Astro 350
Lecture 38
Dec. 5, 2012

Announcements:

- **Discussion 11** – last one! Due today!
- **Homework 11** – last one! Due Friday
- Check syllabus: lowest HW and Discussion score dropped but you are still responsible for all of the material
- **ICES** available online – please do it! I do read and use comments!

Last time: trouble in paradise–cosmological puzzles

- total cosmic density today $\rho_{\rm tot}$ nearly equals $\rho_{\rm crit}$ i.e., $0.98 \leq \Omega_0 \leq 1.02$ *Q: why is this puzzling?*
- CMB temperature is nearly identical in all directions *Q: why is this puzzling?*
- CMB has small T fluctuations *Q: questions raised?*

Flatness Problem

today, density *very* close to critical density

i.e., $\rho_{\text{tot}}/\rho_{\text{crit}}$ very near 1

$\rightarrow 0.98 \leq \Omega_0 \leq 1.02$

for this to be true now, the during nucleosynthesis

$0.99999999999999999999998 \leq \Omega \leq 1.00000000000000000000002$

What set $\Omega = 1$ so precisely?

Horizon Problem

today, CMB T almost same in all directions

but when CMB created, cosmic horizon was much much smaller

CMB regions $> 1^\circ$ apart could not have "coordinated" T

What set the cosmic T so uniformly?

Lumpiness Problem

CMB "spots" due to ΔT

$\rightarrow$ small variations in density $\Delta\rho$ at recombination

What created fluctuations?

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 $\Rightarrow$ 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
- note: $\ddot{a} > 0 \rightarrow$ accelerated expansion!
  vs "ordinary" decelerated expansion
  in U dominated by matter or radiation

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
$e^{60} \simeq 10^{26} = 100,000,000,000,000,000,000,000,000$!

Q: How would this affect the horizon and flatness problems?

Inflation Solves Cosmic Puzzles

1. flatness

imagine a universe that *was* curved *before* inflation
curvature size ("radius") expanded by factor 10^{26}
much more dramatic than pea vs Earth
$\rightarrow$ curvature inflated away! www: balloon analogy

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

quantitatively:
if $|\Omega - 1| \sim 1$ before inflation
$|\Omega - 1| \sim 10^{-50}$ after inflation

2. horizon

▷ tiny initial causal region ($\ll$ atom size: 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

Q: but what about CMB lumpiness?

3. density fluctuations

pre-inflation: microscopic horizon

→ quantum effects important

quantum fluctuations present & *inevitable*

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

inflated to macroscopic scales

→ 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.' '

–Inflationary Cosmologist 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
$\rho_{\rm vac} \approx$ const

What is this component?

known particles/fields won't work (have tried!)

invent new particle/field:

the "inflaton" ϕ

mass $m_\phi c^2 \gtrsim 10^{16}$ GeV $\approx 10^{16} m_p c^2$

exists at high energy/early U.

maybe part of unification of forces

("grand unification")?

Note: essential feature of inflaton ϕ

$\rightarrow$ must be a "scalar" particle = no "spin"

this is critical for giving acceleration

(same goes for dark energy)

- bad news: no scalar particles found in lab until July 4, 2012
- good news: it is now after July 4, 2012

The Higgs Particle

In the (very successful) Standard Model of particle physics
all particles have (very) different masses
how did they get mass?

Peter Higgs (and others), in 1964:

- proposed that space is filled with a *scalar field*
  now called the Higgs field
- particles moving through space can interact with the field
  if interact strongly, hard to move → more inertia → more mass
  if interact weakly, less inertia → less mass
  if don't interact with Higgs field, no mass at all!

Q: how to test this?

How to test this?

associated with every field is a particle

$\rightarrow$ so Higgs field should have associated Higgs particle

• search went on for decades • Higgs particle discovery announced July 4 2012!

Bad news:

Higgs does not have right properties to be inflaton!

Good news:

nevertheless, now we know–Nature does love scalar fields!

Inflation and the CMB

CMB shows:

U. nearly perfectly homog., isotrop.

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 *amount* of fluctuation at different sizes

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 next generation CMB missions

will begin to test

Planck Explorer: launched 2009

cosmology results announced early 2013

Inflation and the Rest of Cosmology

How does inflation fit in with other cosmic events?
don't know when inflation happened,
but can say something about order of events

• at some very early time, very high T
inflaton vacuum energy became larger than other energy forms
  (matter, radiation)
$\rightarrow$ universe *started* inflating

• during inflation: scale factor grew $\times 10^{26}$

Q: effects on matter, radiation: temperature? density?

during inflation, matter density dropped by
$\rho \propto 1/a^3 = (10^{-26})^3 = 10^{-78} \rightarrow$ matter dilulted away!
temperature $T \propto 1/a \rightarrow$ universe supercooled!

so: as inflation stopped, all energy in form of vacuum
then inflaton decays to matter, radiation: "reheating"
universe temperature back to very high T

iClicker Poll: Cosmic Timeline

Which of these is the right order of cosmic events?
from earliest to latest

A baryogenesis= matter produced more than antimatter, nucleosynthesis, inflation

B baryogenesis, inflation, nucleosynthesis

C inflation, baryogenesis, nucleosynthesis

D inflation, nucleosynthesis, baryogenesis

E nucleosynthesis, baryogenesis, inflation

usual hot big bang occurs after reheating
e.g., matter/antimatter difference created (baryogenesis)
then light element formed, atoms formed, galaxies formed

otherwise, inflation dilutes all of these away
and would have to redo them after inflation anyway

Inflation Status

Inflation Scorecard: Fall Semester 2006

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

*Grade deferred till *Planck Explorer*

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?

Q: optimist's response?

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
  for density fluctuation origins, but they're ruled out now

Who's right?

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

Stay tuned!

Epilogue: Living With Inflation

Inflation arises from a marriage of

- ideas about unification of forces (inner space)
- ideas about cosmology (outer space)

something like inflation almost unavoidable if combine these

but much remains to be understood

- how did the universe *start* inflating?
  what made vacuum energy dominant?
- how did the universe *stop* inflating?
  what made vacuum energy revert to matter & radiation?

- what if some regions of the universe are still inflating?
  if so, continuously becoming exponentially larger

$\rightarrow$ and our observable universe is a tiny part of the
  mostly inflating cosmic volume

- how are we so lucky to live in a non-inflating region
  sounds very anthropic...

lesson: if true inflation, profoundly changes our view
of what "the universe" means