Astro 596/496 PC

Lecture 18

March 1, 2010

Announcements:

• PS3 due in class Friday

Last time: began cosmic microwave background

Penzias & Wilson 1965 discovery

Q: antenna temperature? excess?

Q: main physical result?

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

$$T_0(\text{1948 theoretical estimate}) = 5 \text{ K} \quad (1)$$

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

$$T_0(\text{CN excitation, 1941 observation}) = 2.5 \text{ K} \tag{2}$$

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_{antenna} `plot` – consistent with purely thermal
- present all-sky temperature

$$T_0 = 2.725 \pm 0.004 \text{ K} \tag{3}$$

- limits on distortions:

if spectrum has "chemical potential" μ:

$$I_\nu = \frac{2h}{c^2} \frac{\nu^3}{e^{h\nu/kT - \mu} - 1} \tag{4}$$

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

To start, note that the *present* universe must be *transparent* to the CMB

Q: why is this?

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

Q: what technology needed to calculate transparency?

The CMB as a Scattering Problem

recall: *any* observed photon has this life cycle:

- emission
- scattering (possibly none, possibly many times)
- absorption (i.e., detection)

thus: any *detected* = absorbed photon

points back to emission or most recent scattering event

e.g., daytime sky: Sun's emission disk vs off-source scattered blue light

the fact that the CMB is a *background*

to low-z objects $\rightarrow$ late-time U. is *transparent* to CMB

thus: the CMB probes exactly the epoch

when the universe was last able to scatter photons

i.e., the last time U. was *opaque* to its thermal photons

CMB as Cosmic "Baby Picture": Last Scattering Surface

CMB created by (and gives info about)
epoch of cosmic transition: *opaque* $\longrightarrow$ *transparent*

but transparent/opaque transition is
controlled by photon *scattering*
e.g., CMB released at epoch of **"last scattering"** $z_{\rm ls}$
$\rightarrow$ CMB sky map is a picture of the U. then:
"surface of last scattering"
`www: conformal time diagram`

For more detail, e.g., when is $z_{\rm ls}$?
∞ $\rightarrow$ need scattering technology

Highlights from Scattering 101

Collisions: $a + b \to$ stuff

Consider particle beam:

"projectiles," number density n_a

incident w/ velocity v

on targets of number density n_b

Due to interactions, targets and projectiles "see" each other as spheres of projected area $\sigma(v)$: the

cross section

⋆ fundamental measure interaction strength/probability

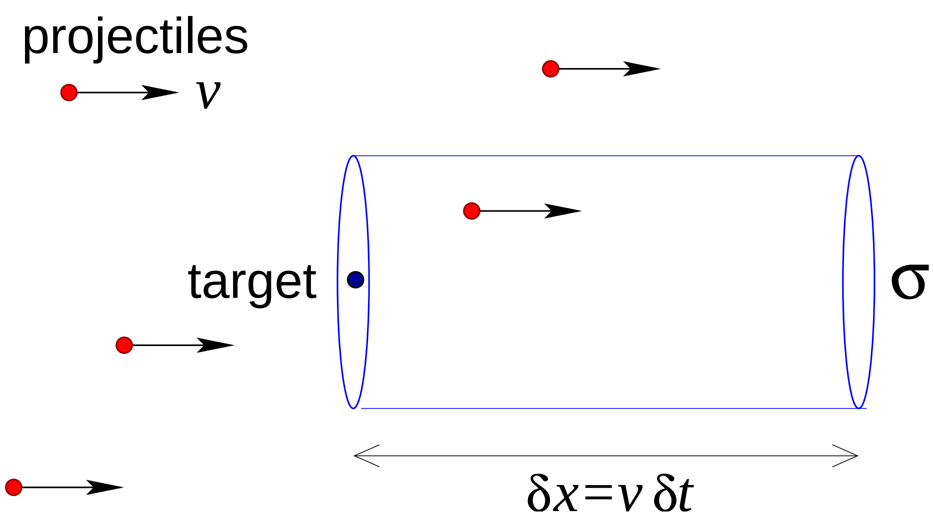
⋆ *atomic, nuke & particle physics meets astrophysics via* σ

in time δt, what is avg # collisions on one target?

Q: what defines "interaction zone" around target?

interaction zone: particles sweep out "scattering tube"

- projectiles see targets as "bulls-eyes" of size σ
  ...and vice versa!
  sets tube cross-sectional area
- tube length $\delta x = v\delta t$



interaction volume swept around target:
$\delta V = \sigma\delta x = \sigma v\delta t$

collide: if a projectile is in the volume

Cross Section, Flux, and Collision Rate

in tube volume δV, # projectiles = $\mathcal{N}_{\text{proj}} = n_a \delta V$
so ave # collisions in δt:

$$\delta \mathcal{N}_{\text{coll}} = \mathcal{N}_{\text{proj}} = n_{\text{a}} \ \sigma \ v \ \delta t \tag{5}$$

so $\delta \mathcal{N}_{\text{coll}} / \delta t$ gives

avg collision rate *per target* b $\boxed{\Gamma_{\text{per}\, b} = n_a \ \sigma \ v = \sigma \ j_a}$

where $j_a = n_a v$ is incident **flux**
Q: Γ units? sensible scalings n_a, σ, v*? why no* n_b*?*

Q: average target collision time interval?
Q: average projectile distance traveled in this time?

estimate avg time between collisions on target b:

mean free time τ

collision rate: $\Gamma = d\mathcal{N}_{\rm coll}/dt$

so wait time until next collision set by $\delta N_{\rm coll} = \Gamma_{\rm per\, b}\tau = 1$:

$$\tau = \frac{1}{\Gamma_{\rm per\, b}} = \frac{1}{n_a \sigma v} \tag{6}$$

in this time, projectile a moves distance: **mean free path**

$$\ell_{\rm mpf} = v\tau = \frac{1}{n_a \sigma} \tag{7}$$

no explicit v dep, but still $\ell(E) \propto 1/\sigma(E)$

Q: physically, why the scalings with n, σ?

Q: what sets σ for billiard balls?

Q: what set σ for $e^- + e^-$ scattering?

Cross Section vs Particle "Size"

if particles interact only by "touching"
(e.g., classical, macroscopic billiard balls)
then $\sigma \leftrightarrow$ particle radii: $\sigma = \pi(r_a + r_b)^2$

but: if interact by force field
(e.g., gravity, EM, nuke, weak)
cross section σ *unrelated* to physical size!

For example: e^- has $r_e = 0$ (as far as we know!)
but electrons scatter via Coulomb (and weak) interaction
"touch-free scattering"

Reaction Rate Per Volume

recall: collision rate *per target* b is $\Gamma_{\text{per}\, b} = n_a \sigma_{ab} v$

total collision rate *per unit volume* is

$$r = \frac{dn_{\text{coll}}}{dt} = \Gamma_{\text{per}\, b} n_b = \frac{1}{1+\delta_{ab}} n_a n_b \sigma v \quad (8)$$

Kronecker δ_{ab}: 0 unless particles a & b identical

Note: *symmetric* w.r.t. the two particles

What if particles have more than one relative velocity?

CMB: Last Scattering?

CMB is a background: all other observed sources closer

- low-z Universe transparent to CMB photons
- CMB *scattering ineffective* for these z

But scattering rate $\Gamma(\mathrm{CMB}-\mathrm{matter})_{\mathrm{per}\gamma} = n_{\mathrm{targ}} c\sigma$

- low-z U. contains atomic matter = scatterers: $n_{\mathrm{targ}} > 0$
- photons can and do interact with atoms/ions/electrons: $\sigma > 0$

$\Rightarrow$ $\Gamma(\mathrm{CMB}-\mathrm{matter}) > 0$: *scattering must occur!*

Q: How can we reconcile these?

Q: Physical meaning, criterion for interaction "effectiveness"?

Particle Interactions in a FLRW Universe: Freezeouts

photon *decouple* plasma → CMB last scattering
when: expansion redshifting & volume dilution stops interactions

$$\Gamma_{\rm scatter} \lesssim H \tag{9}$$

or mean free time "infinite" → $\tau \gtrsim t_H \sim t$
or mean free path "infinite" → $\ell > d_{\rm hor,phys}$
Q: which of these is best to use?

⋆ This criterion of very *general cosmological importance* including CMB but also all of Early Universe!
⋆ Since Γ depends on particle energies → T
and usually Γ *increases* (strongly) with T
$\Gamma \lesssim H$ sometimes known as condition for "**freezeout**"
⋆ *freezeouts a central aspect of much of cosmology*
CMB, big bang nuke, particle dark matter, 21 cm, ...

CMB Epoch: Freezeout of Cosmic Photon Scattering

Our Mission determine CMB release epoch
to do this: need photon scattering in cosmic environments

U. mostly composed of diffuse (gaseous) matter
Q: what are possible states of this matter?
Q: what processes can scatter photons?
Q: which scatter the most, least efficiently?

`Demo: flame in projector beam` *Q: brighter or darker?*

Photon Scattering Agents

Photon scatter off of charged matter: atoms, ions, electrons
mostly H (90% by number, 75% by mass)
rest is mostly He, then traces of others

possible states:

- molecules: H_2 essentially invisible *Q: why?*
- neutral atoms: "H I" – essentially invisible
  unless $E_\gamma =$ level difference, e.g., $E(\mathrm{Ly}\alpha) = E_2 - E_1 = 10.2$ eV
  or $E_\gamma > 13.6$ eV binding
- ionized gas/plasma: free e^- readily scatter photons $e\gamma \to e\gamma$
  at low energy $E_\gamma \ll m_e c^2$, Thompson scattering

$$\sigma_{e\gamma} = \sigma_T = \text{const} = \frac{8\pi}{3}\left(\frac{e^2}{m_e c^2}\right)^2 = 0.665 \times 10^{-24}\ \text{cm}^2$$

Q: p has same charge–why can we ignore $p - \gamma$ scattering?

CMB Epoch: Egregiously Naïve Treatment

Naïve attempt to compute photon "scattering freezeout"

- present baryon density $n_B \approx n_e$ total electron density *Q: why?*
  evolves as $n_e = n_{e,0} \ a^{-3}$
- using this, evaluate scattering rate *per photon*

$$\Gamma_\gamma = n_e \sigma_T c \overset{\text{naïve}}{=} n_{e,0} \sigma_T c \ a^{-3} \sim 5 \times 10^{-21} \ \text{s}^{-1} \ a^{-3} \tag{10}$$

- also know present expansion rate H_0
  evolves roughly as matter-dom: $H = H_0 a^{-3/2}$, so

$$\frac{\Gamma_\gamma}{H} \overset{\text{naïve}}{\simeq} 2 \times 10^{-3} a^{-3/2} = 2 \times 10^{-3} (1+z)^{3/2} \tag{11}$$

  Q: implications of $z = 0$ value?
- this would imply $\Gamma_\gamma > H$ when $z \gtrsim 60$
  Q: what is qualitatively promising about this?
  but quantatively, this is *wrong*: $z_{\text{last scatter}} \gg 60$
  Q: where did we go wrong?