Astro 406
Lecture 40
Dec. 6, 2013

Announcements:

- **PS 12 due now** and that's it
- pay it forward: do your **ICES**
- **Final Exam Dec 20** (2 weeks from now) `www: info online` here, 8:00 to 11:00 am ...sorry!

ASTR 401:
Comments back next week
Paper in final form due **no later than Dec 20**
No extensions are possible!

Last time: left off with cosmic puzzles

- flatness

Q: what's the problem

Cosmic Puzzles: Flatness

Today: $0.9972 \le \Omega_0 \le 1.0038$ Planck 95% confidence range

But Ω evolves:

$$|\Omega - 1| = \frac{c^2}{R_0^2 H^2 a^2} \tag{1}$$

at recombination:

$$0.9999998 \le \Omega_{\mathrm{recomb}} \le 1.0000006 \tag{2}$$

at BBN:

$$0.999999999999999999999998 \le \Omega_{\mathrm{bbn}} \le 1.00000000000000000000006 \tag{3}$$

If Ω was out of these ranges then
today would have $\Omega_0 \ll 1$ or $\Omega_0 \gg 1$

What set $\Omega = 1$?

Cosmic Puzzles: Horizon

particle horizon $d_{\text{hor}}(t)$ is

- physical distance light travels in t
- size of observable U. at t
- *max size of region in causal contact at* t

but: when U is radiation dominated (and matter dom)
$d_{\text{hor}} \sim ct \to 0$ as $t \to 0$
$\Rightarrow$ as $t \to 0$, causal region vanishes
$\rightarrow$ *all points causally disconnected at* $t = 0$*!*

Observe:
T_{CMB} uniform to 1 part in 10^5
but CMB photons on opposite sides of sky
come from regions that haven't communicated
yet today, let alone at recombination!

so $d_{\text{hor}}(t_{\text{rec}})$ = particle hor at recomb
= size of region in causal contact
corresponds to 1° patch on CMB sky
$\rightarrow$ regions $> 1^\circ$ apart on CMB sky
couldn't "thermalize" to same T

`www: CMB temperature map`

Why is the CMB so isotropic?

Cosmic Puzzles: Lumpiness

CMB is not perfectly isotropic:
at high contrast, T fluctuations appear

`www: Planck anisotropy map`

CMB $\Delta T \rightarrow \Delta\rho$ at recombination

What created fluctuations?

Note: these *puzzles* are
not *inconsistencies* in big bang

Q: solutions?

Puzzle Solution I: Initial Conditions

Assume the problem away:

Declare that U. started as

- ▷ highly homogeneous, and
- ▷ highly isotropic, but with
- ▷ tiny fluctuations present

a "just-so" solution

Possible but unsatisfying

most (all?) cosmologists prefer

"generic*" initial conditions:

- ▷ U. begins inhomogeneous
- ▷ w/ large fluctuations

  but then how to get to today?

* *What's a generic universe??*

Puzzle Solution II: Inflation

Basic idea (Alan Guth, 1980):
in very early U., a period of:
exponential expansion
$a(t) = a_i e^{H(t-t_i)}$, with

- a_i scale fac at start of inflation
- $H \approx$ const

if this lasted for a "long time"
i.e., $H\Delta t \sim 60$, or $\Delta t \sim 60/H$
"60 e-foldings"
then U. expanded by factor
$e^{60} \simeq 10^{26}$!

iClicker Poll: What does inflation do for us?

Imagine the *very early U.* suddenly expanded
by a factor $e^{60} \simeq 10^{26}$

What will this do?

A drive $\Omega \to 1$: solve flatness

B solve horizon problem

C solve flatness *and* horizon

∞ D none of the above

Inflation as the Cosmic Elixir

Inflation cures cosmic illnesses
...but how?

Imagine the early U. really suddenly expanded
by a factor $e^{60} \simeq 10^{26}$!
microscopic $\rightarrow$ macroscopic

Q: how does this cure horizon? flatness?

Q: how does this make fluctuations?

Inflation Solves Cosmic Puzzles

flatness

cosmic curvature is length $R(t) = R_0 a(t)$

but Friedmann: $H^2 = 8\pi G\rho/3 - \kappa c^2/R^2$

use $\Omega = \rho/\rho_{\text{crit}} = 8\pi G\rho/3H^2$ to solve for

$$\Omega(t) - 1 = \kappa \left[\frac{c/H(t)}{R(t)}\right]^2 \quad (4)$$

if $|\Omega - 1| \sim 1$ before inflation

then after R increased by e^{60}

$|\Omega - 1| \sim 10^{-50}$ after inflation

$\rightarrow$ curvature inflated away `www: balloon analogy`

explains (*demands!*) $\Omega = 1$ to high precision

horizon

▷ tiny initial causal region ($\ll 1$ Å : microscopic!)

▷ expanded to huge scales ($\gg 1$ Mpc: macroscopic!)

observable U. today (...and far beyond!)

was in causal contact before inflation

$\rightarrow$ was once thermalized

$\rightarrow$ explains CMB isotropy

density fluctuations

pre-inflation: microscopic horizon

$\rightarrow$ quantum effects important

quantum fluctuations present & *inevitable*

like "zero-point energy": $\Delta E \Delta t \gtrsim \hbar$

inflated to macroscopic scales

$\rightarrow$ cosmic structures due to quantum mechanics

How did the Universe get its spots?

From the uncertainty principle!

"Inflation puts the 'bang' in the big bang."

–Alan Guth

The Physics of Inflation

Ingredients:

to fix cosmic puzzles, need:
phase of exponential expansion
(more generally, accelerated expansion)
$\rightarrow$ like acceleration today due to dark energy
coincidence or deep connection??

exponential expansion $\rightarrow$ U. must have
a component with (energy) density
$\rho_{\mathrm{vac}} \approx \mathrm{const}$

Inflation requires universe to have
a negative pressure component

What is this component?

known particles/fields won't work (have tried!)
invent new particle/field:
the "inflaton" ϕ
$m_\phi c^2 \gtrsim 10^{16}$ GeV $\gg m_p c^2$
exists at high energy/early U.
maybe part of unification of forces
("grand unification")?

Inflation and the CMB

CMB shows:

U. nearly perfectly homogeneous and isotropic on large scales

$\rightarrow$ verifies flatness, isotropy

CMB shows:

tiny fluctuations exist by recomb

$\rightarrow$ are these fantastically enlarged quantum fluctuations?!?

but wait–there's more!

fluctuations are *inevitable* in inflation

but also: inflation very specific

about fluctuation *spectrum*

definite $\langle(\delta\rho/\rho)^2\rangle$ at different scales

CMB shows:

fluctuation pattern at $> 1^\circ$ scales

matches inflation prediction

woo hoo!

Future Tests of Inflation

Prediction
inflation $\rightarrow$ gravitational radiation
"gravity wave CMB"
leaves imprint regular CMB
(via polarization pattern)

Not tested yet!
and very very difficult to do
$\rightarrow$ but now in reach of current CMB missions
will begin to test
Planck Surveyor: results to come?

Inflation Status

Inflation Scorecard: Fall Semester 2013

Prediction	Score
flatness	$\star$
isotropy	$\star$
fluctuations	$\star\star\star\star\star$
gravity waves	DF*

*Grade deferred till *Planck Surveyor* results

Pessimist's view

- most of these are really post-dictions
  $\rightarrow$ inflation *invented* to solve these problems
- no fundamental (i.e., particle physics) understanding of inflaton ϕ
- no competing theory as an alternative
  a lack of imagination? a cosmic epicycle?

Optimist's view

- fluctuations impressive, and a *pre*diction
- turn problem around:
  CMB probes inflation ϕ
  $\Rightarrow$ the U. as the "poor man's accelerator"
- there *were* competing theories
  ruled out by the data–and inflation wasn't

Who's right?

- the data will show (esp. gravity waves)
- but still a good idea to
  try to develop competing ideas...

Stay tuned!

Structure Formation

Formation of Cosmic Structures

basic idea:

"the rich get richer and the poor get poorer"

gravity amplifies density fluctuation "seeds"
(e.g., from inflation)
grow to structures we see today

Challenge:
given $\delta\rho$ + known cosmic ingredients
can we understand how we got
from recombination to today?

Jeans (Gravitational) Instability

Sir James Jeans:
if region overdense: what does it do?

competition:
outward expansion, pressure
vs
inward gravity
$\rightarrow$ like hydrostatic equil

during *radiation domination*:
expansion too fast
perturbations barely grow
structure formation stalled until...

during *matter domination* ($z \lesssim 3000$):

perturbations can grow

- dark matter pressureless, begins collapse
  form potential wells for baryons
- baryons stil ionized, pressure too high
  ...until recomb., then begin collapse
  free fall until $v >$ sound speed
  shock forms, gas slowed, heated: virialized