Astro 507

Lecture 18

March 3, 2014

Announcements:

- **Problem Set 3 available; due Friday**
  office hours: 3:10-4pm Thurs., or by appt

Last time: finished cosmic acceleration

Q: theoretical options?

The Cosmic Microwave Background

Cosmic Whiplash

From the Ridiculous to the Sublime

Dark energy: confusing situation
progress difficult

- no guidance from laboratory physics
- observational data very sparse
- job security, but existential doubt

$\Rightarrow$ still the wild west: "cowboy cosmology"

Now turn to the CMB: huge contrast
progress exponential

- underlying physics rock-solid
- observation data aplenty!
- excellent theory-observational concordance
  $\rightarrow$ confidence in big bang framework

$\Rightarrow$ highly developed: "precision cosmology"

The CMB: Warmup

Plan & Schedule:

1. CMB in *homogeneous* universe $\rightarrow$ *isotropic* component
   this week
2. CMB in real *inhomogeneous* universe $\rightarrow$ *anisotropies*
   next month–after inflation has made inhomogeneities

Observational Tools, Issues:

Q: what are CMB observables?

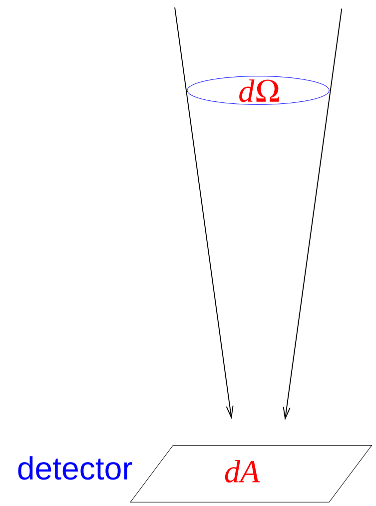
CMB Observables

- (total) brightness pattern across sky
- frequency spectrum across sky
- polarization pattern across sky

Q: how to measure each?
Q: how to quantify each?

Intensity or Surface Brightness

Isolate small region (solid angle $d\Omega$) of sky
by introducing a *collimator*



If source is extended over this region sky,
energy flow received depends on
collimator acceptance $d\Omega$: $d\mathcal{E} \propto dA\ dt\ d\Omega$

so define flux per unit "surface area" of sky:
intensity or surface brightness (or sometimes just "brightness")

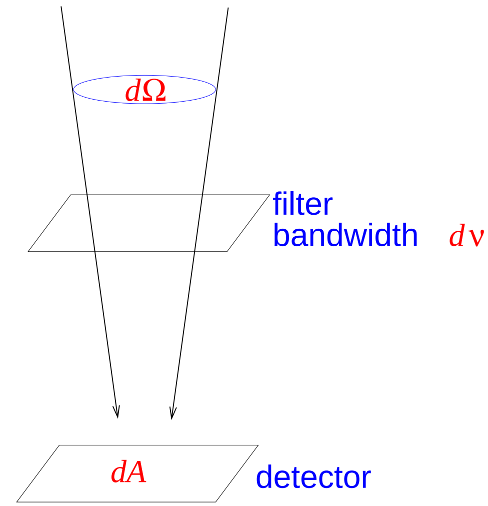
$$I = \frac{d\mathcal{E}}{dt\ dA\ d\Omega} \tag{1}$$

cgs units: $[I] = [\mathrm{erg\,cm^{-2}\,s^{-1}\ sr^{-1}}]$, with sr = steradian

Q: how to measure and quantify frequency dependence?

Specific Intensity

introduce a filter, or grating to disperse by λ
so detector receives small range of frequencies
in $(\nu, \nu + d\nu)$: monochromatic frequency ν
with bandwidth $d\nu$



energy received: $d\mathcal{E} \propto dA\ dt\ d\Omega\ d\nu$

define **specific intensity** or **spectral energy distribution (SED)**

$$I_\nu = \frac{d\mathcal{E}}{dt\ dA\ d\Omega\ d\nu} \tag{2}$$

cgs units: $[I_\nu] = [\mathrm{erg\,cm^{-2}\,s^{-1}\,sr^{-1}\,Hz^{-1}}]$

a less compact but more explicit notation is $dI/d\nu$

Mean Intensity

the direction-averaged **mean or average intensity** is

$$J_\nu = \langle I_\nu \rangle \quad (3)$$

$$= \frac{\int I_\nu \, d\Omega}{\int d\Omega} \quad (4)$$

$$= \frac{1}{4\pi} \int I_\nu \, d\Omega \quad (5)$$

note that here, oppositely-directed rays do *not* cancel
(this is a *scalar* average = undirected)
unlike flux which has as associated direction (normal)

but important special case:

∞ *if* I_ν is *same* in all directions: **isotropic** if measure $I(\theta, \phi)$ over all sky, can write as

$$I_\nu(\theta, \phi) = J_\nu + \Delta I(\theta, \phi) \tag{6}$$

where fluctuation ΔI about mean
by definition has $\langle \Delta I \rangle \equiv 0$

If radiation is blackbody, with $T(\theta, \phi)$ across sky
Q: then what is I? I_ν?

Blackbody Intensity

blackbody: has Planck spectrum

$$I_{\nu,\mathrm{Planck}} \equiv B_\nu(T) = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT} - 1}$$

$$I_{\mathrm{Planck}} = \int d\nu \; I_{\mathrm{Planck}} = B(T) = \frac{2\pi^4}{15} \frac{k^4}{h^3 c^3} T^4 = \frac{\sigma_{\mathrm{SB}}}{\pi} T^4$$

For all-sky blackbody: *spectrum in each direction*

- follows Planck distribution
- characterized by a *single parameter* $T(\theta, \phi)$

Q: backbody I_ν in Rayleigh-Jeans limit $h\nu \ll kT$?

Note: for $h\nu \ll kT$: *Rayleigh-Jeans limit*

$$I_{\nu,\mathrm{Planck}} = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1} \longrightarrow \frac{c^3}{4\pi^2}\nu^2 kT \tag{7}$$

so define "**antenna temperature**"

$$T_{\mathrm{antenna}} \equiv \frac{c^2}{2k}\frac{I_\nu}{\nu^2} \quad \propto \quad I_\nu \tag{8}$$

- a measure of surface brightness *at a single ν or λ*
- practical experimentally: compare astro (i.e., antenna) signal to intensity of source at known "load" $T_{\mathrm{reference}}$

Q: for blackbody, what is magnitude, shape of $T_{\mathrm{antenna},\nu}$ vs ν?
Q: significance of $T_{\mathrm{antenna},\nu}$ if not blackbody pattern?

in Rayleigh-Jeans limit, all-sky blackbody gives

$$T(\theta,\phi) \equiv T_0 + \Delta T(\theta,\phi) \tag{9}$$

where $B(T_0) = J$, and sky average $\langle \Delta T \rangle = 0$

CMB: Discovery

Penzias & Wilson (1965)
"A Measurement of Excess Antenna Temperature at 4080 Mc/s"

- Bell Labs (Holmdel, NJ) radio telescope
- careful checks of systematics! this is most of their paper!
  ...obligatory pigeon story

Q: what did P&W report?

Q: what didn't P&W report?

Excess Antenna Temperature at 4080 Mc/s

Penzias & Wilson (1965)

- $T_{\text{ant},\nu} = 3.5 \pm 1.0$ K at $\nu = 4.080$ GHz
- other properties:

> This excess temperature is, within the limits of our observations, isotropic, unpolarized, and free from seasonal variations (July, 1964 - April, 1965).

Q: what does this imply about thermal/nonthermal components?

Q: why seasonal variations important?

Q: how did P&W know the spectrum is thermal?

Note: the strict empiricism in 2-page P&W writeup:

- *none* of the words "cosmology," "universe," or "background" appear in any form
- not even any direct claim that the signal is extraterrestrial!

Entire P&W interpretive discussion follows:

> A possible explanation for the observed excess noise temperature is the one given by Dicke, Peebles, Roll, and Wilkinson (1965) in a companion letter...

...which is entitled
"Cosmic Black-body Radiation"

CMB Discovery: Precursors and Missed Opportunities

CMB discovery limited not by technology
but by failure of imagination: nobody bothered to look!

• CMB *predicted* years before!
Gamow (1948!): primordial nuke demands thermal radiation;
should persist today
didn't calculate, but could have, $T_0 \sim 4$ K!
his students, Alpher & Herman (1948): explicitly calculate

$$T_0(\text{1948 theoretical estimate}) = 5 \text{ K} \tag{10}$$

these results were ignored & forgotten(!!)

• CMB *measured* years before!

McKellar (1941): **`www: online paper`**

interstellar C-N molecule seen via line multiplets

excited levels populated as expected if

in thermal radiation bath with

$$T_0(\text{CN excitation, 1941 observation}) = 2.5 \text{ K} \quad (11)$$

throwaway line about this being the "temperature of space"!

...but the CMB connection not made until after P&W

CMB history lessons?

Q: take-home message(s) for practice of science?

The Isotropic CMB: Present Data

Spectrum

best data: FIRAS instrument on
Cosmic Background Explorer (COBE)
Fixsen et al (1996):

- `www:` $T_{\rm antenna}$ `plot` – consistent with purely thermal
- present all-sky temperature

$$T_0 = 2.7255 \pm 0.0006 \text{ K}$$

- from Wien's law: spectral peaks are

$$\lambda_{\rm max} = \frac{0.290 \text{ cm K}}{T_0} = 1.06 \text{ mm} \tag{12}$$

$$\nu_{\rm max} = 58.5 \text{ GHz K}^{-1} \, T_0 = 159 \text{ GHz} \tag{13}$$

Note: $\nu_{\rm max}\lambda_{\rm max} \neq c$!

Q: what part of EM spectrum is this? relevant observatories?

Thermal Distortions: Chemical Potential

we will see: spectrum could be distorted but still thermal

if so, would introduce "chemical potential" $\phi = \mu/T$:

$$I_\nu = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT-\phi} - 1} \tag{14}$$

then $\phi < 9 \times 10^{-5}$

also can put limits on distortion by

superposition of blackbody spectra with different T

Polarization

zero on average, but nonzero rms

Q: why can't there be a uniform polarization?

in an isotropic universe: polarization quadrupole

...more on this later

The Physics of the Isotropic CMB

We want to understand:

- what physics leads to the CMB?
- what cosmic epoch(s) does the CMB probe?
- what are the implications of the spectrum exquisitely good Planckian form?

Q: What is relevant physics?
Q: What are relevant cosmic ingredients?
Q: What are irrelevant (presumably?) cosmic ingredients?
Q: What are relevant equations/analyses?

Q: Implications of Planck shape to spectrum?