Astronomy 350L
(Spring 2005)

The History and Philosophy of Astronomy

(Lecture 27: Modern Developments II: Inflation)

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Big Bang Theory: Successes and Problems

• Successes:  - Hubble expansion of galaxies
  - Helium and hydrogen abundance
  - Cosmic microwave background

• Problems:  - Requires fine-tuning in initial conditions
Robert Dicke: Princeton’s Titan

- 1916 - 97
- important contributions both in theory and observation
- cosmic microwave background
  - renewed prediction
  - detection strategy (‘Dicke radiometer’)
  - beaten by Penzias and Wilson who detected CMB by serendipity
- pointed out fundamental riddle with standard Big Bang model (“flatness problem”)
The Flatness Problem

Size of Universe vs. Age

- TINY difference in density in early universe translate into HUGE difference in long-term fate!
The Flatness Problem

- In Einstein’s General Relativity, the universe’s density is reflected in its overall geometry (‘curvature’)

\[ \Omega_0 = \frac{\text{actual density}}{\text{critical density}} \]

- Omega = \Omega_0 > 1: closed
- Omega = \Omega_0 < 1: open
- Omega = \Omega_0 = 1: flat
The Flatness Problem

Omega vs. Age

- Tiny deviations from Omega=1 briefly after Big Bang very rapidly develop into huge ones!
- Flatness Problem: Why is the universe, after billions of years, observed to be still so close to critical (Omega=1)???
The Horizon Problem

• Big Q: Why is the universe so similar in all directions? (‘isotropy’)

All-sky projection of cosmic microwave radiation
The Horizon Problem

• Big Q: Why is the universe so similar in all directions? (`isotropy’)

• $A = B$ requires: (1) causal contact (but there was no time!) (2) fine tuning (to extreme degree)
Standard Big Bang: Fine-Tuning Problem

- Within standard Big Bang model, need to postulate fine-tuning of conditions briefly after the Big Bang

???

- Our Universe appears highly improbable

- Was the universe created with fine-tuned initial conditions so as to allow our existence? (so-called `anthropic principle’)

The Particle Physics Revolution (1970s)

- GUT = Grand Unified Theory
  - 1974:
    Sheldon Glashow and Howard Georgi

- Early in the universe, all 4 forces of nature were unified into one `superforce’
- With time, the forces attain separate identity
The GUT Phase Transition

• $10^{-34}$ seconds after Big Bang: Universe has cooled below critical temperature for Grand Unification (i.e., EM = weak force = strong force)

• Symmetry between strong and electroweak force will be `broken’

• Analogy for `spontaneous symmetry breaking’ (SSB):
  - glasses in dinner table setting
  - initially, they are all of equal status
  - after SSB: symmetry is broken (one glass is special)
The GUT Phase Transition

• Before symmetry breaking (during Grand Unified Era):
  - 3 forces are unified
  - ‘Identity fields’ (technically `Higgs fields’) which eventually are responsible for making forces different, all have zero values

  symmetric state

  broken-symmetry state

  Potential energy

  Higgs field

• After symmetry breaking: Higgs fields have non-zero value strong force is different from electroweak force
Delayed Phase Transition: `False Vacuum’

- Higgs field does not immediately `roll away’ from zero point
- Universe remains for a while in high-energy state - so-called `false vacuum’
Weird Properties of the False Vacuum

• ‘False vacuum’ has never been observed in laboratory, but we can speculate about its behavior!
• False vacuum has negative pressure (=tension)

Normal gas

- positive pressure
- expanding bubble loses energy

False Vacuum

- negative pressure
- expanding bubble gains energy
Alan Guth: Inventing Inflation

- Born 1947 (New Brunswick, NJ)
- 1980: Professor at MIT
- 1981: Inflationary Universe
  - “Spectacular Realization: Universe did go through an episode of tremendous expansion briefly after the Big Bang”
- natural solution for Big Bang fine-tuning mystery
Weird Properties of the False Vacuum

• `False vacuum’ has negative pressure (=tension)

• According to Einstein, negative pressure has repulsive gravity (`anti-gravity’)

\[ \rho + \frac{3P}{c^2} \]

• expanding universe, containing false vacuum, creates more and more false vacuum → runaway expansion → inflation
Guth’s Inflationary Universe

- Universe expands by tremendous factor ($\sim 10^{50}$) between $10^{-34}$ and $10^{-32}$ seconds
The End of Inflation

- Inflation ends when Higgs field finally `rolls down’ into `true vacuum’ (minimum energy) state
- strong force is now distinguished from electroweak one
- universe now contains only positive pressure material

Diagram:
- Symmetric state
- Broken-symmetry state
- Potential energy
- False vacuum
- True vacuum
- Higgs field
Inflation solves the Flatness Problem

• Even if universe started out with curvature, inflation will smooth this out, and drive universe to flatness!

Exponential Expansion of space

• Important prediction: Omega = 1 (“Space is flat”)

• Spectacularly confirmed in 2003 by WMAP satellite
Inflation solves the Horizon Problem

- Inflation has blown up microscopic region in early universe (small enough for causal interactions) to size way beyond our current observable universe.
The Multiverse

• maybe there are (infinitely?) many distinct universes, each one triggered by a phase transition, leading to inflation?!

• eternal inflation (A. Linde)
  - eternal (no beginning in time)
  - self-reproducing
The Dark Side of the Universe

• Big Q: What is the universe made of?

• consensus view of early 21st century (WMAP):
  - 4% normal matter (‘baryons’)
    (stars, gas, people…)
  - 23% dark matter
  - 73% dark energy

• Dark Energy has negative pressure, and thus blows apart universe (2nd inflation-like episode?)

• Is Dark Energy connected to inflaton field?
The Inflationary Universe

• 1970s: Realization that Big Bang has problems
  - flatness problem
  - horizon problem
  - magnetic monopole problem

• 1980s: Inflationary Universe Theories developed
  - Alan Guth first proposes inflation (1981)
  - inflation is triggered during GUT symmetry breaking
  - universe spends some time in `false vacuum’ state
  - false vacuum drives space apart at accelerating pace

• Present-day cosmic acceleration
  - Dark Energy has negative pressure (anti-gravity)
  - we ve just entered 2\textsuperscript{nd} inflation-like phase of runaway expansion