Astro 596/496 PC
Lecture 19
March 3, 2010

Announcements:
- PS3 due next time in class

Last time: CMB observed–isotropic component
- most of CMB signal isotropic: $I_0 \gg \Delta I$
- spectrum: thermal, single temperature $T_0 = 2.725 \pm 0.001$ K
  no departures from Planck down to $\sim 10^{-4}$ level
- context `www: diffuse photon backgrounds`

CMB theory–a scattering problem
Q: implications of ability to see cosmic objects to $z = 8$?
Q: where/when do CMB photons probe?
Q: physical significance of CMB sky image?
Q: when will an observer stop seeing the CMB?
Q: what sets "effectiveness" of cosmic scattering processes?

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

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?
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

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

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

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*

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

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

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

  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?

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 ↔ opaque
neutral ↔ transparent

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

- plasma → neutral H
- photon last scattering → free streaming
- drunken stagger → 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^-: *Thompson 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 Thompson Scattering

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

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

▷ interaction strength *energy-independent*: σ_{T} a constant
▷ an *elastic* process: photon energy *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 Thompson:
Q: implications for post-recomb (i.e., observed) CMB spectrum?

CMB Spectrum: The Magic of Thompson Scattering

Thompsom 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 Thompson scattering:

⋆ simultaneous freezeout of all photons (all ν)

⋆ photon spectrum *preserved*

Q: implications of observed Planckian CMB spectrum?

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!

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

Q: real-Universe complications?

in the real Universe, non-Thompson 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 Thompson scattering (excellent approx!)

Then: scattering rate per photon is

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

and last scattering when $\Gamma_\gamma \simeq H$

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 $n_{e,\text{free}}$ effect separately:

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

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

- "ionization fraction"

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

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 $T_{\text{rec}}, z_{\text{rec}}$?
Q: zeroth-order treatment of $X_e(T)$?