Astro 406
Lecture 34
Nov. 15, 2013

Announcements:

- **PS 10 due now**
- **PS 11 due next Friday** penultimate problem set!
- ASTR 401: make appointment to meet

Last time: our future in an accelerating universe
fun fact: if acceleration continues
photons "have trouble catching up" with galaxies
$\rightarrow$ only travel a finite comoving distance as $t \rightarrow \infty$
$\rightarrow$ we will only ever see a finite portion of the cosmos!

Today and the rest of the course: the past

A Puzzling Measurement in the *Mad Men* Era

Spring 1965:

- Rev. Martin Luther King Jr leads march on Selma AL
- Beatles play Shea Stadium
- first successful launch of unmanned Saturn I rocket
  nine Apollo Saturn V rockets went to the Moon 1968–1972
- astronomers Arno Penzias & Robert Wilson

were using radio telescope to study interstellar gas clouds

`www: Penzias and Wilson at Bell Labs`

made careful measurements, noticed that
when pointing radio telescope ("horn") away from clouds
signal readout dropped, but did *not* go to zero
no matter where pointing "off source"

Q: what are possible explanations?

What is all this noise?

Bell Labs radio telescope reads out nonzero signal even when pointed away from any sources

Possibilities:

Problem with telescope?

- instrumental noise?
  Penzias & Wilson carefully checked system
  characterized noise–too small to explain signal
- contamination/damage to antenna?
  scraped off pigeon droppings

Result: after careful checking
Penzias & Wilson could not explain away signal
$\rightarrow$ forced to conclude: **Signal is real!**

Penzias & Wilson reported their result
in *2-page scientific paper* `www: their paper`
devoted to showing how they checked antenna noise
and which made *no attempt to interpret signal*

mysterious radio signal properties:

- **isotropic** (as far as they could measure)
- **unpolarized** (as far as they could measure)
- **unchanging with seasons** *Q: which implies what?*
- measured at $\nu = 4080$ MHz or $\lambda = c/\nu = 7.35$ cm
  with "antenna temperature" $T_{\text{ant}} = 3.5 \pm 1$ K
  Q: how do they know the radiation is thermal?

Q: what other properties of signal would be useful to measure?

Mysterious Radio Signal

mystery signal does not change with seasons
$\rightarrow$ not related to Earth, or solar system
$\rightarrow$ comes from our Galaxy or beyond

in fact: all other know sources of radiation
observed to lie *in front* of this mystery signal

- signal comes from great distance: **cosmic**
- signal is **background** to all else

antenna temperature: really *intensity* or *surface brightness*
T_{ant} gives temperature a blackbody would need
to give observed intensity I_ν at ν
$\rightarrow$ always possible to define for any signal
$\rightarrow$ does not necessarily mean the observed signal is thermal

essential to measure *spectrum*
quickly done, found to have *blackbody* form!

peak around $\lambda_{\mathrm{max}} \approx 1$ cm: **microwave**
which corresponds to temperature $T \approx 3$ K

Q: is this hot or cold?

Q: what does this all mean?

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"

Cosmic Microwave Background Radiation

mystery signal: cosmic microwave background radiation = **CMB**
Universe today filled with radiation
• isotropic – had to be! confirms cosmological principle!
• blackbody = thermal
the universe has a temperature

CMB temperature: present measurement

$$T_0 = 2.725 \pm 0.001 \text{ K} \tag{1}$$

note precision!
cosmic temperature known to within better than 0.05%!

spectrum: blackbody `www: CMB spectrum (FIRAS)`
purely thermal (so far): `www: CMB spectrum residuals`

∞

Q: what do we learn from the thermal nature of the radiation?
Q: what do we learn from the fact that T_0 is so chilly?

The CMB Demands a Hot Big Bang

observe *thermal* (Planck) CMB spectrum today

thermal systems have come into *equilibrium*
which has occured due to interactions that exchange
energy and momentum

Conclude:
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***

The Physics of the Isotropic CMB

We want to understand:

- what physics leads to the CMB?
- what cosmic epoch(s) does the CMB probe?
  when was this thermodynamic equilibrium established

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?

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* $\rightarrow$ *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"

the question becomes: *when did last scattering occur?*

The Early Universe

We know something about the future
now turn back to past

our procedure: run the movie backwards
given present contents of U,
how would it have acted in the past?

Q: present contents?

Q: how would they act in early U?

Looking Back

Observed facts:

the Universe today composed of:

- photon radiation: blackbody, $T \sim 3$ K
- normal matter: mostly H and He
- dark matter: weakly interacting *Q: why?*
- dark energy: constant density (?)

in past: $a \ll 1$

- $T \propto 1/a$: universe *hotter*
- radiation $\rho_{\rm rad} \propto a^{-4}$, matter $\rho_{\rm m} \propto a^{-3}$: *denser*
- dark energy unimportant (?) *Q: why?*

Cosmic Ingredients in the Past: Recipes for the Present

normal matter: well studied in the lab!
known properties for different ρ, T
$\rightarrow$ use known physics to deduce cosmic history of matter and radiation!

For starters:
Q: What is ordinary cosmic matter mostly made of today?

Q: how does the CMB interact with it?

Hydrogen History

ordinary matter (i.e., made of atoms): mostly *hydrogen*

today: universe cold, H is in neutral *atomic* form

H atoms: quantum orbits and energy levels
state $n \in 1, 2, 3, \ldots$ has energy

$$E_n = -\frac{E_1}{n^2} = -\frac{13.6 \text{ eV}}{n^2} \tag{2}$$

ground state: $E_1 = -13.6$ eV
negative? yes! must supply 13.6 eV to unbind the atom
$\rightarrow$ *binding energy* is $B_{\text{H}} = 13.6$ eV

photons absorbed by H *only* when E_γ is same
as energy level difference

otherwise, H atoms *transparent* to photons
...just like the gas in the room is transparent to light

today: most of the U is transparent to H

Q: when would this have been very different?

The Atomic Age

laboratory atomic physics:
hydrogen binding $B_{\mathrm{H}} = 13.6$ eV

So: matter with $kT < few$ eV ($T < 10^4$ K)
$\Rightarrow$ electrons bound to nuclei: atoms!
i.e., electrically neutral gas particles

but if $kT > few$ eV
free e^-, nuclei
ionized "plasma" of charged particles
`www: laboratory hydrogen plasma`

So: early Universe $kT \gg 1$ eV ionized
but as cooled, became neutral
epoch of (re)combination

iClicker Poll: Illuminating a Flame

Experiement: shine projector light through a flame

How will flame appear on the screen?

A brighter than the rest of the screen

B dimmer than the rest of the screen

C same brightness as the rest of the screen

Q: why the result? implications?