Summer Student Program Lecture

The AMiBA Project

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Outline

1. Introduction
   - Cosmic Microwave Background (CMB)
   - Galaxy Clusters

2. CMB and Interferometer

3. AMiBA: Goals, Spec, Simulations
   - CMB Angular Power-Spectra
   - Galaxy Cluster Survey via the Sunyaev-Zel’dovich Effect (SZE)

4. AMiBA Current Status

5. Summary
Introduction
Cosmic Microwave Background: Powerful Probe of Cosmology

CMB + complementary astrophysical data enable us to fix the fundamental cosmological parameters.

Total density = critical density i.e. our universe is spatially flat.
What we don’t know...

- **Nature of Dark Matter** [WIMPs or MACHO?]:
  - Cold/Hot Dark Matter? Self-interaction?
- **Nature of Dark Energy** [\(\Lambda\) or Q?]:
  - DE Equation-of-State, \(w = (P/\rho) < -1/3\), and its possible evolution
- **Re-ionization of the Universe**: first stars/galaxies
  - When and How it happened?: \(z=11\) to 6?
- **Cosmic structure formation**
  - \(\sigma_8\), biasing between mass (DM) and light (galaxies)
- **Initial conditions of the Universe**: inflation model
  - Gravitational Wave
  - Primordial power index: \(P(k) = A_k^\alpha\)

Astrophysists are proposing various methods for extracting observational evidence to answer the questions.
Angular Power Spectrum, $C_l$

- Decomposing **patterns of structures** in spherical harmonics

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

"Fourier transform" of anisotropy on the sphere

- Rotational invariance (averaging over $m$)

**Angular power spectrum**

\[
C_l = \frac{1}{2l + 1} \sum_{m} \langle a_{lm} a_{lm}^* \rangle
\]

$C_l$ is the variance of structures on scale $l$,

\[
l \sim 180 \left( \frac{\theta}{1 \text{deg}} \right)^{-1}
\]

$\Delta T \sim 100 \ \mu K$
Observations of CMB T-Power Spectrum

Primary CMB:
Detailed physics worked out in cosmological perturbation theory

Secondary CMB:
Perturbations in non-linear regimes

Re-ionization from first stars and galaxies

Non-Gaussian signal

Acoustic Oscillations

Diffusion damping

Super horizon

Structure formation

\[ l \sim \pi / \theta \]
Galaxy Clusters (星系団)

- being most massive, gravitationally-bound structures in the universe with \( M > 10^{14} \, M_{\text{sun}} \).

- contain:
  - Visible galaxies (10^2-10^3),
  - Diffuse ionized gas (1-10 keV)
  - Dark Matter (80% in mass).

– sensitive cosmological probes, since they are the most rapidly evolving population.

– useful astrophysical probes, observed in many wavelengths:
  - Weak Gravitational lensing
  - Sunyaev-Zel’dovich Effect
Energy transfer from **hot cluster gas** to **cold CMB** via inverse Compton scattering

\[ y \equiv \int_0^{\lambda_{\text{LSS}}} d\tau \frac{k_B(T_e - T_{\text{CMB}})}{m_e c^2} \approx \int \frac{k_B T_e}{m_e c^2} \sigma_T n_e dl \propto \int dl P_e \]

**Spectral distortion of CMB spectrum**
Power of SZE

SZE brightness independent of distance (z),
while X-ray/Optical/Lensing signal of clusters gets fainter

What we seek for is a 10-100 $\mu$K weak signal!!

(Carlstrom et al. 1999)
Cluster Survey via the Thermal SZE

Evolution of Number Counts of SZE Clusters

Cosmological test with structure formation (0<z<a few)

Complementary to CMB constraints on cosmology

Figure from literature (simulated SZE survey with 8m SPT)
2. CMB and Interferometer
To measure the weight of a frog which is attached to a Jumbo-Jet:

In single-dish observations:

\[(M + m) - M' = m\]

- \(M\): weight of Jumbo with frog
- \(M'\): weight of Jumbo without frog

Measurement of CMB anisotropy:

\[\frac{m}{M'} < 10^{-5}\]
**Observable: Complex Visibility, \(V(u,v)\)**

\[
V(\vec{u}) = \int d^2x \ A(\vec{x}) I(\vec{x}) \exp[2\pi i \vec{u} \cdot \vec{x}]
\]

- \(I(x)\): intensity map on the sky
- \(A(x)\): antenna primary beam pattern
- \(u = d/\lambda\): baseline vector

Visibility is Fourier Transform of intensity pattern \(I(x)\) attenuated by \(A(x)\)

\[
V(\vec{u}) = \text{FT}[A(\vec{x})I(\vec{x})]
\]

Angular power spectrum directly measured by interferometer!!

\[
C_l \mid_{l=2\pi u} \approx \langle V(\vec{u})V^*(\vec{u}) \rangle
\]
Fringes from Drift-Scanning

Fringes from 2-element AMiBA prototype (2002-2004)
CMB Interferometers

- Typical angular sizes ~ 1 degree – 10 arcmin
  - small antennas, and/or, low frequency (10-100GHz)
- CMB anisotropy = diffuse, weak signal (10-100μK)
  - close-packed, or compact array to maximize sensitivity
- Observing strategies, different from traditional ones
  e.g., no geometrical delay to create fringes when tracking

\[ \Delta \theta = \frac{1}{\Delta u} \approx 20\arcmin \left( \frac{d}{60\text{cm}} \right)^{-1} \left( \frac{\lambda}{3\text{mm}} \right) \]

CBI @ 26-36 GHz, 13 elements, Chile (1999~)
DASI @ 26-36 GHz, 13 elements, South Pole (1999~)
3. Array for Microwave Background Anisotropy

Positioned as the 1st astronomical project initiated, designed, and led by Taiwan (2000~)
AMiBA Collaboration

- AS Institute of Astronomy & Astrophysics (ASIAA)
- NTU Department of Physics/Astronomy
- NTU Department of Electrical Engineering
- Australia National Telescope Facility
- University of Carnegie Mellon
- Jet Propulsion Laboratory/TRW
- Major Contractors: ALONG, Vertex, CMA

2000-2004 MoE, Taiwan
2003-2008 Academia Sinica, Taiwan
2004-2008 NSC, Taiwan
[2000-2002 Design]
[2002-2005 Build]
[2005-2007 Commissioning/Operation]
AMiBA Team: Dedication @ Mauna-Loa (3400m), Hawaii (Oct 2006)
AMiBA Science Goals

Science Objectives:

**CMB structure @ l=800-10,000**: or \( \Delta \theta = 20'-2' \)

(1) CMB Power Spectrum and Structure at high-\( l \) [small scales]
Primary / Secondary (SZE) anisotropy (\( l=800-3000 \), \( l=1000-6000 \))
\( \rightarrow \) Initial condition of DM density fluctuations (\( \sigma_8 \))

(2) Galaxy-Cluster Survey via the Sunyaev-Zel'dovich Effect (SZE)
- Evolution of number counts of galaxy clusters, \( N(z) \)
  \( \rightarrow \) Dark Energy Equation-of-State
- Clustering properties of clusters
  \( \rightarrow \) information of large-scale structure formation
- Probing high-z universe (\( z>1 \))

Simulated AMiBA

![Graph showing CMB power spectrum and structure](image-url)
AMiBA Site: Mauna-Loa (3400m)

Mauna Kea (4200m)

Platform (6m)

Hexapod Mount

Control Container
AMiBA Specifications

- **7 / 13 / 19-element interferometer**
  - Co-mounted on a 6m platform
  - 21 / 78 / 171-baseline
  - Cassegrain D=60,120cm antennas
- **Dual channel 84-104GHz (3mm)**
  - HEMT cooled to 15K
  - Tsys = 80K
- **Full polarization capability**
  - Dual polarizer: Linear X,Y
- **Correlator**
  - Analog, complex, 4-lags
  - N = 42 / [156] / [342]-correlators
- **Angular scales and sensitivities**
  - FoV = 22’ (D=60cm), 11’ (D=120cm)
  - 2’ -6’ resolution
  - Down to 1.5mJy per 2’ beam in 1hr (15uK)
AMiBA – A Hexapod Telescope

http://amiba.asiaa.sinica.edu.tw

Receiver

Correlator box

Optical telescope

Shelter

60cm antenna

Free Rx hole

Carbon fiber platform

Hexapod jack

0<Azimuth<360deg, Elevation > 30deg

Polarization: +/-30deg

(June, 2006)
AMiBA: Better uv-sampling: $S(u,v)$

Traditional interferometer
[2-axes: Azimuth, Elevation]

AMiBA with active platform rotations
[3-rotation DoF: Az, El, Pol]

UV-track due to earth rotation while tracking a target

PSF is an Inverse FT of the uv-sampling function:

$$B(\vec{x}) = \mathcal{F}^{-1}[S(\vec{u})]$$
Typical SEDs of Galaxies

Dust/Synchrotron foreground emission minimized at 3mm

![Graphs showing typical SEDs of galaxies with increased emphasis on dust emission at 3mm wavelength.](image)

**Fig. 1.**—Data points show the radio through infrared spectral energy distributions of four representative galaxies from our sample of 17 listed in Table 1. The data are obtained from NED (Radio data points), the NRAO VLA Sky Survey (Condon et al. 1998), the Westerbork Northern Sky Survey (Rengelink et al. 1997), and from Rigopoulou et al. (1996), Benson (1999), and Liszt et al. (1999). The solid curves show polynomial fits to the data. For the M82 spectrum, the straight lines indicate the spectral index that would be derived for the source at \( z = 0 \) and \( z = 3 \) between observing frequencies of 1.4 and 350 GHz.
AMiBA Data Analysis Flowchart

Simulated or observed CMB signals:
- Inflationary
- SZ effects
- Lensing effects
- Cosmic strings

Data Taking
(with AMiBA configuration)

Fringe/lag data to visibilities

Power-Spectrum Estimation
(maximum-likelihood analysis)

Map Making
(maximum-entropy method, etc.)

1. SZ Effects
2. Polarizations
3. Cosmological Parameters
   \( \Omega_{\text{tot}}, \Omega_b, \Omega_{\text{cdm}}, \Omega_{\text{DE}}, H_0, \sigma_8, w, n_s, n_T, \tau_c, \text{etc.} \)
Expected Performance of AMiBA

AMiBA Science (1)

Measurement of CMB Angular Power Spectra
Full 19-elements Performance

CMB Temperature Anisotropy

$\frac{l(l+1)c^{2}}{2\pi}$ (in $\mu$K$^2$)

- WMAP
- ACBAR
- CBI (2005)
- AMiBA (7 dishes of 60cm)
- AMiBA (19 dishes of 1.2m)
- Simulated AMiBA (19-elements)

<table>
<thead>
<tr>
<th>WMAP</th>
<th>ACBAR</th>
<th>CBI (2005)</th>
<th>AMiBA (7 dishes of 60cm)</th>
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P.J.H. Wu et al. 2004 (MPLA, 19, 1019)
7-element Performance in 1 month

CMB Temperature Anisotropy

Simulated AMiBA (7-elements)

P.J.H. Wu et al. 2004 (MPLA, 19, 1019)
Expected Performance of AMiBA

AMiBA Science (2)

Search for High-z Galaxy Clusters via the Sunyaev-Zel’dovich Effect
AMiBA: Probing Small-Scale Anisotropy

Input Primary + Secondary (CMB+SZE) sky @ 94GHz

AMiBA will target angular scales smaller than WMAP to study cluster-sized structures (~1Mpc) via the thermal S-Z effect (T-SZE)
Simulated AMiBA Deep Survey

Primary CMB + T-SZE ($\Lambda$CDM, preheating) = CMB+TSZE sky @94GHz

Simulated AMiBA survey
- 400ks integration over 1deg$^2$ (14 nights)
- 20cm gap between adjacent dishes filters out primary CMB contamination

- Sensitivity: 1.1mJy per 2' beam: K. Umetsu et al. 2004 (MPLA, 19,933)
Redshift distribution of SZE Clusters from a simulated AMiBA deep survey

AMiBA will detect ~100 clusters ($\Omega=10\text{deg}^2$) in 1 year, assuming 8hrs-integration per night.

N(z) peaked at $z\sim0.9$

Mass limit: $M_{\text{lim}} = 1.5 \times 10^{14} \text{ M}_\odot/\text{h}$

K. Umetsu et al. 2004 (MPLA, 19933)
4. AMiBA Current Status
Site Development: April 2004-August 2006

Mount commissioning: started in Jan 2005
Receiver and correlator on-site testing since late 2005
First Planet Fringes: Jupiter

Sep 8, 2006
Noise-filtered fringes of Jupiter taken with drift-scan mode, shown for 21 (/ 42) baselines

Jupiter
(point source for AMiBA):
850Jy @94GHz

Fringes-to-Visibility transformation (a=1,2,3,4)

\[
\hat{V}_a = T_{ab} \left[ K_{bj} P_{jd} \right]^{-1} c_d \equiv T_{ab} \left( \hat{K}^{-1} \right)_{bd} c_d
\]
AMiBA First Image: Jupiter (850Jy, Point source)

September 9, 2006
12 scans combined at transit
Net integration = "12s"

Dirty image

\[ I(\tilde{x}) = \text{FT}^{-1}[S(\tilde{u})V(\tilde{u})] \]

End-to-end verification of the system = hardware + software (i.e. analysis pipelines)

Synthesized beam FWHM (6')
More First Images (Sep 2006)

Elongated structure of an extend source nicely recovered (Flux~200Jy @ 3mm)

Fainter targets [point sources] with Flux~170Jy @ 3mm

Figures here from J.H. Proty Wu (NTU/Phys)
Fainter Target: Uranus (7.3Jy@94GHz)

- 16 drift scan observations
- No signal seen in fringes, for < 40Jy sources
- Signal only detected after image synthesis

Dec 22, 2006

Image reconstruction from 16 drift-scans, with a net integration of “16s”

But took a few hours for completing 16 drift scans...

Only 23 (/ 42) baselines were available, resulting in a poor UV-coverage and a highly distorted image

Noise rms =~ 1Jy/beam (in 16s, 23 baselines)
Clusters are faint, extended radio sources

Theoretical model predictions for the T-SZE towards nearby, massive clusters:

For AMiBA with 6′ synthesized beam, clusters at z=0.1-0.2 are extended sources.

Due to their large angular size, their fluxes at 60cm can be as large as 200-300mJy for very massive systems.
Two-Patch Tracking (1)

Off-source (P2)
(Blank sky)

On-source (P1)
(Target)

AMiBA FoV

Sky frame

Dec

R.A.
Two-Patch Tracking (2)

Correlator output (fringes)

DC + Ground em.

Transit (tracking center)

DC + Ground em. + Signal

Transit (tracking center)
## Two-Patch Tracking: Pros & Cons

### Pros

1. Allowing a **long on-source integration**, up to the limitation by the system stability (i.e., 1/f noise etc.)
2. Differentiate (P1-P2) in fringe domain, **removing the slowly-varying DC-signal** due to (1) the system and (2) ground emission

### Cons

- Observation time is twice of the single patch: \( \sigma \sim (s_b^2/t)^{1/2} \)
- Differentiation (P1-P2) increases RMS noise by a factor of \( \sqrt{2} \)
- In total, the net sensitivity is worse by a factor of \( (2^{1/2})^2 = 2 \)
  \( \rightarrow \) 100mJy/beam in 1hr
- However, the observing efficiency for extended, faint sources is much better than drift-scanning
First SZ Effect Detection: A2142 (z=0.09)

Estimated flux (@60cm, or u=200) is 300mJy, being consistent with the 30GHz observation by VSA.

About 6σ detection in 5hr x 2P observations (2-3 nights)
Possible Science with AMiBA

“Multi-Wavelength Study of Clusters”

DM vs. Baryons in A2142

Subaru Rc-band image

DM contours

Rc-band luminosity

X-ray contours

X-ray image

DM contours

Lensing + X-ray + Optical + SZE, probing the cluster physics

Weak lensing, X-ray, and optical study of 7-merging clusters of galaxies by Okabe & Umetsu (2007)
**Next Steps and Key Issues**

**Next Targets:** Aiming at starting CMB observations in a few months

- Quasars (point like) (100 - 1000mJy) : < a-few hrs x 2-patch tracking
- Bright SZE clusters (100 - 300mJy) : (5--50hrs) x 2-patch tracking
- Diffuse CMB power spectrum (rms<50mJy) : ~ a few months?

Practically, t < 6-8hrs integration per night

**Key Issues:**

- System efficiency improvement to increase “sensitivity”:
  - Receiver-antenna alignment within 2-3 arcmin for <~2% efficiency loss
  - Currently, efficiency parameter $\eta = 0.3–0.4$, while ~0.6 expected
- Identify and minimize systematics, which limits the sensitivity
  - Ground-emission pickup measurement and shielding: cf. CBI found several $\mu$K contribution in a synthesized image
  - Stability of the system for a long integration: $1/f$-noise, whiteness of noise
Summary

- In April 2007, AMiBA has made a first detection towards the S-Z effect by a galaxy cluster, and has observed a few more massive clusters for Cluster/Cosmology studies.
- After improving sensitivities in a few months, AMiBA will start to measure T-Cl or detect SZE clusters to get science results out.
- AMiBA is also stimulating international collaborations, and is providing young scientists with many chances to be leaders.