AMIBA: FIRST-YEAR RESULTS FOR SUNYAEV-ZEL'DOVICH EFFECT

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We discuss the observation, analysis, and results of the first-year science operation of AMiBA, an interferometric experiment designed to study cosmology via the measurement of Cosmic Microwave Background (CMB). In 2007, we successfully observed 6 galaxy clusters ($z < 0.33$) through the Sunyaev-Zel'dovich effect. AMiBA is the first CMB interferometer operating at 86–102 GHz, currently with 7 close-packed antennas of 60 cm in diameter giving a synthesized resolution of around 6 arcminutes. An observing strategy with on-off-source modulation is used to remove the effects from electronic offset and ground pickup. Formalism of the analysis is given and preliminary science results are summarized. Tests for systematic effects are also addressed. We also discuss the expansion plan.

Keywords: Cosmology; cosmic microwave background; galaxy cluster.

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1. Introduction

Cosmic Microwave Background (CMB) provides a window to study not only the beginning phase of the Universe but also its evolution history. The recent observational foci have been on the CMB polarization and on the Sunyaev-Zel'dovich

(S-Z) effect induced by galaxy clusters. Polarization in CMB provides information complementary to what can be learned from the temperature anisotropy. The discovery and characterization of the polarization not only confirms the cosmological interpretation of the origin of the temperature anisotropy and large-scale structures, but also improves the accuracy with which we measure parameters in our cosmological model, such as the epoch of reionization. So far detection of CMB polarization has been reported by DASI,¹ CBI,^{2,3} CAPMAP,⁴ BOOMERANG,⁵ WMAP,⁶ MAXIPOL,⁷ and QUAD.⁸ On the other hand, the S-Z effect is a good medium through which to study the cluster physics.^{9,10} Because it is induced by the largest structures in the universe, the galaxy clusters, it enables us also to investigate some intrinsic properties of the cosmos such as the Hubble parameter and the baryon to matter ratio. Here we report results from Array for Microwave Background Anisotropy (AMiBA) in 2007, which focused on the S-Z observation.

AMiBA is also named as ‘Y.T. Lee Array for Microwave Background Anisotropy’. It is an interferometric experiment initiated in Taiwan in 2000 and dedicated on Mauna Loa, Big Island, Hawaii on October 3, 2006. It has dual-channel receivers operating at 86–102 GHz, designed to have full polarization capabilities. Currently it has 7 close-packed antennas of 60 cm in diameter giving a synthesized resolution of 6 arcminutes, expandable to a total of 19 elements with a synthesized resolution of about 2 arcminutes. Its first-phase setup, the 7-element system (AMiBA-07 hereafter; see Fig. 1), focuses on targeted S-Z observations and the measurement of CMB temperature power spectrum (see Sec. 2). The project has been funded for an expansion to 13 elements (AMiBA-13 hereafter) with dishes of 1.2 m in diameter. The 13-element system is expected to start operating in the early 2009.

The receiver-antenna elements are reconfigurable on a six-meter platform, which is driven by a hexapod mount. Each element has a cooled heterodyne receiver, consisting of HEMT amplifiers of 46 dB in amplification, subharmonic mixers, and 2–18 GHz IF amplifiers. For each baseline, the signals from two dual-channel receivers are cross-correlated in an analogue 4-lag correlator, whose outputs then lead to two complex visibilities for the upper and lower frequency bands (see Sec. 4). The cross correlation between the L and R modes (the dual channels) of a pair of receivers enables the measurement of the four Stokes parameters, T, Q, U, and V. The typical receiver noise temperatures are below 100K. Table 1 summarizes the specifications of AMiBA.

2. The Sciences

AMiBA is designed to achieve the following science goals:

- (1) Targeted S-Z observations to determine cluster physics and to study the cosmic origin when jointly analyzed with X-ray and lensing data.
- (2) S-Z survey to investigate large-scale structure and background cosmology.

Fig. 1. The 7-element AMiBA with its hexapod mount.

Table 1. AMiBA Specifications

Common features	
Receiver: Dual-channel MMIC (L and R)	Platform: 6 m configurable; carbon fiber
Operation frequency: 86–102 GHz	Correlator: analog (bandwidth 16 GHz)
Site: Mauna Loa, Big Island, Hawaii (3400 m in elevation)	
Mounting system: Hexapod ($\pm 30^\circ$ in polarization; 30° – 90° in elevation)	
7-element (AMiBA-07)	
Antenna: 60-cm Cassegrain; carbon fiber	Synthesized resolution: 6 arcmin
FOV: 23 arcmin	Observation type: targeted
13-element (AMiBA-13)	
Antenna: 120-cm Cassegrain carbon fiber	Synthesized resolution: 2 arcmin
FOV: 11 arcmin	Observation type: targeted and survey

- (3) Observation of primary CMB for both temperature and polarization to constrain background cosmology.
- (4) Search for the imprints of cosmic defects to constrain fundamental physics such as SUSY GUT, string theory, hybrid inflation, etc.¹¹
- (5) Search for missing baryons.

The 7-element system focuses on (1) and (3), with major effort on (1) for 2007. It has baselines of three different lengths, 65 cm, 113 cm, and 130 cm, giving synthesized resolutions of 10', 6', and 5' and the corresponding multipole numbers of $\ell \sim 1200$, 2100 and 2400 respectively. At the lower end of the ℓ range, very well studied results from literature are available for cross-check. At the higher end, the secondary CMB anisotropies are expected to dominate, especially the S-Z effect, and this regime is much less explored in literature. Recent literature seems to suggest that there is excess power in this regime as compared with the theoretical expectation for the S-Z effect.¹²

The S-Z effect is induced by the interaction between the CMB photons and the hot electrons at the core of a cluster. This interaction shifts the original Planck distribution of CMB photons towards higher frequencies on average. The discrepancy from Planck distribution can be theoretically modeled as

$$\frac{\Delta I(x)}{I_0} = \Delta_{\text{thermal}}(x, y, T_e) + \Delta_{\text{kinetic}}(x, \tau, v_p), \quad (1)$$

where

$$\Delta_{\text{thermal}}(x, y, T_e) = y [g(x) + \delta_T(x, T_e)], \quad (2)$$

$$\Delta_{\text{kinetic}}(x, \tau, v_p) = -\beta \tau h(x), \quad (3)$$

$$y = \frac{k\sigma_T}{m_e c^2} \int T_e n_e dl, \quad g(x) = h(x) \left(\frac{x}{\tanh(x/2)} - 4 \right), \quad (4)$$

$$\beta = \frac{v_p}{c}, \quad \tau = \sigma_T \int n_e dl, \quad h(x) = \frac{x^4 e^x}{(e^x - 1)^2}, \quad x = \frac{h\nu}{kT_{\text{CMB}}}, \quad I_0 = \frac{2(kT_{\text{CMB}})^3}{(hc)^2}, \quad (5)$$

c is the speed of light, m_e is the electron mass, n_e is the electron number density in the cluster, T_e is the electron temperature, k is the Boltzmann constant, h is the Planck constant, T_{CMB} is the CMB temperature, and σ_T is the Thomson cross section. Δ_{thermal} is the S-Z thermal effect, a consequence of the inverse Compton scattering. Δ_{kinetic} is the S-Z kinetic effect, due to the peculiar motion of the cluster. $\delta_T(x, T_e)$ is a correction term for relativistic effect.

Within the AMiBA frequency range, 86–102 GHz, Eq. (1) gives a negative value. This provides a very powerful tool for discriminating between galaxy clusters and other astronomical sources, because the latter normally emit photons that have much higher temperature than CMB and therefore induce an increment in intensity rather than a decrement as by clusters. By measuring such an intensity deficit and its profile, we hope to probe not only the cluster physics but also the related cosmic origins.

3. Observations

Before embarking on the science observation, many simulations and hardware tests were implemented, including the performance simulation for different dish configurations, beam pattern measurement, radio alignment, delay measurement and

Fig. 2. The u - v coverage of a typical observation by AMiBA-07 (left) and its corresponding noise-weighted point spread function (the dirty beam; right). In the left plot, the dots show the u - v modes sampled by a typical AMiBA-07 observation while the coloring indicates the relative sensitivity in the u - v space.

correction, pointing calibration, ground pickup measurement, etc. The AMiBA-07 operates at 86–102 GHz (see Tab. 1), the choice of which is for suppressing the synchrotron radiation and dust emission. The seven antennae of 60 cm in diameter are close-packed giving the shortest and longest baselines of 65 cm and 130 cm respectively. This configuration gives 21 baselines, each of which resolves two frequency bands centered at about 90 and 98 GHz. For better imaging quality, we observe each target with eight evenly divided polarization angles of the platform to achieve better coverage in the u - v space. Figure 2 shows the u - v coverage of a typical observation and its corresponding noise-weighted point spread function, the so-called dirty beam. The Full Width at Half Maximum (FWHM) of the beam is about six arcminutes. The field of view is about 23 arcminutes.

To minimize, if not to completely remove, the effects from the ground pickup and from a DC component in the electronics, we adopt a ‘2-patch’ observing strategy that switches on and off the target. In this mode, a leading patch that contains the target of our interest is tracked for four minutes, and then a tailing patch of a blank sky is tracked for the same period of time. The two trackings follow an identical path in azimuth and elevation and therefore share the same contribution from the ground pickup, so that a subtraction of the two runs will leave only the signal of the target. The CMB contributes differently in the two patches but this background component is theoretically expected to be much weaker than the system noise for the current observations. To calibrate the data, we observed planets roughly every 3 to 4 hours using exactly the same observing strategy.

Figure 3 shows a typical example by using the 2-patch observing strategy. The left panel is the image constructed from the leading patch that contains Abell Cluster 2142, while the middle panel is that from the tailing patch of the blank sky.

Fig. 3. An example for using the 2-patch observing strategy. The source patch (left) and the tailing patch (middle) are both dominated by the foreground in the same way, so that a subtraction of the two reveals the signal of the source (right), an Abell Cluster 2142.

Table 2. Basic properties and model parameters of the AMiBA-07 clusters derived from X-ray observations.^{13,14,15,16,17,18,19,20,21,22} The last column shows the time integrated to produce the results in this paper.

Cluster	z	T_X	β	Θ_c	$Y_{2500}(\text{mJy})$		integ. hours
		(KeV)			30 GHz	145 GHz	
A2142	0.089	8.68 ± 0.12	1.0 ± 0.3	221.4 ± 8.4	-	-	4.6
A2163	0.202	12.2 ± 1.0	0.674 ± 0.010	87.5 ± 2.5	143	533	6.0
A2261	0.224	8.82 ± 0.35	0.516 ± 0.013	15.7 ± 1.1	40	440	8.2
A2390	0.232	10.13 ± 1.10	0.67	52.0	78	-	11.2
A1689	0.183	9.66 ± 0.20	0.609 ± 0.005	26.6 ± 0.7	57	460	9.4
A1995	0.322	8.59 ± 0.70	0.770 ± 0.80	38.9 ± 5.0	19	-	4.4

It is clear that in both patches the cluster signal is dominated by other components that appear the same in both patches. A subtraction of the two patches reveals the cluster signal, which is only about 1% of the foreground in intensity (see the right panel of Fig. 3).

The targets chosen for AMiBA-07 observations in 2007 are 6 nearby Abell clusters with a redshift range of $0.08 < z < 0.33$. Their X-ray core radii are around or below one arcminute except for A2142, which is almost 4 arcminutes. Some basic properties derived from X-ray observations are summarized in Table 2.^{13,14,15,16,17,18,19,20,21,22} With the 2-patch observing strategy, the chosen targets were observed for several hours over a span of between few days and few months. The last column in Table 2 shows the time integrated to produce the results in Sec. 5.

4. Data Analysis

For the details of our data analysis, please refer to Ref. 23. Here we summarize the process. In interferometry, for a source field $S(\mathbf{x}; \mathbf{x}_s)$ with an offset $\mathbf{x}_s$ to the center of the synthesized primary beam $B(\mathbf{x})$, the visibility of an u - v mode $\mathbf{k}$ that

corresponds to a baseline b is

$$\begin{aligned}
 v^b(f, \tau_s) &= \tilde{S}(\mathbf{k}; \mathbf{x}_s) \otimes \tilde{B}(\mathbf{k}), \\
 &= \left\{ \tilde{S}(\mathbf{k}; \mathbf{0}) \exp[i\mathbf{k} \cdot \mathbf{x}_s] \right\} \otimes \tilde{B}(\mathbf{k}), \\
 &= \left\{ |\tilde{S}(\mathbf{k}; \mathbf{0})| \exp[(\Theta(\mathbf{k}) + \mathbf{k} \cdot \mathbf{x}_s)i] \right\} \otimes \tilde{B}(\mathbf{k}), \\
 &= \{M(\mathbf{k}) \exp[(\Theta(\mathbf{k}) + 2\pi f\tau_s)i]\} \otimes \tilde{B}(\mathbf{k}), \tag{6}
 \end{aligned}$$

where $f = |\mathbf{k}|/2\pi$, a tilde denotes the Fourier transform of a quantity, $\otimes$ denotes a convolution, $\tilde{S}(\mathbf{k}; \mathbf{0}) = M(\mathbf{k}) \exp(i\Theta(\mathbf{k}))$ is the Fourier coefficient of $S(\mathbf{x}; \mathbf{0})$ with modulus $M(\mathbf{k})$ and phase $\Theta(\mathbf{k})$, and τ_s is the differential delay of the source center to the receivers along the direction of the baseline, i.e. $\tau_s = \mathbf{x}_s \cdot \mathbf{k}/|\mathbf{k}|$. The data directly recorded by AMiBA is in the format of the so-called ‘lag’, which is the real product of channel outputs from two receivers. These lag outputs can be modeled as

$$c^b(\tau_m, \tau_s) = \Re \left\{ \int_{f_1}^{f_2} v^b(f, \tau_s) R^b(f) \exp[2\pi(f - f_0)\tau_m i + \phi^b(f)i] df \right\}, \tag{7}$$

where τ_m is the delay time applied between the two receiver outputs, the subscript $m = 1-4$ denotes the four delays, $R^b(f)$ is the frequency response of the baseline b , $\phi^b(f)$ is the instrumental phase difference between the two channel paths that go into the correlator, f_0 is the LO frequency (84 GHz), and f_1 and f_2 indicate the upper and lower ends of the response frequency range i.e. $[f_1, f_2] = [86, 102]\text{GHz} = f_0 + (\text{IF frequency range})$.

To obtain the visibilities from the lag data for further analysis such as power spectrum estimation and image construction, we need to invert Eq. (7). Due to conservation of degree of freedom, the four lag outputs convert to complex visibilities of only two frequency bands, namely $[f_1, f_d]$ and $[f_d, f_2]$. They are related as

$$c_m^b = U_{mj}^b v_j^b, \tag{8}$$

where the lag vector c_m^b is defined as

$$c_m^b \equiv c^b(\tau_m), \quad m = 1-4, \tag{9}$$

and similarly the ‘visibility vector’ representing the two band-visibilities is (see Eq. (7))

$$\mathbf{v}^b = \begin{bmatrix} v_1^b \\ v_2^b \\ v_3^b \\ v_4^b \end{bmatrix} = \begin{bmatrix} \Re\{v^b([f_1, f_d])\} \\ \Im\{v^b([f_1, f_d])\} \\ \Re\{v^b([f_d, f_2])\} \\ \Im\{v^b([f_d, f_2])\} \end{bmatrix}. \tag{10}$$

The τ_s is irrelevant in this process since the purpose is to reconstruct the visibilities from the lag data, regardless how the source field is positioned in the FOV. Here U_{mj}^b is a 4×4 transformation matrix. By injecting controlled $\mathbf{v}^b$ into the interferometer and record the output $\mathbf{c}^b$, we can determine the $\mathbf{U}^b$ in Eq. (8). This process is called

‘calibration’, for which we use the planets of known flux. Finally an inversion of the calibrated $\mathbf{U}^b$ enables the transform from the lag outputs back to the band-visibilitys, i.e.

$$v_j^b = [\mathbf{U}^b]_{jm}^{-1} c_m^b. \quad (11)$$

Once given the lag data and a calibrated $\mathbf{U}^b$, we can use Eq. (11) to construct the band-visibilitys $v^b([f_1, f_d])$ and $v^b([f_d, f_2])$. In real observations, we verified that a calibration on $\mathbf{U}^b$ every four hours controls the calibration error to be well within 10%. For the system performance of each hardware components and how that affects our analysis result, please refer to Ref. 24.

Along the analysis pipeline, the data were flagged according to various criteria at different stages. In the lag space, we first flagged out data with bad pointings, non-Gaussian noise (mainly using the K-S test²⁵ and the approaches in Ref. 26), over-high receiver temperature, over high/low noise level, and outliers in the time domain. Drift scans on planets were also implemented every night to identify malfunctioning baselines. In the visibility space, we further flagged out the outliers.

Based on these calibrated visibilitys, an inverse Fourier transform yields a real-space map. Because the u - v coverage for interferometric data in general is not complete nor uniform, the maps obtained from a direct inversed Fourier transform will contain a convolution effect. To clean this out, we use the standard packages MIRIAD and AIPS.

5. Results

In September 2006, AMiBA-07 obtained its first image of Jupiter with a drift scan. Figure 4 shows the lag data of the drift scan and Fig. 5 the resulting image. We spent the following months to study the instrumental properties, to fine tune our system, to study the ground pickup, and to find an optimal observing strategy. During this period, Saturn, Mars, Venus, and Crab Nebula were also observed to study the system. In February 2007 when testing the 2-patch observing strategy (see Sec. 3), we detected for the first time an extragalactic object, the quasar IAU03252226 of 550 mJy in flux (see Fig. 5).

With such a success and further fine tuning of the system, we detected our first S-Z cluster in April 2007, the Abell 2142, with a central S-Z decrement of around -300 mJy. The integration time was less than 6 hours (12 hours in real time due to the 2-patch observation), achieving an S/N ratio of more than 7. In 2007, we observed a total of 6 S-Z clusters (see Tab. 2). Using the formalism described in the previous section, we obtained their images as shown in Fig. 6. The flux decrement at the center of each plot is evident, as expected as the S-Z signal at the AMiBA frequency of around 90 GHz. For more details of these results, please refer to Ref. 23.

Based on the calibrated visibilitys, we pursue further for science analysis. This includes the investigation of Hubble parameter,²⁷ baryon to dark matter relations,²⁸ foregrounds,²⁹ scaling relations,³⁰ and cluster modeling.³¹

Fig. 4. The fringes of a drift scan on Jupiter. Each panel corresponds to one of the 21 baselines, each with two sets (gray and black) of 4 lag outputs from 2 correlators.

Fig. 5. First image of Jupiter (left) and a quasar (right) observed by 7-element AMiBA. All baselines were used to produce the Jupiter image while only the shortest baselines were used to generate the quasar image and therefore with a slightly lower resolution.

To verify that our detections of S-Z clusters are real, we implemented several tests. One is that for the 2-patch observations with two blank-sky patches no signal was detected. Another is that a second pipeline²⁴ produced consistent results for A2142 to high accuracy (see Fig. 7). We also implemented the sum-and-difference test. In this test, the data for A2142 were divided in the temporal domain into two subsets of equal size and then processed separately. Both showed a clear signal in the resulting image (see the left and middle panels in Fig. 8) while their difference

Fig. 6. S-Z clusters imaged by 7-element AMiBA in 2007.

Fig. 7. A side-by-side comparison of the A2142 S-Z images produced by our main analysis pipeline²³ and by a second working pipeline²⁴. Both were cleaned by Miriad.

revealed no signal but noise (right panel in Fig. 8). Their sum is very close to what is shown in Fig. 7. All these tests give us confidence that the signals we observed are indeed from the S-Z clusters rather than from the instrument or from the foreground.

6. Future

In 2008, the 7-element system continues to serve while the dishes are being upgraded to 1.2 m in diameter. The science goals at this stage are to observe more S-Z clusters and to measure the CMB temperature power spectrum from $\ell \sim 1000$ up to a few thousands. The construction of the 13-element system is expected to be finished

Fig. 8. Images of A2142 from the equally divided two subsets of the data show a clear S-Z signal of flux decrement (left and middle), while their difference (right) indicates no signal but noise.

by the end of 2008. The 13-element AMiBA will aim to detect 50–100 S-Z clusters per year. The peak-flux limit is about 3.3 mJy/beam, giving a mass limit of about 2×10^{14} solar mass.

7. Conclusion

In 2007, we used the 7-element AMiBA to have successfully observed 6 S-Z clusters. This is our first science result marking a milestone for the project. It also provides the first information in literature for S-Z clusters at the frequency range of 86–102 GHz. Various tests show that the system performs to the design expectation. The current ongoing expansion will boost the capability in studying not only the S-Z science but also the CMB cosmology.

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