Astro 350

Lecture 32

Nov. 14, 2012

Announcements:

- **Discussion 9** due today
- **Discussion 10** up today, due Wed after break
- **Homework 9** due at start of class Friday

  Office Hours: instructor–today 1pm, or by appt

  TA: tomorrow 9:30-10:30 am

A Gut Feeling for Cosmic Geometry: *Taste the Three Possibilities!*

Big Picture of ASTR350: a cosmic roller coaster ride

- from solar system to stars: *success*!
  gravity explains solar system motions, light bending
  gravity + lab physics explains lives and deaths of stars
- galaxies and the Universe today: *surprise and mystery*!
  dark matter? dark energy??
- the Early Universe: more success or more mystery?

Predicted cosmic history

heat from big bang $\to$ Universe began at enormous temperature
but then expanded and cooled

Hot Cold

quarks $\to$ neutrons, protons, e $\to$ nuclei,e=plasma $\to$ atoms

Last time: The atomic era

- expanding cooling early universe undergoes transition from ionized to neutral
- and so also undergoes transition from opaque to transparent

If true – prediction:
U should be full of *thermal = blackbody* radiation

Observed! ...accidentally, by Penzias & Wilson (1965)
★ Nobel Prize (1978) – first cosmology Nobel Prize
"for their discovery of cosmic microwave background radiation"

Q: what is CMB appearance across the sky?

CMB Temperature Mapping: Observations

observe: CMB T **very** uniform!
$\rightarrow$ U. very isotropic!

turn up contrast:
• "dipole": hotter on one side of sky, cooler on other
max diff $\Delta T = \pm 3.4 \times 10^{-3}$ K
$\rightarrow \Delta T/T \sim 10^{-3}$
interpretation:
Q: what do you think?
hint: what really observed is **spectrum**:
λ_{peak} slightly smaller on one side of sky, slightly larger in the other side

CMB dipole:
due to our motion relative to cosmic rest frame
"peculiar vel" $v = 370$ km/s $= 0.83$ million mph!
Q: what would contribute to this peculiar velocity?

subtract dipole, then: more fluctuations
occur at all angular scales
typical $\Delta T \sim 2 \times 10^{-5}$ K
$\Delta T/T \sim 10^{-5}$: tiny!
discovery 1991 `www: COBE`
precision measurements 2003-today `www: WMAP`

CMB fluctuation discovery:
NASA's Cosmic Background Explorer (COBE), 1992
Nobel Prize: 2006, George Smoot & John Mather – 2nd cosmo Prize
"for their discovery of the blackbody form and anisotropy of the cosmic microwave background radiation"

CMB not perfectly isotropic!
Q: what does this tell about Early Universe?

CMB Temperature Fluctuations ("Anisotropies")

CMB temperature differences in different directions

$$(\Delta T)_{\text{avg}} = (T_{\text{obs}} - T_{\text{avg}}) \approx 0.00001 T_{\text{avg}} \tag{1}$$

i.e., differences are in 5th decimal place!
very tiny effect, a huge technology challenge to measure

Small fluctuations are big deal!
what causes T differences? differences in density!
high density: more compressed = hotter
low density: less compressed = cooler

so measuring $\Delta T \rightarrow$ cosmic density fluctuations existed

Q: what happens to overdensites over time? underdensities?

Evolution of Cosmic Density Fluctuations

consider *overdense* region: *higher* ρ than average

so: higher gravity than average

$\rightarrow$ expands less than average

$\rightarrow$ pulls in surrounding matter

$\rightarrow$ *becomes even more dense* than average

$\rightarrow$ lather, rinse, repeat!

a "positive feedback loop" $\rightarrow$ runaway process

"gravitational instability" leads to high-density regions today!

in *underdense* regions: same ideas but opposite sign

$\rightarrow$ matter drained away to denser neighbors

$\rightarrow$ em leads to low density regions today: voids gravitational instability

Twitter/Text/Tattoo/Bumpersticker version:

"the rich get richer, the poor get poorer"

tiny density fluctuations at recombination
amplified by gravity over time $\rightarrow$ "seeds" of
galaxies, clusters, superclusters, you, me today!

So: "spots" on CMB are our ancestors!

but raises question:
How did the Universe get its spots in the first place?
We'll get back to this–look for answer in very early Universe...

Relativity and Cosmology: The Curvature of Space

Recall Friedmann "energy" equation

$$(\text{expansion rate})^2 = H^2 = \frac{8\pi}{3} G\rho - \frac{K}{a^2} \tag{2}$$

Newton: K corresponds to $-$(total energy)

Einstein General Relativity:

K measures the *curvature* of space!

(if nonzero: $K = \pm c^2 / R_{\text{curv}}^2$)

- $K > 0 \rightarrow$ positive curvature
- $K < 0 \rightarrow$ negative curvature

$K = 0 \rightarrow$ no curvature ("flat")

Q: what does it mean for space to be curved? Geometry!

Geometry of the Universe

⋆ $K > 0$ positive curvature, roughly: "like a sphere"
parallel lines eventually meet!
triangle angles sum $> 180°$;
volume finite ("closed" universe)

⋆ $K < 0$ negative curvature, roughly: "like a saddle"
parallel lines eventually diverge!
triangle angle sum $< 180°$;
volume $= \infty$

⋆ $K = 0$ no curvature: "flat," geometry Euclidean
parallel lines keep same distance
triangle angle sum $= 180°$;
volume $= \infty$

Einstein: **geometry is experimental question** *Q: how anwer?*

The CMB and Cosmic Geometry

the CMB is a cosmic goldmine!
example: geometry

CMB and cosmic triangles
- CMB fluctuations have all sizes
  but largest on scale $d_{\text{horizon}} \approx ct_{\text{recom}}$
- fluctuations of this size $\to$ *isosceles triangle*

NASA WMAP (2003):
can measure angular size θ of fluctuations
see if triangle has angle sum 180° or not
`www: WMAP diagram`

iClicker Poll

vote your conscience!

WMAP 2003: measured geometry of Universe
Which did they find?

A positive curvature: "spherical"

B no curvature: "flat" = Euclidean

C negative curvature: "hyperbolic"

The Geometry of the Universe

WMAP 2003: no measurable evidence for curvature!
either positive or negative!

Best fit to data: **geometry Euclidean = flat!**
volume infinite!

more technically:
curvature, "radius" $> 100 \times$ size of observable U
(flat $\Leftrightarrow$ curvature radius $= \infty$)

also note:
from Friedmann: if $K = 0$, then $\rho = \rho_{\text{crit}}$ now and always!
this is how CMB tells us $\Omega = 1$ today

These results cry out for explanation!

Early Universe Cosmology Scorecard

Recall strategy:

- inventory universe today
- extrapolate back to early epochs
- apply known laws of nature
- identify observable consequences ("fossils") persisting today
- measure fossils $\rightarrow$ learn about early U!

First attempt–the "atomic age"

Inventory:
hydrogen gas and blackbody radiation in expanding U

Predictions:
atoms: expect transition when particle energies $\approx$ atomic binding
$\Rightarrow$ recombination: ionized $\rightarrow$ neutral
matter+radiation: photon-electron scattering
$\Rightarrow$ loss of free e^-: opaque $\rightarrow$ transparent

Observable consequence:

"liberated" photons persist $\rightarrow$ observable today

The Test: look for thermal radiation

- CMB detected! thermal, nearly isotropic
- bonus–fluctuations $\rightarrow$ cosmo parameters, "seeds" for structure

Bottom line:

extrapolated back to redshift $z \sim 1000$!

$t \sim 400,000$ yr $\sim 0.00003 t_0$! 99.997% of the time to big bang

big bang working extremely well!

gives confidence to push back farther!

Q: next stop?

Hint: pre-recombination, U ionized $\rightarrow$ atoms ripped apart

Q: as collisions more energetic, what's next to be smashed?

After recombination (e.g., now)
• nuclei and electrons bound together as atoms
Before recombination ($t < 400,000$ yrs)
• nuclei and electrons unbound, free $\rightarrow$ at recombination: atoms first born!

What breaks next?
• electrons: no known substructure
  i.e., not "made of pieces" but truly indivisible!
• nuclei: definitely made of pieces!
  protons and neutrons!

So expect another transition *before* recombination
"ionized" protons and neutron $\rightarrow p, n$ bound in nuclei
at transition: nuclei first born!
big bang nucleosynthesis

Prelude to Nucleosynthesis

consider an atomic nucleus, e.g., ^{4}He$=\boxed{2p+2n}$

Naively, expect it to fly apart

Q: why?

Q: why doesn't it?

Q: what does this imply about things made of n,p = baryons*?*

The Nuclear Force and Nuclear Structure

In nucleus:

Electrical repulsion between protons (like charges)

but stable: repulsion overcome by attractive force

nuclear force between p, n ("baryons")

How strong?

nuclei: size $r_{\text{nucleus}} \sim few \times 10^{-15}$ m $\approx 10^{-5} \text{r}_{\text{atom}}$

2 p electric repulsion at $r = 10^{-15}$ m

$$E_{\text{electromagnetic}} = \left[\frac{1}{4\pi\epsilon_0}\right] \frac{e^2}{r} = 1.4 \times 10^6 \text{eV} = 1.4 \text{ MeV} \qquad (3)$$

$\sim$ million times atomic binding!

Nuclei in a Nutshell

nuclei are quantum objects governed by nuclear force
i.e., like "juiced" atoms, with stronger force

- still energy levels: ground, excited states
- stronger force $\rightarrow$ larger binding energy $BE \sim few$ MeV
- still unbound if given energy $> BE$ ("sticking strength")

Nuclear force + quantum levels $\rightarrow$ binding
weakest binding: deuterium $d = \boxed{\text{np}}$, $BE = 2.2$ MeV
strongest light nucleus (below C):

$^4\text{He} = \boxed{\text{2n+2p}}$, $BE = 26$ MeV

^{4}He $= \alpha$ so stable, *no stable nuclei at mass 5, 8*
"would rather be alphas!"

mass 5 decays $\rightarrow \alpha + n/p$
mass 8 decays $\rightarrow 2\alpha$