Astro 406
Lecture 35
Nov. 18, 2013

Announcements:

- **PS 11 due Friday** penultimate problem set!

Last time: cosmic microwave background radiation

Q: observed properties? what do they tell us?

Q: where do CMB photons point back to?

cosmic recombination

Q: who? what? when? where?

cosmic microwave background: **CMB**

observed properties

- angular distribution: (almost) perfectly isotropic radiation
- spectrum: thermal = Planck form, $T = 2.725\ K$

implications

- isotropy: validates cosmological principle
- Planck spectrum: U once in *thermodynamic equilibrium*
  $\Rightarrow$ matter & radiation was once hot and dense enough
  to exchange energy and come into equilibrium
  the early Universe was a hot, dense state: **big bang**

cosmic (re)combination

- at high $T \gg B_{\mathrm{H}}$ hydrogen binding, atoms *ionized*
  into nuclei and electrons
- Universeexpanded, cooled: density & T dropped
- atoms formed: $p + e \rightarrow \mathrm{H}$

The Physics of Cosmic Recombination

Procedure:
follow physics of expanding, cooling H gas
going from ionized $\rightarrow$ neutral

ask: what observable traces ("fossils")
would this leave behind and remain today?
("cosmic archaeology")

Q: guesses as to what fossils might remain?

A Photon's Life

take the viewpoint of "Fabio the photon"

when U. ionized: γ_{Fabio} "sees" free e^-, nuclei
can **scatter** off both
but e^- lower mass, same amount of charge $\rightarrow$ more important

$\gamma + e^- \rightarrow \gamma + e^-$: *Thomson scattering*
think of photon as EM wave = oscillating E field

- E field shakes e^-
- accelerating e^- re-radiates

Q: photons of which energy (frequency) are scattered?
Q: energy of scattered/re-radiated photons?
Q: effect of scatterings on photon spectrum? isotropy?

Thomson scattering: nonrelativistic, classical view

- incoming radiation with frequency ν
  classically has $\vec{\mathcal{E}}$ field oscillating with ν
- field "shakes" e^- with same frequency ν, if $v \ll c$
- accelerated e^- radiates: is like "little antenna"
- *emitted radiation* is at same frequency ν
- scattered photon directions random,
  but preferentially in plane of original radiation

Scattering effect on radiation:

- frequency and thus energy unchanged
  $\rightarrow$ *pre-scattering spectrum preserved!*
- scattered directions retain "memory" of initial directions
  but if initial photon field is isotropic
  scattered radiation also isotropic

CMB thermal and isotropic character
reflects thermal and isotropic conditions in early universe!

The Birth of Atoms

when Universe ionized:
▷ all γs scattered vigorously
▷ Universe **opaque**, a "cosmic fog" of photons

now let the U. recombine

$$p + e \rightarrow \mathrm{H} + \gamma \quad (1)$$

how does this story change when U. neutral?
Q: what energies/wavelengths/freqs can be absorbed by atoms?
recall: in *hydrogen atoms* $E_n = -13.6/n^2$ eV
$\rightarrow E_n = E_1 + 13.6(1 - 1/n^2)$ eV
Q: when $T < 1$ eV, what level(s) occupied in H?
Q: implications?

Thermal Photons After Recombination

when U. neutral:
atoms only absorb γ at characteristic Es (lines)
$\rightarrow$ atoms only interact with photons having
enough energy to promote e^{-}s

but in hydrogen, $E_n = -13.6/n^2$ eV
$\rightarrow$ ground state $E_1 = -13.6$ eV
if $kT < 1$ eV, H can't access excited states:

$$E_2 = E_1 + 10.2 \text{ eV} \tag{2}$$

$\rightarrow$ first excited state at $E_2 - E_1 \gg kT \simeq E_\gamma$
$\rightarrow$ cosmic photons too feeble to raise H out of ground state!

So: *in neutral universe*
atoms transparent to cosmic γs! thermal photons "see" nothing!
$\Rightarrow$ *CMB photons travel freely*

The Cosmic Fog Clears

So: When $T \gtrsim 1$ eV:
- U. ionized
- free e^- constantly scatter cosmic photons

When $T \lesssim 1$ eV:
- U. neutral
- bound atoms "invisible" to cosmic photons

That is: ionized $\rightarrow$ neutral transition
also opaque $\rightarrow$ transparent

When did this happen?
Again: take photon's (Fabio's) point of view
Q: what physically controls opaque/transparent?
Q: how to quantify this?

When Exactly was Recombination?

Key effect: photon scattering off free e^-

quantify by scattering rate:

$\Gamma_{\text{scatter}} = \#$ scatterings/sec

$\Rightarrow \tau_{\text{scatter}} \equiv 1/\Gamma_{\text{scatter}} = \#$ sec/scatter = "mean free time"

Scattering depends on free e^- density n_e

- expansion: $n_e \propto a^{-3} = (1+z)^3$
- atomic physics: $n_e \propto e^{-13.6 \text{ eV}/kT}$

    Q: behavior at $T \gg 13.6$ eV? $T \ll 13.6$ eV?

Q: quantitative condition for opaque/transparent?

Q: Hint–when does scattering become rare?

Freezeout and Last Scattering

When does scattering stop?

When it takes "forever" to occur!

i.e., when mean time τ_{scatter} between scatterings

has $\tau_{\text{scatter}} >$ age of U. $= t$

$\rightarrow$ scattering "shut down" after $\Gamma t = \#$ future scatterings < 1

$\rightarrow$ when $\Gamma t = 1$ time of "last scattering"

"freezeout" of photon interactions with matter

Note: Freezeouts are key cosmological events:

- departures from equilibrium
- can leave behind observable "fossils"

Cosmic Recombination Quantified

first pass: atomic physics alone
$\rightarrow e^{-13.6 \text{ eV}/kT}$ factor only
no cosmology added–no expansion
$kT \sim 1$ eV at $z \sim few \times 1000$

full treatment: follow freezeout
detailed calculation in cosmological environment:
$z_{\text{recomb}} \simeq 1100$
at $t \approx 400,000$ yrs

photon life since recomb:
Q: what happens? What doesn't happen?

Recombination and Photons: Summary

For blackbody photons, recombination marks:

- last time a typical photon, $E_\gamma \sim kT$,
  could interact with matter
- "freezeout of electromagnetic interactions"

Since recombination:

- photons (mostly) unscattered: "fossils"
- travel freely in straight lines
- can and do redshift
- observable today!

cosmic microwave background (CMB)

iClicker Poll: The CMB Forever?

Today we observe CMB photons that have travelled unscattered since recombination

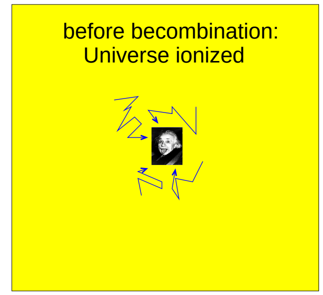
Will there ever be a time when we can't see the CMB?

A no way!

B yes way!

C depends on the future cosmic expansion history

CMB: What Does an Observer See?



pre-recombination: γs scattered
observer sees only nearby sources

post recomb, $t > t_{\text{recomb}}$:
thermal photons travel freely, redshift

Q: which photons seen at t (where/when emitted)?
Q: what happened to the photons that were here at t_{recomb}?
Q: who can see "our" photons now, and where are these observers?
Q: are there any times t when we cannot *see any thermal photons?*

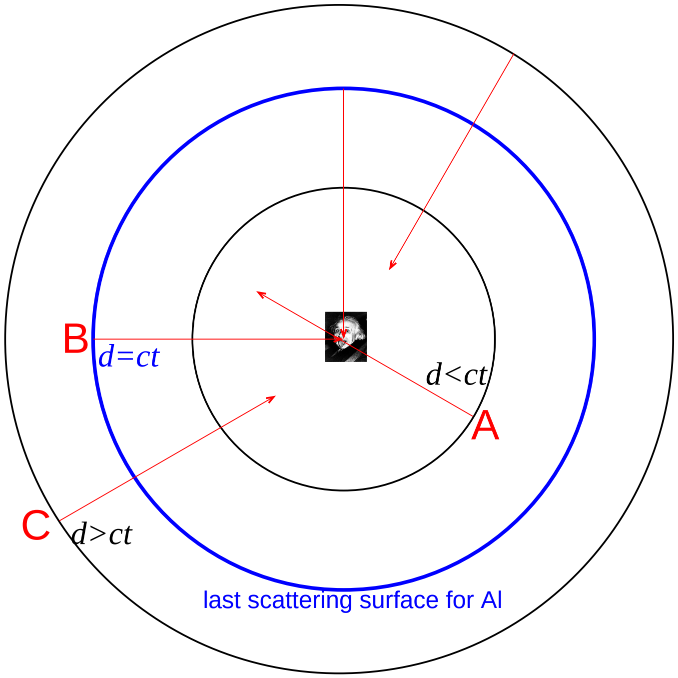
after recombination: γ travel freely

at time t after: travel $d \sim ct$

A: γs already past us

B: γs arriving

C: γs yet to come



at t, see sources at $d_{\text{ls}} \sim ct$

surface of last scattering

"edge of observable universe"

advances outward as universe ages!

redshifts as the universe expands

The CMB is a Baby Picture

Thus:

- CMB = snapshot of U at recomb.!
- γs last scattered at $t_{\rm rec} \sim 400,000$ yr: ancient!
- came from $d_{\rm ls} \approx d_{\rm horizon} \sim ct_0 \sim$ "cosmic (particle) horizon"

the CMB is a cosmic baby picture
of the infant universe as $t = 400,000$ yr $= 0.00003\ t_0$