Astro 350
Lecture 39
Dec. 2, 2011

Announcements:

- HW11 due now–no more!
- **Final Exam**: Tue Dec 13, 8-11am `www: info online`
- Discussion Question *second chance*
  can do up to 2 missed questions for half credit each
  must turn in by end of next Wed Dec 7
- **ICES** available online – please do it!
  I do read and use comments!

Last time: Inflation in the Early Universe
Q: what is it? How it is different from (more than) the usual expansion of the universe?
Q: what puzzles does it solve? How are they solved?

Primordial Puzzles

Why the cosmological principle?

- *Flatness*: Ω exceedingly close to 1 in early U
  or else today $\Omega \to 0$ or ∞
- *Horizon*: CMB temperatures nearly identical in regions that (apparently) were never in contact

How did the universe get its spots?

- *Lumpiness*: CMB temperature fluctuations
  $\to$ small density fluctuations in the Early U

Inflation

idea: Early U had period of rapid *accelerated* expansion

- during inflation, scale factor grew by $e^{60} \simeq 10^{26}$!
- expansion accelerated–like dark energy now

Inflation Solves Cosmic Puzzles

flatness

curvature inflated away `www: balloon analogy`

horizon

- ▷ tiny initial causal region ($\ll$ atom size: microscopic!)
- ▷ expanded to huge scales ($\gg$ 1 Mpc: macroscopic!)

diagram: cosmic spacetime with, without inflation

density fluctuations

pre-inflation: microscopic horizon

$\rightarrow$ quantum effects important

quantum fluctuations present & *inevitable*

if no expansion, or decelerating expansion

$\rightarrow$ fluctuations undone soon after created

but if *accelerated* expansion

"nearby" fluctuations soon far apart, carried at speed $> c$

can't be undone $\rightarrow$ inflated to macroscopic scales

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")?

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