The Expansion of Space and Time

A Visual Simulation Report

---

1. Introduction

The universe has been expanding ever since the Big Bang occurred approximately 13.8 billion years ago. This expansion is not the motion of galaxies through space, but rather the expansion of space itself. To understand this phenomenon, cosmologists use a mathematical function called the **scale factor**, denoted as a(t), which tells us how distances in the universe change over time.

This report discusses a simulation and the resulting graph that shows the behavior of the scale factor a(t) over cosmic time, from shortly after the Big Bang to the present day and potentially beyond. The goal is to illustrate how the universe grew in size and how this growth rate changed during different epochs of cosmic history.

---

2. The Scale Factor a(t)

In cosmology, the **scale factor** a(t) is a dimensionless quantity that describes how the distances between non-gravitationally bound objects in the universe change with time. It's normalized such that a(tnow)=1, where tnow is the current age of the universe.

- When a(t)=0, the universe is at a singularity — the **Big Bang**.
- As a(t) increases, the universe expands.
- The **slope** of a(t) tells us the expansion rate: steep early on (rapid inflation), slower during matter domination, and accelerating again in the dark-energy-dominated era.

In the simulation, the scale factor was modeled with the approximate formula:

$a(t) \propto t^{2/3}$

which corresponds to a **matter-dominated universe**. This model is accurate from about 50,000 years after the Big Bang until a few billion years ago.

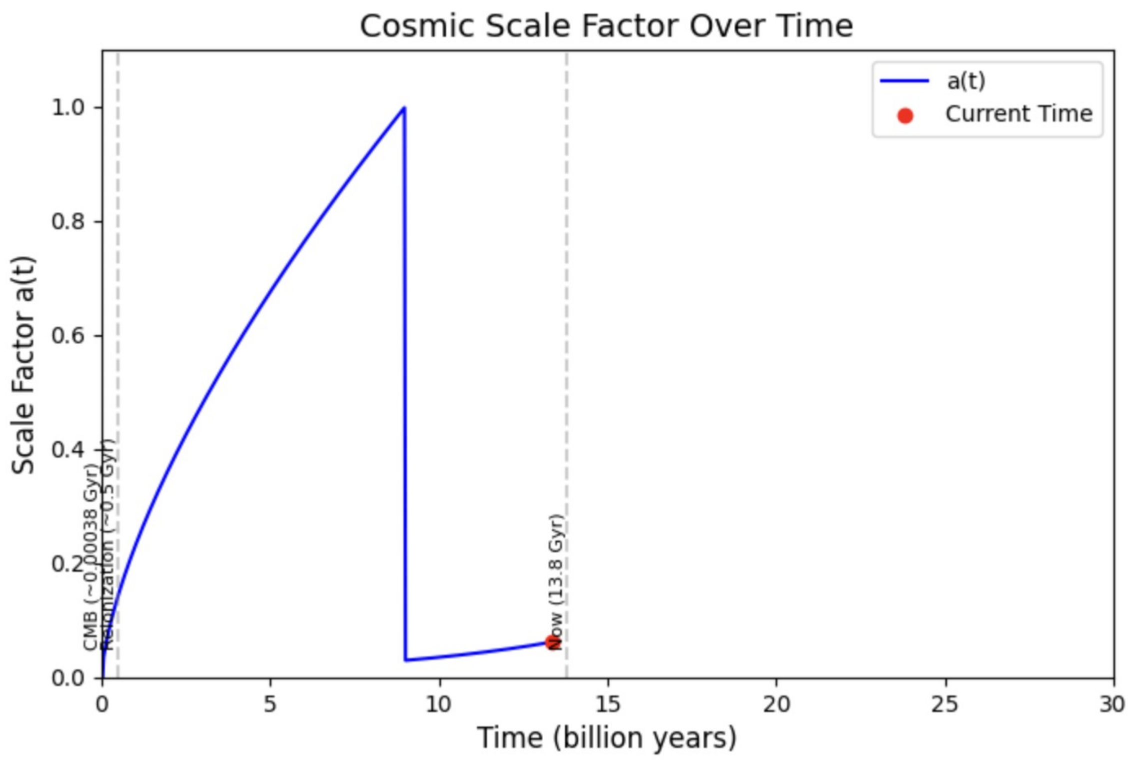
---

3. The Simulation

The graph produced shows:

- The **x-axis**: Time in billions of years since the Big Bang.
- The **y-axis**: The scale factor a(t), normalized to 1 at the present time (13.8 billion years).
- A **red dot** marking the "current time".
- Annotations for important cosmic milestones such as:

- **Recombination (~0.38 million years)**: When atoms formed and the universe became transparent.
- **Reionization (~0.5 Gyr)**: When early stars ionized the hydrogen again.
- **Present Day (~13.8 Gyr)**.



---

4. Interpretation of the Graph

- **Early Universe (0 – 1 Gyr)**: The curve is very steep. This reflects **rapid expansion** during the early matter-dominated period, following an even more rapid phase of inflation.
- **Mid-Universe (~1 – 9 Gyr)**: The slope gradually reduces, indicating a slowing expansion rate.
- **Late Universe (9 – 13.8 Gyr)**: The curve begins to steepen again — this is due to **dark energy** becoming the dominant force driving expansion. The expansion is now **accelerating**.

5. Limitations and Extensions

The simulation used a simplified model (matter-dominated universe) and ignored transitions between radiation, matter, and dark energy domination. More accurate modeling would involve solving the Friedmann equations with proper contributions from:

- Radiation
- Matter

- Dark energy (cosmological constant Λ)

Future enhancements could:

- Use Planck satellite parameters for better cosmological accuracy
- Animate the expansion dynamically
- Show comoving vs proper distances

---

6. Conclusion

The expansion of space is a cornerstone of modern cosmology. The simulation and its graph help us visualize how the universe has evolved over time — from the extreme density of the early universe to the accelerating expansion we observe today. While simplified, this model provides key insight into how time and space stretch, offering a powerful tool to understand our cosmic history.