Astro 507

Lecture 20

March 7, 2014

Announcements:

- **Problem Set 3 due now**
  congratulations! celebrate after class
- **Preflight 4 posted, due 9am next Friday**

Last time: began the physics of the CMB

Q: implications of ability to see cosmic objects to $z \sim 10$*?*

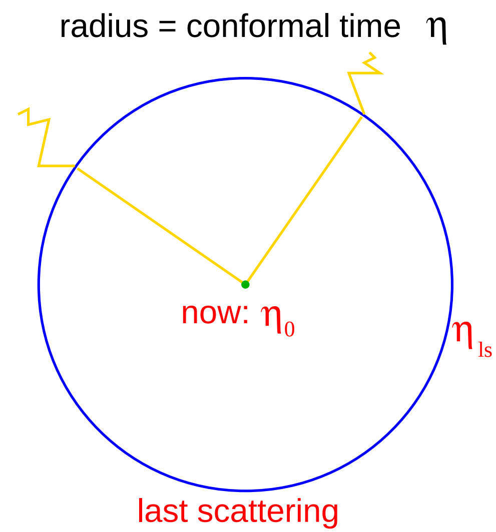
`www: SPT sky map`

Q: where/when do CMB photons probe?

Q: physical significance of CMB sky image?

Q: when will an observer stop seeing the CMB?

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

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

$\Rightarrow$ $\Gamma(\mathrm{CMB-matter}) > 0$: *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 $\rightarrow$ CMB last scattering
when: expansion redshifting & volume dilution stops interactions

$$\boxed{\Gamma_{\text{scatter}} \lesssim H} \tag{1}$$

or mean free time "infinite" $\rightarrow \tau \gtrsim t_H \sim t$
or mean free path "infinite" $\rightarrow \ell > d_{\text{hor,phys}}$
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 $\rightarrow T$ 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

free electrons scatter photons
at low energies, cross section constant: Thomson

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

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

Q: what is scattering rate per photon?

CMB Epoch: Egregiously Naïve Treatment

- 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*

$$\Gamma_\gamma = n_e \sigma_T c \overset{\text{naïve}}{=} n_{e,0} \sigma_T c\ a^{-3} \sim 5 \times 10^{-21}\ \text{s}^{-1}\ a^{-3} \tag{2}$$

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

compare scattering and expansion rates:

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

Q: implications of $z = 0$ value?

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

U. mostly composed of diffuse (gaseous) matter

Q: what are possible states of this matter?

Q: how does each interact with photons?

Q: which absorbs/scatters the most, least efficiently?

`Demo: flame in projector beam`
Q: brighter or darker?
Q: why do we get the result we do?

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

molecules: H_2 essentially invisible *Q: why?*

neutral atoms: "H I" – essentially invisible
unless $E_\gamma =$ level difference, e.g., $E(\text{Ly}\alpha) = E_2 - E_1 = 10.2$ eV
or $E_\gamma > 13.6$ eV binding

ionized gas/plasma: *free e^- readily scatter photons* $e\gamma \to e\gamma$
at low energy $E_\gamma \ll m_e c^2$, Thomson scattering
$\sigma_{e\gamma} = \sigma_T$

Q: lesson for CMB

The CMB and Recombination

In cosmic matter, photon scattering controlled
by availability of **free electrons** – bound e don't count!

▷ ionized U: e^- abundant, scattering rapid

▷ neutral U: H essentially transparent to thermal background

ionized $\leftrightarrow$ opaque
neutral $\leftrightarrow$ transparent

CMB originates in **(re)combination**
in transition $p + e \rightarrow \mathrm{H} + \gamma$ "the fog clears"

- plasma $\rightarrow$ neutral H
- photon last scattering $\rightarrow$ free streaming
- drunken stagger $\rightarrow$ sober sprint

∞

Q: what (directly) determines when photons decouple *from plasma?*
Q: how is recombination different from decoupling? related?

Recombination and Decoupling

decoupling set by *freezeout* of scattering
as seen by photons $\rightarrow$ when $\Gamma_{\text{scatter,per}\gamma} \lesssim H$
U. transition: opaque $\rightarrow$ transparent
sets *"cosmic photosphere"* at which CMB released

(re)combination is when $p + e \rightarrow \text{H} + \gamma$
U. transition: ionized $\rightarrow$ neutral

these are *logically and physical distinct* epochs
but close in time and physically *related*:
photon scattering dominated by *free e^-*: *Thomson scattering*
and free e^- abundance drops enormously at recombination
$\rightarrow$ recombination leads to decoupling

Q: pre-decoupling, what should photon spectrum be?
Q: how are photon, plasma temperatures related?

Cosmic Thomson Scattering

Pre-decoupled photons in thermal equilib with plasma
$\rightarrow$ initially I_ν is Planck spectrum, $T_\gamma = T_e$
Thomson scattering continues until free e gone

Fun facts about Thomson scattering $e\gamma \rightarrow e\gamma$

- interaction strength *energy-independent*: $\sigma_{\rm T}$ a constant
- an *elastic* process: photon energy essentially *unchanged*
- a "two-to-two" reaction: photon number *conserved*
- scattering *anisotropic* relative to initial photon direction
  angular distribution (scattering per solid angle $d\Omega$)

$$\frac{d\sigma}{d\Omega} = \frac{1}{2}\left(\frac{e^2}{m_e c^2}\right)^2 \left(1 + \cos^2\theta\right) \tag{4}$$

includes a *quadrupole* component $\rightarrow$ creates polarization!

Assume that recomb is a freezeout *only* of Thomson:
Q: implications for post-recomb (i.e., observed) CMB spectrum?

CMB Spectrum: The Magic of Thomson Scattering

Thomson implications for cosmic last scattering:

- σ_T energy-indep $\rightarrow$ simultaneous freezeout at all freq ν
- elastic scattering $\rightarrow$ no change in spectral *shape*
  only changes photon directions
- photon number cons $\rightarrow$ don't add or subtract to spectrum
- anisotropic scattering w.r.t. initial photon direction
  but *if* initial directions isotropic $\rightarrow$ no net anisotropy created

magic of Thomson scattering:

⋆ simultaneous freezeout of all photons (all ν)
⋆ photon spectrum *preserved*

Q: implications of observed Planckian CMB spectrum?
Q: implication of number conservation of Thomson/Compton?

The CMB Demands a Hot Big Bang

observe *thermal* (Planck) CMB spectrum today
$\Rightarrow$ *thermal* CMB spectrum *pre*-decoupling!
$\Rightarrow$ in early U: photons thermalized, coupled to matter!

Cosmic matter & radiation once in "good thermal contact"
$\rightarrow$ but this requires much higher T, ρ than seen today
$\rightarrow$ CMB demands Universe went through *hot*, *dense* early phase
$\Rightarrow$ CMB $\rightarrow$ *hot big bang*

Compton/Thomson scattering conserves photon number
but Planck spectrum has fixed number density at T
$\Rightarrow$ **early Universe needed photon number-changing processes**
e.g., bremsstrahlung $e +$ nucleus $\rightarrow e +$ nucleus $+ \gamma$
moreover: we will see that $n_\gamma \sim 10^9\ n_{\text{baryon}}$
$\Rightarrow$ need huge photon source! *Q: ideas?*

Q: real-Universe complications?

in the real Universe, non-Thomson processes operate

most notably: as recombination begins, *neutral H* present
resonant emission and absorption due to H lines
does lead to *non-thermal distortions* in CMB

but turns out distortions are at high frequency
i.e., nonthermal perturbations expected to be significant
only at $h\nu \gtrsim 40kT$
why this scale? we will see...

Last Scattering: Including Recombination

Recombination Revisited

For simplicity, we will assume baryons are only protons

`www: laboratory hydrogen plasma`

and will consider only Thomson scattering (excellent approx!)

Then: scattering rate per photon is

$$\Gamma_\gamma = n_{e,\mathrm{free}} \sigma_T c \ \propto \ n_{e,\mathrm{free}} \tag{5}$$

and last scattering when $\boxed{\Gamma_\gamma \simeq H}$

last scattering/decoupling controlled by *free electron density*

$n_{e,\mathrm{free}}$ changes due to

- cosmic volume expansion $\propto a^{-3}$
- recombination: free e^- lost to neutral H

rewrite to account for each $n_{e,\mathrm{free}}$ effect separately:

$$n_{e,\mathrm{free}} = X_e n_{e,\mathrm{tot}} = X_e n_{\mathrm{baryon}} \tag{6}$$

- baryon density $n_{\mathrm{b}} \propto a^{-3} \propto T^3$
gives volume dilution

- "ionization fraction"

$$X_e \equiv \frac{n_{e,\mathrm{free}}}{n_{e,\mathrm{free}} + n_{e,\mathrm{bound}}} = \frac{n_p}{n_p + n_{\mathrm{H}}} = \frac{n_p}{n_{\mathrm{b}}} \tag{7}$$

unchanged by volume dilution
only depends on recombination thermodynamics:
i.e., $X_e = X_e(T) = X_e(z)$

in homogeneous U
Q: what changes photon number density after recombination?
Q: what changes spectrum after recombination?
Q: naïve estimate of recombination $T_{\mathrm{rec}}, z_{\mathrm{rec}}$?
Q: zeroth-order treatment of $X_e(T)$?

Recombination: Improved Naïve View

Given hydrogen binding energy

$$B_{\mathrm{H}} = E(p) + E(e) - E(\mathrm{H}) = 13.6 \text{ eV}$$

simple estimate of recomb epoch goes like this:

Binding sets energy scale, so
★ when particle energies above B_{H}: U ionized,
★ otherwise: U neutral
→ naïvely expect transition at $T_{\text{rec,naive}} = B_h \sim 150,000$ K

But we know $T = T_0/a$, so estimate recomb at

$$\left.\begin{aligned} a_{\text{rec,naive}} &= \frac{T_0}{T_{\text{rec,naive}}} &\sim 2 \times 10^{-5} \\ z_{\text{rec,naive}} &= \frac{T_{\text{rec,naive}}}{T_0} - 1 &\sim 50,000 \end{aligned}\right\} \text{wrong!}$$

Q: guesses as to what's wrong?
Q: how to do this right?