# Big Bang Nucleosynthesis

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# 1 Content

## 2 Introduction to Big Bang Theory

The Big Bang theory is the prevailing cosmological model for the universe from the earliest known periods through its subsequent large-scale evolution. The model describes how the universe expanded from a very high-density and high-temperature state, and offers a comprehensive explanation for a broad range of phenomena, including the abundance of light elements, the cosmic microwave background (CMB), large scale structure and Hubble's law. If the known laws of physics are extrapolated to the highest density regime, the result is a singularity which is typically associated with the Big Bang. Physicists are undecided whether this means the universe began from a singularity, or that current knowledge is insufficient to describe the universe at that time. Detailed measurements of the expansion rate of the universe place the Big Bang at around 13.8 billion years ago, which is thus considered the age of the universe. After the initial expansion, the universe cooled sufficiently to allow the formation of subatomic particles, and later simple atoms. Giant clouds of these primordial elements later coalesced through gravity in halos of dark matter, eventually forming the stars and galaxies visible today.

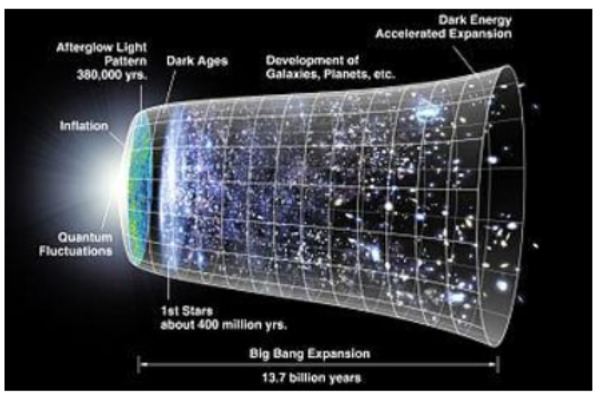



Figure 1: Timeline of the metric expansion of space

American astronomer Edwin Hubble observed that the distances to faraway galaxies were strongly correlated with their redshifts. This was interpreted to mean that all distant galaxies and clusters are receding away from our vantage point with an apparent velocity proportional to their distance: that is, the farther they are, the faster they move away from us, regardless of direction. Assuming the Copernican principle (that the Earth is not the centre of the universe), the only remaining interpretation is that all observable regions of the universe are receding from all others. Since we know that the distance between galaxies increases today, it must mean that in the past galaxies were closer together. The continuous expansion of the universe implies that the universe was denser and hotter in the past. The Big Bang theory offers a comprehensive explanation for a broad range of observed phenomena, including the abundance of light elements, the CMB, large scale structure, and Hubble's Law. The framework for the Big Bang model relies on Albert Einstein's theory of general relativity and on simplifying assumptions such as homogeneity and isotropy of space. The governing equations were formulated by Alexander Friedman, and similar solutions were worked on by Willem de Sitter. Since then, astrophysicists have incorporated observational and theoretical additions into the Big Bang model, and its parametrization as the Lambda-CDM model serves as the framework for current investigations of theoretical cosmology. The Lambda-CDM model is the current "standard model" of Big Bang cosmology, consensus is that it is the simplest model that can account for the various measurements and observations relevant to cosmology.

# 3 Nucleosynthesis

## 3.1 Defination

Nucleosynthesis is the process that creates new atomic nuclei from pre-existing nucleons, primarily protons and neutrons. The first nuclei were formed about three minutes after the Big Bang, through the process called Big Bang nucleosynthesis. It was then that hydrogen, helium and lithium formed to become the content of the first stars, and this primeval process is responsible for the present hydrogen/helium ratio of the cosmos.

## 3.2 History of nucleosynthesis theory

The first ideas on nucleosynthesis were simply that the chemical elements were created at the beginning of the universe, but no rational physical scenario for this could be identified. Gradually it became clear that hydrogen and helium are much more abundant than any of the other elements. All the rest constitute less than 2nuclei.

Arthur Stanley Eddington first suggested in 1920, that stars obtain their energy by fusing hydrogen into helium and raised the possibility that the heavier elements may also form in stars. This idea was not generally accepted, as the nuclear mechanism was not understood. In the years immediately before World War II, Hans Bethe first elucidated those nuclear mechanisms by which hydrogen is fused into helium.

The goal of the theory of nucleosynthesis is to explain the vastly differing abundances of the chemical elements and their several isotopes from the perspective of natural processes. The primary stimulus to the development of this theory was the shape of a plot of the abundances versus the atomic number of the elements. Those abundances, when plotted on a graph as a function of atomic number, have a jagged saw tooth structure that varies by factors up to ten million. A very influential stimulus to nucleosynthesis research was an abundance table created by Hans Sues and Harold Urey that was based on the unfractionated abundances of the non-volatile elements found within unevolved meteorites. Such a graph of the abundances is displayed on a logarithmic scale below, where the dramatically jagged structure is visually suppressed by the many powers of ten spanned in the vertical scale of graph.

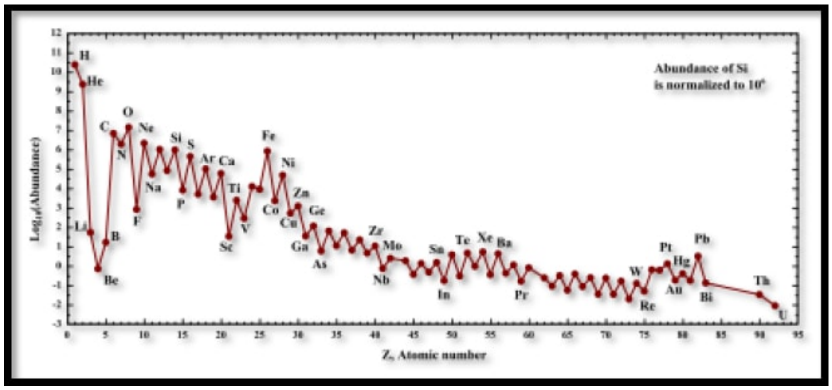



Figure 2: Abundance table created by Hans Sues and Harold Urey

# 4 Einstein theory of Big Bang

We all know about Einstein and about his amazing theories. The special theory of relativity came about when he was thinking in the patent office and thinking what would happen if we could move at the speed of light. Do we see standing waves? After his ground-breaking work on the special theory of relativity he set out to for the journey on the discovery of general theory of relativity.Most of us know that he realized that gravity and acceleration are the same things when he thought that people couldn't differentiate whether they are on the earth or on a satellite accelerating at g. But how did he realize about curvature of space due to acceleration is an interesting story not known by many. We know that the length of an object reduces along the direction of its travel and stays the same perpendicular to it. Einstein considered about this effect on a rotating disc. We know that the circumference of the disc will decrease as it is along the direction of motion but its radius remains constant which is a contradiction and this Einstein resolved by assuming that space bends due to acceleration. Now how is this related to big bang. Einstein assumed the universe to be stable but his equations predicted that this is impossible and the universe should either expand or contract. So, he added a constant to his equation to stabilize our universe Some people say that he committed this is one of the two major mistakes he committed in his life, the other being his unacceptance of the quantum theory. Hubble's observation that the universe is expanding proved that the universe is expanding and led to the idea that initially everything could have been at one place. But years later when dark matter were discovered people realized that the Einstein constant that had no explanation accidently had a physical implementation as dark matter. In a recently discovered work of his it was realized that Einstein had already predicted that if the universe was expanding then new matter must be created which is dark matter

# 5 Hubble's Law

When most people believed in an essentially static and unchanging universe, the question of whether or not it had a beginning was really one of metaphysics or theology. One could account for what was observed equally well on the theory that the universe had existed forever or on the theory that it was set in motion at some finite time in such a manner as to look as though it had existed forever. But in 1929, Edwin Hubble made the landmark observation that wherever you look, distant galaxies are moving rapidly away from us. In other words, the universe is expanding. Hubble's law is considered the first observational basis for the expansion of the universe and today serves as one of the pieces of evidence most often cited in support of the Big Bang model. The law is often expressed by the equation v = H0D, with H0 the constant of proportionality - Hubble constant - between the "proper distance" D to a galaxy, which can change over time, unlike the comoving distance, and its velocity v, i.e. the derivative of proper distance with respect to cosmological time coordinate. In the 1920s, when astronomers began to look at the spectra of stars in other galaxies, they found something most peculiar: there were the same characteristic sets of missing colors as for stars in our own galaxy, but they were all shifted by the same relative amount toward the red end of the spectrum(as a consequence of the Doppler effect of light) which means that nearly all of them are moving away from us. More surprising still was the finding that Hubble published in 1929: even the size of a galaxy's redshift is not random, but is directly proportional to the galaxy's distance from us. Or, in other words, the farther a galaxy is, the faster it is moving away! And that meant that the universe could not be static, as everyone previously had thought, it is in fact expanding. The current expansion of the universe means that at earlier times objects would have been closer together. In fact, it seemed that there was a time, about ten or twenty thousand million years ago, when they were all at exactly the same place and when, therefore, the density of the universe was infinite and the universe may have started with an explosion which is popularly known as the Big Bang.

# 6 Observations in support of Big Bang Nucleosynthesis (BBN)

## 6.1 Observation 1

Abundance of Helium in terms of mass fraction (Yp )= 0.2477. This observation was made by M. Peimbert, V. Luridiana, A. Peimbert on the basis of new atomic physics computations of the recombination coefficients of He I and of the collisional excitation of the H I Balmer lines together with observations and photoionization models of metal-poor extragalactic H II regions.

This observation is a very strong verification of Big Bang Nucleosynthesis Theory. According to theory, during nucleosynthesis all the free neutrons are swept up and bound into nuclei. Once bound in this way, the strong interaction between the protons and neutrons stabilizes the neutrons preventing them from decaying. By the time that nucleosynthesis starts, the decay of free neutrons has shifted the p/n ratio to 87/13. Out of every 200 particles 26 neutrons will combine with 26 protons to form 13 helium nuclei. This leaves 148 protons, so the mass ratio of the nuclei produced is: (13*4)/(13*4+200-26*2)=26More refined calculations show that the exact proportions of the elements produced depend on the density of protons and neutrons and the expansion rate of the universe during the period of nucleosynthesis (both influence the rate at which particles can interact with each other). Helium comes out in the region of 24–25

### 6.2 Observation 2

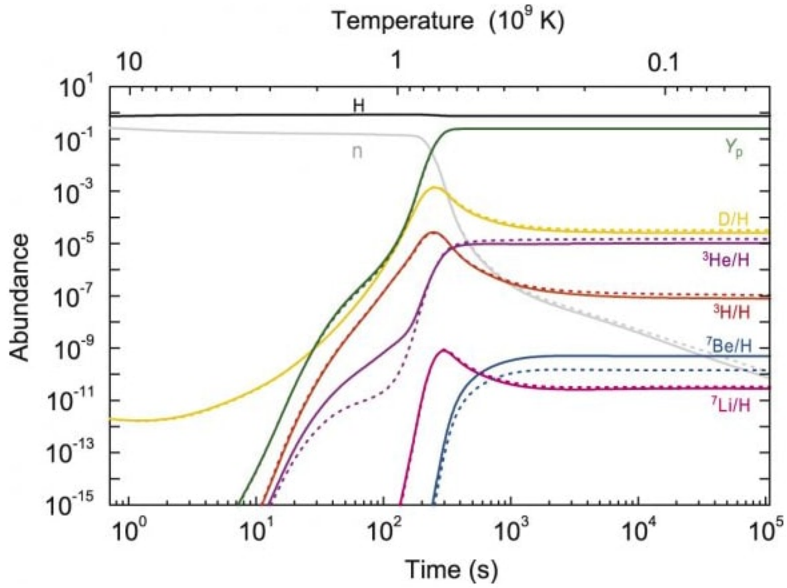
Abundance of Deuterium was determined by John M. O'Meara, David Tytler, David Kirkman, Nao Suzuki, Jason X. Prochaska, Dan Lubin Arthur M. Wolfe by analyzing SNR spectra of HS 0105+1619 in both low and high resolution. The low resolution spectra were obtained using the Kast double spectrograph on the Shane 3 meter telescope at Lick observatory. The high resolution spectra were obtained using the HIRES spectrograph on the Keck-I telescope. They found that the D/H ratio is log(D/H) = 4.48. Using this value baryon density was calculated and it was found that b*h*h = 0.0213.

Baryon density can be calculated using BBN and helium density mass fraction (which itself is obtained from BBN) and it was found that b* h*h = 0.02122. Thus we can see that this observation is in accordance with the theory.

## 7 Observations which can't be explained by Big Bang Nucleosynthesis

Martin Asplund, David L. Lambert, Poul Erik Nissen,Francesca Primas, Verne V. Smith studied stars from the uvby- catalogue of Schuster Nissen and from the Li abundance survey of very metal-poor stars by Ryan et al. They found two observations which are incompatible with Big Bang Nucleosynthesis. WMAP-based analysis of the cosmic microwave background implies b*h*h = 0.0224 ,which in standard Big Bang nucleosynthesis corresponds to an abundance of log (o7Li ) = 2.65 . This predicted abundance of 7 Li is about a factor of three larger than the measured abundance of lithium on the Spite plateau (The Spite plateau is a baseline in the abundance of lithium found in old stars orbiting the galactic halo.). Thus, the open question is – "How does one account for the factor of 3 between observation and prediction?" Their results suggest that there may be a 6Li plateau parallel to the Spite plateau for 7Li with the implication that the major fraction of the 6Li may have been synthesised prior to the onset of star formation in the Galaxy. The 6Li abundance of the plateau exceeds by a large factor the 6Li expected from a standard Big Bang. Thus, the open question is – "How does one account for the high abundance of 6Li in some metal-poor stars?"

## 7.1 Modifications done in BBN theory to account for above problem




One assumption in Big Bang nucleosynthesis is that all of the nuclei are in thermodynamic equilibrium, and that their velocities conform to classical Maxwell-Boltzmann distribution. But the Maxwell-Boltzmann describes what happens in what is called an ideal gas. Suqing Hou and Jianjun He propose that nuclei in the plasma of the early photon period of the universe behaved slightly differently than thought (in the same way as real gases are different from ideal gases). They applied non-extensive statistics and got the value shown by dotted line. New values confirm to observation.