INFLATIONARY COSMOLOGY: IS OUR UNIVERSE PART OF A MULTIVERSE?

--- Alan Guth ---

Massachusetts Institute of Technology

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The Conventional Big Bang Theory

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What it describes: How the early universe expanded and cooled, how the light chemical elements formed, and how the matter congealed to form stars, galaxies, and clusters of galaxies.
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★★ What caused the expansion? (The conventional theory describes only the **aftermath** of the bang. It says nothing about what banged, why it banged, or what happened before it banged.)

★★ Where did the matter come from? (The theory assumes that **all matter** existed from the very beginning.)
What is Inflation?

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Gravitational Repulsion.
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(a) was never taught to me when I was a student; and

(b) is so far-reaching in its consequences that it can change our picture of the universe.
**Miracle of Physics # 1: Gravitational Repulsion**

⭐ Since the advent of general relativity, physicists have known that gravity can act repulsively.

⭐ In GR, pressures can create gravitational fields, and negative pressures create repulsive gravitational fields.

⭐ Einstein used this possibility, in the form of the “cosmological constant,” to build a static mathematical model of the universe, with repulsive gravity preventing its collapse.

⭐ Modern particle physics suggests that at superhigh energies there should be many states with negative pressures, creating repulsive gravity.
Sequence of Events

Inflation proposes that a patch of repulsive gravity material existed in the early universe — for inflation at the grand unified theory scale, the patch needs to be only as large as $10^{-28}$ cm. (Since any such patch is enlarged fantastically by inflation, the initial density or probability of such patches can be very low.)

The gravitational repulsion was the driving force behind the big bang. The patch was driven into exponential expansion, with a doubling time of maybe $\sim 10^{-38}$ second.

The patch expanded exponentially by a factor of at least $10^{28}$ (100 doubling times), but it could have expanded much more. At the end, the region destined to become the presently observed universe was about the size of a marble.
The repulsive-gravity material is unstable, so it decayed like a radioactive substance, ending inflation. The decay released energy which produced ordinary particles, forming a hot, dense “primordial soup.” The universe continued to coast and cool from then onward.

Key feature: During the exponential expansion, the density of matter and energy did NOT thin out.

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★ The negative energy of gravity cancelled the positive energy of matter, so the total energy was constant and possibly zero.
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★ The total energy of the universe today is consistent with zero. Schematically,

\[
\text{Total Energy} = \text{Matter \\
& Radiation} + \text{Gravity} = 0.
\]
Evidence for Inflation

1) Large scale uniformity. The cosmic background radiation is uniform in temperature to one part in 100,000. It was released when the universe was about 380,000 years old. In standard cosmology without inflation, a mechanism to establish this uniformity would need to transmit energy and information at about 100 times the speed of light.
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**Inflationary Solution:** In inflationary models, the universe begins so small that uniformity is easily established — just like the air in the lecture hall spreading to fill it uniformly. Then inflation stretches the region to be large enough to include the visible universe.
2) “Flatness problem:”

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★ If we assume that the universe is homogeneous (same in all places) and isotropic (same in all directions), then there are only three possible geometries: closed, open, or flat.

★ According to general relativity, the flatness of the universe is related to its mass density:

\[ \Omega(\text{Omega}) = \frac{\text{actual mass density}}{\text{critical mass density}}, \]

where the "critical density" depends on the expansion rate. \( \Omega = 1 \) is flat, \( \Omega > 1 \) is closed, \( \Omega < 1 \) is open.
A universe at the critical density is like a pencil balancing on its tip:

If $\Omega$ in the early universe was slightly below 1, it would rapidly fall to zero — and no galaxies would form.

If $\Omega$ was slightly greater than 1, it would rapidly rise to infinity, the universe would recollapse, and no galaxies would form.
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To be as close to critical density as we measure today, at one second after the big bang, $\Omega$ must have been equal to one to 15 decimal places!
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**New ingredient:** Dark Energy. In 1998 it was discovered that the expansion of the universe has been accelerating for about the last 5 billion years. The “Dark Energy” is the energy causing this to happen.
3) **Small scale nonuniformity:** Can be measured in the cosmic background radiation. The intensity is almost uniform across the sky, but there are small ripples. Although these ripples are only at the level of 1 part in 100,000, these nonuniformities are now detectable! Where do they come from?
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**Inflationary Solution:** Inflation attributes these ripples to *quantum fluctuations*. Inflation makes generic predictions for the spectrum of these ripples (i.e., how the intensity varies with wavelength). The data measured so far agree beautifully with inflation.
Ripples in the Cosmic Microwave Background
Spectrum of CMB Ripples

Planck Collaboration, 2013
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Roughly speaking, inflation is driven by a metastable state, which decays with some half-life.

After one half-life, half of the inflating material has become normal, noninflating matter, but the half that remains has continued to expand exponentially. It is vastly larger than it was at the beginning.

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We would be living in one of the infinity of pocket universes.
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It is larger by 120 orders of magnitude!
The Multiverse and the Cosmological Constant Problem

One of the thorniest problems in particle theory is to understand why the energy density of the vacuum (equivalent to the cosmological constant) is 120 orders of magnitude smaller than the (expected) Planck scale.

The multiverse offers a possible (although controversial) solution.

If there are $10^{500}$ different types of vacuum (as in string theory), there will be many with energy densities in the range we observe.

The vacuum energy affects cosmic evolution: if it is too large and positive, the universe flies apart too fast for galaxies to form. If too large and negative, the universe implodes.

It is therefore plausible that life only forms in those pocket universes with incredibly small vacuum energies, so all living beings would observe a small vacuum energy. (Anthropic principle, or observational selection effect.)
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