THE EARLY UNIVERSE

Is the Big Bang Model Perfect?

NO

Flatness Problem

Isotropy Problem

Anti-Matter Problem
What is the Flatness Problem?

Observations show that the Universe is close to the “marginally bound” case.

The Universe is now ~15 billion years old, so at the time of the Big Bang, the matter density ($\rho_m$) must have been equal to the critical density ($\rho_{crit}$) out at least 50 significant digits.

$$1.00000000000000000000000000000000000000000000000000000000000000000000000000000000000000000000$$

If we had deviated a little too low, the Universe should have been so open no matter coalesced to form stars.

If we had had too high a density, the Universe should have collapsed upon itself by now.

What is the Isotropy Problem?

The Cosmic Microwave Background Radiation (CMB) shows that the Universe is extremely uniform in all directions.

But with the Big Bang model, the different parts of the Universe were never in contact, so they should not have all settled into the same temperature.

Apparently, the Universe must have been well mixed almost from the start.
What is the Anti-Matter Problem?

Quantum mechanical models indicate that there should be equal amounts of matter and antimatter. But we live in a matter Universe.

Inflationary Universe Theory

The Universe rapidly expanded at $\tau = 10^{-35}$ s but it only lasted for $10^{-24}$ s. During this time, space – but not matter – ballooned out by a factor of $10^{50}$. This does not violate Einstein’s dictate of $v < c$, because matter did not travel through space faster than $c$. 
Inflationary Universe Theory

Diameter 1: $1 \text{ fm} = 10^{-15} \text{ m}$ diameter of a proton

Diameter 2: $10^{50} \text{ fm} = 10^{35} \text{ m} = 10^{27} \text{ AU} = 10^{21} \text{ pc} = 10^{15} \text{ Mpc}$

16.3 billion light years

(about half the size of today’s Observable Universe)

Removes Flatness Problem

When we only see a small part of the curved Earth, it appears flat to us. Likewise, the Universe appears flat because we only see a very small part of it.
The Observable Universe

The part of the Universe that we can observe lies within a sphere centered on the Earth called the Cosmic Particle Horizon. Its radius is equal to the distance that light has traveled since the start of the expansion.

Removes Isotropy Problem

The small part of the Universe we observe was previously very close together (i.e., intimate, mixed, thermalized) – close enough that it had mixed prior to the Inflationary event.

So the Cosmic Background Radiation we see in all directions comes from a very small region of the early Universe.
Removes the Anti-Matter Problem?

NO

[Extra-credit for whoever solves it!]

Need to Learn a Little
Quantum Mechanics
Quantum Mechanics

Quantum Mechanics is the branch of physics that explains the behavior of nature on the atomic scale and smaller. The submicroscopic world of quantum mechanics is significantly different from the ordinary world around us. A certain amount of fuzziness, or uncertainty, enters into the description of reality.

Heisenberg Uncertainty Principle

This principle states that there is a reciprocal uncertainty between position and momentum (equal to the mass of the particle times its velocity).

\[ \Delta x \cdot \Delta p = h / 2\pi \]

The more precisely you try to measure the position of a particle, the more unsure you become of how the particle is moving (i.e., its velocity). Conversely, the more accurately you determine the momentum of the particle, the less sure you are of its location.

These restrictions are not a result of errors in making measurements; they are fundamental limitations imposed by the nature of the Universe.
Heisenberg Uncertainty Principle

There is an analogous uncertainty involving Energy and Time.

\[ \Delta E \cdot \Delta t = \frac{\hbar}{2\pi} \]

One cannot know the energy of a system with infinite precision at every moment in time. Over short time intervals, there can be great uncertainty about the amounts of energy in the subatomic world.

\[ E = m c^2 \quad \text{so} \quad \Delta E = \Delta m c^2 \]

\[ \Delta m \cdot \Delta t = \frac{\hbar}{2 \pi c^2} \]

For an electron-positron pair:

\[ \Delta t = \left( \frac{1}{\Delta m} \right) \left( \frac{\hbar}{2 \pi c^2} \right) = 6.44 \times 10^{-22} \text{ s} \]
Spontaneous Production

During this brief moment of $6.44 \times 10^{-22}$ s, an electron and positron can spontaneously appear and then disappear. The greater the amount of matter that appears spontaneously, the shorter the time interval it can exist before it disappears into nothingness. This bizarre state of affairs is a natural consequence of quantum mechanics.

Virtual Pairs

Spontaneous creation happens anywhere and at any time. Quantum mechanics says that if a process is not strictly forbidden, then it must occur. Pairs of every type of particle and antiparticle are constantly being created and destroyed at every location across the Universe. We have no way of observing these pairs directly without violating the uncertainty principle. For this reason, they are called virtual pairs. They do not “really” exist – they “virtually” exist.
Antiparticles

No particle can appear spontaneously by itself, however. For each particle created there is a second, almost identical antiparticle made. Equal amounts of matter and antimatter come into existence and then disappear.

A particle and an antiparticle are identical in almost every respect except that they carry opposite electric charges. Because particles and antiparticles come and go in pairs, the total electric charge in the Universe remains constant. This kind of balance between matter and antimatter is known as symmetry.

Pair Production

In some circumstances, virtual pairs can become real pairs of particles and antiparticles, which is known as pair production. Two gamma rays can convert their energy into pairs of particles and antiparticles.

To create a particle and an antiparticle having a total mass $M$, the incoming gamma-ray photons must possess an amount of energy $E$ that is greater than or equal to $Mc^2$. The gamma rays disappear upon colliding, and a particle and an antiparticle appear in its place.

These particles and antiparticles come from nature’s ample supply of virtual pairs. The gamma rays provide a virtual pair with so much energy that the virtual particles can appear as real particles.
Annihilation

The inverse process, in which a particle and antiparticle collide with each other and are converted into high-energy gamma rays, is known as annihilation.

\[ \text{particle} + \text{anti-particle} \leftrightarrow \gamma + \gamma \]

During the Inflationary Epoch

During the Inflationary Epoch, space was expanding with explosive vigor. All space was seething with virtual pairs of particles and antiparticles.

Normally, a particle and an antiparticle have no trouble getting back together in a time interval (Δt) short enough to be in compliance with the uncertainty principle.

During Inflation, however, the Universe expanded so fast that particles were rapidly separated from their corresponding antiparticles. These virtual particles became real particles. The Universe was flooded with particles and antiparticles.
Expansion Effects

Initially, collisions between particles and antiparticles produced numerous high-energy gamma rays. As these gamma rays collided, they turned back into the particles and antiparticles from which they came. So the rate of pair production was equal to the rate of annihilation:

\[ p^+ + p^- \leftrightarrow \gamma + \gamma \]

Expansion Effects

As the Universe continued to expand, all of the gamma-ray photons became increasingly redshifted, so the temperature of the radiation field went down.

The temperature (i.e., speed, energy) eventually became so low that the gamma rays no longer had enough energy to create particular kinds of particles and antiparticles.

Collisions of particles and antiparticles continued to add photons to the cosmic radiation background, but collisions of photons could no longer replenish the supply of particles and antiparticles.

\[ p^+ + p^- \rightarrow \gamma + \gamma \]
Protons and Neutrons

When the Universe was about 0.0001 seconds old, the temperature of the radiation field fell below $10^{13}$ K. The Universe was now cooler than the threshold temperatures of both protons and neutrons.

No new protons or neutrons appeared, but the annihilation of protons with antiprotons and of neutrons with antineutrons continued throughout space.

This wholesale annihilation dramatically lowered the matter content of the Universe, while simultaneously increasing the radiation content.

Electrons

A little later, when the Universe was about 1 second old, its temperature fell below $6 \times 10^9$ K, the threshold temperature for electrons and positrons.

A similar annihilation of pairs of electrons and positrons further decreased the matter content of the Universe while raising its radiation content.

This radiation field, which fills all space, is the primordial fireball that dominates the Universe for the next several hundred thousand years.
Neutrons and Neutrinos

The early Universe must have been populated with vast numbers of neutrinos and antineutrinos.

\[ n \rightarrow p + e^- + \nu \quad \text{and} \quad p + e^- \rightarrow n + \nu \]

This reaction kept the number of neutrons approximately equal to the number of protons. This balance was maintained only as long as electrons were abundant. By the time the Universe was about 2 seconds old, no neutrons were being formed.

Up until this time the neutrinos were contained by the high density, but now they decoupled from matter. They formed a neutrino background, which is estimated to have temperature around 2 K.

Neutrons

Free neutrons have a half-life of 10.5 minutes – if they do not combine with a proton during this time, they will be gone from the Universe. Before many could decay, they began to combine with protons to form deuterium. But remember from the Proton-Proton chain that the production of deuterium is the bottleneck in the chain of creating helium. Deuterium is easily destroyed by photons before the next step in the chain occurs.

\[
\begin{align*}
^1_1\text{H} + ^1_1\text{H} & \rightarrow ^2_1\text{H} + e^+ + \nu \\
^2_1\text{H} + ^1_1\text{H} & \rightarrow ^3_2\text{He} + \gamma \\
^3_2\text{He} + ^3_2\text{He} & \rightarrow ^4_2\text{He} + 2^1_1\text{H}
\end{align*}
\]
Helium

When the Universe was about 3 minutes 45 seconds old, the background radiation had cooled enough that its photons no longer had enough energy to break up the deuterium.

By this time, most of the neutrons had decayed into protons.

The remaining free neutrons combined with protons and rapidly made helium. The result is what we find today – about 1 helium for every 10 hydrogen.

Nucleosynthesis

When the young Universe was about 15 minutes old, it was now too cool for further nucleosynthesis. The elements created so far are hydrogen, helium, lithium, and beryllium. The heavier elements would only be formed much later by nuclear reactions in stars.
THE EARLY UNIVERSE

What Caused the Inflation?

Radius of observable universe (standard model)
Radius of observable universe (inflationary model)
Inflationary epoch

Distance (cm)

Time after Big Bang (s) → Present
Four Forces of Nature

Gravity
Electromagnetism
Strong Force
Weak Force

Quarks

Protons and Neutrons are composed of quarks. The most common varieties are the “up” (u) quarks and the “down” (d) quarks.

A Proton is composed of two up quarks and one down quark; a Neutron is made of one up quark and two down quarks.

The Strong force holds quarks together, while the Weak force is at work whenever a quark changes from one variety to another.

\[ d \rightarrow u + e^- + \nu \]
Three Forces Explained

**EM, Weak, and Strong Forces** are explained by Quantum Mechanics as interacting by the exchange of various types of virtual particles.

Physicists have not been able to develop a Quantum Mechanical description of Gravity. Einstein’s General Theory of Relativity is considered to be a Classical description.

Unified Weak and EM Forces

Current theories state that the Weak and EM forces should be identical to each other for particles with energies greater than 100 GeV. At these energies, electromagnetic interactions become indistinguishable from Weak interactions.

Above 100 GeV (T~10^{16} K), the EM and the Weak force are “unified” into a single **Electroweak Force**. (Symmetry is restored above 100 GeV – Spontaneous Symmetry Breaking occurs below 100 GeV.)
Grand Unified Theory

Above $10^{14}$ GeV ($T\sim10^{27}$ K), the Strong force is unified with the Electroweak, in what is known as the **Grand Unified Theory (GUT)**.

Above $10^{19}$ GeV ($T\sim10^{32}$ K), Gravity *may* be unified with the GUT, giving a **Supergrand Unified Theory** or a **Theory of Everything (TOE)**.

Early Expansion

Because Physicists do not yet have a TOE, we remain ignorant of what was going on during the first $10^{-43}$ second of the Universe’s existence. But by the end of the Planck time, the expansion and cooling of the Universe had caused the energy of particles to fall to $10^{19}$ GeV.

At $t = 10^{-43}$ sec there was a spontaneous symmetry breaking in which gravity was “frozen out”. The temperature was about $10^{32}$ K.

As the Universe expanded, its temperature decreased and the energy of particles decreased as well. At $t = 10^{-35}$ sec, the energy of particles had fallen to $10^{14}$ GeV and the temperature was $10^{27}$ K. At this time, the Strong force “froze out”.

Inflation Occurred

Physicists hypothesize that before the Strong force decoupled from the Electroweak force, the Universe was in an unstable state called a False Vacuum.

They hypothesize that the energy associated with a quantity called the inflaton field had a nonzero value.

At this time, the Universe went to a True Vacuum, which released this energy.
Vacuums

Initially, the universe (represented by the black dot) was in a high-energy "false vacuum" state. The universe began a "slow roll" toward the lower-energy true vacuum state, releasing energy that triggered a tremendous expansion of the universe. The universe "rolled" back and forth around the true vacuum state, eventually settling down in the state of minimum energy.

Inflation’s Effect

When the Inflationary Epoch had ended, about $10^{-32}$ sec after the Big Bang, the Universe had increased in scale by a factor of roughly $10^{50}$.

Example: $10^{-12}$ m $\rightarrow$ $10^{38}$ m

$= 10^{35}$ km $= 10^{27}$ AU $= 10^{21}$ pc $= 10^{15}$ Mpc

$= 3$ thousand billion billion lightyears ($3 \times 10^{21}$)
More Events

At $t = 10^{-12}$ s, the temperature was $10^{15}$ K and the energy of particles had fallen to 100 GeV, and there was a final spontaneous symmetry breaking and “freeze-out” that separated the EM force from the Weak force.

At $t = 10^{-6}$ s, quarks were able to form, and subsequently other particles (protons, neutrons, electrons) came into existence.

At $t = 10^{-4}$ s, production of protons and neutrons ceased.

At $t = 1$ s, production of electrons ceased.

Today’s Universe

How did the Universe go from an initial, extremely smooth state to a very lumpy one of today?
Density Fluctuations

The Universe is not uniform – somehow at some point in its history, density fluctuations occurred. From these density enhancements formed stars, galaxies, and clusters of galaxies.

But what sized objects formed first?

Complex Structure

Did large scale, “Top-Down” structures form first? Or did small scale, “Bottom-Up” formation occur quicker?

Top-down theories assume that large structures formed first and then fragmented to form galaxies. Bottom-up theories hypothesize that small structures formed first and then merged to build larger ones.

Both theories assume that the Universe was not initially absolutely smooth. As the Universe expanded, the higher density regions accumulated mass because they exerted a slightly larger than average gravitational force on the surrounding material.
Dark Matter

One issue that complicates the development of large-scale structure is the mass associated with dark matter, which could be 90% of the total.

**Hot dark matter**  Light-weight particles moving quickly (e.g., neutrinos).

**Cold dark matter**  Massive particles moving slowly (e.g., WIMPS).

Calculations indicate most, but not all, of the dark matter must be cold. This contributes to and bolsters the case for the Bottom-Up scenario of large-scale structure development.

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Current Cosmological Model

The current model assumes a flat Universe with a cosmological constant.

\[
\Omega_m = 0.27, \quad \Omega_\Lambda = 0.73, \quad \Omega_0 = \Omega_m + \Omega_\Lambda = 1.00
\]

In this model, the cosmological constant has made the expansion speed up over time, so that the expansion was slower in the distant past.

Show Video
# Timeline of the Early Universe

<table>
<thead>
<tr>
<th>Time</th>
<th>Event Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$10^{-43}$ sec</td>
<td>End of Planck Time – Gravity freezes out</td>
</tr>
<tr>
<td>$10^{-35}$ sec</td>
<td>Strong Force freezes out – Inflation occurs</td>
</tr>
<tr>
<td>$10^{-12}$ sec</td>
<td>Weak and EM Forces freeze out</td>
</tr>
<tr>
<td>$10^{-6}$ sec</td>
<td>Confinement of quarks</td>
</tr>
<tr>
<td>$10^{-4}$ sec</td>
<td>Production of protons and neutrons ends</td>
</tr>
<tr>
<td>1 sec</td>
<td>Production of electrons ends</td>
</tr>
<tr>
<td>2 sec</td>
<td>Universe becomes transparent to neutrinos</td>
</tr>
<tr>
<td></td>
<td>Free neutrons begin to decay: [ n \rightarrow p + e^- + \nu ]</td>
</tr>
<tr>
<td>3m45s</td>
<td>Deuterium is formed and then Helium is formed</td>
</tr>
<tr>
<td>15 min</td>
<td>Creation of Helium ceases</td>
</tr>
<tr>
<td>2500 yr</td>
<td>Universe goes from Radiation to Matter Dominated</td>
</tr>
<tr>
<td>300,000 yr</td>
<td>Atomic hydrogen is formed</td>
</tr>
<tr>
<td></td>
<td>Universe becomes transparent to photons</td>
</tr>
<tr>
<td></td>
<td>(creation of Cosmic Background Radiation)</td>
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Time Line Diagram