Discovering Signals from the Beginning of the Universe with Microwave and Millimeter-Wave Spectroscopy

Brad Johnson
Columbia University
How can we see beyond our cosmic horizon?

The Known Universe -- https://www.amnh.org/

Our cosmic horizon in space

we are here

last scattering surface

z = 1100

z = 0
How can we see beyond our cosmic horizon?

1) B-mode polarization anisotropy produced by inflationary gravitational waves.

2) Spectral distortions in the CMB.
Outline of the Talk

1) Overview of CMB Spectral Distortions
   $y$, $\mu$, recombination lines

2) Prospects for Measuring CMB Spectral Distortions
   (Abitbol et al. (2017) MNRAS, 471, 1126-1140)

3) Investigating Anomalous Microwave Emission in
   the S140 Star-Forming Region (Abitbol et al. (2018)

4) A Novel Spectrometer for Discovering Signals from
   the Beginning of the Universe – RISE Funded
CMB Spectral Distortions

- **μ-type distortions** are the result of particles interacting with photons during the very early universe when photons were in equilibrium with matter ($z > 3 \times 10^5$).

- **γ-type distortions** are produced later ($z < 3 \times 10^5$) when Compton scattering becomes an inefficient mechanism for energy exchange; this is the same mechanism that produces the thermal Sunyaev-Zel’dovich effect in galaxy clusters.

- A **recombination line spectrum** should have been produced when hydrogen and helium nuclei in the primordial plasma captured electrons during recombination, producing emission lines distinctly different from the usual CMB blackbody spectrum ($10^3 < z < 10^4$).
The 2006 Nobel Prize in Physics was awarded jointly to John C. Mather and George F. Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."
MEASUREMENT OF THE COSMIC MICROWAVE BACKGROUND SPECTRUM BY THE COBE\(^1\) FIRAS INSTRUMENT

J. C. Mather,\(^2\) E. S. Cheng,\(^2\) D. A. Cottingham,\(^3\) R. E. Eplee, Jr.,\(^4\) D. J. Fixsen,\(^5\) T. Hewagama,\(^6\) R. B. Isaacman,\(^4\) K. A. Jensen,\(^6\) S. S. Meyer,\(^7\) P. D. Noerdlinger,\(^5\) S. M. Read,\(^6\) L. P. Rosen,\(^6\) R. A. Shafer,\(^2\) E. L. Wright,\(^8\) C. L. Bennett,\(^2\) N. W. Boggess,\(^2\) M. G. Hauser,\(^2\) T. Kelsall,\(^2\) S. H. Moseley, Jr.,\(^2\) R. F. Silverberg,\(^2\) G. F. Smoot,\(^9\) R. Weiss,\(^7\) and D. T. Wilkinson\(^10\)

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**TABLE 1**

**Errors and Dependence on Galactic Plane Exclusion Angle from 20° to 40°**

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Value</th>
<th>(\sigma)</th>
<th>Systemic Error</th>
<th>Galactic Range</th>
<th>95% CL</th>
</tr>
</thead>
<tbody>
<tr>
<td>(T_0) (K)</td>
<td>2.726</td>
<td>0.00001</td>
<td>0.005</td>
<td>(\pm 0.000012)</td>
<td>0.010</td>
</tr>
<tr>
<td>(\mu) (10(^{-5}))</td>
<td>-12</td>
<td>8</td>
<td>-1 to -21</td>
<td>33</td>
<td></td>
</tr>
<tr>
<td>(y) (10(^{-6}))</td>
<td>3</td>
<td>8</td>
<td>-9 to +14</td>
<td>25</td>
<td></td>
</tr>
</tbody>
</table>

Note.—There is no known significant source of systematic error for \(y\) or \(\mu\) besides the Galaxy. The quoted \(\sigma\) includes the effect of the simultaneous solution for a temperature shift and Galactic emission as well as \(y\) or \(\mu\).
CMB Spectral Distortion Signals

![Graph showing spectral distortion signals with annotations for recombination lines, y-distortion, and μ-distortion.]

B-modes for comparison
2) Prospects for Measuring CMB Distortions
Prospects for measuring cosmic microwave background spectral distortions in the presence of foregrounds

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We investigated the detectability of the $\mu$ and $\gamma$ spectral distortions using NASA’s proposed PIXIE mission as the test case.

Kogut et al. (2011) JCAP, 07, 025.
Could PIXIE measure $y$ and $\mu$?

Problem: Galactic Signals

Credit: NASA/JPL-Caltech/ESO/R. Hurt
Planck all-sky foreground maps

- LFI 30 GHz
- LFI 44 GHz
- LFI 70 GHz
- HFI 100 GHz
- HFI 143 GHz
- HFI 217 GHz
- HFI 353 GHz
- HFI 545 GHz
- HFI 857 GHz
Forecast Performance Including Galactic Signals

Galactic Signals

- **Free-free** or Bremsstrahlung emission is **unpolarized** radiation from electron-ion collisions. The free-free spectrum decreases as a power law $\beta = -2.15$, for electron temperatures between 500 and 20,000 K.

- **Synchrotron** radiation originates from cosmic ray electrons spiraling in Galactic magnetic fields. The synchrotron spectrum follows a power law with spectral index typically around $\beta = -3$, and it theoretically can be **up to 75% polarized**.

- **Thermal dust** emission comes from interstellar dust grains that are heated by ambient radiation from stars in the Galaxy. The emission obeys a modified blackbody spectrum at a temperature of 18 K and spectral index $\beta = 1.8$ up to 800 GHz (at even higher frequencies two component models are used). The dust has been measured to be approximately **5% polarized on average** over the sky but up to 20% polarized in regions of low optical depth.

- The **cosmic infrared background (CIB)** is the collective infrared radiation emitted by cosmic sources throughout the history of the Universe.
Anomalous Microwave Emission

• **Anomalous Microwave Emission (AME)** includes emission that does not correlate with dust, synchrotron, or free-free.

• The **physical mechanism behind the AME is not understood**, and we do not yet have reliable estimates of the degree to which it is polarized.

• The current prevailing theory for AME is that **small asymmetrical dust grains spin rapidly** and emit electric dipole radiation.

• **The polarization of spinning dust arises when grains align with the local magnetic field.**

• Other theories propose contributions from ferromagnetic dust grains and their associated magnetic dipole radiation.
Models Exist for Galactic Signals

Table 1. Foreground model motivated by Planck data. All SEDs, $\Delta I_X$, are in units of Jy sr$^{-1}$. For each component, we also give the value of $\Delta I_X(v_r)$ at $v_r = 100$ GHz for reference.

<table>
<thead>
<tr>
<th>Foreground</th>
<th>Spectral radiance (Jy sr$^{-1}$)</th>
<th>Free parameters and values</th>
<th>Additional information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal dust</td>
<td>$x = \frac{h\nu}{kT_D}$, $\Delta I_D(v) = A_D x^{\beta_D} \frac{x^3}{e^x - 1}$</td>
<td>$A_D = 1.36 \times 10^6$ Jy sr$^{-1}$</td>
<td>$\Delta I_D(v_r) = 6608$ Jy sr$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\beta_D = 1.53$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_D = 21$ K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CIB</td>
<td>$x = \frac{h\nu}{kT_{CIB}}$, $\Delta I_{CIB}(v) = A_{CIB} x^{\beta_{CIB}} \frac{x^3}{e^x - 1}$</td>
<td>$A_{CIB} = 3.46 \times 10^5$ Jy sr$^{-1}$</td>
<td>$\Delta I_{CIB}(v_r) = 6117$ Jy sr$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\beta_{CIB} = 0.86$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$T_{CIB} = 18.8$ K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Synchrotron</td>
<td>$\Delta I_S(v) = A_S \left( \frac{\nu}{\nu_0} \right)^{\alpha_S} \left[ 1 + \frac{1}{2} \omega_S \ln \left( \frac{\nu}{\nu_0} \right) \right]$</td>
<td>$A_S = 288.0$ Jy sr$^{-1}$</td>
<td>$\Delta I_S(v_r) = 288$ Jy sr$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\alpha_S = -0.82$</td>
<td></td>
<td>10 per cent prior assumed on $A_S$ and $\alpha_S$</td>
</tr>
<tr>
<td></td>
<td>$\omega_S = 0.2$</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\nu_0 = 100$ GHz</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Free–free</td>
<td>$\nu_{FF} = \nu_{FF} \left( T_e / 10^3 \text{ K} \right)^{3/2}$</td>
<td>$A_{FF} = 300$ Jy sr$^{-1}$</td>
<td>$\Delta I_{FF}(v_r) = 972$ Jy sr$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta I_{FF}(v) = A_{FF} \left( 1 + \ln \left[ 1 + \left( \frac{\nu}{\nu_{FF}} \right)^{\sqrt{3}/\pi} \right] \right)$</td>
<td></td>
<td>${ T_e, \nu_{FF} } = { 7000 \text{ K}, 255.33 \text{ GHz} }$</td>
</tr>
<tr>
<td>Integrated CO</td>
<td>$\Theta_{CO}(v) = \text{CO template}(v)$</td>
<td>$A_{CO} = 1$</td>
<td>$\Delta I_{CO}(v_r) = 1477$ Jy sr$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta I_{CO}(v) = A_{CO} \Theta_{CO}(v)$</td>
<td></td>
<td>Template in Jy sr$^{-1}$</td>
</tr>
<tr>
<td>Spinning dust</td>
<td>$\Theta_{SD}(v) = \text{SD template}(v)$</td>
<td>$A_{SD} = 1$</td>
<td>$\Delta I_{SD}(v_r) = 0.25$ Jy sr$^{-1}$</td>
</tr>
<tr>
<td></td>
<td>$\Delta I_{SD}(v) = A_{SD} \Theta_{SD}(v)$</td>
<td></td>
<td>Template in Jy sr$^{-1}$</td>
</tr>
</tbody>
</table>

Forecast PIXIE performance with Fischer/MCMC analysis.

PIXIE would not detect $\mu$ predicted by nucleosynthesis given expected effects from Galactic foreground signals.

3) Investigating Anomalous Microwave Emission in the S140 Star-Forming Region

Maximilian H. Abitbol¹, Glenn Jones¹, Bradley R. Johnson¹, Clive Dickinson², Stuart Harper²

1) Department of Physics, Columbia University
2) Jodrell Bank, University of Manchester
3) Investigating Anomalous Microwave Emission in the S140 Star-Forming Region

Designed project in spring 2016.
Applied for observing time at Green Bank Telescope in summer 2016.
Awarded observing time at end of 2016 (GBT17A-259). ← 5th year review
Observations took place in spring 2017.
Analysis is done, first ApJ paper near submission.
Why study AME?

- Emission mechanism is not understood.
- Important foreground for B-mode studies if polarized.
- Foreground for future recombination line studies.
- Good entry-point project for my group.
- We’re learning how to make spectropolarimetric observations and analyze data.
Result from Planck Collaboration

HII region = interstellar ionized hydrogen.
Green Bank Telescope (GBT)
Green Bank Telescope (GBT)

- Sited in Green Bank, West Virginia
- Gregorian reflecting telescope
- Diameter = 100 meters
- Focal length = 60 meters
- Observations possible between 0.1 and 116 GHz
- Our observations used the C-band receiver (4 to 8 GHz) and the VEGAS spectrometer.
Green Bank Telescope (GBT)

- **Primary mirror** (paraboloid) 100 m
- **Secondary mirror** (ellipsoid)
GBT Receivers
VEGAS: Versatile GBT Astronomical Spectrometer

**Diagram Description:**
- **Corrugated Horn**
- **OMT**
- **Pol X**
- **Pol Y**
- **Noise Source**
- **Signal Splitter**
  - Bank A = 4.575 GHz
  - Bank B = 5.625 GHz
  - Bank C = 6.125 GHz
  - Bank D = 7.175 GHz
- **3.95 to 8 GHz**
- **3 Gbps**
- **8 Bit**
- **1.5 GHz**
- **16,384 Channels per Bank**
- **Resolution = 91.552 kHz**
- **65,536 Channels Total**
- **Ethernet**
- **ROACH (FPGA)**
- **Computer**

**Specifications:**
- **Bandwidth = 1.25 GHz**
- **10.5 GHz**
- **8.5 to 10.35 GHz**
- **1.5 GHz**
- **3 Gbps**
- **8 Bit**

**Notes:**
- *Columbia University in the City of New York*
Observations

- Observations took place April 3, 5, 10; June 3, 4; July 31, 2017
- 18 hours of observations:
  - 10 hours mapping
  - 8 hours polarization calibration
- “daisy” scan strategy produces circular map (see right)
- Absolute calibration:
  - Radio galaxy 3C 295 (z = 0.464)
- Time dependent calibration:
  - Noise source switched at 25 Hz
- Polarization calibration:
  - 3C 245, 3C 273, 3C 280
Observations

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• polarization calibration:
  3C 245, 3C 273, 3C 280
Results: Map from Bank A
Results: Map from Bank A

GBT Bank A

Lat (deg)  
6.5  
6.0  
5.5  
5.0  
4.5  
4.0  
106.0  
106.5  
107.0  
107.5  
108.0  
108.5  

Lon (deg)

Flux (mJy/pixel)

0  
5  
10  
15  

-5  
-10  
-15  

S140

point sources

point sources
Results: Map from Bank B
Results: Map from Bank C

![Map of GBT Bank C](image)

- **Lat (deg)**: 4.0 to 6.5
- **Lon (deg)**: 106.0 to 108.5
- **Flux (mJy/pixel)**: -15 to 15

The map shows the distribution of flux across the GBT Bank C region, with higher values indicated in yellow and lower values in dark blue.
Smooth Maps for Combined Analysis
Smooth Maps for Combined Analysis
Results: Spectra

UCHII Region Model

- without GBT data
- with GBT data
- External data
- GBT data

Flux [Jy] vs. Frequency [GHz]
Results: Spectra

Spinning Dust Model

- Dashed line: without GBT data
- Solid line: with GBT data
- Black dots: External data
- Red dots: GBT data

Frequency [GHz]

Flux [Jy]

spinning dust component
Spectra Without Our Measurements

HII region = interstellar ionized hydrogen.
Spectra **With** Our Measurements

**S140 Region Intensity Spectrum**

- Spinning Dust Fit with GBT data
- UCHII Region Fit with GBT data
- Haslam, Reich, WMAP, Planck, and DIRBE data

**HII region =** interstellar ionized hydrogen.
4) A Novel Spectrometer for Discovering Signals from the Beginning of the Universe

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1) Department of Physics, Columbia University
2) Department of Electrical Engineering, Columbia University
Spectra
Figure 6 – The cosmological recombination radiation created in the redshift range $z \approx 10^3 - 10^4$. The presence of helium in the Universe gives rise to unique features in the recombination spectrum. This fingerprint of the recombination era in principle allows us to test our understanding of the recombination history which is one on the fundamental ingredients for the computations of the CMB anisotropies.
Measuring Cosmological Parameters

\[ \Omega_b = 0.02 \]

\[ \Delta I_\nu \text{ [J m}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}] \]

\[ \nu \text{ [GHz]} \]

\[ 10^{-26} \]

\[ 10^{-27} \]

\[ 10^{-28} \]

\[ 0.1 \]

\[ 1 \]

\[ 10 \]

\[ 100 \]

\[ 1000 \]
$Y_P = \frac{\rho(^{4}\text{He})}{\rho_{\text{baryon}}}$

\[ Y_P = 0.1 \]

\[ Y_P = 0.1 \]
Pathfinder Spectrometer (PSPEC)

With RISE support, we will build a prototype instrument and use it as a test bed for learning how to:

(i) perform the essential high-precision calibration measurements
(ii) manage radio frequency interference (RFI)
(iii) characterize the instrument beam
(iv) mitigate the effects of systematic errors
(v) characterize bright Galactic signals.
Pathfinder Spectrometer (PSPEC)
Conclusions

1) CMB Spectral Distortions provide a way to study the early Universe (z > 1100).

2) Measurements will be challenging.

3) Entry point -- we observed an AME region with GBT.

4) RISE Funded PSPEC project is just beginning.
Standard Model of Cosmology

http://map.gsfc.nasa.gov/media/060915/
The 2006 Nobel Prize in Physics was awarded jointly to John C. Mather and George F. Smoot "for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation."
What does this anisotropy image tell us?

The image implicitly tells us this is true.

\[ B_\nu = \frac{2h\nu^3}{c^2} \left[ \exp \left( \frac{h\nu}{kT_o(1+z)} \right) - 1 \right]^{-1} \text{ where } T_o = 2.73 \text{ [K]} \]
Time Dependent Calibration

![Graph showing diode power calibrated on 3C295 across different sessions and frequency bands. The graph indicates variations in diode power across different frequency bands and sessions with distinct markers and colors for each session.](image-url)