output in three groups of 8 bits.\textsuperscript{1} Last, each card also has four pulse-width-modulated (PWM) output channels; the PWM carrier is a 15 kHz, 0-5 V square wave.

\section{Temperature Sensor Readout}

As mentioned in \S2.9, CCAM uses two types of cryogenic temperature sensors. The diode sensors are accurate from room temperature down to approximately 2 K. With a constant bias current, the voltage across the diode is a (monotonic) function of the temperature of the sensor. However, 2 K is not low enough to measure the temperatures achieved by the

\textsuperscript{1}Alternatively, each group of 8 bits can be configured as digital inputs; however, we do not use any of the digital channels as inputs.
sorption refrigerator system. The ruthenium oxide (ROX) sensors can be used from 40 K down to 0.1 K, providing the range necessary to measure the coldest parts of the system. ROX’s are resistive sensors whose resistance increases as the temperature decreases. Each type of sensor needs a specific type of bias and readout circuit.

### 3.2.1 Diode Bias and Readout

The diode bias and readout circuit is straightforward. We use a card designed and built by Mark Devlin’s group at the University of Pennsylvania containing 24 diode bias/readout channels. Each channel contains a current source that produces a 10 µA bias current. The bias current flows through the diode, and the voltage across the leads is measured and amplified with a Burr-Brown INA114 instrumentation amplifier before being digitized by the DAS. The diode voltage is a two-lead measurement, so voltage drop due to the resistance of the cryogenic wiring contributes to the measured voltage. However, this effect is small: the wire resistance on any given channel is <50 Ω total which produces a voltage drop of less than 0.5 mV with a 10 µA bias current. At 300 K, a 0.5 mV voltage offset corresponds to a ∼0.2K temperature error; at 3 K, only 0.02 K. As the diode channels are not used to monitor “critical” temperatures, these errors are negligible. In order to recover the temperature, amcp uses a lookup table with the standard DT-670 or DT-470 (depending on the channel) calibration curve.

### 3.2.2 ROX Bias and Readout

The ROX sensors use a different bias and readout system (also designed and built by Mark Devlin’s group). It consists of two separate cards, one generating an AC bias voltage at 200 Hz that biases the sensors and is also sent to the DAS as a reference. The bias signal is fed into a comb of bias resistors. Each ROX channel has two 900 kΩ resistors in series with the ROX to provide an approximate current bias for each sensor (see Fig. 3.3) Though the bias card has provisions for up to three separate bias lines, each with different excitation voltages, we only use one bias voltage for all ROX’s.
Figure 3.2: Simplified circuit diagram for diode bias/readout circuit. The grounds in the diode card are tied to the dewar case, and there are no sensor ground connections inside the dewar.

The voltage across the ROX (which, given the constant current bias, is proportional to the resistance) is amplified by an Analog Devices AD624 low-noise instrumentation amplifier with a gain of 100, bandpass-filtered, and digitized. The digitized waveform is then demodulated in software using the reference signal sent to the DAS to recover a DC voltage proportional to the amplitude of the AC voltage across the ROX. The voltage-to-resistance calibration is determined when the dewar is warm by connecting a range of known 0.01%-tolerance resistors in place of the ROX on each channel, fitting a straight line to the ADC counts vs. known resistance, and storing the coefficients of the fit in amcp’s configuration file. The ROX resistances are then converted to temperatures via a lookup table. Unlike the diodes, the ROX resistance is a four-lead measurement.

3.2.3 Cryogenic Break-Out Board

The only housekeeping connections to the dewar are two 50-pin cables: one for the heaters and the other for the diode and ROX biases and readouts. The task of routing these signals to appropriate connectors is handled by the Cryogenic Break-Out Board (CBOB), a printed circuit designed for BLAST. The CBOB is mounted on the Detector Box 4K.
Figure 3.3: Simplified circuit diagram for the ROX bias and readout system. The AC-coupled ROX signals are demodulated in software using the reference signal. Again, the sensor return is not grounded inside the dewar. The readout and bias cards are grounded to the dewar case.

baseplate and has two MDM51 connectors (one on each end) for the heat and temperature signals corresponding to the two 50-pin cables. The traces on the CBOB PCB route signals from the MDM51 connectors to one of six MDM25 connectors mounted to the top of the board. In addition, the CBOB holds the 900 kΩ resistors for the ROX bias. By putting these resistors inside the dewar, the number of ROX bias lines needed is reduced dramatically. Last, the CBOB also provides a convenient place to heatsink the housekeeping cables at 4 K.

Cables attached to the MDM25 connectors then distribute the wires to temperature sensors and heaters in FB1, FB2, and the Detector Box.
3.3 Heater Control

The Heater Break-Out Box (HBOB) allows us to monitor, control, and otherwise access heater lines going into the CCAM dewar. The HBOB interfaces with the DAS system to automate $^4$He/$^3$He sorption refrigerator cycling and PID control of selected measurement points inside the dewar. It incorporates various Vector cards in order to accomplish these tasks and others, listed below:

- Optoisolate Pulse-width-modulated (PWM) signals from DAS crate.
- Filter PWM signals to recover the control signal.
- Amplify control signal to power heaters.
- Control gas-gap heat switches for sorption fridges.
- Provide a way of monitoring the current sent to computer-controlled heaters.
- Allow access to heaters that bypasses control circuitry.
- Power all of the circuitry and heaters.

Each of these will be described in the following sections. The HBOB control software was written by Eric Switzer.

The HBOB is contained in an Alodined, electrically conductive 4U (7” tall) rackmount enclosure and is built around a card cage for standard Vector 4112-4 style Plugbords. Each card socket is wired with $+12$ V, $-12$ V, and ground from internal 1.5 A-rated voltage regulators. The card cage is mounted to an aluminum plate wired with heater resistors; the rightmost (looking from the front) card socket is designated for a standalone circuit to temperature-control the aluminum plate (currently not implemented).

The HBOB front panel contains 32 BNC panel connectors, three 37-pin D-sub connectors, and one 50-pin D-sub connector. The BNC connectors are arranged into two groups. The first group consists of the top two rows of 10 BNC’s each — these are the bypass/monitor BNCs whose functions will be described below (see §3.3.3, §3.3.4, §3.3.5).
Each bypass/monitor BNC has an accompanying LED above it to indicate whether or not that channel is currently being controlled by the computer. The second group is the bottom two rows of six BNC’s each — these are the current monitors and are also described in the aforementioned sections.

The two rightmost 37-pin connectors are used to interface with the digital output channels of the ADC cards. The remaining 37-pin connector is an output to carry the current monitor signals to another break-out card (mounted in the UPenn crate) where it combines with other miscellaneous housekeeping signals into one cable to be digitized by the DAS system. This allows us to record the current monitors along with the other housekeeping data. The 50-pin connector is the heater output to the dewar. All heater current is returned to the HBOB, and the HBOB case is grounded to the cryostat via the equipment rack. The back panel has only connectors to the external power supply (+/-15 V and +28 V).

3.3.1 Optoisolator Card

In order not to create unintended ground loops, we want to decouple the grounds between the DAS crate and the HBOB. For the 24 on/off digital outputs, this is easy. Because they are open-collector and each open-collector output is optoisolated on the DAS card, all we have to do is make sure that the pull-up and ground originate inside the heater box (see, for example, 3.3.3). The PWM outputs, however, are not optoisolated, so an optoisolator card was built (by Eric Switzer). It utilizes Fairchild H11L1M optoisolators, which come in a 6-pin DIP. Because the optoisolators also act as logic inverters, we added an additional inverter for each channel to recover the original PWM signal.

The H11L1M optoisolators, we found, have a significant propagation delay (approximately 1 ms); in addition, the turn-off time is longer than the turn-on time by another millisecond. These issues limit the useful range of the 15 kHz PWM signal to 10%–90% duty cycle. The H11N1M is nearly an order of magnitude faster and is pin-compatible with the H11L1M should it ever be necessary to utilize more of the PWM range.
3.3.2 PWM Filter Cards

In order to recover the control signal from the PWM output, we low-pass filter it. We use commercially-available 8-pole active filter modules made by Avens Signal Equipment\(^2\) in two flavors. The first filter card uses four filter modules with a cutoff frequency of 30 Hz. These are used for controlling slow-moving temperatures (most importantly, the sorption fridge charcoal pumps). The second card uses four 120 Hz low-pass filters for heater channels that may require faster response (for example, the detector board servo).

3.3.3 High-Power Heater Amplifier Cards

Each power amp card is based around an Apex Microtechnology\(^3\) PA75 dual power op-amp in a TO-220 package. It is configured in a parallel configuration, with a non-inverting master amp \((G \sim 8)\) and a unity-gain slave. They are configured to deliver approximately 3 W to a 200 Ω heater resistor. A circuit diagram is shown in Fig. 3.4.

Because we restrict the range of the PWM signal, we first subtract off a DC offset from the input using IC1. The components shown in the schematic result in an effective “zero” of the PWM signal at roughly 13.5-14%. IC2 is an active diode clamp meant to prevent negative voltages from being amplified by the power amp section. This is to avoid a potential inadvertent positive-feedback scenario from occurring in the temperature control servo loop.

The power amp section is as described before. The feedback loop of the master has a capacitor to roll off the gain at high frequencies. The 1 Ω resistors on the output of each side of the power op-amp are recommended by the manufacturer to improve current-sharing between the two sides. The diodes protect the output stages from high-voltage transients that could occur when the relay is switched and current is flowing. The output of the master/slave combination has an RC snubber to damp high-frequency oscillations that occur when driving inductive loads with \(V_{\text{out}} < 0\). Even with just a wirewound power resistor as a load we saw output-stage oscillations at \(\sim 10\) MHz that were eliminated with

\(^2\)http://www.avens-filter.com/
\(^3\)http://www.apexmicrotech.com/
the snubber. These oscillations are apparently due to the non-complementary NPN design of the output stage of the PA75. The input clamp should prevent the output from ever swinging negative; however, we have left the snubber in the circuit as a precautionary measure.

The output of the PA75 can only swing to within $\sim$2 V of its negative supply rail. In order to produce output near zero volts, the negative supply current must be less than approximately -2 V. We use a 7908 −8 V voltage regulator to provide the negative supply for the PA75 and still stay within its 40 V total supply voltage range.

The relay is a 1 A mini relay from Tyco Electronics/Axicom. The 392 Ω resistor and coil resistance act as the pull-up for the ADC board’s digital output. Pin E on our card is connected to an LED indicator on the front panel of our heater control box while pin 6 goes to the ADC board’s opto-isolated digital control transistor and returns to the heater board ground via pin 10.

The last section (IC4) is the current monitor. Because the output voltage of the power amplifier is higher than the supply voltage of all the other IC’s, including the current monitor, it is possible to exceed the common-mode input voltage range of the INA114. We use a voltage divider in order to bring the voltage back into range, and then set the gain for the INA114 to give a logical value for the output (10 V/amp in this case). The downside to this approach is that any error in the voltage divider resistor matching is magnified, leading to a output-voltage-dependent offset in the current monitor output. We currently use 0.1% tolerance resistors for the voltage divider.

3.3.4 Low-Power Heater Amplifier Cards

The low-power heater amplifier cards are functionally identical to the high-power circuits with a few notable exceptions:

- The PA75 power amplifier is replaced with a single OP-77 configured as a unity-gain buffer.
- The current monitor dropping resistors and/or gains are different.
• In order to prevent applying too much power to any given heater, the output is configured such that the heater load is the bottom resistor of a voltage divider. The upper resistor is chosen to limit the power dissipation in the load resistor at full output.

The last item implies that the voltage read out on the monitor/bypass front panel BNC is larger than the voltage across the load by a factor of $\sim 10-100$. This was a conscious decision in order to retain the use of the on-board current monitor even while the card is operating in bypass (relay-open) mode.

### 3.3.5 Heatswitch Control Card

Each of the gas-gap heatswitch control card’s four channels simply uses a voltage divider whose components are chosen to deliver 4.0V across the 10kΩ heatswitch heater resistor (Fig. 3.5). Each channel uses the same INA114-based current monitor stage and relay switching circuit as the previous cards. Because we have only three heatswitches, one of the channels is currently unused.
Figure 3.4: Circuit diagram for high-power heater amplifiers. The heavy line represents the high-current signal path. The heater current is returned to the HBOB and grounded to the HBOB case.
Figure 3.5: Heat switch control circuit. Like all the other heaters, the heater current is returned to the HBOB.
Figure 3.6: CCAM Housekeeping system. For a detailed connection diagram, see Appendix A.1.
Chapter 4

Optics

4.1 Optics Requirements

The goal for CCAM and ACT is to achieve diffraction-limited optical performance with a spatially-Nyquist-sampled array of detectors. Unlike a horn-coupled bolometer array, our bare array is sensitive to radiation from a $2\pi$ solid angle. Therefore the optics must be designed to control stray illumination which requires a well-defined pupil stop to limit the illumination of the primary mirror. In addition, because bolometers are inherently broadband devices\(^1\), filters are needed to define the observing bandpass and control loading on the detectors and cryogenics.

4.2 Warm Optics

As was mentioned in section 1.6, CCAM was designed to couple to a primary mirror, secondary mirror, and their associated structure originally designed as a test system for the WMAP satellite experiment. Though the mirrors were numerically optimized and the shapes are not the simple conic sections of traditional telescopes, the surfaces can be well-approximated by an off-axis Gregorian design. Reference [28] gives the parameters

\(^1\)Pop-up TES detectors of this type were originally used for X-ray telescopes; CCAM is the first mm-wave application of this technology.
Table 4.1: Parameters for the WMAP primary and secondary mirrors, from [28]

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Base</th>
<th>Best Fit</th>
<th>Equiv. Parabola</th>
</tr>
</thead>
<tbody>
<tr>
<td>Focal length, ( f_p ) (cm)</td>
<td>90</td>
<td>90</td>
<td>207</td>
</tr>
<tr>
<td>Primary projected radius, ( r_p ) (cm)</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>Offset parameter, ( y_c ) (cm)</td>
<td>105</td>
<td>104.03</td>
<td>⋯</td>
</tr>
<tr>
<td>Interfocal distance, ( 2c ) (cm)</td>
<td>45</td>
<td>43.58</td>
<td>⋯</td>
</tr>
<tr>
<td>Secondary eccentricity, ( e )</td>
<td>0.45</td>
<td>0.4215</td>
<td>⋯</td>
</tr>
<tr>
<td>( \beta ) (deg)</td>
<td>12.06</td>
<td>13.77</td>
<td>⋯</td>
</tr>
<tr>
<td>( \alpha ) (deg)</td>
<td>-31.12</td>
<td>-33.06</td>
<td>⋯</td>
</tr>
</tbody>
</table>

for the base and best-fit Gregorian designs; these are reproduced in table 4.2 and shown schematically in figure 4.1. These best fit parameters were used for the initial simulations\(^2\) of CCAM’s optical design. The final design and optimization of the cold optics was done (by Joe Fowler) with a full numeric model of the mirror surfaces.

We characterize the system’s optical performance by the Strehl ratio \( S \), which is defined as the ratio of the peak intensity of an optical system’s actual point spread function to that of an ideal system free from optical aberrations. Thus a Strehl ratio of 1 describes a system that is completely free from any geometric aberrations; \( S \geq 0.8 \) is our definition of a “diffraction-limited” optical system. Even at that level, however, optical aberrations will cause noticeable distortions in the point-spread function (PSF). Thus, we (somewhat arbitrarily) choose \( S \geq 0.95 \) as our minimum acceptable Strehl ratio. The Strehl ratio can be approximately represented by

\[
S \simeq \exp\left(-\left(2\pi\sigma\right)^2\right) \tag{4.1}
\]

where \( \sigma \) is the RMS wavefront error.

### 4.3 Cold Optics

An earlier design for ACT\(^3\) used cold off-axis mirrors in order to reimagine the sky (via the Gregorian focus) onto the detectors with dichroic beamsplitters used to separate the bands.

\(^2\)All simulations were done using the CodeV software package from Optical Research Associates, Inc. http://www.opticalres.com/

\(^3\)Because CCAM is a testbed for ACT technologies, the CCAM optics are based on the ACT design.
Figure 4.1: Ray trace drawing of the WMAP optical system. Figure courtesy Joe Fowler.
for the three arrays. Both of these ideas presented us with a number of problems.

First, the off-axis mirrors proved to be troublesome. In our initial simulations, we found it impossible to design a optically-satisfactory mirror system that met our requirements. An off-axis mirror system can be designed to focus radiation from one point onto another point without difficulty. However, re-imaging a finite-sized patch of sky is difficult because rays from one point on the sky end up “looking” at a different part of the mirror than rays from another point on the sky. This situation is generically true for any off-axis system which is not focused at infinity; however, the effect is magnified for the fast focal ratios required to re-image the relatively slow (∼f/3) rays from the secondary onto the detectors at ∼f/1. The effect of this situation is that rays from different points in the field-of-view focus at different distances and with different magnifications. Three separate off-axis mirror systems, as in one option that was considered, would also have presented packaging challenges for the design of the cryostat.

Second, the dichroic filters have a maximum available size of roughly 6 inches in diameter. The filters act as frequency-dependent beamsplitters, reflecting radiation below some cutoff frequency and transmitting radiation above. In order to separate the frequency components and direct them to different locations, they are mounted at a 45-degree angle to the incoming beam. This angle further reduces the effective area of the filter as seen by the incoming light (as well as increasing the amount of space in the optical path taken up by the filter). With a smaller detector array this likely would not have been a problem; however, it was difficult to design an optical system for ACT that could accommodate both dichroics and not vignette the beam at the corners of a 32×32 array. In addition, because ACT uses three widely-spaced frequency bands, the first of the two dichroic filters would have needed a broad-band anti-reflection (AR) coating in order to pass, say, the two higher frequency bands without excessive reflection. Last, it was found that dichroic beamsplitters do not stay flat when cooled[35].

After considering various designs, it was decided to abandon the cold mirror idea and proceed instead with a refracting system. Though lenses present their own technical chal-
lenses (reflection, cooling, and mechanical mounting of possibly fragile lenses), the optical design is greatly simplified. The dichroic filters were similarly dismissed, and we chose instead to design a camera with three completely separate optical paths looking at three separate but nearby regions on the sky, arranged in a triangular configuration. The 270 GHz channel is closest to the center of the telescope beam; it is the most sensitive to optical aberrations because of its smaller diffraction spot size. This choice of camera architecture can, for small values of the telescope chop amplitude, drastically reduce the amount of sky mapped by all three frequency channels. For example, with a 1.5-degree chop amplitude, the three-color sky coverage is reduced by half compared to a system with dichroics where all channels look at the same region of sky.

The CCAM optics are a single-band version of the full ACT optics, optimized for use with the WMAP mirrors and an 8x32 TES array, though a slightly larger array could be used without significant degradation in optical performance at the edges. Our “optics tube” contains three lenses, four filters, and baffling to reduce stray radiation. One might wonder: “Why three lenses? Couldn’t you easily reimage the sky with just one?” The answer is “probably”, but you lose the ability to form an image of the primary mirror inside the dewar — essential for controlling spillover without a feed horn.

For our first simulations with refracting reimaging systems, we used materials already familiar to radio astronomers: high-density polyethylene and quartz. HDPE was used with great success in the CAPMAP experiment[36] and the techniques to machine and anti-reflection-coat HDPE lenses are well understood[37]. Figure 4.2 shows a system using three HDPE lenses compared to a similar system using quartz. Though the optical quality excellent ($S > 0.99$ at all points in the field), the lenses are highly curved and thus have a high central thickness. This is due to the low index of refraction of HDPE ($n = 1.5$), which requires strongly curved surfaces in order to achieve the desired optical power. The high curvature results in a very thick lens which, due to the low thermal conductivity of HDPE, would take an unacceptably long time to cool to 4K. In addition, the high curvature reduces the effectiveness of a simple single-layer $\frac{\lambda}{4}$ AR coating, which might have necessitated the
development of an alternative, more complicated means of AR-coating the lens.

Z-cut quartz and fused silica (amorphous quartz), with indices of 2.1 and 2, respectively, are perhaps the next logical choices. Our group has used quartz in the past for infrared-blocking filters, and both are obtainable in the diameters and thicknesses needed. Indeed, the system using quartz produces lenses that are both flatter and thinner than HDPE lenses. In addition, AR-coating quartz would have been relatively straightforward, as any of a number of polymers with an index of around 1.45 would have worked. However, quartz has low thermal conductivity and would have taken an appreciable amount of time to cool (on the order of 10-20 hrs)\textsuperscript{4} [38]. Machining quartz and fused silica would also have been extremely difficult. In addition, because of its high infrared absorption, we would have needed an IR blocking filter ahead of the quartz in order to allow it to cool completely.

This left us searching for a suitable material. We considered silicon ($n = 3.4$), germanium ($n = 4$), and sapphire ($n = 3.1$). Sapphire was rejected for cost reasons, and germanium for availability. Because the semiconductor industry is based on silicon, availability was not a problem. We tested silicon wafers in a 4K cryostat and found that they cooled to 4K rapidly when mounted in a suitable holder. Silicon can be machined, albeit with some difficulty, meaning complicated lens shapes could be considered. The last remaining issue, reflection, was considered a solvable problem and its solution is described in section 4.3.2.

The final CCAM optical system (designed by Joe Fowler) is shown in Fig. 4.3.

4.3.1 Lens design

The lenses for CCAM are made of high-resistivity (>10,000 Ω-cm) pure silicon. It meets our needs for transmission, refractive index, and thermal conductivity. In order to simplify their construction and AR coating, the lenses are plano-convex so that only one side needs to be machined to an aspheric shape. The lens shape was optimized to balance image quality for an $8 \times 32$ TES array with the requirement that the primary mirror is reimaged.

\textsuperscript{4}In retrospect, this seems entirely reasonable as the whole cryostat itself takes approximately 2 days to cool to 4 K. However, at the time it was a concern.
Figure 4.2: Preliminary CCAM optics designs using high-density polyethylene (top) and quartz (bottom) lenses. Note the large curvature and central lens thicknesses in the HDPE system compared to the quartz lenses. The rays from the secondary arrive from the left; the detector plane is at the far right. Strehl ratios are $> 0.98$ at all positions on the focal plane for both systems.

inside the dewar. The lens diameters, and thus the maximum cross-sectional area of the incoming light beam, were constrained by the diameter of readily available, suitably thick high-resistivity silicon wafers.

In order to get the right shape, the silicon is first ground to a spherical shape close to the final shape. The remainder of the silicon is machined using single-point-diamond tooling on a CNC lathe. The silicon was machined by Nu-Tek Precision Optical Corp.\(^5\)

Two of the lenses are mounted at 4 K; the third, because it comes after the band-defining filter, is mounted at 0.6 K to reduce its thermal emission and thus loading on the detectors.

\(^5\)http://www.nu-tek-optics.com/
Figure 4.3: The final cold CCAM optics. The top panel is a view from the side; the bottom panel is a view from above. Not shown is the neutral density filter, placed just after the first lens. Figure from Joe Fowler.

The lenses are held in copper mounts that are machined slightly oversize to account for the extra contraction of copper relative to silicon at low temperatures. The mounts use Spira EMI/RFI gasket material to take up the radial and axial slack and provide a thermal connection between the lens and mount. The lens and filter mounts were designed by Judy Lau.
4.3.2 Anti-Reflection Coating

The anti-reflection coating was the subject of much development and is explained in detail by Lau, et al. [39]. To summarize the many months of work, we now have an anti-reflection coating that achieves $\sim 1\%$ reflection at 145GHz, is mechanically and thermally robust, and is relatively simple compared to some of the alternatives considered (ranging from laser drilling and deep etching of holes to “slumping” fused silica into the required shape to polymers grown on the surface of the lens).

The coating is made from Cirlex\(^6\), a laminate made of multiple sheets of DuPont Kapton polyimide film bonded together under high pressure without the use of adhesives. Unlike Kapton, it is available in thicknesses suitable for machining to the desired lens profile. The Cirlex is machined by the Princeton machine shop to match the lens shape. It is then glued to the lens using Emerson & Cuming Stycast 1266 epoxy and a Teflon gluing jig machined to shape to ensure a thin (<0.001 inch), even coat of glue.

4.3.3 Filters

CCAM uses four filters, three of which were made for us by Carole Tucker and collaborators at Cardiff University. The first two filters are metal-mesh low-pass filters to help limit the radiation into the optics tube. Their cutoff frequencies are different, at 8 cm\(^{-1}\) (240 GHz) and 7 cm\(^{-1}\) (210 GHz), so that any above-cutoff harmonics in the transmission of either filter will be attenuated by the other. The 8 cm\(^{-1}\) is mounted on the 70K shell; the 7 cm\(^{-1}\) at 4K. The third filter is a metal-mesh band-defining filter, also mounted at 4K. Because any radiation originating behind the band-defining filter is unfiltered, that volume has to be kept below 1K to minimize the loading on the detectors. The transmission spectra of the band defining filter and the 7 cm\(^{-1}\) low-pass filter are shown in figure 4.4. The spectrum of the 8 cm\(^{-1}\) filter was measured separately and found to be similar to that of the 7 cm\(^{-1}\) filter.

The remaining filter is a neutral density filter (NDF). Because we initially plan to observe

\(^6\)Cirlex is made by Fralock, Inc: http://www.fralock.com/
Figure 4.4: Filter transmission spectra for the band-defining (top) and 7 cm$^{-1}$ low-pass (middle) filters; their product is shown in the bottom plot. There is a transmission harmonic in the low-pass filter at twice the filter cutoff frequency. For a blackbody at 2.7K, the power transmitted through this harmonic is approximately 0.5% of the power transmitted in-band. The third filter, not shown, transmits $<3\%$ at the frequencies covered by the harmonic, producing $<0.02\%$ leakage overall.
from Princeton, NJ, we expect the sky temperature to emit at \( \sim 100 \text{K} \). The detectors, however, will saturate at a sky temperature of about 30K given our bandpass. Thus we need to attenuate the signal in order to be able to see anything at all. Unfortunately, this reduces our signal-to-noise, but is a necessary evil. The NDF is a 1/2-inch thick disk of Eccosorb MF110 microwave absorber. It is anti-reflection coated with a single layer of 0.012” thick Teflon film on either side.\(^7\) The Teflon is “glued” to the Eccosorb using Dow Corning high vacuum grease and captured in a copper mount. We calculate that it will transmit roughly 9% of the incoming radiation from the sky. Because the NDF is mostly absorptive (and thus emissive), its temperature needs to be controlled so that temperature changes in the filter do not appear as “signals”. To accomplish this, we attach three heater resistors symmetrically around the outer periphery of the copper mount which are servo-controlled to \( \sim 4 \text{K} \) by the housekeeping system.

### 4.4 Predicted Optical Performance

The final CCAM cold optics were optimized and analyzed by Joe Fowler. The optimization criteria included a small but positive lens edge thickness, a fixed central lens thickness, a plano-convex geometry for each lens, and cold stop image quality in addition to Strehl ratio at the focal plane. The lenses were optimized for an 8x32 array of detectors, though a somewhat larger array \((12 \times 32)\) could be used with no appreciable reduction in image quality at any point on the focal plane. As can be seen from Fig. 4.5, the predicted optical performance is excellent. All points on the field show Strehl ratios > 0.95. In addition, the image of the primary mirror formed inside the dewar allows for a cold Lyot stop to define the illumination on the primary.

\(^7\)Though the ‘ideal’ thickness for a single layer \( \frac{\lambda}{2 \sqrt{n}} \) AR coating for MF110 is 0.014”, we decided to make the layer as thin as possible in order to keep the NDF mount from touching the lens just past it. This choice results in an increase in reflection of \( \sim 1\% \) per surface.
Figure 4.5: Strehl ratios over one half of an 8x32 focal plane in CCAM. The left side of the figure at $x=0$ is the left-right symmetry centerline of the off-axis WMAP optics. To get the full Figure from Joe Fowler.
Chapter 5

Detectors and Readout

The heart of CCAM is its detectors. CCAM uses transition-edge-sensor (TES) bolometers using a “pop-up device” (PUD) architecture developed by Harvey Moseley and his colleagues at NASA’s Goddard Space Flight Center. The detectors are coupled to a multiplexed SQUID readout system developed at NIST by Kent Irwin’s group. We have successfully utilized these systems to characterize the detectors for use in CCAM.

5.1 TES basics

A bolometer is simply a device that turns absorbs incoming radiation, increasing the temperature of the device (see Fig. 5.1). The change in resistance is then measured to indicate the amount of power incident on the detector. A TES bolometer is no different than a neutron-transmutation-doped (NTD) germanium thermistor bolometer in this regard; what differs is the underlying device physics. These characteristics, in turn, determine how the detectors are read out.

An NTD bolometer is a resistor with a negative temperature coefficient; when current-biased, the output is a voltage that varies inversely with the resistance $R(T)$ of the bolometer. The output voltage is then amplified using a low-noise cooled JFET, typically with an AC bias at $\sim$100Hz.

A TES, on the other hand, is a superconductor held near the midpoint of its super-
conducting transition by an external bias voltage. On transition, a superconductor has a very sharp resistance vs. temperature curve with a large positive temperature coefficient. In other words, the resistance changes dramatically for a very small change in temperature (see Fig. 5.1), leading to a detector with high sensitivity to small changes in incoming power. The resistance of the TES is inferred using the circuit shown in Fig. 5.2: With a large enough bias resistor $R_{bias}$ ($R_{bias} \gg R_{TES}$, the voltage across the TES is held nearly fixed via the small shunt resistor). If the incident power increases, the TES resistance also increases, which leads to a drop in the bias power $V^2/R$ dissipated in the TES. This drop in bias power very nearly compensates for the increase in incident radiation power, keeping the device biased near the middle of its superconducting transition. This so-called “electrothermal feedback”, a completely passive feedback process occurring within the TES itself, not only increases the dynamic range of the device but also increases its speed \[40\][41].
Figure 5.2: Left: TES bias circuit and SQUID readout. $R_{\text{bias}}$ is much larger than $R_{\text{TES}}$; similarly, $R_{\text{shunt}}$ is much smaller than $R_{\text{TES}}$. The current in the TES couples into the SQUID via a series inductor. Right: Theoretical response of the SQUID to magnetic flux at $1.4I_c$, $2I_c$, and $2.6I_c$, from bottom to top. As the figure shows, biasing the SQUID at $I = 2I_c$ produces the largest response (see Eq. 5.1).

5.2 TES arrays

In order to build a camera with a large number of detectors, it is clearly advantageous to use an architecture that minimizes the effort to fabricate and assemble the complete array. CCAM uses an architecture at NASA/Goddard Space Flight Center called the “pop-up detector” (PUD). The detectors are fabricated in linear arrays as shown in Fig. 5.3. Each pixel is supported by four legs that serve as mechanical support as well as the weak thermal link to the bath temperature. In order to create a two-dimensional array, the chips are folded so the legs extend behind the pixel and the two folded sides meet. This brings the electrical connections out behind the pixels and allows the chips to be stacked to form a two-dimensional array. This design produces an close-packed array of detectors that fills the focal plane with > 90% filling factor.

The array used in CCAM for the measurements described here is a single linear array
Figure 5.3: Top: single 32-pixel TES chip. For folding, the regions near the slots in each edge are cut out and the chip is folded in a folding jig designed by Toby Marriage. Bottom: A complete 12×32 array for SHARC-II, which uses a similar architecture. From[42].

containing 32 pixels made by Jay Chervenak at Goddard. The pixels use a bismuth absorber to couple radiation from the sky into the device. In addition, for all the tests, the chip was left flat (i.e. not folded).

5.3 SQUID readout

Because the TES is voltage biased, its output is a current that varies inversely with the incident power. In order to measure and amplify the current output, CCAM uses a SQUID
circuit as shown in Fig. 5.2. The current through the TES is sent through an inductor which couples into a SQUID via its magnetic field. The SQUID magnetometer then produces an output which is periodic in the magnetic flux through it:

\[ V = \frac{R}{2} \left( I^2 - [2I_c \cos(\pi \phi / \phi_0)]^2 \right)^{\frac{1}{2}} \]  

(5.1)

where \( I \) is the current flowing through the device, \( R \) is the resistance of each Josephson junction, \( I_c \) is the SQUID “critical current,” \( \phi \) is the magnetic flux through the SQUID, and \( \phi_0 \) is the magnetic flux quantum, \( \hbar/2e \).

From equation 5.1, one can see that for values of the bias current \( I \geq 2I_c \), the quantity inside the square root is positive-definite, and there are no “dead spots” in the response of the SQUID to magnetic flux. If \( I > 2I_c \), the response is dominated by the constant bias current term, reducing the amplitude of the term that varies with the magnetic field. The ideal SQUID bias point is \( I = 2I_c \), which ensures maximum response to changing magnetic flux and eliminates values of \( \phi \) where the SQUID does not respond. This is shown schematically in Fig. 5.2.

Because the SQUID readout is periodic, it is not particularly useful unless the output is linearized. This is accomplished through the use of magnetic flux feedback in a so-called “flux-locked loop” (FLL) configuration. An inductor placed near the SQUID carries a feedback current sent from the room-temperature electronics. The feedback signal is calculated using a proportional-integral (PI) algorithm to cancel the change in the SQUID output. In this configuration, the SQUID output always remains constant as the feedback varies to keep the output fixed. The signal, then, becomes the feedback current that is applied to the feedback inductor.

With our readout system, the output of the stage 1 (S1) SQUID at 0.3K is then further amplified by a stage 2 (S2) SQUID (also at 0.3K) and once again by a “Series Array” (SA) of SQUIDs at 4K to provide high gain and interface with the room-temperature electronics [43][44][45].
5.4 Multiplexing

Reading out a single flux-locked SQUID requires four wires: One pair to supply the bias current and SQUID output and one pair to supply current to the feedback inductor. Multiplying this number for a 32×32 array in ACT would result in 4096 wires for each of the three cameras, not including the lines needed to bias the detectors themselves. The NIST time-domain multiplexing system[21] dramatically reduces this wire count, correspondingly reducing the cryogenic thermal load and labor needed to build the readout system.

The system is shown in Fig. 5.4. Each column contains 32 S1 SQUIDs, one per detector.¹ The bias current is sent to all of the SQUIDs in a given row (row \( i \)), turning them all on. Simultaneously, the necessary feedback values for all of the SQUIDs in the row, calculated by the warm electronics based on the PI control algorithm, are applied to each column.² (column \( j \)) The output for each column \( j \) is then the output of SQUID \( ij \), which is then used for calculating the feedback in that position for the next cycle. The electronics then shut off the bias for row \( i \) and turn on row \( i + 1 \), allowing the readout of all detectors in that row.

For an \( i \times j \) (row × column) array, a non-multiplexed readout system would require \( 4ij \) lines for its S1 SQUIDs. In the case of CCAM, which uses a 32x1 multiplexer (ignoring the dark SQUID), this would result in a total of 128 wires. Using the NIST multiplexing system, which uses a pair of feedback lines for every column, the wire count is reduced to \( 2i + 2j \) wires, resulting in 66 lines. While this is a significant reduction, the real advantages are seen in the case of a large array such as ACT’s 32×32 array: instead of 4096 wires, only 128 wires are necessary for all 1024 S1 SQUIDs. Adding in the S2 and SA lines for each column brings the total wire count to 384 – still better than a factor of 10 reduction.

¹The actual multiplexors also have a “dark” 33rd SQUID that is not connected to a detector.
²Note that, because all of the feedback inductors in a column are wired in series, the feedback applied is wrong for all of the rows except the one currently being read out. However, this is fine because the SQUIDs for those rows are not turned on, and you don’t read them out.
Figure 5.4: Time-domain SQUID multiplexer diagram. The “Row Select” lines choose which row (i.e. which S1 SQUID in each column) will be read out. All of the detectors in a given column couple to a single S2 SQUID and Series Array amplifier. Additional columns could be connected to the Row Select lines at the right. Figure from [18]

5.5 Detector Characterization

For the results presented in this work, CCAM used an unfolded 32×1 detector package assembled by Michael Niemack using detectors fabricated by Jay Chervenak at Goddard
Space Flight Center. The detector characteristics are summarized in Table 5.1 and pictures are shown in Fig. 5.5. In order to characterize our detector system, we ran numerous tests, of which a subset are presented here. First, we took Johnson noise measurements with the TES’s superconducting to determine the resistances of the shunt resistors that produce the near-voltage bias across each TES. Then we examined the noise spectra of a few biased detectors in order to find the noise floor and frequency response of the system. Last, we measured the time constant of the detectors using an optical source.

<table>
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<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
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<tr>
<td>Leg width</td>
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</tr>
<tr>
<td>Leg thickness</td>
<td>1.4 µm</td>
</tr>
<tr>
<td>$T_c$</td>
<td>400—450 mK</td>
</tr>
<tr>
<td>TES normal resistance</td>
<td>32—40 mΩ</td>
</tr>
<tr>
<td>TES bar geometry</td>
<td>3 bars per square</td>
</tr>
<tr>
<td>Absorber type</td>
<td>Bi + SiO</td>
</tr>
<tr>
<td>Absorber thickness</td>
<td>1175 Å + 500 Å</td>
</tr>
<tr>
<td>Absorber resistance</td>
<td>30 Ω/□</td>
</tr>
</tbody>
</table>

Table 5.1: CCAM flat TES chip characteristics. Each TES has an aspect ratio of 1.8:1 (length:width). Each pixel is square. The “bar geometry” describes gold bars patterned on the TES to reduce noise[46].
Figure 5.6: Left: Circuit configuration for measuring the shunt resistance using Johnson noise. Compared with Fig. 5.2, the above circuit has a superconducting TES ($R_{\text{TES}} = 0$), and the non-ideal stray resistance is shown explicitly. $R_{\text{bias}}$ and $R_{\text{fb}}$ are both approximately 2.2 kΩ. Right: Equivalent noise circuit with noiseless resistors. $(i_n')^2$ is the noise current in the TES circuit, split between the two resistors $R_{\text{shunt}}$ and $R_{\text{stray}}$ in parallel. The TES bias line is left floating. $(i_n')^2$ is multiplied by the mutual inductance ratio $M = L_{\text{TES}}/L_{\text{fb}}$ to get $i_n'^2$ in the SQUID feedback line which is measured as a voltage $v_n^2$ at the output of the readout electronics.

### 5.5.1 Shunt Resistance

The shunt resistor in each TES bias circuit is an essential element. For a given bias current through the TES circuit shown in Fig. 5.2, the shunt resistor determines where on the superconducting transition the TES is biased. We measure the shunt resistance for each channel by leaving the TES unbiased so it remains superconducting. The circuit then reduces to the parallel resistance of the shunt resistor and stray (or “parasitic”) resistance in the connections and circuitry of the TES branch. By measuring the noise voltage at the output of the warm electronics, you can then infer the shunt resistance if the ratio of stray resistance to shunt resistance is known a priori. This ratio is measured by putting a known current into the TES bias circuit and measuring the fraction of the current that goes into the TES branch.

The noise spectral density is given by the expression for Johnson noise across a resistor[47]:

$$(i_n')^2 = 4k_BT/R_L$$

(5.2)
where $T$ is the resistor temperature and $R_L$ is the resistance. In our case, $R_L$ is the parallel combination of $R_{\text{shunt}}$ and $R_{\text{stray}}$.

Of the total noise current $(i_n')^2$ (see Fig. 5.6), the fraction $(i_n'')^2 = (i_n')^2 \times R_{\text{shunt}}/(R_{\text{stray}} + R_{\text{shunt}})$ passes through the inductor in the TES loop, $L_{\text{TES}}$. This inductor couples the noise current into the S1 SQUID. The feedback electronics calculate the appropriate response current, $i_n''$, to send to the feedback inductor $L_{fb}$ to null the SQUID output. Because $L_{fb}$ has less inductance than $L_{\text{TES}}$, it requires more current than what flows through $L_{\text{TES}}$ in order to bring the output back to zero. The ratio $M = L_{\text{TES}}/L_{fb}$ is the current gain provided by the unequal inductances. The multiplexer chips used in CCAM have $M = 14.8$.

The measured output voltage $v_n^2$ is the result of the noise current $i_n''$ passing through the feedback resistor $R_{fb}$. The noise voltage of the feedback resistor, $v_{fb}^2$, is two orders of magnitude smaller than the noise due to the current in the TES circuit. Therefore, we can safely neglect the noise added by the feedback resistor.

The procedure, then, is to measure $v_n^2$, infer the value of $(i_n'')^2$ using the known $M$ and $R_{fb}$ values, and then substituting the expression in Eq. 5.2 for $(i_n')^2$ to solve for the value of $R_L$:

$$R_L = 4k_B T \times (R_{fb} \times M)^2/v_n^2 \quad (5.3)$$

$R_L$ is just the parallel resistance of $R_{stray}$ and $R_{shunt}$, and the ratio $R_{stray}/R_{shunt}$ is known. $R_{stray}$ can then be eliminated and the value of $R_{shunt}$ can be determined.

We measured the noise spectrum with an HP 3562A dynamic signal analyzer. The average low-frequency white noise power spectral density from DC to $\sim 1$ kHz was measured by eye on the screen. For these measurements, the detector temperature was held constant at 309 mK and $R_{fb} = 2267 \ \Omega$. The TES bias connector at room temperature was left floating. Because the TES bias resistor $R_{bias} \gg R_L$, its contribution to the noise current $(i_n')^2$ is negligible (see Eq. 5.2).

Typical values of the noise voltage ranged from $v_n = 2$ to $3 \ \mu V/\sqrt{Hz}$. The results are shown in Fig. 5.7. The shunt resistance varies from 1.3 m$\Omega$ to 2.3 m$\Omega$ (ignoring outliers), increasing smoothly from one end of the chip to the other. While this sounds catastrophic,
it simply results in the each detector being biased at a different point on its transition. While likely not ideal for noise performance or dynamic range, it did not severely affect our observations.

At the same time, the $f_{3db}$ point of the noise spectra were measured and used to calculate the inductance in the TES loop of each channel. The average inductance was calculated to be 233 nH, with a standard deviation of 13nH among the channels.

### 5.5.2 Detector NEP

Channels 00 and 13 were chosen to investigate the detector noise equivalent power\(^3\) (NEP). For these measurements, we biased the detectors at three bias points each in order to look at the detector noise under realistic operating conditions. The detectors were looking at a

\(^3\)Because acquiring noise spectra, especially at low frequencies, is so time consuming, we chose to only measure the spectrum for two detectors.
6.2 K absorptive load placed near the focus at the entrance to the optics tube. We used the HP3562A signal analyzer and recorded spectra with a 100 Hz and 5 kHz range for each detector at each bias point. The two spectra were then combined, and a single-pole low-pass transfer function was fit to data. To calibrate the spectra into NEP, I-V curves were acquired and a current-to-power responsivity was derived.

We found NEP’s of $1.5 \times 10^{-17}$ and $3.2 \times 10^{-17}$ W/$\sqrt{\text{Hz}}$ for channels 00 (Fig. 5.8) and 13 (Fig. 5.9), respectively, biased at $\sim 45\%$ of the TES normal resistance $R_n$. Channel 00 showed increasing noise as the detector bias was increased. However, Channel 13 showed different behavior: When biased at 31% of its normal resistance, its low-frequency NEP was actually slightly higher than at 45% $R_n$. At 72% $R_n$, the NEP was higher than both of the lower bias points. A study of more detectors is required in order to investigate this further.

The measured NEPs are somewhat higher than we expect based on prior estimates[22]; however, these detectors are not the final configuration for the ACT bolometer arrays. In addition, we expect the rolloff frequency to be related to the thermal time constant of the detectors which should dominate the response time and thus show up as a rolloff in the measured noise spectrum. However, as we will see in §5.5.3, the $\sim 1$-2 kHz noise rolloff evident in the noise spectrum does not match the response time measured directly.

Finally, it should be noted that the SQUID noise adds in quadrature to the detector noise, but it is expected to be much smaller. In fact, when we allow the fit to include a constant, white-noise offset, the routine returns a negative offset, indicating that the SQUID does not seem to contribute significantly to the overall NEP at low frequencies. If the noise power spectrum extended to higher frequencies, it is likely that the SQUID noise component could be fitted and extracted, as it is expected to be white at frequencies much higher than the detector noise rolloff.

5.5.3 Detector time Constant

The detector time constant was measured directly using a broadband D-band (140 GHz) noise source (see Appendix B for details) shining directly into the cryostat window. The
Figure 5.8: Noise spectra for channel 00 at 30%, 46%, and 65% $R_n$, from top to bottom. A single-pole low-pass transfer function was fit to each spectrum to derive the best-fit parameters on each plot.
Figure 5.9: Noise spectra for channel 13 at 31%, 45%, and 72% $R_n$, from top to bottom. A single-pole low-pass transfer function was fit to each spectrum to derive the best-fit parameters on each plot.
source was modulated with an optical chopper wheel at frequencies from 4 to 200 Hz. During data taking, the chop frequency was varied in a quasi-random manner to avoid creating a systematic effect from long-timescale drifts in the output power of the source. In addition, the power at 4 Hz was used as a reference to track the drifts in the source: data were taken alternately at the measurement frequency and 4 Hz, and the change in power between the 4 Hz reference periods on either side of a given measurement was used to correct the measured amplitude. The detector outputs for a few chop frequencies are seen in Fig. 5.10.

To determine the time constant, each time series was Fourier transformed and the amplitude of the power spectrum at the chop frequency was plotted as a function of chop frequency. The resulting curve was then fit with a single-pole low-pass filter, resulting in an $f_{3dB}$ of 58.8$\pm$0.6 Hz for channel RS6, corresponding to $\tau = 1/2\pi f = 3$ ms (Fig. 5.11). The rest of the working channels each had an $f_{3dB}$ of between 50-60 Hz.

5.6 Conclusions

We have measured characteristics of the TES array used in CCAM. The shunt resistor chip was found to have a shunt resistance that varied by position from one end of the chip to the other. Detector NEP was measured for two channels at various bias points; unfortunately, no underlying trend was found that could be used to determine the optimum bias point. Measuring more detector NEP’s would be required in order to find the ideal detector bias. Finally, we measured the time constant of the detectors using a chopped millimeter-wave source. We find a 3 dB rolloff point of 58.8$\pm$0.6 Hz, corresponding to a time constant $\tau = 1/2\pi f = 3$ ms.
Figure 5.10: Time series data for input chop frequencies of 6, 20, 50, and 200 Hz. The top pane in every pair is the same scale to facilitate comparison by eye; the lower plots in each pair scaled to have the same number of chop periods.
Figure 5.11: Frequency response of one CCAM detector (channel RS6) to externally modulated optical power. The dashed line is the best-fit single-pole low-pass filter response curve with $f_{3dB}=58.8$ Hz.
Chapter 6

Observations from Princeton

In the fall and winter of 2005, CCAM successfully observed from the roof of Jadwin Hall in Princeton, New Jersey. Because the atmosphere in New Jersey is so bright (\( \sim 100 \text{K at } 150 \text{ GHz} \)), all observations were performed with a 9%-transmissive neutral density filter (NDF, described in §4.3.3) to attenuate the signal before it reaches the detectors. The maps and other intermediate data products in this section were provided by Eric Switzer. A plate scale analysis by Michael Niemack, resulting in a value of 0.055°/mm, was also used for many of the results shown here. Michael Niemack’s I-V curve analysis program was also used.

6.1 Sky NEP

The fundamental unit of sensitivity for a bolometric receiver is the noise effective power, or NEP. The NEP is the signal strength required to reach a signal-to-noise ratio of 1 in a 1 Hz bandwidth. CCAM has one data set from the night of Dec. 2, 2005 where the telescope was pointed at 64.2° altitude and 194.5° azimuth in a fixed “stare” observation for \( \sim 300 \text{ s} \). The data were low-pass filtered and downsampled in real time to \( \sim 300 \text{ Hz} \) before being recorded to the computer.

In order to calculate the NEP, the data were first cut by excluding detectors that were either not responsive (biased too high or too low), “dark”, or for which it was otherwise...
impossible to determine a DAC unit-to-watt responsivity. Each of the remaining detector
timestreams was then multiplied by its responsivity and Fourier-transformed to generate
an NEP spectrum. Each spectrum was calibrated into power units using the responsivity
derived from the I-V curve analysis. The spectra of four representative detectors are shown
in Fig 6.1.

![NEP Spectra](image)

Figure 6.1: NEP spectra for four typical channels. The dashed line on each indicates the
average NEP over the 5-40 Hz range. The rolloff at high frequencies is due to the real-time
anti-aliasing filter applied to the timestreams before downsampling.

The NEP was determined by finding the level of the white part of the noise spectrum.
For these numbers, we looked at the region between 5 and 40 Hz, to avoid both the effects
of low-frequency $1/f$ noise with a knee at $\sim$2-3 Hz (most likely from the atmosphere, as the

---

1The data were multiplied by a Hanning window function prior to the FFT operation.
Channel | NEP (W/√Hz) | NEP error (W/√Hz)
--- | --- | ---
RS16 | 7.59×10^{-17} | ± 6.5×10^{-19}
RS17 | 2.06×10^{-17} | ± 2.0×10^{-19}
RS18 | 1.93×10^{-17} | ± 1.8×10^{-19}
RS19 | 5.22×10^{-17} | ± 4.2×10^{-19}
RS21 | 2.03×10^{-17} | ± 2.0×10^{-19}
RS22 | 2.05×10^{-17} | ± 1.9×10^{-19}
RS23 | 2.13×10^{-17} | ± 2.0×10^{-19}
RS24 | 1.34×10^{-17} | ± 1.7×10^{-19}
RS25 | 1.85×10^{-17} | ± 1.9×10^{-19}
RS27 | 2.62×10^{-17} | ± 8.0×10^{-19}
RS28 | 1.64×10^{-17} | ± 1.8×10^{-19}
RS29 | 1.77×10^{-17} | ± 2.1×10^{-19}
RS30 | 1.60×10^{-17} | ± 1.9×10^{-19}

Table 6.1: Noise Equivalent Power (NEP) for the working detector channels in CCAM for a fixed-position observation.

The NEP’s for all working channels are plotted in Fig 6.2 and printed in Table 6.1. The NEP is not a strong function of the TES bias point. Because the measured NEP is a quadrature sum of the detector NEP and sky NEP, it is likely that the sky NEP dominates, leading to little observed change as a function of bias voltage. However, taking data at more bias points would be useful to see if the NEP varies in each detector as the bias changes. If the inherent TES noise is due, as we expect, to Johnson noise, the NEP should decrease as the TES bias increases ($i_n^2 \propto 1/R$).
Figure 6.2: NEP’s for each working channel versus bias point.

### 6.2 Sidelobe Measurements

The first astronomical source detected with CCAM was the moon. Due to its brightness ($\sim$250K) and angular extent ($\sim$0.5° diameter), it produces a strong signal that is easily seen even with the NDF. While a bright source is necessary for measuring the sidelobe response of the telescope, using an extended source requires a model of both the telescope beam and the source’s brightness distribution in order to disentangle the effects of the beam and the source.
6.2.1 Main Beam

In order to map the telescope’s main beam, we observed Saturn. Because Saturn is a weak source, the maps made from the observations were averaged together to produce a final composite map shown in Fig 6.3. The first thing one notices about the map is that the beam is asymmetric, being wider than it is tall. One possible cause of this is the asymmetric illumination of the primary mirror in the \(x\) and \(y\) directions caused by the Lyot stop in the optics tube. Though the optics would prefer having a stop surface tilted relative to the plane normal to the central ray, an untilted stop was used for ease of fabrication, which results in different primary mirror illumination widths in the two directions. To investigate this possibility, we construct a model beam to determine the effective area of the primary mirror to compare with optical simulation predictions.

At a given wavenumber \(k\), the diffraction pattern from a uniformly-illuminated elliptical aperture with semimajor axes \(a\) and \(b\) is given by:

\[
I(\theta, \phi) = I_0 \left[ \frac{J_1(k\beta)}{k\beta} \right]^2
\]

(6.1)

where \(\beta = \sqrt{a^2\theta^2 + b^2\phi^2}\). Because CCAM observes over a finite bandwidth from \(\sim 130 - 160\) GHz, we build the telescope response by summing over functions of the form in Eq. 6.1 for each \(k\) with the appropriate weights given the shape of the CCAM bandpass (See Fig. 4.4). This composite beam is then convolved with a “top hat”, representing the square pixel shape, extending 0.055° on the sky. This produces the beam profile shown in Fig 6.4. The major effect of the two operations described above is to “wash out” the sidelobe structure seen in the simplest model.

This model was then used to determine the effective area of the primary mirror. In the case of single-frequency diffraction from a circular aperture, the beam full-width at half-maximum (FWHM) varies inversely with the aperture diameter. In the case of an elliptical aperture, this holds true independently for the two orthogonal directions. However, because our beam is convolved with a square pixel whose projection on the sky is \textit{independent} of the aperture diameter, this scaling will not hold strictly true for CCAM.
Figure 6.3: Composite contour map of Saturn. The contour levels are at 200, 400, 600, and 800 attowatts (1 aW = 1×10^{-18} W). The beam is flattened in the vertical direction, with an eccentricity $e = 0.42$. 
Figure 6.4: Left: Various beam profiles for the indicated frequencies, scaled by the transmission of the bandpass filter at that frequency. Right: Final beam resulting from a sum of components like those shown on the left convolved with a square pixel.

Figure 6.5: Left: $R^2$ goodness-of-fit contours as a function of $x$ and $y$ primary mirror effective radii. The top contour has a value of 0.90, and the peak $R^2$ value corresponds to $(x, y) = (0.38 \text{ m}, 0.50 \text{ m})$. Right: Saturn data with the model beam subtracted. Scale is in attowatts.
Figure 6.6: Beam slices in $x$ (left) and $y$ (right) directions. In each, the solid line is the data, the dashed line is the computed best-fit model, and the dotted line is the best-fit 2-d Gaussian.

In order to determine the effective aperture radii in the $x$ and $y$ directions, the model beam was computed for a variety of aperture dimensions between 0.30 and 0.50 m in $x$ and 0.40 and 0.60 m in $y$. The $R^2$ goodness-of-fit statistic was computed for each beam realization, resulting in a maximum value of $R^2 = 0.90$ for $(x, y) = (0.38 \text{ m}, 0.50 \text{ m})$. However, a 2-d Gaussian beam fit to the data also results in an $R^2$ value of approximately 0.90. Unfortunately, the noise level of the map is too high to determine which model is preferred. The primary mirror illumination radii predicted from CodeV optical simulations are $(x, y) = (0.647 \text{ m}, 0.649 \text{ m})$[48] — much more circular than derived in the preceding analysis. The $y$-direction differs from the prediction by approximately 20%, and the $x$-direction differs by over 40%. It is unlikely that the observed beam asymmetry is caused by asymmetric primary mirror illumination.

Another possibility is that the beam asymmetry is due to the time constant of the detectors. Because the telescope scans in azimuth, maps made from CCAM data will be stretched horizontally due to the detector response time. A simple order-of-magnitude estimate for this effect is given by the scan speed of the beam on the sky, $2^\circ$/sec, multiplied by the time constant $\tau \approx 3 \text{ ms}$, gives a half-width at half-maximum (HWHM) of $0.006^\circ$ ($\sim 0.4'$). The beam HWHM in the vertical direction, which should be unaffected by the time-
constant broadening, is \(\sim 0.07\) degrees, an order of magnitude larger than the expected effect from the time constant. When added in quadrature, the time constant effect adds negligible additional width to the beam pattern. Reproducing the horizontal beam HWHM of \(\sim 0.085\) degrees would require a time constant of roughly 25 ms, or \(\sim 7\) Hz, and is strongly ruled out by the time constant measurement in § 5.5.3.

Last, we considered the possibility that diffraction at the detectors affected the beam profile. The detectors sit at the base of a “funnel”-shaped cutout that looks like a trapezoid in a cross section through the vertical axis. In the horizontal direction, the cutout spans the width of the detector array (>3 cm). Such an aperture is not likely to produce a beam that is elongated in the horizontal direction.

6.2.2 Moon Model and Data

In order to model the signal from the moon, we use the best-fit beam parameters from the Saturn analysis and then convolve that beam with a model of the brightness distribution of the moon. The moon was modeled as a disk whose brightness falls off toward the outer edge. The brightness temperature of the moon varies as approximately \(\sqrt{\cos \psi}\), where \(\psi\) is the lunar latitude [49]. The resulting model beam was then scaled by the expected signal strength for the moon passing through our optical system to determine the overall optical efficiency. The moon temperature was assumed to be 250 K and the atmosphere to be 75 K \((e^{-\tau} = 0.74)\). In addition, the transmission of the low-pass, bandpass, and neutral density filters were taken into account.

The results for one channel are shown in Fig. 6.7. As can be seen, the model describes the data fairly well out to approximately 0.25° from the center. However, past that, the model falls off more rapidly than the measured beam profile. The derived combined optics transmission and detector coupling efficiency is between 43-48% for most of the channels. We expect at best 50% detector absorption efficiency and roughly 80% optical transmission, or an upper limit of \(\sim 40\)% combined.

One possibility for the excess power observed is out-of-band high-frequency leakage. For
Figure 6.7: Y slice through center of moon map (solid curve) with model described in text (dashed curve). The vertical scaling of the model was adjusted to match the peak of the measured signal to determine the optical transmission and detector coupling efficiency.

A 250 K source, the amount of power transmitted in the 7 cm$^{-1}$ low-pass filter transmission harmonic (see Fig. 4.4 in §4.3.3) is nearly 25% of the in-band transmission. However, because the 8 cm$^{-1}$ low-pass filter also attenuates this signal, the overall power transmitted in this harmonic is <1% of the in-band transmission — too low to make a significant correction to the measured transmission and coupling efficiency. It is still possible, however, that there is additional high-frequency leakage besides what is described above; measuring this leakage is a priority for ongoing CCAM tests.
6.3 Covariance: Time-Ordered Data

The covariance matrix of a given dataset is an essential part of understanding the correlations in the data. In this case, we are primarily interested in correlations between different detectors on the focal plane. The covariance matrix $C_{\mu\nu}$ is defined as:

$$C_{\mu\nu} \equiv \frac{1}{N-1} \left\langle (t_{i\mu} - \bar{t}_{\mu})(t_{i\nu} - \bar{t}_{\nu}) \right\rangle_i$$

(6.2)

where $\mu$ and $\nu$ represent detectors, $t_{i\mu}$ is the $i$th data point for detector $\mu$, $\bar{t}_{\mu}$ is the mean of the time series for that detector, and $N$ is the total number of data points.

For observations with the telescope scanning in a region free from bright sources, the covariance matrix was calculated at each of the steps in the mapmaking process. First, the covariance matrix is computed for the raw, unprocessed timestreams, shown in Fig 6.8. The data are highly correlated, but this is unsurprising as the timestreams are dominated by a large, long-timescale, common-mode drift as seen in the figure. The long-term drifts are removed from the data using a high-pass filter whose cutoff frequency is below the scan frequency (0.2 Hz). The covariance matrix is recalculated, again revealing a highly-correlated dataset (Fig. 6.9). Now, with the drift removed, the covariance is dominated by the scan-synchronous magnetic field pickup from the SQUID readout system. The pickup is removed by fitting and subtracting a template to the scan-synchronous signal from each detector.

The final covariance matrix is shown in Fig. 6.10. The off-diagonal elements are $\lesssim 20\%$ of the diagonal components in most cases. The cleaning procedure eliminates most of the correlated noise between pixels and recovers timestreams with low correlations between channels. The remaining correlations could be due to imperfect cleaning or from the atmosphere. Alternatively, they could be caused by electromagnetic coupling between adjacent detector channels.

Projecting down through the correlation matrix along the diagonal, we arrive at an average pixel-to-all-other-pixels correlation, shown in Fig. 6.12.
Figure 6.8: Left: Raw timestreams for four typical working channels scanning across a source-free region of the sky. The common-mode drift is evident. Right: Detector-detector covariance matrix for the raw timestreams. The color scale on the right is in Watts$^2$.

Figure 6.9: Left: “De-drifted” timestreams for four typical working channels scanning across a source-free region of the sky. The dominant feature is the scan-synchronous magnetic field pickup in the SQUID amplifiers. Right: Detector-detector covariance matrix for the dedrifted timestreams. The color scale on the right is in Watts$^2$. 
Figure 6.10: Upper left: De-drifted and template-subtracted timestreams for four typical working channels scanning across a source-free region of the sky. The scan-synchronous signal is mostly absent. Upper right: Detector-detector covariance matrix for the timestreams. It is strongly diagonal, with off-diagonal elements $\lesssim 20\%$ of the diagonal elements. The color scale on the right is in watts$^2$. Bottom: Surface plot of the de-drifted and template-subtracted covariance matrix above. The vertical scale is Watts$^2$. 
6.4 Covariance: Map

Finally, we investigated the pixel-to-pixel covariance of the Saturn maps. Because the detector array in CCAM is oriented horizontally, we only looked at slices of constant \( y \) through the center of the beam. The maps as provided had Saturn centered in each map; in order to calculate the covariance, each 1-d map was expanded and then shifted by the amount corresponding to the position of that pixel on the sky using the measured plate scale. The regions with no sky data in each expanded and shifted map were padded with a constant calculated from the average of the data points at the ends of each map (away from the source). Failure to do this results in strong correlations between channels, as the sharp transitions at the start of the regions with no data would be common to each channel. Some of these 1-d maps are shown in Fig. 6.11.

![Figure 6.11: Horizontal slices through the Saturn maps for the indicated detector channels for use in the map covariance analysis. The flat regions to the left and right of each peak are the padded cells used to eliminate discontinuities and possible spurious correlations between pixels.](image)

Once the correlation matrix is calculated, we project down through the correlation ma-
trix along the diagonal. Thus, we arrive at an average pixel-to-all-other-pixels correlation, shown in Fig. 6.13. Because Saturn is clearly visible in the maps, we expect to see its effects in the correlation matrix as well. Indeed, compared with Fig. 6.12, we can see the additional correlated power out to \( \sim 3 \) pixels away. This power corresponds to the beam profile computed in §6.2.1 (dashed line in Fig. 6.13). The negative correlation power is likely an artifact of the padding procedure described in the previous paragraph.

Figure 6.12: Projection down the diagonal or “diagonal average” of the correlation matrix computed from the de-drifted and filtered timestreams from §6.3.
Figure 6.13: Stepped curve is the projection down the diagonal or “diagonal average” of the correlation matrix computed from the maps of Saturn. The dashed line is the modeled beam from §6.2.1, not a fit to the correlation matrix projection.

6.5 Conclusions

We have observed the sky with CCAM and made measurements of its noise properties, beam profile, and pixel-to-pixel correlations. The measured NEP’s compare well with estimates from the ACT proposal. The beam profile can be well-described by a model using an elliptical primary mirror aperture. However, CodeV simulations of the telescope indicate nearly circular primary mirror illumination. In addition, neither the detector time constant, nor diffraction near the detectors can explain the shape. The source of the beam shape is still under investigation. Last, the correlation matrix between detectors of a time series
with no astronomical source in view was found to be strongly diagonal after time-series processing, and the width of the correlations generated from maps of Saturn agrees well with the measured beam profile.
Chapter 7

Conclusion

“This is the end. My only friend, the end.” – The Doors.

Studies of the Cosmic Microwave Background are pushing to ever-smaller angular scales. By observing at higher resolutions, we can study physics at various energy scales, from the inflationary epoch to the recombination era to the recent universe via the Sunyaev-Zeldovich effect. The Atacama Cosmology Telescope is designed to observe the CMB and make maps with heretofore-unseen detail.

We have successfully demonstrated a novel new camera, CCAM, for observations of the CMB. CCAM incorporates many new technologies that will also be utilized in the ACT.

We have built a new cryostat for CCAM that houses two pulse-tube refrigerators, two independent helium adsorption refrigerator systems, reimaging optics, and a TES detector array and multiplexed SQUID readout system. The cryostat performs as expected and has provided a robust and reliable platform for optics and detector engineering tests.

Our housekeeping system allows us to record cryostat temperatures as well as monitor them in real time. In addition, we developed hardware to automate sorption refrigerator recycling and implement servo control of various temperature stages inside the cryostat. These systems have been working well for the past six months.

The optics have been characterized with both simulations and direct observation of astronomical sources. Various avenues were pursued in developing an optical design for
CCAM. Cold off-axis mirrors were investigated and rejected, and refracting optical systems utilizing various dielectric materials were simulated. The final design, using anti-reflection-coated silicon lenses, should provide excellent image quality and control primary mirror illumination sufficiently. The measured plate scale agrees with the predictions from ray-tracing simulations. The measured main beam shape agrees with a simple model of the beam. More work on modeling the brightness distribution of the moon will be required to characterize the sidelobe structure more fully.

The detector and SQUID multiplexing system work as expected. The measured detector noise on the sky compares well with early estimates. The time constant was measured with a chopped source and found to be approximately 3 ms. Though this is slower than we had anticipated, it should still be fast enough for CMB observations.

Finally, the pixel-to-pixel covariance of the detectors was measured in order to test the mapmaking process. After removing long-timescale drifts and scan-synchronous magnetic pickup, the recovered covariance matrix is nearly diagonal. In addition, the measured pixel-to-pixel correlations constructed from maps of Saturn agree with the observed beam measured directly from the composite map.

The future looks bright for CCAM and ACT. Currently, it is planned that ACT will be delivered and installed on site at Cerro Toco in the fall of 2006. In the meantime, CCAM will test an 8×32 array of TES detectors to be used in MBAC for the first light observations with ACT shortly after its installation in Chile.
Figure 7.1: CCAM mounted on its base with the WMAP REU mirrors installed.
Figure 7.2: The sun setting over CCAM.
Appendix A

Housekeeping Diagram

Below is a detailed diagram of the connections between the components of the housekeeping system.
Figure A.1: Connections for the housekeeping system. Everything except the cryostat is in the "housekeeping rack" shown in Fig. 3.6.
Appendix B

D-band Noise Source

The noise source used in the chopped time constant measurements (§5.5.3 was originally built for the MINT experiment\[25\]). It was designed to produce correlated D-band noise for the four MINT receivers. Because D-band noise can be useful to have around, we resurrected it for CCAM.

B.1 Design

The noise source starts with a Q-band (33-50 GHz) noise diode. This diode has an ENR\(^1\) of 20 dB, producing the equivalent power of a 29,000 K thermal source. This signal is then amplified by 75 dB and then fed into a Millitech frequency tripler which puts the noise signal into the 99-150 GHz frequency band (D-band). Originally, a waveguide switch was used to turn the output on and off, and the signal was split four ways with D-band power splitters. A block diagram of the noise source is shown in Fig. B.1.

The entire system was designed to be as thermally stable as possible. The components inside the noise source are mounted to a thermally-regulated plate, and the entire enclosure is insulated with styrofoam.

\(^1\)“Excess Noise Ratio” – the amount of power emitted by a component in excess of its physical temperature, expressed in dB. An ENR of 10 dB corresponds to a component emitting the same amount of power as a 2900 K thermal source (10dB greater than 290K, i.e. room temperature).
B.2 Spectrum

MINT observed in two frequency bands (139.2-141.2 GHz and 149.2-151.2 GHz) that are “folded” on top of one another in the mixing conversion to our 4-6 GHz intermediate frequency band. However, because we can phase switch our local oscillators, we calculate a complex correlation function which allows us to separate the lower frequency band from the upper when Fourier-transformed. Joe Fowler analyzed the data and found no noise source power in the upper sideband. Fig. B.2 shows a plot of the reconstructed noise source spectrum in the lower sideband. The power level in the upper sideband is at least a factor of 30 below the level shown in the plot.

To determine whether this effect made sense, we made a measurement of the frequency spectrum of the noise source output. We used a swept Q-band HP oscillator into the noise source’s Q-band amplifiers, and measured the power out of the frequency tripler using an HP 432A power meter and D-band detector.

The measured noise source output spectrum is shown in Fig. B.2. The shape is dominated by the frequency response of the Q-band amplifier system. The gain drops off sharply above 47 GHz which, when tripled, corresponds to a frequency of 141 GHz. The upper sideband, which begins at at 149.2 GHz, is well above the amplifier rolloff point.
Figure B.2: The noise source spectrum for the receiver A-D baseline, calculated from the observed correlation function. Data courtesy Joe Fowler.

B.3 Optical Chopper

We used a New Focus\(^2\) model 3501 optical chopper wheel and controller to modulate the noise source for the CCAM time constant measurements. The 3501 controller uses a phase-locked loop to control the chopper wheel speed, and a frequency stability of $\delta f < 0.01$ Hz is attainable at low ($< 10$ Hz) chop frequencies. Using the 2-slot chopper wheel we could modulate the signal at frequencies from 4 Hz to 210 Hz.

B.4 Waveguide Switch

Though it has not been used for CCAM, the waveguide switch could be of use in the future. The waveguide switch is actuated by a stepper motor to switch on and off the noise signal when desired, and the position of the switch is read by a rotary encoder. A diagram of the switch is shown in Fig. B.4. It has detents every 90 degrees of rotation. The stepper

\(^2\)http://www.newfocus.com/
motor would turn the switch until it approached one of the detents. The stepper motor was then shut off, allowing the switch to “fall” into one of the detents. A plot of the switch transmission as a function of angle is shown in Fig. 6.

The noise source switching was repeatable to well-within $\pm 0.25^\circ$, and within that range the data can be corrected for the slight variation in transmission as a function of angle[50].
Figure B.4: Waveguide switch schematic, showing dimensions in inches for scale. Courtesy Yeong Loh
Figure B.5: Waveguide switch transmission as a function of angle. Data courtesy Joe Fowler
Appendix C

Original Introduction

If you’ve made it this far, congratulations – you’ve made it to the end (unless you like reading bibliography entries). As a reward, please enjoy the original introduction to my thesis, reproduced below for your reading pleasure – AMA

“McCroskey: Jacobs, I want to know absolutely everything that’s happened up till now.

Jacobs: Well, let’s see. First the earth cooled. And then the dinosaurs came, but they got too big and fat, so they all died and they turned into oil. And then the Arabs came and they bought Mercedes-Benzes. And Prince Charles started wearing all of Lady Di’s clothes. I couldn’t believe it.” – Airplane II: The Sequel

C.1 The Cosmic Microwave Background

A long, long time ago the Universe, as we have come to call it, was formed. Of course, back then it wasn’t called the Universe because there was nobody around to call it anything. If there were, however, they probably would have called it “Ow, that’s hot!” for, indeed, it was.

Despite the lack of air conditioning, the Universe somehow managed to get some physics done. In the first hundred seconds, it not only managed to expand exponentially through a scalar-field-driven inflationary epoch, but also sneak in baryogenesis as well as light-element
nucleosynthesis. In a scientific trifecta the likes of which were not seen again until 1905, the Universe would have guaranteed itself a full professorship at the university of its choosing had any existed at the time.

Guaranteed that its tenure was secure, the Universe was content to rest on its laurels for the time being. While it grew ever more bloated and corpulent, the Universe’s density and temperature dropped further. After about 380,000 years of lassitude, however, the Universe was once again ready to make its mark on the physics community\(^1\).

You see, before this time, the Universe had been very hospitable to free protons and electrons but strenuously against the coupling of the two. Any time a proton and electron would try to join forces to create a neutral hydrogen atom, a pesky photon in thermal equilibrium with the rest of the Universe would tear the two asunder in a fit of jealous rage\(^2\).

The Universe eventually cooled to the point where the photons’ thermal energy was no longer enough to split up the proton and electron. Once this occurred, the union previously denied to these two particles and their cohorts suddenly\(^3\) became a veritable necessity due to the strength of the electromagnetic force. The Universe transformed from an opaque plasma to a transparent space filled with neutral atoms, and the photons previously strongly coupled to the charged elementary particles were “decoupled” and free to propagate without further interaction through the Universe\(^4\).

Because these photons were in thermal equilibrium with the Universe before decoupling, their energy spectrum followed the Planck distribution. In the billions of years following decoupling, the further expansion of the Universe redshifted these photons to ever lower energies. The thermal spectrum remained, though shifted to lower temperatures. Today, we see these redshifted thermal photons as the Cosmic Microwave Background, a 13.7-billion-year-old relic from the hot Big Bang\(^5\).

\(^1\)In all fairness, it should be noted that the physics community at the time consisted solely of elementary particles, a notoriously easy group to please.

\(^2\)The photon denies this ever happened and claims it is still looking for the “real” ionizing radiation.

\(^3\)In the cosmological sense.

\(^4\)Of course, this isn’t exactly true. See Section 1.3.

\(^5\)Though, honestly, it doesn’t look a day over 13.65.
For its effort, the Universe would have received the Nobel Prize in Physics — had it only existed at the time. Instead, Arno Penzias and Robert Wilson received the 1978 (A.D.) Nobel Prize in Physics for their 1965 detection of the CMB. In the nearly 30 years after their initial detection, further experiments showed the CMB to be isotropic, unpolarized, and remarkably thermal (see Fig. 1.1).
References


