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THE YUAN-TSEH LEE ARRAY FOR MICROWAVE BACKGROUND ANISOTROPY

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ABSTRACT

The Yuan-Tseh Lee Array for Microwave Background Anisotropy (AMiBA) is a millimeter wavelength interferometer dedicated to studying the cosmic microwave background (CMB) radiation. The initial configuration of seven 0.6m telescopes mounted on a 6-m hexapod platform, was dedicated in October 2006 on Mauna Loa, Hawaii. Scientific operations began with the detection of a number of clusters of galaxies via the Sunyaev Zel'dovich Effect.

Subject headings: instrumentation: interferometers; millimeter; telescopes

1. INTRODUCTION

The Yuan-Tseh Lee Array for Microwave Background Anisotropy (AMiBA)[12] is a platform-mounted 7-element interferometer operating at 3-mm wavelength to study the structure of the cosmic microwave background (CMB) radiation. It is constructed as part of the Cosmology and Particle Astrophysics (CosPA) Project, funded by the Taiwan Ministry of Education Initiative on Academic Excellence. This Excellence Initiative was aimed at stimulating interdisciplinary research and large scale integration of independent research programs. CosPA is designed to jump start a program of research in cosmology, with both theory and experimental projects, while incorporating research in high energy physics, development of infrastructures for optical astronomy in Taiwan, as well as accessing observing time on a 4-m class optical telescope.

AMiBA is a collaboration between principally the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA), the National Taiwan University (NTU) Physics and Electrical Engineering Departments, and the Australia Telescope National Facility (ATNF). The project was started in 2000. A two-element prototype was deployed in 2002 to Mauna Loa (elevation 3396 m) in Hawaii for testing of design concepts. Site development was completed in 2004. The AMiBA mount was delivered and installed in 2005, while the platform was delivered and integrated in 2006. With the integration of the first seven elements of the array and successful first light, the AMiBA was dedicated in October 2006, and named after then Academia Sinica President Yuan Tseh Lee for his important contributions in promoting the growth of astronomy in Taiwan. Figure 1 shows the AMiBA at the dedication ceremony.

The aim of AMiBA is to study the spatial structures of the CMB radiation (Ho et al. 2008; Wu et al. 2008a). Since its initial detection by Penzias & Wilson (1965), the CMB has been recognized as the definitive signature of the Big Bang which began the expansion of the Universe. Subsequent studies have established the properties of this relic residual radiation after its decoupling from the matter in the early universe around $z \simeq 1100$: a mean temperature of 2.725 K (present) with minute fractional anisotropies at the level of 10^{-5} (COBE, Mather et al. 1990; Smoot et al. 1992), and polarization at the level of a few to 10% of temperature fluctuations (DASI, Kovac et al. 2002: WMAP, Kogut et al. 2003; Page et al. 2007: Nolta et al. 2008: CBI, Readhead et al. 2006: QUaD, Pryke et al. 2008). In particular, the CMB structures seen on various angular scales by COBE and then WMAP (Bennett et al. 2003; Spergel et al. 2007; Komatsu et al. 2008) demonstrated that the angular power spectrum of CMB anisotropies is a powerful probe of our cosmological model of the Universe. AMiBA is built to sample the angular range $2'$ to $20'$, corresponding to spherical harmonic multipoles $l = 800$–8000, at a wavelength of 3 mm, with full polarization. These capabilities complement existing, on-going, and planned experiments. The angular scales sampled by AMiBA address the higher order acoustic peaks of the CMB structures to further constrain cosmological models. AMiBA also aims

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to search for, and study distant high redshift clusters of galaxies whose hot intracluster gas will distort the CMB spectrum via the Sunyaev Zel'dovich Effect (hereafter SZE, Sunyaev & Zel'dovich 1970, 1972; Rephaeli 1995; Birkinshaw 1999; Carlstrom, Holder, & Reese 2002). The optical and X-ray surface brightness of clusters of galaxies decrease rapidly with increasing redshift due to cosmological redshift dimming, while the detectable SZE is close to being independent of redshift because it is a spectral distortion of the CMB radiation which itself increases in intensify with increasing redshift, $T_{\rm CMB}(z) \propto (1+z)$. Thus SZE measurements are potentially more sensitive for finding clusters of galaxies beyond a redshift $z \sim 1$, and will be an important probe for the matter distribution in the high-redshift universe.

In this paper, we describe the design and construction of AMiBA, the first observational results, and the scientific potential of this instrument.

2. DESCRIPTION OF THE INSTRUMENT

The basic characteristics of AMiBA are summarized in Table 1.

2.1. *Design and Construction of AMiBA*

Interferometry at 3 mm

With the funding of the CosPA/AMiBA projects in 2000, a workshop was held to define the scientific objectives and the design of AMiBA (Lo et al. 2001; Liang 2002). *The first design criterion was to operate at 3-mm wavelength.* This was to take advantage of the sweet spot at 3 mm where the SZE decrement is large and minimally-contaminated by the Galactic synchrotron emission and dust foregrounds and the population of cluster and background radio sources. Operations at 3 mm also complement the wavelength coverage of other existing and planned CMB instruments: interferometers such as CBI at 30GHz (Padin et al. 2002), AMI at 15GHz (Scaife et al. 2008), SZA[13] at 30GHz (90GHz), and VSA at 30GHz (Watson et al. 2002); bolometer arrays such as ACT,[14] APEX-SZ,[15] and SPT.[16] *The second design criterion was to choose interferometry.* This was a somewhat difficult choice as many new CMB projects were then planning to use bolometer arrays, which held the promise of a greater inherent sensitivity because of the broad wavelength coverage and a greater speed because of the multiple elements of the detector arrays. The choice of interferometry was based on the desire to utilize cross correlations to suppress systematic effects, since the ability for bolometers to integrate down to theoretical noise was unknown at that point. Furthermore, ASIAA had the experience of working in millimeter wavelength interferometry from being a partner on the Submillimeter Array (SMA) project (Ho et al. 2004). AMiBA was seen as an extension and application of the technical capabilities within ASIAA. Interferometry is also a natural way to sample simultaneously the spatial structures on various scales and to construct a map by Fourier inversion.

[13] http://astro.uchicago.edu/sza/
[14] http://www.hep.upenn.edu/act/act.html
[15] http://bolo.berkeley.edu/apexsz
[16] http://pole.uchicago.edu

Platform mounted interferometer and hexapod drive

The third design criterion concerns the angular sizescales to be pursued. The first acoustic peak of the CMB was already known to be on the order of 40′ while the secondary peak was expected to be at 20′. Hence AMiBA aimed at angular scales from 2–20 arcmin, in order to extend the coverage of angular sizescales by one more order of magnitude. The choice of 3-mm wavelength meant the required baselines were 0.6 m to 6 m. A maximum baseline of 6m immediately suggested that this interferometer is small enough to be mounted on a platform. *The fourth design criterion was therefore to choose a carbon fiber platform for weight and stiffness considerations.* The platform was made with multiple holes for mounting the receiver packages, to accommodate multiple baseline configurations. ASIAA staff member Philippe Raffin designed the platform, which was manufactured by Composite Mirrors Applications. A single rigid platform has the advantages of a stable differential pointing, a stable baseline solution without differential delay tracking, no mutual shadowing by individual reflectors, and a single drive system. However, a platform also means the interferometer does not have different projected baselines because of earth rotation. *The fifth design criterion was the choice of a hexapod mount, which provides six degrees of freedom (which are tightly constrained) in driving the telescope and rotating the platform.* By rotating the reflectors with respect to the celestial source, additional *uv*-spacings are sampled. The rotation of the platform, defined as the polarization angle of the platform, also allows us to set different orientations of the receivers relative to the ground, which is useful for discriminating between various environmental effects and checking for ground pick-up. The hexapod mount is designed and built by Vertex Antennentechnik, Duisburg, Germany. To protect the telescope from the elements, we use seven retractable steel trusses covered by a PVC fabric, which is manufactured by American Spaceframe Fabricator.

Reflectors

The individual reflectors are built in carbon fiber in order to minimize their weight. They were designed by Philippe Raffin and Jeff Kingsley, and manufactured by CoTech, Taichung, Taiwan. The design includes baffles to shield against crosstalk between individual elements, and GorTex covers to shield against direct solar irradiation. Replicating an accurate carbon fiber surface against a steel mold was not simple, and some hand polishing was required. Depositing the actual reflecting surface and a protective coating was also not simple especially for the 1.2m size. Nevertheless, a collaborative effort between ASIAA and CoTech was successful in delivering the reflectors. Laboratory measurements and outdoor beam pattern measurements showed that their performances met the specifications.

Receiver system

The sixth design criterion was to choose heterodyne receiver systems, which operate between 84 and 104 GHz. This choice of frequency covers an excellent region of atmospheric transparency. The design, construction, and integration of the receiver systems, were made by the

ASIAA staff led by Ming-Tang Chen. Dual polarization capabilities are provided by waveguide orthomode transducers, which follow the circular corrugated feedhorns and the circular-to-linear polarizers. Each polarization is then fed into a JPL monolithic-microwave-integrated-circuit (MMIC) InP HEMT low noise amplifier (LNA) cooled to 15K. These LNAs designed by Huei Wang of the NTU EE-department, performed well with measured noise temperatures of 35-50K across a 20GHz bandwidth. Because the sky signals were first amplified before their subsequent mixing with LO signals, the subharmonically pumped mixers (SHM) using the same MMIC technology can be operated at room temperatures and do not need to be cryogenically cooled. The dewars are therefore fairly small, and standard CTI22 refrigerators are adequate. The packages which feed the LO signals to the mixers and processed the down-converted IF signals are designed and built by Tah-Hsiung Chu and his group at NTU EE-department. Phase locked base LO signal at 21 GHz is doubled to 42 GHz and then phase switched with Walsh functions before being combined with the sky signal at the SHM. Variable attenuators and amplifiers, before and after mixing, control the IF levels before correlation. Slope equalizers, phase stabilized cables, and adjustable delays are used to further adjust the IF signals. We measure the effective receiver temperatures across the 2–18 GHz IF window to be 60–80 K.

Correlator system

The seventh design criterion was to choose a wide band correlator with analog technology. This is a joint development effort between ASIAA and ATNF, with Chao-Te Li, Derek Kubo, and Warwick Wilson leading the effort (Li et al. 2004). A digital correlator would have required sampling at too high a rate to be practical. The AMiBA correlator uses balanced diode mixers to multiply the signals from each pair of antennas. After application of the 4 different lags, the cross-correlated signal is then digitized and read out with integrated circuits designed by Tzi-Dar Chiueh of the NTU EE Department. The readout ICs demodulate the phase-switched signals and accumulate the counts for specified times. Because of the small number of lags to cover a large bandwidth, the conversion to complex visibility is strongly affected by gain variations over the passband, differential delays between lags, and non-linear phase response for each lag. The lag-to-visibility transformation is calibrated with a noise source. This is discussed further by Lin et al. (2008).

2.2. *Performance of the AMiBA*

Drive System and Pointing

The hexapod drive system is more complex than the conventional azimuth-elevation drive systems used in radio astronomy. The difficulty lies in the necessity of driving all six hexapod jacks without over-extension or collisions. Vertex Antennentechnik provided the control software which needed to be debugged during operations. Because the drive software is proprietary, diagnosis and corrections required the attention of Vertex every time, and took several months of effort. The performance of the drive system was checked via pointing and tracking tests (Koch et al. 2008a). Pointing of the AMiBA utilized an optical telescope mounted on the platform. We identified the misalignment of the anchor cone and the mount, the tilt of the optical telescope with respect to the mount, the flexure in the platform as a function of the platform polarization angle, and local platform deformation. We also measured the repeatability of pointing on both short and long timescales, and we performed photogrammetry to measure the stability of the platform. Pointing was found to be repeatable at the $4''$ level on a timescale of several hours. The absolute rms pointing error appears to be about $0.8'$ for the platform set at zero polarization angle, and up to $3'$ if the platform is allowed to rotate to different polarization angles. However, with the implementation of an interpolation table, absolute rms pointing can be reduced to $0.4'$ over all sky. This is less than 10% of the primary beams of the 60cm reflectors, and is within specifications for the operation of the 7-element compact array (Koch et al. 2008b). However, when the 1.2m reflectors are deployed, pointing needs to be improved by a factor of 2.

Deformation of the Platform

The segmented approach instead of a monolithic design for our carbon fiber platform resulted in unforeseen difficulties. The glue joints that attach the six outer segments to the central hub were simply not stiff enough. In spite of several attempts by Composite Mirror Applications to strengthen the joints with additional plates and brackets, the platform still deforms under operational loads. Especially when the platform is rotated in polarization angle, a saddle-shaped deformation pattern is present. Fortunately, the deformation appears repeatable when measured with photogrammetry which means that it can be modeled. Maximum deformation at the edge of the platform under simulated full loading is 0.38mm. The maximum deformation in the inner 3m of the platform is more modest at 0.120mm, and within specifications for the operation of the 7-element compact array. The deformation is due principally to the platform not being stiff enough, and also because the stresses from the drive system are transmitted to the platform in spite of a steel interface ring (Koch et al. 2008b). The immediate ramification is that the individual primary beams of the interferometer elements will be mis-pointed relative to each other. This is equivalent to the primary mirror of a single dish telescope being deformed under gravity or atmospheric distortion. The equivalent adaptive optics approach for an interferometer involves adjusting the gains and phases of the individual elements either through a look-up table or via self calibration if the signals are strong enough. The advantage of an interferometer is that we can adjust the signals before adding or multiplying.

Receivers and Electronics

Between the first proto-typing of parts in 2002, and the first science campaign in 2007, many improvements to the receiver systems and associated electronics were made. These include the noise coupler, MMIC subharmonic mixers, MMIC amplifier, GaAs pHEMT MIMIC doubler, power dividers, phase shifters, active temperature and power level controls for both receiver and correlator electronics, and miniaturization of the IF/LO modules using MMIC technology. The production receivers deployed on the platform have good performance, with overall system temperatures on the order of 80K. The achieved sensitivity is about 65 mJy per hour of integration under good sky conditions (Chen et al. 2008; Lin et al. 2008). Figure 2 shows the AMiBA fully loaded with all the receivers and correlator modules.

2.3. *First Science Results from the AMiBA*

First Light

First light with the 7-element AMiBA was achieved in September 2006. The array of 60 cm reflectors was in the close-pack configuration on the platform. The image of Jupiter shown in Figure 3 is the first end-to-end test of the system, including the pipeline for data analysis. The 1-minute exposure time was adequate since Jupiter had a flux density of 844 Jy@@@. The image was constructed from multiple scans to provide better *uv*-coverage. Successful images were obtained for Saturn, Venus, and the Crab Nebula, all with fluxes on the order of 200 Jy. In particular, the measured angular size of the Crab Nebula is consistent with existing optical and radio images. In December 2006, using Saturn as the calibrator, Uranus was imaged with a flux density of 11 ± 4 Jy, consistent with the expected level of 7.3 Jy.

Using the detected fluxes for Saturn and Jupiter, the overall system efficiency was estimated to be 0.3–0.4 for each of the baselines of the interferometer. The decreased efficiency is attributed to the narrower correlator response, antenna spillover, blockage, and the misalignment of the individual 0.6 m reflectors with respect to the radio axis of the platform. When these reflectors are shimmed on the platform to improve their alignments, we anticipate some improvements in the efficiency.

Imaging Clusters of Galaxies

To detect the much fainter SZE signals from clusters of galaxies, we need to integrate longer. We also need to worry about ground pick-up of local terrestrial signals. The interferometer has the advantage over a bolometer array in that the cross correlation will suppress extended low level emission which enters the system through the sidelobe response of the reflectors. However, structures on angular scales corresponding to the interferometer baselines will still persist. The design of the baffles around the edges of the reflectors helps further suppression, but we did not exercise the option of installing ground shields. Instead we employ a two- or three-patch observing technique where the target source is preceded and/or followed by tracking over the same range of azimuth and elevation just traversed by the source. This allows us to subtract and cancel the terrestrial ground and sky emission. This is the AMiBA equivalent of the position-switching technique used in single dish radio astronomy. As shown in Figure 4, and in Wu et al. (2008b), this procedure is quite successful and we have mapped the SZE decrement towards a number of clusters.

Our companion papers in this volume demonstrate the early science results from AMiBA. Chen et al. (2008) describe the technical aspects of the instruments in detail. Wu et al. (2008b, 2008c) describe the observations and data analysis for the first year of AMiBA data. Lin et al. (2008) describe the careful calibration of the AMiBA data and an alternate pipeline for data analysis. Koch et al. (2008a, 2008b) describe the performance of the hexapod mount and the carbon fiber platform. Nishioka et al. (2008) discuss the integrity of the AMiBA data and its statistical properties. Liu et al. (2008) discuss the contributions from foreground contamination. Umetsu et al. (2008a, 2008b) discuss the combination of AMiBA SZE and Subaru weak lensing data in order to probe the structure of dark matter and to derive the cluster gas mass fractions. Koch et al. (2008c) derive the value of the Hubble constant H_0 from AMiBA and X-ray data on the clusters. Huang et al. (2008) derive cluster scaling relations between the SZE and X-ray observables. Liao et al. (2008) derive scaling relations of cluster properties using AMiBA SZE data alone. Finally, Molnar et al. (2008) discuss the potential of AMiBA data in its 13-element configuration to constrain the intra-cluster gas distributions.

Expansion to 13-elements

While the initial 7-element 0.6m reflectors have been commissioned, we are proceeding with the expansion of the AMiBA to its 13-element configuration. In this configuration, we will upgrade from 0.6m to 1.2m antennas. This will increase the collecting area by a factor of ~ 7.4, and the speed of the interferometer by a factor of almost 60 in single pointed observations. We will place the 13 elements over the platform to generate the longest possible baselines, which will result in angular resolutions up to $2'$. The correlator is also being expanded in order to handle the larger number of cross correlations.

In this second phase of AMiBA operations, the first science target will be to measure the power spectrum of the CMB to the higher multipole numbers in order to measure the shape at and beyond the second acoustic peak. Accurate measurements of the angular power spectrum of CMB temperature anisotropies through $l \sim 4000$ up to $l \sim 8000$ (Park et al. 2003) will allow us to see secondary effects such as the SZ effects (Lin et al. 2004) and possible cosmic string structures (Wu 2004). The second science target will be to resolve cluster SZE structures on the sky in order to compare with dark matter structures as deduced from weak gravitational lensing studies (Umetsu & Broadhurst 2008; Broadhurst et al. 2005, 2008; Okabe & Umetsu 2008). The third science target will be to survey for the distribution of galaxy clusters via the SZE (Umetsu et al. 2004). To obtain redshifts of cluster candidates, optical follow up observations will be conducted with ground-based telescopes.

At the time of the publication of this paper, the expansion is already in progress. We anticipate first operations during 2009.

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Table 1. Basic Characteristics of the AMiBA

Components	Specifications
Interferometer elements	7 0.6-meter (13 1.2-meter), f/2.0 Cassegrain
Telescope mount	hexapod
Telescope backup structure	6-meter carbon fiber platform
Primary reflector	monolithic carbon fiber
Surface accuracy	30 microns rms
Secondary reflector	carbon fiber, fixed
Array configuration	rings at 0.6m spacings
Available baselines	0.6 - 6.0 meters
Operating frequencies	94 GHz
Maximum angular resolution	$2'$
Primary beam field of view	$23'$ ($11'$)
Receiver band	86–102 GHz
Number of receivers	7 (13) dual polarization MMIC IP HEMT
Correlator	4-lag analog 2×21 (78) baselines
Flux-density sensitivity	65 (8) mJy per beam in 1 hour

Note. — The bracketed values will apply after the system upgrade to 13-elements with 1.2-meter antennas.

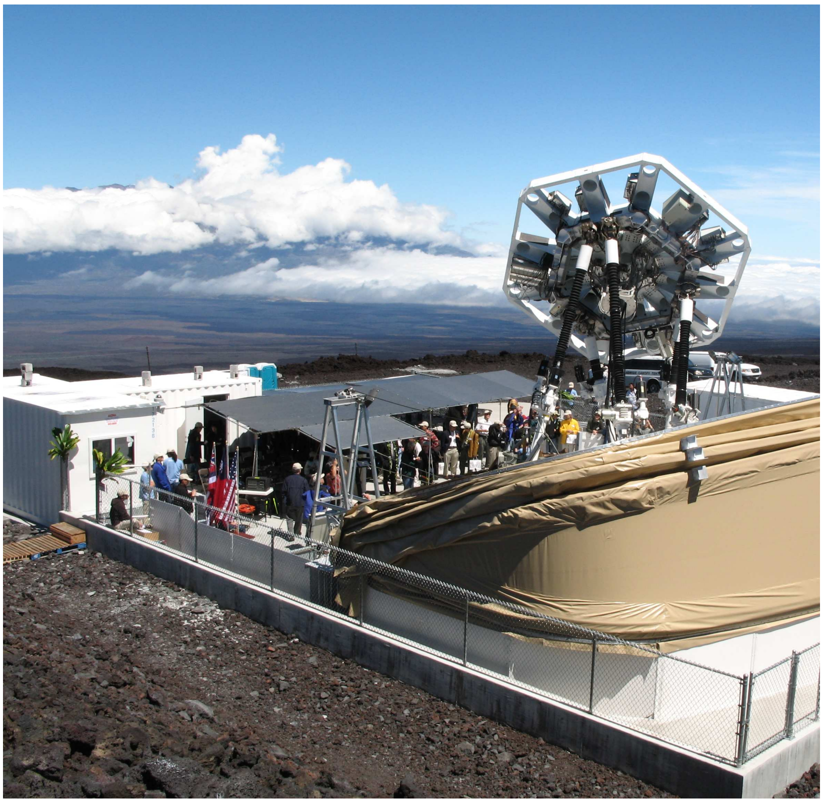

FIG. 1.— View of the AMiBA telescope on Mauna Loa, in October 2006, during dediction.

Fig. 2.— A close-up of the AMiBA telescope. The left panel shows the initial configuration of seven 0.6 m antennas co-mounted on a 6 m platform. Shown in the right panel are the receiver packages mounted on the platform together with various electronics such as the correlator and LO/IF systems. The reflectors and receivers can be deployed at various locations on the platform in order to achieve different projected baselines.

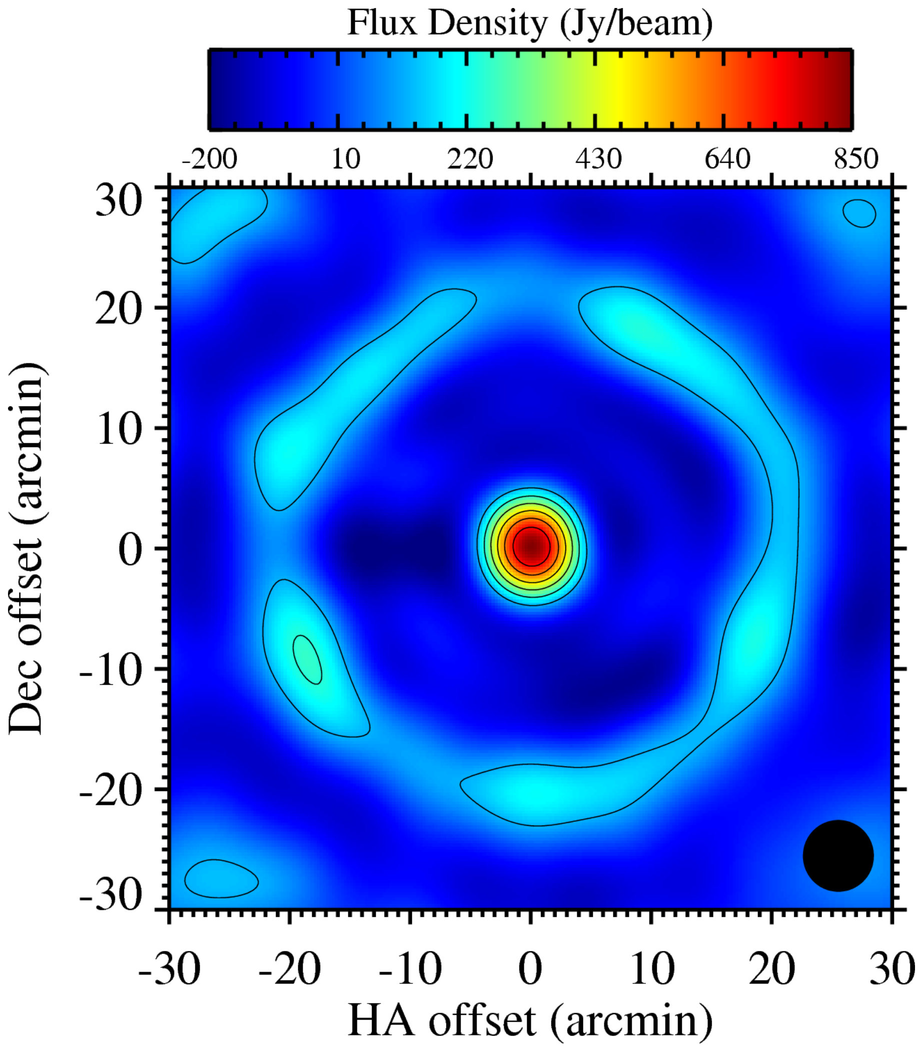

Fig. 3.— The first light image of Jupiter obtained by AMiBA in October 2006. This was a verification of the receiver and correlator systems as well as the pipeline software developed to calibrate and image the interferometer data.

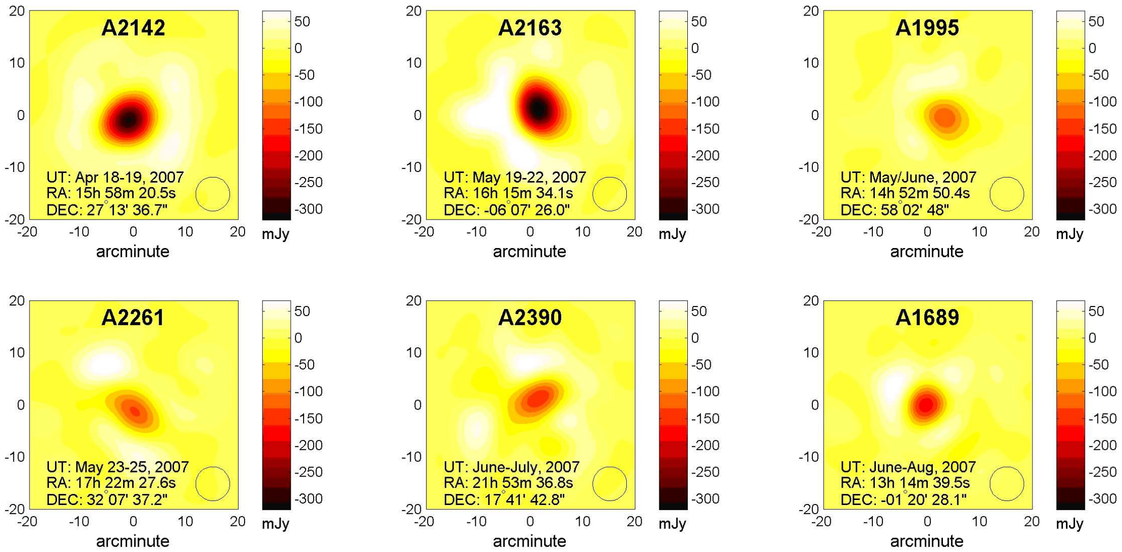

Fig. 4.— The first AMiBA images of the SZE decrement towards six massive clusters of galaxies.