Astro 507

Lecture 19

March 9, 2020

Announcements:

- **Preflight 4 due Friday noon**
- COVID-19 update: **don't come to class if you are sick**
  stay tuned for updates

Last time (online): finished cosmic acceleration

Today: Cosmic Microwave Background

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

CMB: cosmic, all-sky electromagnetic radiation
Q: what are CMB observables?

CMB Observables

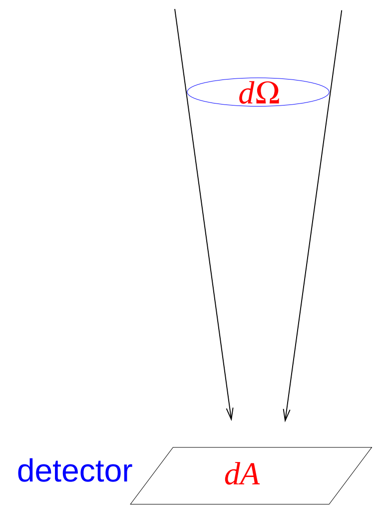
observables are those of electromagnetic radiation

- (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")

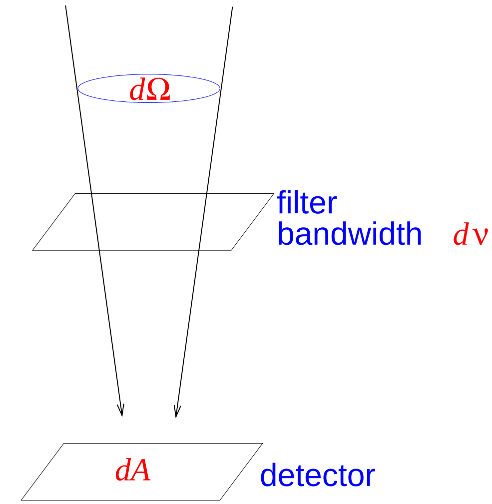
$$I = \frac{d\mathcal{E}}{dt \ dA \ d\Omega} \tag{1}$$

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**
also called the "monopole" first term in spherical harmonic series

$$
\begin{aligned}
J_\nu &= \langle I_\nu \rangle &(3)\\
&= \frac{\int I_\nu \; d\Omega}{\int d\Omega} &(4)\\
&= \frac{1}{4\pi} \int I_\nu \; d\Omega &(5)
\end{aligned}
$$

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

$$
\begin{aligned}
I_\nu(\theta, \phi) &= J_\nu + \Delta I(\theta, \phi) && (6) \\
&= \text{monopole} + \text{anisotropies} && (7)
\end{aligned}
$$

where anisotropies measure fluctuation ΔI about mean
and by definition have $\langle \Delta I \rangle \equiv 0$

Important special case: **blackbody radiation**
completely characterized by temperature T
Q: given T, what is I? I_ν?

Blackbody Intensity

blackbody radiation 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*

$$I_{\nu,\mathrm{Planck}} = \frac{2h}{c^2}\frac{\nu^3}{e^{h\nu/kT}-1} \longrightarrow \frac{c^3}{4\pi^2}\nu^2 kT \tag{8}$$

so define "**antenna temperature**"

$$T_{\mathrm{antenna}} \equiv \frac{c^2}{2k}\frac{I_\nu}{\nu^2} \quad \propto \quad I_\nu \tag{9}$$

- 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

$$T(\theta,\phi) \equiv T_0 + \Delta T(\theta,\phi) \tag{10}$$

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)

- $T_{\mathrm{ant},\nu} = 3.5 \pm 1.0$ 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

$$T_0(\text{1948 theoretical estimate}) = 5 \text{ K} \tag{11}$$

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

$$T_0(\text{CN excitation, 1941 observation}) = 2.5 \text{ K} \qquad (12)$$

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

$$\lambda_{\rm max} = \frac{0.290 \text{ cm K}}{T_0} = 1.06 \text{ mm} \quad (13)$$

$$\nu_{\rm max} = 58.5 \text{ GHz K}^{-1}\ T_0 = 159 \text{ GHz} \quad (14)$$

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" μ:

$$I_\nu = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT - \mu/T} - 1} \tag{15}$$

then $\mu/T < 9 \times 10^{-5}$
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?
...more on this later

Q: what about redshifting effect on T? I? I_ν?

CMB redshifting:

- Wien says $\lambda_{\mathsf{max}} T = const$, and since $\lambda \propto a$,
  $T = T_0/a = (1+z)T_0$

- total (integrated) intensity $I = \sigma_{\mathsf{SB}} T^4/\pi$
  and thus observers at z would see $I(z) = I_0/a^4 = (1+z)^4 I_0$
  and conversely, $I_0 = I(z)/(1+z)^4$
  $\Rightarrow$ cosmological dimming of surface brightness
  (true for any I)

Q: what sets ε_γ? Ω_γ? n_γ?

Derived CMB Properties

the CMB is a blackbody, and thus:
the temperature completely determines its properties!

energy density

$$\varepsilon_{\gamma,0} = \frac{\pi^2}{15} \frac{(kT_0)^4}{(\hbar c)^3} = 0.26057 \text{ eV/cm}^3 \tag{16}$$

evolving as $\varepsilon_\gamma = \varepsilon_{\gamma,0}/a^4 = (1+z)^4 \ \varepsilon_{\gamma,0}$
Q: c.f. starlight? `www: cosmic radiation backgrounds`

equivalent mass density

$$\rho_{\gamma,0} = \frac{\varepsilon_{\gamma,0}}{c^2} = 4.6451 \times 10^{-34} \text{ g/cm}^3 \tag{17}$$

and thus

$$\Omega_{\gamma,0} = 5.04 \times 10^{-5} \ \left(\frac{0.7}{h}\right)^2 \tag{18}$$

number density

$$n_{\gamma,0} = \frac{2\zeta(3)}{\pi^2}\left(\frac{kT_0}{\hbar c}\right)^3 = 410.73 \text{ photons/cm}^3 \tag{19}$$

with $\zeta(3) = \sum_{n=1}^{\infty} 1/n^3 = 1.202\ldots$

Q: is this a lot or a little? what's a useful comparison?

Q: physical implications of blackbody form of CMB?

Planck Form: Implications

The observed CMB is consistent, at high precision, with
a purely Planckian form
that is: to high precision, **the CMB is a perfect blackbody**

but a blackbody spectrum:
- characterizes a system in thermodynamic equilibrium at T
- is independent of the size, shape, or composition of the system in equilibrium
- see extras below for more on this

thus the CMB implies that
the Universe once attained thermodynamic equilibrium
i.e., the Universe was once "*in good thermal contact*"
...we'll make this notion more precise

Note also that the *present* universe
must be *transparent* to the CMB

Q: why is this? what's the evidence?

Q: what does this imply about epoch probed by CMB?

The present Universe is transparent to the CMB

e.g., high-redshift radio sources (quasars) are visible
thus the CMB is now *decoupled* from cosmic matter
and has been, at least to largest observed sources $z \gtrsim 10$

thus: for at least $z \lesssim 10$, matter and radiation
in the Universe were *not held in equilibrium*

the equilibrium and thermalization needed to come earlier

- higher density
- higher temperature

the Planckian CMB points to a hot, dense early Universe

Q: what technology needed to calculate transparency?

For Radiation Transfer Fans

ignoring for now cosmological dimming,
and ignoring scattering (isotropic universe still!)
radiation transfer says

$$\frac{dI_\nu}{ds} = -n_{\mathsf{abs}}\sigma_\nu \; I_\nu + j_\nu \tag{20}$$

with *absorption cross section* σ_ν and *emission coefficient* j_ν

as usual, rewrite as

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu \tag{21}$$

with *optical depth* $d\tau_\nu = n_{\mathsf{abs}}\sigma_\nu \; ds$
and *source function* $S_\nu = j_\nu / n_{\mathsf{abs}}\sigma_\nu$

the solution to transfer equation has character

$$I_\nu \xrightarrow{\tau \gg 1} S_\nu \xrightarrow{\text{thermal}} B_\nu(T) \quad (22)$$

- *if sightline is optically thick* then
  observed intensity is source function, and furthermore
- *if source is thermal at T* then
  source function is Planckian

in other words:
a blackbody spectrum implies
an optically thick source in theromdynamic equilibrium

and so the Planckian CMB spectrum tell us
- *the Universe was once optically thick*
- *the Universe was once in thermodynamic equilibrium*