Origin of the Universe

Katsushi Arisaka

University of California, Los Angeles
Department of Physics and Astronomy

arisaka@physics.ucla.edu
Seven Phases of Cosmic Evolution

14 billion years ago

Origin of Particles
Origin of Structure
Origin of Life
Origin of Consciousness
Expansion of Universe

Size of Universe $\propto \sqrt{\text{Time}}$

Horizon $\propto cT$

Size

Beginning

Today

Time
Temperature of Universe

Temperature = \frac{1}{\text{Size}}

- Temperature = 2.7 \degree \text{K}
- Temperature = 3,000 \degree \text{K}
- Size: Beginning, 300,000 years, Today
Cosmology
The Fate of the Cosmos

Low density—universe expands forever

High density—universe collapses

Big Bang

Present time

Copyright © 2005 Pearson Prentice Hall, Inc.
Geometry of the Universe

Open \( \Omega < 1 \)

Flat \( \Omega = 1 \)

Closed \( \Omega > 1 \)
Cosmic Microwave Background (Discovered in 1964)

- T = 300,000 years after the Big Bang
- Temperature = 3,000°K
- z = 1,100

Today:

3000°K/1,100 = 2.7°K

Sun/Earth

Transparent

Opaque
All the electrons were bound by Hydrogen and Helium Nuclei. → **Atoms formed.**

The Universe became transparent. Photons were released. → **Radiation decoupled.**

---

**Cosmic Microwave Background (CMB)**
Two Fundamental Problems of Big Bang Cosmology

- **Horizon Problem**
  - At early Universe, Size $\gg$ Horizon.
  - Why is CMB so uniform in every direction?

- **Flatness Problem**
  - $|\Omega - 1|$ grows proportional to the size of the Universe.
  - Why is $\Omega$ of today close to 1?
Expansion of Universe

Expansion of Universe: Horizon $\propto cT$

- **Beginning**: 300k Years
- **Today**

Within 1°
The horizon problem: When observed in diametrically opposite directions from Earth, cosmic background radiation appears the same even though there hasn’t been enough time since the Big Bang for them to be in thermal contact.
The flatness problem: In order for the universe to have survived this long, its density in the early stages must have differed from the critical density by no more than 1 part in $10^{15}$. 

\[ |\Omega - 1| \propto \text{Size of Universe} \]
Inflation in Early Universe

Size

Beginning

Today

Time

Horizon $\propto cT$

Inflation
Inflation, if correct, would solve both the horizon and the flatness problems.

This diagram shows how the horizon problem is solved – the points diametrically opposite from Earth were in fact in contact at one time.
The flatness problem is solved as well – after the inflation the need to be exceedingly close to the critical density is much more easily met:
WMAP Power Spectrum

Universe is Flat. ⇒ Inflation
Geometry of the Universe

Open $\Omega < 1$

Flat $\Omega = 1$

Closed $\Omega > 1$
The Accelerating Universe \((1998)\)

\[ \Omega_\Lambda = 0.7 \]

After inflation, the expansion either...
- first decelerates, then accelerates
- or always decelerates
- or collapses
- expands forever

Density of Our Universe

- $\Omega_{\text{Total}} = \Omega_\Lambda + \Omega_{\text{Matter}} = 1.0$

- Universe is Flat.  $\implies$ Inflation

- 73% is Dark Energy.  $\implies$ Accelerating

$\Omega_{\text{Matter}}$ and $\Omega_\Lambda$ are two of “Just Six Numbers”
Density Fluctuations
This graph now includes the accelerating universe. Given what we now know, the age of the universe works out to be 13.7 billion years.
Particle Physics
Elementary Particles (~1970)

- Electron: $10^{-10}$ m
- Atom: $10^{-14}$ m
- Nucleus: $10^{-15}$ m
- Particle: $< 10^{-18}$ m
- Quark: $< 10^{-18}$ m
Quark Model

Proton: $+ \frac{2}{3} + \frac{2}{3} - \frac{1}{3} = 1$

Neutron: $+ \frac{2}{3} - \frac{1}{3} - \frac{1}{3} = 0$
### Fermions

**1973**

- Elementary particles: “Fermions”

<table>
<thead>
<tr>
<th></th>
<th>Particle</th>
<th>Anti-Particle</th>
</tr>
</thead>
</table>
| **Quarks** | $u$  
$u$  
$d$  
$d$  
$s$  
$s$  | $\bar{u}$  
$\bar{d}$  
$\bar{d}$  
$\bar{s}$  
$\bar{s}$  |
| **Leptons** | $\nu_e$  
$e^-$  
$e^-$  
$\nu_e$  
$\mu^-$  
$\mu^-$ | $\bar{\nu}_e$  
$\bar{e}^+$  
$\bar{e}^+$  
$\bar{\nu}_e$  
$\bar{\nu}_\mu$  
$\bar{\nu}_\mu$ |
SLAC
(Stanford Linear Accelerator Center)

1 mile long
Fermi Lab near Chicago

6km Circumference
1+1=2 TeV

Proton + Anti-proton
Discovery of more quarks

1974 – 1994
- More quarks and leptons were discovered.

- 1974  Ting (BNL) & Richter (SLAC)  $J/\Psi = c\bar{c}$
- 1975  Perl (SLAC)  $\tau$-lepton
- 1978  Lederman (FNAL)  $\Upsilon = b\bar{b}$
- 1994  CDF/D0 Group (FNAL)  $t$ (top quark)

All discovered at US National Labs (Many Nobels!)
Elementary Particles

<table>
<thead>
<tr>
<th>Charge</th>
<th>Fermion</th>
<th>Boson</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2/3</td>
<td>up, charm, top</td>
<td>photon</td>
</tr>
<tr>
<td>-1/3</td>
<td>down, strange, bottom</td>
<td>gluon</td>
</tr>
<tr>
<td>0</td>
<td>electron neutrino, muon neutrino, tau neutrino</td>
<td>Z boson</td>
</tr>
<tr>
<td>-1</td>
<td>electron, muon, tau</td>
<td>W boson</td>
</tr>
</tbody>
</table>

Three Families of Matter

+ Anti-particles
Today’s Universe

Elementary Particles

Fermion

Charge

Quarks

+2/3

-1/3

0

Leptons

-1

Boson

Charge

Force Carriers

0

0

0

±1

Three Families of Matter
Now Time = 14B yrs, Temp. = 2.7 °K (3×10^{-4} eV)

- **Fermions:**
  - Lepton: \( \nu_e \) \( \sim 1 \)
  - Baryon: \( \begin{array}{c} \bar{\nu}_e \\ e^- \\ p \\ n \end{array} \) \( \sim 4×10^{-10} \)
  - Ratio (in numbers):
    - \( \nu_e : e^- : p : n \approx 1 : 4×10^{-10} : 4×10^{-10} : 1×10^{-10} \)

- **Bosons:**
  - Photon: \( \gamma \) \( \approx 1 \)
  - No anti-particles
  - \( \# \) Photon : \( \# \) Baryon = 1 : \( \sim 4×10^{-10} \)
  - \( \# \) p = \( \# \) e^-

---

Katsushi Arisaka

6/23/2011
Expansion of Universe

Size of Universe $\propto \sqrt{\text{Time}}$

Horizon $\propto cT$
Temperature of Universe

Temperature = \frac{1}{\text{Size}}

- **2.7°K**
- **3,000°K**

Beginning - 300,000 years - Today

Katsushi Arisaka
Relation between Temperature and Time

T: Temperature
t : time

\[ T = \frac{1.5 \times 10^{10}}{\sqrt{t(\text{sec})}} ^{\circ K} \]
\[ = \frac{1.3}{\sqrt{t(\text{sec})}} \text{MeV} \]
Thermal Equilibrium

- If thermal energy is greater than twice the mass of particles,
  \[ E > 2 \text{mc}^2 \]
  Photon $\leftrightarrow$ Particle + Anti-particle

Example:

\[ m_e = 0.511 \text{ MeV} \]
if \( E > 1.022 \text{ MeV} \)
\[ \gamma \leftrightarrow e^- + e^+ \]
Fermions:
- Lepton: $\nu_e$, $e^-$, $\bar{\nu}_e$, $e^+$
  - Ratio: $1$, $1$, $1$, $1$
- Baryon: $p$, $n$
  - Ratio: $\sim 4 \times 10^{-10}$, $\sim 1 \times 10^{-10}$

Bosons:
- Photon: $\gamma$
  - Ratio: $1$

Time = 1 sec, Temp. = $10^{10}$ oK (1.3 MeV)

Horizon $\sim 3 \times 10^8$ m
Time = $10^{-4}$ sec, Temp. = $10^{12}$ oK ($\sim$100 MeV)

- **Thermal Equilibrium of Protons and Neutrons**
  - $n \leftrightarrow p + e^- + \bar{\nu}_e$
  - $n + e^+ \leftrightarrow p + \bar{\nu}_e$
  - $n + \nu_e \leftrightarrow p + e^-$

- **Lepton Dominant Era**

- **Fermions:**
  - **Lepton:**
    - $\nu_e$: 1
    - $e^-$: 1
    - $\bar{\nu}_e$: 1
    - $\nu_e$: 1
  - **Baryon:**
    - $p$: $\sim 2 \times 10^{-10}$
    - $n$: $\sim 2 \times 10^{-10}$

- **Bosons:**
  - **Photon:** $\gamma$: 1

- Horizon $\sim 30$ km
Quark → Hadron Phase Transition

- u-quarks and d-quarks are bound together to form protons and neutrons.

- No anti-quarks

Quark-gluon Plasma

Horizon ~ 3 km
Time = $10^{-6}$ sec, Temp. = $10^{13}$ oK ($\sim 1$ GeV)

 Thermal Equilibrium of Photons, Leptons and Quarks

- Photon $\leftrightarrow$ Lepton + Anti-lepton
  - $\gamma \leftrightarrow e^- + e^+$
  - $\gamma \leftrightarrow \mu^- + \mu^+$
  - $\gamma \leftrightarrow \nu + \bar{\nu}$
- Photon $\leftrightarrow$ Quark + Anti-quark
  - $\gamma \leftrightarrow u + \bar{u}$
  - $\gamma \leftrightarrow d + \bar{d}$
  - $\gamma \leftrightarrow s + \bar{s}$

- $\#\text{photon} \sim \#\text{lepton} \sim \#\text{quark}$

Horizon $\sim 300$ m
Mass of Particles

Generation

I  II  III

u  c  t

d  s  b

ν_e  ν_μ  ν_τ

Spin ½  Fermions

Spin 1  Gauge bosons

Spin 0  Higgs boson
Elementary Particles

Universe at $t = 1 \mu$sec

Charge

Fermion

<table>
<thead>
<tr>
<th>Charge</th>
<th>Quarks</th>
<th>Leptons</th>
</tr>
</thead>
<tbody>
<tr>
<td>+2/3</td>
<td>$u$ up</td>
<td>$\nu_e$ electron neutrino</td>
</tr>
<tr>
<td>-1/3</td>
<td>$d$ down</td>
<td>$\nu_\mu$ muon neutrino</td>
</tr>
<tr>
<td>0</td>
<td>$c$ charm</td>
<td>$\nu_\tau$ tau neutrino</td>
</tr>
<tr>
<td>-1</td>
<td>$s$ strange</td>
<td>$e$ electron</td>
</tr>
<tr>
<td></td>
<td>$b$ bottom</td>
<td>$\mu$ muon</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\tau$ tau</td>
</tr>
</tbody>
</table>

Boson

<table>
<thead>
<tr>
<th>Charge</th>
<th>Force Carriers</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>$\gamma$ photon</td>
</tr>
<tr>
<td>0</td>
<td>$g$ gluon</td>
</tr>
<tr>
<td>±1</td>
<td>$Z$ boson</td>
</tr>
<tr>
<td></td>
<td>$W$ boson</td>
</tr>
</tbody>
</table>

+ Anti-particles

Three Families of Matter
Unification of Forces

Electro-Weak Unification

Relative strength of force vs. temperature (K)

- Strong force
- Electromagnetic force
- Weak force
- Gravity

100 GeV

10^{15} \rightarrow 10^{16} \rightarrow 10^{19} \text{ GeV}

Copyright © Addison Wesley.
Time = $10^{-10}$ sec, Temp. = $10^{15}$°K ($\sim$100 GeV)

Electro-weak Unification

- Electro-Magnetic force = Weak force
- The highest energy we can study by the accelerators

Horizon $\sim 3$ cm
Universe at $= 0.1 \text{ nsec}$

### Elementary Particles

#### Fermion
- **Up Quark** ($u$): Charge $+2/3$
- **Down Quark** ($d$): Charge $-1/3$
- **Charmed Quark** ($c$): Charge $+2/3$
- **Strange Quark** ($s$): Charge $-1/3$
- **Bottom Quark** ($b$): Charge $0$
- **Electron Neutrino** ($\nu_e$): Charge $0$
- **Muon Neutrino** ($\nu_\mu$): Charge $0$
- **Tau Neutrino** ($\nu_\tau$): Charge $0$
- **Electron** ($e$): Charge $-1$
- **Muon** ($\mu$): Charge $-1$
- **Tau** ($\tau$): Charge $-1$

#### Boson
- **Photon** ($\gamma$): Charge $0$
- **Gluon** ($g$): Charge $0$
- **$Z$ Boson** ($Z$): Charge $0$
- **$W$ Boson** ($W$): Charge $\pm 1$

#### Three Families of Matter
- **Family I**: $u$, $d$, $e$
- **Family II**: $c$, $s$, $\mu$
- **Family III**: $t$, $b$, $\tau$

**+ Anti-particles**
Unification of Forces

Grand Unification

Gravitational force

Strong force

Electromagnetic force

Weak force

Electroweak force

100 GeV

$10^{16}$ GeV

$10^{19}$ GeV

$10^{23}$
Grand Unification

- Strong-Force = Electro-Magnetic force = Weak force
- Quark = Leptons

- Everything (except gravity) is unified.

- Inflation might happen?

Size ~ 30 cm

Horizon ~ $3 \times 10^{-24}$ cm

Time = $10^{-34}$ sec, Temp. = $10^{29}$ oK ($\sim 10^{16}$ GeV)
Inflation in Early Universe

Size

Beginning  Today  Time

Horizon $\propto cT$

Inflation
Unification of Forces

- Strong force
- Electromagnetic
- Weak force
- Electroweak
- GUT force

Relative strength of force vs. temperature (K):
- Gravity: 100 GeV
- 10^{15} K
- 10^{16} GeV
- 10^{19} GeV
- 10^{32} K

Plank Epoch
Planck Epoch

- Gravitational Effect (Curvature of the space)
- Quantum Mechanical effect

- We can not define space-time any more at earlier stage.

< Plank Scale >

Size ~10^{-33} cm
Physicists’ View of Early Universe

Fiat lux
Let there be light
Physicists’ View of Early Universe

Lorentz Invariance
Local Gauge Invariance
Structure of DNA

Molecule of DNA

© Rothamsted Experimental Station, 1997, 1998
Symmetry Breaking

Simple

Symmetry Break Down

Complex
The Beginning

- Everything was the same ↔ Perfect symmetry.
  - All the particles are the same as photons.
  - All four forces are the same.

- The Universe was 10 dimension.
Early Universe & Unsolved Problems

<table>
<thead>
<tr>
<th>Time (sec)</th>
<th>Temp. (°K)</th>
<th>Energy (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-45}$</td>
<td>$10^{30}$</td>
<td>$10^{18}$</td>
</tr>
<tr>
<td>$10^{-40}$</td>
<td>$10^{25}$</td>
<td>$10^{15}$</td>
</tr>
<tr>
<td>$10^{-35}$</td>
<td>$10^{20}$</td>
<td>$10^{12}$</td>
</tr>
<tr>
<td>$10^{-30}$</td>
<td>$10^{15}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^{-25}$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^{-20}$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^{-15}$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^{-10}$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^{-5}$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$1$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^3$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^6$</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
<tr>
<td>$10^9$ year</td>
<td>$10^{10}$</td>
<td>$10^{10}$</td>
</tr>
</tbody>
</table>

**Notes:**
- **Planck Epoch**
- **Grand Unification**
- **Inflation**
- **Dark Matter**
- **Electro-Weak Unification**
- **Matter-Radiation Decoupling**
- **Dark Energy**