The Big Bang Theory

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The Big Bang theory is the currently accepted theory of the origin of the universe. According to this theory, the observable universe was formed approximately 13.8 billion years ago when it exploded from an incredibly hot, dense point, known as a singularity. The universe has been expanding ever since and will continue to do so.

History of the Big Bang Theory [1]

Since ancient times, there has been much philosophical speculation regarding the origin of the universe. Aristotle believed that the universe was eternal, though medieval Jewish and Islamic philosophers believed that it had a beginning.

In 1848, Edgar Allen Poe wrote an essay entitled *Eureka: A Prose Poem*, in which he argued from metaphysical principles that the universe undergoes periodic expansions and contractions.

In the 1910s, Vesto Slipher and later Carl Wilhelm Writz determined that most spiral nebulae (spiral galaxies) were receding from Earth, but they failed to grasp the cosmological significance of this discovery.

The first theoretical evidence for the Big Bang came from Alexander Friedmann in 1922, when he showed that Albert Einstein's theory of general relativity predicted that the universe was either expanding or contracting. Einstein was so upset with this result that he introduced a cosmological constant into his theory which would make the universe static. Later he said that this was his biggest blunder.

In 1927, Georges Lemaitre proposed an expanding model of the universe in order to explain the observed redshifts of spiral nebulae, forecasting the Hubble law. He independently derived Friedmann's equations for an expanding universe.

In 1929, Edwin Hubble provided compelling observational evidence for an expanding universe. He found that galaxies were receding from Earth (and each other) at a rate proportional to their distance. This became known as the Hubble law.

In 1931, Lemaitre hypothesized that the universe was expanding from a primeval atom, thus laying down the groundwork for the Big Bang theory. Later George Gamow became a proponent for this theory.

During the 1940s, Fred Hoyle proposed a rival theory, known as the Steady State theory, by which the universe was expanding yet eternal. According to this theory, matter was constantly being created in the empty spaces left behind by the expansion. In 1949, Hoyle sarcastically coined the term "Big Bang" to describe the rival theory.

From around 1950 to 1965, support for each of these theories was roughly evenly divided, with slight favor given to the Big Bang theory, since it could roughly predict the observed cosmological abundences of hydrogen and helium, which the Steady State theory could not do. By the early 1960s, quasars and radio galaxies were discovered at large distances in support of the Big Bang theory.

The final blow to the Steady State theory came in 1965 with Penzias and Wilson's discovery of the cosmic microwave background radiation (CMB), a clear remnant of the Big Bang.

In 1979, Alan Guth and Alexei Starobinski independently proposed the idea of inflation, in which the universe underwent an exponential growth period early in its history. This solved many problems with the original Big Bang theory.

In 1986, Andrei Linde proposed the idea of eternal inflation.

In 1990, measurements from the COBE satellite showed that the CMB spectrum matches a 2.725 Kelvin blackbody spectrum to very high precision. Small anisotropies in this radiation (around 1 part in 100,000) were also discovered. These anisotropies are believed to eventually led to the formation of stars and galaxies.

In 1998, measurements of distant supernovae indicated that the expansion of the universe is accelerating.

From 2003 to 2010, the WMAP satellite took very detailed pictures of the universe, indicating that the universe was 13.7 ± 0.1 billion years old. (The currently accepted figure is 13.798 ± 0.037 billion years.) WMAP also accurately determined the composition of the universe, which is approximately 4% ordinary matter, 25% dark matter, and 70% dark energy.

Timeline of the Big Bang (Traditional View) [2]

Planck Epoch ($0 - 10^{-43}$ s)
During this epoch, our current understanding of physics breaks down, so we can only speculate what happened. The universe is believed to have been confined to a tiny hot dense point of size roughly equal to the Planck length, or approximately 10^{-35} m. All four forces are believed to have been unified during this epoch in a supersymmetric state. By the end of this epoch, symmetry breaking resulted in the separation of gravity from the electronuclear force, resulting in expansion.

Grand Unification Epoch (10^{-43} s - 10^{-36} s)
During this epoch, the universe began to expand and cool. The electronuclear forces remained unified during this epoch, which ended when the strong nuclear force separated from the electroweak force. This transition should have produced large amounts of magnetic monopoles, which are not observed. The theory of inflation, proposed by Alan Guth, explains the lack of magnetic monopoles, among other things.

Electroweak Epoch (10^{-36} s - 10^{-12} s)
During this epoch, the electroweak force remained unified. This epoch began with the inflationary epoch and ended when the weak force separated from the electromagnetic force. Baryogenesis, whereby the universe developed a small imbalance (about 1 part in a billion) of matter over antimatter, is also believed to have occurred during this epoch.

> **Inflationary Epoch (10^{-36} s - 10^{-32} s)**
> During this epoch, the inflaton field caused an exponential expansion of the universe, by a linear factor of at least 10^{26}. At the end of this epoch, the inflaton field decayed into ordinary particles (quarks, antiquarks, and gluons), in a process known as reheating.
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> **Note:** According to the eternal inflation model, inflation has always been going on, so perhaps the universe (more commonly known as the multiverse) didn't have a beginning. However, the *observable* universe did have a definite beginning in every model.

Quark Epoch (10^{-12} s - 10^{-6} s)
At the beginning of this epoch, the weak force separated from the electromagnetic force, resulting in the four forces known today. Via the Higgs mechanism, all elementary particles acquired mass due to their interaction with the Higgs field. During this epoch, the universe was still too hot for quarks to bind together into hadrons, i.e., protons and neutrons.

Hadron Epoch (10^{-6} s - 1 s)
At the beginning of this epoch, the universe cooled down enough for hadrons to form. By the end of this epoch, neutrinos decoupled from hadrons and began traveling freely through space. Also at the end of this epoch, the majority of hadrons and anti-hadrons annihilated each other, leaving behind leptons and anti-leptons to dominate the mass of the universe.

Lepton Epoch (1 s - 10 s)
This epoch is characterized by the domination of leptons and anti-leptons. By the end of this epoch, most leptons and anti-leptons annihilated each other, leaving behind a small residue of leptons as well as a large number of photons.

Photon Epoch (10 s - 380,000 yr)
During this epoch, the mass-energy of the universe was dominated by photons, which were still interacting frequently with protons, electrons, and (eventually) nuclei.

> **Nucleosynthesis (3 min - 20 min)**
> During this epoch, the universe cooled enough for atomic nuclei to form via nuclear fusion. Free neutrons combined to form deuterium, which then rapidly underwent fusion into helium-4. Nuclear fusion only lasted for 17 minutes, since by the end of this time, the universe had cooled sufficiently for it not to continue. By this time, all neutrons had been incorporated into helium nuclei, resulting in the observed 3:1 mass ratio of hydrogen over helium.
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> **Matter Domination (70,000 yr)**
> At this time, the mass/energy density of matter (atomic nuclei) and radiation (photons) were equal. Cold dark matter began to dominate, leading to growing inhomogeneities, eventually leading to the formation of large-scale structures, i.e., stars, galaxies, clusters, and superclusters.
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> **Recombination (380,000 yr)**
> At this time, the universe cooled enough for the first atoms (hydrogen and helium) to form. Once this happened, photons became free and the universe became transparent. The first free photons from this time are now observed as the CMB, which has now cooled to just 2.725K.

Reionization (150 million years - 1 billion years)
During this epoch, the first stars and quasars formed, due to gravitational collapse. Their intense radiation reionized the surrounding universe, which as a result, was mainly composed of plasma.

Star and Galaxy Formation (1 billion years - present)
The first large-scale structures (galaxies, clusters, and superclusters) formed from gravitational collapse, followed by the formation of stars within them.

Eternal Inflation and the Multiverse [3]

According to Alan Guth's original model of inflation, the universe inflated due to a "false vacuum" phase with positive vacuum energy. The false vacuum decayed into regions (bubbles) of "true vacuum" which expanded at the speed of light. A big problem with Guth's original theory was that no mechanism was known for inflation to end. This became known as the "graceful exit" problem.

The eternal inflation model is a modification of this model which solved the graceful exit problem. In this model, parts of the universe are always in this false vacuum phase, and thus inflate. Eternal inflation, also known as chaotic inflation, is the most widely currently accepted theory of inflation. According to the chaotic inflation model, there were quantum fluctuations in the inflaton field, resulting in variable rates of inflation. This leads to the idea of a multiverse, consisting of an unimaginably large (perhaps infinite) number of "baby universes", each experiencing their own big bang and perhaps their own values of physical constants and even their own laws of physics. Most of these baby universes are unstable and thus inhospitable for life, but a few of them, such as ours, are hospitable. This may offer an explanation of the anthropic principle and why our universe seems to be remarkably tuned toward the formation of life.

References:

[1] http://en.wikipedia.org/wiki/History_of_the_Big_Bang
[2] http://en.wikipedia.org/wiki/Timeline_of_the_Big_Bang
[3] http://en.wikipedia.org/wiki/Eternal_inflation