# The Cosmic Microwave Background Radiation

B. Winstein, U of Chicago

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<th>What is it? How its anisotropies are generated? What Physics does it reveal?</th>
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Lecture #2: Measuring the Cosmic Microwave Background

- Radio telescopes
- Receiver Types
- Sources of Noise
- Sensitivities
- Observing trade-offs and strategies
- From raw data to power spectra
Looking at a Point on the Sky

R.H. Dicke and colleagues, mid 1940s
Elements of a Radio Telescope

- Antenna
- Amplifier
- Filter
- Power Meter
- Amplifier
Elements of a Radio Telescope

- Antenna
- Amplifier (low-noise, high bandwidth)
- Filter (selects $\Delta\nu$)
- Power Meter (measures $<E^2>$)
- Amplifier (low frequency (DC))
Antenna Pattern

Diffraction limit: \[ A \Omega = \lambda^2 \]

- \( A \): collecting area
- \( \Omega \): beam solid angle
- \( \lambda \): wavelength

Near side lobes
Far side lobes
Main beam
CMB Flux

- **Planck Spectrum:**

\[ B_n = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1} W/m^2/str/Hz \]

- **Example:**
  - beam FWHM = 8°; beam area = 8 cm²
  - \( \nu_0 = 90 \) GHz; \( \Delta \nu = 10 \) GHz

- **The CMB flux on the horn is then:**
  - 2.5 x 10^{-13} Watts
Radiation Detection

Coherent Detectors
(phase preserving)
[Bolometric Detectors tomorrow]
Signal Level from the CMB

- Gain: $10^6$
- Amplifier: low-noise, high bandwidth
- Filter: selects $\Delta v$
- Power Meter: measures $<E^2>$
- Amplifier: low frequency (DC)
- 3$^0$ radiation

Gain: $10^6$
Amplifier: low-noise, high bandwidth
Filter: selects $\Delta v$
Power Meter: measures $<E^2>$
Amplifier: low frequency (DC)
SLAC Summer Institute, Lecture #2
Heterodyne Receivers

• With coherent receivers one can “mix down” the radio frequency to an intermediate frequency (IF)

• Eg (84-100 GHz) x 82 GHz = 2-18 GHz
  – Signal can be manipulated on coax
  – Amplifiers are lower noise
Multistage RF amplification 1st stage most important (like photomultipliers)

CAPMAP: Chicago, Miami, Princeton
IF signals on coax (2-18 GHz)

Power detector
CAPMAP Receivers

- horn & lens
- MMIC HEMT amplifier
- Warm section
- LO chain & power amp
- IF section

Figures by M. Hedman
Crawford Hill, NJ
7 meter radio telescope
The Measurement of Thermal Radiation at Microwave Frequencies

R. H. Dicke*
Radiation Laboratory, Massachusetts Institute of Technology, Cambridge, Massachusetts
(Received April 15, 1946)

The connection between Johnson noise and blackbody radiation is discussed, using a simple thermodynamic model. A microwave radiometer is described together with its theory of operation. The experimentally measured root mean square fluctuation of the output meter of a microwave radiometer (0.4°C) compares favorably with a theoretical value of 0.46°C. With an r-f bandwidth of 16 mc/sec., the 0.4°C corresponds to a minimum detectable power of $10^{-16}$ watt. The method of calibrating using a variable temperature resistive load is described.

INTRODUCTION

Since radio waves may be considered infrared radiation of long wave-length, a hot body would be expected to radiate microwave energy thermally. In order to be a good radiator of microwaves, a body must be a good absorber and the best thermal radiator is the "blackbody."

Although their discoveries were historically unconnected, there is a very close connection between "Johnson noise" of resistors and thermal radiation. The thermal fluctuations of electrons in a resistor set up voltages across the resistor. These "noise voltages" are of such a magnitude that a noise power per unit frequency of $\delta T$ can be drawn from the resistor. $k$ is Boltzmann's constant; $T$ is the absolute temperature of the resistor.

The connection between thermal radiation and Johnson noise can best be shown by considering the system of Fig. 1.

An antenna is connected to a transmission line which is in turn terminated by a resistor. The radiation impedance of the antenna is assumed to be equal to the characteristic impedance of the coaxial line, i.e., the antenna is "matched" to the line. Also the resistor is assumed to "match" the line. When a transmission line is terminated by a "matched" load, the running waves in the transmission line incident on this load are completely absorbed without reflection. The antenna is completely surrounded by black

* Now at Palmer Physical Laboratory, Princeton University, Princeton, New Jersey.
** This paper is based on work done for the Office of Scientific Research and Development under contract OES-Mc-262 with the Massachusetts Institute of Technology.
Atmospheric Noise

• The Atmosphere will both absorb incident radiation and emit its own radiation

• These are connected by Kirchoff’s Law

\[ T_D = T_S e^{-\tau} + T_C (1 - e^{-\tau}) \]
Atmospheric Noise continued

\[ T_D = T_S e^{-\tau} + T_C (1 - e^{-\tau}) \]

<table>
<thead>
<tr>
<th>Optical Depth</th>
<th>Detector Signal</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \tau )</td>
<td></td>
</tr>
<tr>
<td>0</td>
<td>( T_S )</td>
</tr>
<tr>
<td>( \infty )</td>
<td>( T_C )</td>
</tr>
<tr>
<td>0.2</td>
<td>45 K (( T_C = 250 ) K)</td>
</tr>
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</table>
Atmospheric Absorption

**Fig. 1.1.** The transmission of the earth’s atmosphere for electromagnetic radiation. The diagram gives the height in the atmosphere at which the radiation is attenuated by a factor 1/2.
Amplifier Noise

• Ideal amplifier: power generated (with NO input) depends on its (physical) temperature $T$ and $\nu$

$$p = \frac{h \nu}{e^{h \nu / kT} - 1} d\nu \Rightarrow kT d\nu$$

• State-of-the-art 90 GHz amplifiers:
  – $T$ (physical) = 10 K
  – $T$ (noise) = 45 K
Components of the Signal

- 3 K from the CMB
- 45 K from Amplifier Noise
- 45 K from Atmospheric Noise

\[ \approx 100 \text{ K system temperature} \]
Sensitivity of the Radiometer

How well can we measure the temperature at a point on the sky?

\[ \Delta T = \frac{T_{sys}}{\sqrt{\Delta \nu \times t_{obs}}} \]

\[ = \frac{1 \text{mk}}{\sqrt{\text{sec}}} \text{ in our case} \]

Where does this come from?
Radiometer Sensitivity
a la Dicke

Antenna Noise as a pulse train:

\[ \frac{1}{\Delta v} \]

\(\Delta v\) is receiver bandwidth

- \(T_{\text{system}} = 100\ \text{K}\)
- \(T_{\text{signal}} = 1 \ \mu\text{K} = 10^{-8}\) of system Temp.
  - need \(10^{16}\) pulses
- Take \(\Delta v = 10\ \text{GHz}\)
  - Count for \(10^6\) seconds for 1\(\sigma\)
- Challenge to keep systematics (amplifier drifts, atmospheric noise, etc.) under control during this large integration time.
Calibration of Radiometers

• Shine various BBs on the system and measure the response, check linearity, etc.
  – Allows expressing signal levels in terms of equivalent temperatures
  – In the field, LN₂, the moon, and a few of the planets are useful for this purpose
Astronomical Effects

• Planets
• Galactic Emission
  – Synchrotron
  – Bremstrahlung
  – Dust
• Extra-galactic sources
  – Radio sources
  – Hot gas in Galaxy clusters (SZ effect)
  – Gravitational Lensing (Lecture 3)

Use multiple frequencies
Pick quiet regions
Instrumental Effects

- Amplifier Drifts
  - Use “Dicke switching”
- Electrical Grounding
  - Critical with such high gains
- Mechanical pickup
  - telescope motion; mechanical refrigerator
- Optics/ground pickup
  - shield radiometer from the 300K ground
- Thermal regulation
  - Gains vary with temperature
Still looking at one spot …

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<tr>
<th>Power</th>
<th>$W = k(T_1 + T_{sys})G\Delta \nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power with gain drift</td>
<td>$W + \Delta W = k(T_1 + T_{sys})(G + \Delta G)\Delta \nu$</td>
</tr>
<tr>
<td>Change in power</td>
<td>$\Delta W = \Delta G\Delta \nu k(T_1 + T_{sys})$</td>
</tr>
<tr>
<td>Signal change</td>
<td>$W + \Delta W = k(T_1 + \Delta T + T_{sys})G\Delta \nu$</td>
</tr>
<tr>
<td>Change in power</td>
<td>$\Delta W = G\Delta \nu k\Delta T$</td>
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Sensitivity limit due To Gain drifts:

$$\frac{\Delta T}{T_{sys}} = \frac{\Delta G}{G}$$
Dicke Switching/Chopping

Power at 1
\[ W_1 = k(T_1 + T_{sys})G\Delta\nu \]

Power at 2
\[ W_2 = k(T_2 + T_{sys})G\Delta\nu \]

difference
\[ W \equiv W_1 - W_2 = k(T_1 - T_2)G\Delta\nu \]

Gain drift
\[ W + \Delta W = k(T_1 - T_2)(G + \Delta G)\Delta\nu \]

Signal change
\[ W + \Delta W = k(T_1 - T_2 + \Delta T)(G)\Delta\nu \]

Sensitivity limit due To Gain drifts:
\[ \frac{\Delta T}{T_{sys}} = \frac{T_1 - T_2}{T_{sys}} \frac{\Delta G}{G} \]
8 seconds of data (0.01 sec samples)

unswitched

switched
15 minutes of “bad” data
15 minutes of good data
Noise Powers
(amplifier + atmosphere)

“1/f” noise

“unswitched”

“switched”
Power Spectra Sensitivity: Cosmic variance

\[ \frac{\partial C_l}{C_l} = \sqrt{\frac{2}{2l+1}} \]
Cosmic Variance + noise

\[ \frac{\partial C_l}{C_l} = \sqrt{\frac{2}{2l+1}} \langle 1 + \frac{4\pi w}{C_l} \rangle \]

where \( w \) : total experimental “weight” [\( \mu K^2 \)]
Cosmic Variance + noise + finite sky

\[
\frac{\partial C_l}{C_l} = \sqrt{\frac{2}{2l+1}} \left\langle \frac{1}{\sqrt{f_{\text{sky}}} C_l} \right\rangle + \frac{4\pi w}{C_l} \sqrt{f_{\text{sky}}}
\]

where

\( f_{\text{sky}} \): fraction of the sky observed

\( w \): total experimental “weight” [\( \mu K^2 \)]
Cosmic Variance + noise + finite sky + finite beam size

\[ \frac{\partial C_l}{C_l} = \sqrt{\frac{2}{2l+1}} \left\langle \frac{1}{\sqrt{f_{\text{sky}}}} + \frac{4\pi w}{C_l} \sqrt{f_{\text{sky}}} e^{l^2\sigma_b^2} \right\rangle \]

where

\[ f_{\text{sky}} \]: fraction of the sky observed

\[ w \]: total experimental “weight” [\( \mu K^2 \)]

\[ \sigma_b \]: beam rms
Effect of Finite Beam Size

“MAP” beam: 0.24 deg.

“CAPMAP” beam: 0.05 deg.
Choosing the Observing Strategy

• Depends on l-coverage desired
• Depends on sensitivity desired
• Frequent switching desired
• Frequent redundancies
• Multiple time scales
SENSITIVITY SIMULATIONS
(using CfCP 32-node cluster)

sample variance
detector noise

Capsize study, varying sensitivity
Data Processing

• Calibrate; de-glitch time series
• Bin in sky coordinates
• Offset removal
  – Mean, slope, quadratic?
• Make a map
  – Pixels will be correlated
• Run likelihood for power in l-bands ($C_l$s)
  – Capmap: inversion of 5760x5760 matrix
• Run likelihood for cosmological params.
Radiometer Offsets!

Residual Structure, μK vs. azimuth pixel
Modes with High S/N
Modes with High S/N
Mean removed
Want to measure a variance

$\Rightarrow$ multiple spots

$$l(\sigma) = \prod_{i=1}^{N} \frac{1}{\sqrt{\sigma_{N_i}^2 + \sigma_s^2}} e^{-\frac{Q_i^2}{2(\sigma_{N_i}^2 + \sigma_s^2)}}$$

**Essence of Analysis**

$\sigma_{N_i} = \text{noise at } i^{th} \text{ pixel}$ (used to be understood!

$\sigma_s = \text{signal "noise"}$

$Q_i = \text{measured temperature at } i^{th} \text{ pixel}$
Final Check: Null Tests

• Create maps that should have no signal
  – First 1/2 of data minus second 1/2
  – Alternate signs on samples in each pixel
  – Day minus night
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