Astro 350

Lecture 32

Nov. 9, 2011

Announcements:

- HW 9 due next time
  Typo! Q1(e): should read "*cannot* explain"
  Office hours: after class today
  TA: tomorrow 2-3pm
- Discussion Question 9 due today
- Hour Exam: grading continues!

Last time: finished with the future
onward to the past!

A Puzzling Measurement

Spring 1965:

- Rev. Martin Luther King Jr leads march on Selma AL
- Beatles play Shea Stadium
- 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 not attempt to interpret signal

mysterious radio signal found to be :

- isotropic (as far as they could measure) *Q: meaning?*
- unchanging with seasons *Q: which implies what?*

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

signal found in radio: electromagnetic radiation
$\rightarrow$ essential to measure *spectrum*
quickly done, found to have blackbody form! *Q: what's that?*
peak around $\lambda_{\rm max} \approx 1$ cm: **microwave**
which corresponds to temperature $T \approx 3$ K *Q: hot or cold?*

Q: what does this all mean?

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 = has 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`

CMB: enormously important cosmological clue and goldmine!
need to figure out what it means

The Early Universe

For the rest of the course: look back to the past
try to develop (and test!) understanding of what happened

Strategy: run the movie backwards

Inputs:

- known (or suspected) present contents of U
- known (or suspected) laws of nature

Output:

- "pre" dictions about the past behavior
- and consequences that are observable today

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Q: present cosmic contents?
Q: how would each act in early U?

Looking Back

Cosmic Inventory: Universe today composed of

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

Run movie backwards: in the past

▷ T higher

▷ radiation, matter hotter, denser

▷ dark energy unimportant (?)

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

Temperature and Atoms

Universe has temperature! cold today, hotter in past

For a gas of atoms, as temperature goes *up*

What is affect on average atom?

A hotter = higher average speed, higher average energy

B hotter = lower average speeds, higher average energy

C hotter = higher average speed, lower average energy

D hotter = lower average speed, lower average energy

The History of Atoms

Today:

- normal matter* (i.e., made of atoms) is mostly gas
  mostly ($\sim 70\%$) hydrogen, with $\sim 28\%$ helium, 2% "metals"
- cosmic temperature $T \approx 3$ K
- cosmic average density very low:
  $\rho_{\rm crit} \approx 10 m_{\rm hydrogen}$/cubic meter

Q: how do atoms behave in these conditions?

Q: in past, higher T & ρ–what transition expected?

Q: what sets transition temperature?

*Tech lingo: "made of atoms (really, protons & neutrons)" = "baryonic"

The Atomic Age

laboratory atomic physics:
in atoms, electrons attracted, bound ("stuck") to nuclei
- takes energy input to rip apart, unbind
- well-defined "binding energy" needed to tear apart

So: in gas with particle energy < atomic binding energy
  i.e., $kT < E_{\text{bind,atoms}} \sim 1$ eV ($T \lesssim 10,000$ K)
$\Rightarrow$ electrons bound to nuclei: atoms!
i.e., electrically neutral gas particles

but if particle energy > atomic binding energy
  i.e., $kT > 1$ eV, $T > 10,000$ K
atoms ripped apart $\rightarrow$ gas of free e^-, nuclei
ionized "plasma" of charged particles
www: laboratory hydrogen plasma
  more familiar plasma examples: flames, neon lights

So the history of atoms in cosmos is:

- early Universe ($T > 10,000$ K) ionized
  no atoms could survive–torn apart
- but as cooled, became neutral
  atoms were stable, *had* to form
- so *must* have been a time of transition: key moment!
  the epoch of (re)combination
  plasma "condensation" $\rightarrow$ birth of atoms!

Procedure:

- follow physics of expanding, cooling H gas
  in bath of thermal radiation *Q: what is λ/color?*
- through ionized $\rightarrow$ neutral transition
- then ask ourselves: what observable traces ("fossils")
  would this leave behind? ("cosmic archæology")

Q: guesses?

Thermal Radiation in the Early Universe

Recall: light $\leftrightarrow$ heat connection
namely: "glow" of object at T = blackbody radiation
peak emission (color): $T \propto 1/\lambda_{\text{peak}}$
but recall: photons have $E_\gamma \propto 1/\lambda$, so $T \propto E_\gamma$ (check!)

What color was the cosmic thermal glow?
When Universe $T \sim few1000$ K, similar to $T_{\text{surface},\odot}$
$\rightarrow$ peak emission is visible to eye!
$\rightarrow$ you could have seen cosmic radiation
(but better wear the asbestos suit...)

Key issue:

- how do the thermal photons interact with the hydrogen?

In particular:

- how does light respond to a neutral vs ionized gas?

Demo: pass light thru flame

Q: flame region looks brighter? darker? same as rest of screen?

Q: implications for cosmic recombination?