Exploring the Hot and Cold Universe

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Group Members

- **Jack Hughes** at RU since Sept 1996 (PhD: Columbia)
- **Prasiddha Arunachalam** grad student
- **Peter Doze** grad student
- **Alumni/ae:**
  - Steven Boada (Texas A&M) Data science
  - Amruta Deshpande (Florida, Rutgers) Data science
  - Luke Hovey (East Stroudsburg, Rutgers) Los Alamos National Lab
  - Kris Eriksen (Middlebury, Arizona) LANL
  - Felipe Menanteau (Católica, Cambridge) NCSA, Illinois
  - Neelima Sehgal (Yale, Rutgers) Assoc Prof, StonyBrook
  - Carles Badenes (PhD: Barcelona) Assoc Prof, Pittsburgh
  - Jessica Warren (Vassar, Rutgers)
  - Cara Rakowski (Brown, Rutgers) Patent Office
Job Prospects

Recent RU astronomy PhD graduates obtained jobs in industry, teaching colleges, NASA centers, government labs, academic post-docs, and research universities

http://www.physics.rutgers.edu/ast/group-ast.html

American Astronomical Society (resource for careers):

http://aas.org

Job Register

https://jobregister.aas.org

Astrophysics Jobs Rumor Mill - Postdoc & Term (>200 PD jobs, ~100 tenure-track faculty jobs this season)

http://www.astrobetter.com/wiki/Rumor+Mill
The Cold Part
The cosmic microwave background—the radiation left over from the Big Bang—was detected by Penzias and Wilson in 1965 in New Jersey!

Published as “A Measurement of Excess Antenna Temperature at 4080 Mc/s”

1978 Nobel Prize in Physics to Penzias and Wilson
NASA COBE (Launched 1989)

Measured nearly perfect blackbody spectrum with a temperature of 2.725 +/- 0.002 K

Blackbody radiation comes from objects in thermal equilibrium

Cosmic Microwave Background (CMB)
NASA/COBE satellite
4-yr all-sky maps

- Top: 0 - 4 K scale \(<T>\sim 2.7\) K

- Middle: emphasize dipole from Earth’s motion (1 part out 1000)

- Bottom: after subtraction of dipole; cosmic anisotropy at 1 part out of 100,000

2006 Nobel Prize in Physics to Mather and Smoot
• CMB is the relic of a hot early phase of the Universe

• Strong evidence that the Universe went through a hot, dense “Big Bang” phase

• CMB comes to us from a time when the Universe had cooled enough for atoms to form (~380,000 yrs)
Evolution of Universal Density

Linear theory \(\rightarrow\) “clean” physics

Basic elements well understood
Analyzing the CMB

\[ T(\hat{n}) = \sum_{l=0}^{\infty} \sum_{m=-l}^{l} a_{lm} Y_{lm}(\hat{n}) \]

\[ C_l = \frac{1}{(2l+1)} \sum_{m=-l}^{l} \langle |a_{lm}|^2 \rangle \]

Primordial CMB power spectrum fit by 6 parameter \( \Lambda \)-Cold Dark Matter (\( \Lambda \)CDM) model: baryon density, CDM density, \( \Lambda \), amplitude and tilt of the matter power spectrum, and optical depth to reionization
Anisotropies

COBE

WMAP

CMB angular power spectrum
The Push for Higher Resolution CMB Maps

Sudeep Das for the ACT collaboration
Atacama Cosmology Telescope

Custom built 6-m telescope and mm-wave camera

Measure arcmin-scale fluctuations in the Cosmic Microwave Background (vs. ~10 arcmin for WMAP and ~5 arcmin for Planck)

Proposed in 2000, funded in 2003


Upgraded for polarization in 2013

Approved for AdvancedACTPol (2016-…)

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March 31, 2020

Seminar in Physics

J.P. Hughes
ACT Site

5200 meters high in the Atacama desert of the Chilean Andes

Cerro Toco

Latitude: 23 deg south
Not far from the ALMA site

~45 minute drive from San Pedro de Atacama
The ACT Site, Telescope, and Sensors

• High: One of the highest telescopes on Earth
• Dry: 0.49 mm median Precipitable Water Vapor
• 6-m primary mirror; off-axis Gregorian design
• Three 1000 pixel arrays of Transition Edge Sensors
• Observing frequencies: 148, 218, 277 GHz
• Diffraction limited (~1 arcmin resolution)
• Scans in azimuth 2° per second
• Low ground pick-up (groundscreens)

Funded by the NSF
Making Maps

Challenge - data from telescope/sensors (right) doesn’t look like the sky (below). Noise is complicated, includes correlations between detectors from atmosphere, etc.

First task is to convert time-ordered-data streams into maps: use multiple “views” of CMB sky on different timescales and with different pixels to construct a maximum likelihood map.

ACT uses custom-built software running on SciNet – large supercomputer at CITA

The goal is an unbiased estimate of all modes from degree to arcmin scales
Even with good maps, clusters are buried in the CMB. At 148 GHz, clusters appear as decrements in the ACT data.
These fluctuations are the seeds of all structure in the Universe.

We use them as inputs to large N-body simulations that track the gravitational forces in the expanding Universe.
ACT Discovery Highlights 2011-2013

Standard Cosmological Model

ACT first detected 7 acoustic peaks in the CMB
Sievers et al 2013, JCAP, 10, 60
Das et al 2014, JCAP, 4, 14

ACT, the South Pole Telescope, the WMAP satellite and the Planck satellite have provided the cornerstone for the standard $\Lambda$CDM cosmological model.
The CMB illuminates the Universe!
Lensed CMB

Rule of 2-3
ACT Discovery Highlights 2011-2013

Gravitational Lensing

First measurement of the gravitational lensing convergence of the CMB
Das et al 2011, PRL 107(2):021301
Combined with ACT’s power spectrum first detected dark energy using only CMB data.
Sherwin et al 2011, PRL 107(2):021302

Selected by Physics Today as one of only seven Discovery Highlights of 2011.
The discovery of ACT-CL J0102-4915, a high redshift, merging galaxy cluster, the most extreme known, nicknamed “El Gordo” because of its high mass (more than $2 \times 10^{15} \, M_\odot$).


Highlighted in Discover Magazine 2012 Year in Science issue; also on NPR “All Things Considered”
Power spectrum of the temperature of the CMB (TT) and the E-mode polarization signal (EE) from 3 months of observations in 2014 with ACTPol.

Naess et al 2014, JCAP, 1410, 007
The Hot Part
Growth of Structure

🔹 CMB anisotropies are fluctuations in the mass density of the Universe when it was 380,000 yrs old

🔹 The fluctuations evolve under gravity (Einstein’s General Theory of Relativity) and expansion to form the observed distribution of mass (traced by galaxies)

🔹 In other words, the CMB anisotropies are the seeds of all structure in the Universe – from people and planets to stars and galaxies!

🔹 Here’s how they evolve
Early ($z=18.3$) Age=0.21 Gyr

Now ($z=0$) Age=13.6 Gyr
Clusters of Galaxies

Largest organized systems in the Universe

- 10’s to 1000’s of galaxies covering 25 Mpc$^3$ ($10^{75}$ cm$^3$)
  - Typical galaxy velocity $\sim$ 100 – 1000 km s$^{-1}$
  - Velocity distribution determines cluster’s gravitational mass

- Intracluster medium filled with hot ($10^6$-$10^8$ K), low density ($<10^{-3}$ atoms/cm$^3$) gas
  - Mass of gas is 5-10 times the entire stellar mass in galaxies
  - Gas not primordial, must have been processed through stars.
  - Amount of gas and its temperature determines cluster’s gravitational mass

- Total mass up to $10^{15}$ M$_\odot$ ($10^{48}$ gm)
  - Only $\sim$10% of the mass is baryonic (i.e., normal matter) – the nature of the rest (the so-called “dark matter”) is unknown – DM is known to exist only because of its gravitational effects.
Clusters of Galaxies (example)

X-ray (ROSAT)

Optical
(Central region)
Clusters of Galaxies (example)

X-ray (ROSAT)

Optical (Central region)
Clusters of Galaxies (example)

X-ray (ROSAT)  

SZ (Planck)
Physics of the Sunyaev-Zel’dovich Effect (SZE)

Inverse Compton scatter
- Net energy change of photon in a Compton collision:
  \[ \frac{\Delta \varepsilon}{\varepsilon} = -\frac{h \nu_0}{m_e c^2} + \frac{4kT}{m_e c^2} \]
- Optical depth for Thomson scattering
  \[ \tau_e = n_e \sigma_T l \]
- Comptonization parameter
  \[ y = \int \frac{kT_e}{m_e c^2} n_e \sigma_T dl \]

Galaxy Cluster

HOT Electrons

Electrons in a cluster are hot \( \sim 10^7 \) K
CMB photons are cold \( \sim 2.7 \) K
So photons tend to get boosted in energy
This distorts the CMB blackbody spectrum
Physics of the (thermal) SZE

- Kompaneets (1956) eqn.
  - Describes how photon field evolves in energy and “time”
    \[
    \frac{\partial n}{\partial y} = \frac{1}{x_e^2} \frac{\partial}{\partial x_e} x_e^4 \left( \frac{\partial n}{\partial x_e} + n + n^2 \right)
    \]
  - where \( x_e \equiv \frac{h \nu}{k T_e} \).
  - We can drop the \( n \) and \( n^2 \) terms and then set \( x_e = x \equiv \frac{h \nu}{k T_{\text{CMB}}} \).
  - Solution for the spectral change due to scattering is:
    \[
    \frac{\Delta u_\nu}{u_\nu} = y \frac{x \exp x}{\exp x - 1} \left( \frac{\exp x + 1}{\exp x - 1} - 4 \right)
    \]
- In this approximation, locations of the minimum, maximum, and null are independent of \( T_e \)

\[
\frac{\Delta I_\nu}{I_\nu} \approx -2y \quad y = \int \frac{k T_e}{m_e c^2} n_e \sigma_T d\ell
\]

SZE is quite small; typically only \( 10^{-3} \) of the CMB itself.
Thermal SZ effect

- Inverse Compton Scattering
  - Hot cluster electrons boost energy of CMB photons
- Spectral Signature
  - SZ null at ~220 GHz
- Redshift independent
  - “clean” cluster selection
- tSZ Effect proportional to $n_eT$
  - probes cluster pressure

Planck stacked images of confirmed clusters in 9 frequency bands showing decrements, null, and increments
Why An SZ Survey for Clusters?

- Clusters are exponentially sensitive to the growth of structure in the Universe
- Can set constraints on the cosmological model
- SZE is redshift independent
- SZE integrated Y parameter is tightly correlated to cluster mass with low scatter
- SZE has strong sensitivity to cluster mass
- kSZE measures velocity field – can also probe growth of structure
X-rays from ACT Clusters

68 SZE clusters
(49 in S82; 19 beyond) with
ACT S/N>4.0

X-ray fluxes
from ROSAT All
Sky Survey in
0.1-2.4 keV
band

Curves show
estimated fluxes
for $10^{15} \, M_\odot$ and
$4 \times 10^{14} \, M_\odot$
clusters

$F_x(0.1-2.4 \, \text{keV})$ (ergs cm$^{-2}$ s$^{-1}$)
Cosmological Constraints

- ACT equatorial clusters (15 at $z > 0.2$) + BBN + H0 (i.e., no CMB)
- Fixed scaling relations, different models (from Bode et al. 2012, Trac et al. 2011)

![Cosmological Constraints Diagram]

Hasselfield et al. (2013)
Cosmological Constraints

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Interest area of research focus on ACT: to obtain weak lensing mass calibration

Hasselfield et al. (2013)
Merging/Interacting Clusters

Another area of research

ACT-CL J0245–5302  AS0295

Cluster merger sims (ZuHone11) 3:1 mass ratio; \( b = 500 \text{ kpc} \)

Doze, JPH, Keeton, Raney, Battaglia, Hilton, Knowles, Moodley, Sifon, et al

March 31, 2020  Seminar in Physics  J.P. Hughes
advanced ACTPol Survey:
20,000 square degrees, complete overlap with LSST

started 2016
High Speed Shock Waves

When a wave moves faster than the sound speed it becomes a shock wave. This produces a nearly discontinuous change in the pressure, temperature, and density of the medium.
High Speed Shock Waves

Terrestrial shock waves are fairly rare
Typically result from supersonic motion and explosions
High Speed Shock Waves

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Bullet at Mach 2.5 plus muzzle blast, Schlieren imaging

https://www.youtube.com/embed/BUREX8aFbMs
Knots in Kepler’s SNR

- Identify compact knots in intensity or redshift using *Chandra*
  - Knot types: 9 ejecta (N, NE, SW); 3 CSM; 2 knots matched to optical (Sankrit+16)
- Determine proper motion and radial velocity

**4 epochs:** 2000, 2004, 2006, 2014 (49 ks, 46 ks, 741 ks, 139 ks)
Knots in Tycho’s SNR

- Knots not so compact in Tycho – more like blobs – but also visible in intensity or redshift using Chandra
- Determine radial velocity

Composition/Emission mechanism

Ejecta velocity from Si-K

Warren, JPH, et al 2005

Sato & JPH 2017
How to Quantify Differences in Morphology?

Phase-averaged Fourier power-spectrum

Wavelet-transform size analysis

Typical size for each structure

Smooth model
Clumpy model
Tycho’s SNR

Central region
What is the Genus Statistic?

- A method to analyze topology (in 2D & 3D)
- One calculates the homology count (# of holes and clumps) as a function of contour (intensity) level

![Genus diagram](https://via.placeholder.com/150)

Usually in terms of RMS from mean
What is the Genus Statistic?

Genus statistics

Genus $= 0$

Genus $= -1$

Genus $= +1$

Genus $= -2$

Genus $= +2$

\[ G \equiv \text{(number of isolated high-density regions)} - \text{(number of isolated low-density regions)} \]
Comparison with Hydro Models

Smooth model (which includes only RTI during SNR evolution) is a much poorer fit than the clumpy model (with ad hoc structure for ejecta introduced soon after the explosion).

Figure 10. Comparison of the genus curves for the smooth model (top) and the clumpy model (bottom) with the smoothing $\sigma = 6$ pixels ($= 2''/4$). The dot and broken lines show the analytic models for the Gaussian and $\chi^2$ distribution, respectively. The blue lines show the genus curves for Tycho’s SNR with the smoothing $\sigma = 5$ pixels ($= 2''/46$).
Observational Resources

Southern African Large Telescope: RU has 10% share of observing time

Advanced ACTPol: Large area sky survey of CMB for multiple science goals. RU closely involved in Galaxy Cluster. Significant upgrade to Simons Observatory in process

Swift, Chandra, XMM-Newton, NuSTAR: Operating X-ray satellites for cluster confirmation and detailed follow-up study