Big Bang

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 accounts for the fact that 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 , large scale structure and Hubble 's Law . If the known laws of physics are extrapolated beyond where they have been verified , there is a singularity . Some estimates place this moment at approximately 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 to form stars and galaxies .

Since Georges Lemaître first noted , in 1927 , that an expanding universe might be traced back in time to an originating single point , scientists have built on his idea of cosmic expansion . While the scientific community was once divided between supporters of two different expanding universe theories , the Big Bang and the Steady State theory , accumulated empirical evidence provides strong support for the former . In 1929 , from analysis of galactic redshifts , Edwin Hubble concluded that galaxies are drifting apart ; this is important observational evidence consistent with the hypothesis of an expanding universe . In 1965 the cosmic microwave background radiation was discovered , which was crucial evidence in favor of the Big Bang model , since that theory predicted the existence of background radiation throughout the universe before it was discovered . More recently , measurements of the redshifts of supernovae indicate that the expansion of the universe is accelerating , an observation attributed to dark energy 's existence . The known physical laws of nature can be used to calculate the characteristics of the universe in detail back in time to an initial state of extreme density and temperature .

Overview

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 center 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 .

Large particle accelerators can replicate the conditions that prevailed after the early moments of the universe , resulting in confirmation and refinement of the details of the Big Bang model . However , these accelerators can only probe so far into high energy regimes . Consequently , the state of the universe in the earliest instants of the Big Bang expansion is still poorly understood and an area of open investigation and speculation .

The first subatomic particles to be formed included protons , neutrons , and electrons . Though simple atomic nuclei formed within the first three minutes after the Big Bang , thousands of years passed before the first electrically neutral atoms formed . The majority of atoms produced by the Big Bang were hydrogen , along with helium and traces of lithium . Giant clouds of these primordial elements later coalesced through gravity to form stars and galaxies , and the heavier elements were synthesized either within stars or during supernovae .

The Big Bang theory offers a comprehensive explanation for a broad range of observed phenomena , including the abundance of light elements , the cosmic microwave background , 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 Friedmann , 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 standard model of Big Bang cosmology , the simplest model that provides a reasonably good account of various observations about the universe .

= = Timeline = =

= = = Singularity = = =

Extrapolation of the expansion of the universe backwards in time using general relativity yields an infinite density and temperature at a finite time in the past . This singularity signals the breakdown of general relativity and thus , all the laws of physics . How closely this can be extrapolated toward the singularity is debated ? certainly no closer than the end of the Planck epoch . This singularity is sometimes called " the Big Bang " , but the term can also refer to the early hot , dense phase itself , which can be considered the " birth " of our universe . Based on measurements of the expansion using Type Ia supernovae and measurements of temperature fluctuations in the cosmic microwave background , the universe has an estimated age of 13 @.@ 799 ± 0 @.@ 021 billion years . The agreement of these three independent measurements strongly supports the ?CDM model that describes in detail the contents of the universe .

= = = Inflation and baryogenesis = = =

The earliest phases of the Big Bang are subject to much speculation . In the most common models the universe was filled homogeneously and isotropically with a very high energy density and huge temperatures and pressures and was very rapidly expanding and cooling . Approximately 10 ? 37 seconds into the expansion , a phase transition caused a cosmic inflation , during which the universe grew exponentially . After inflation stopped , the universe consisted of a quark ? gluon plasma , as well as all other elementary particles . Temperatures were so high that the random motions of particles were at relativistic speeds , and particle ? antiparticle pairs of all kinds were being continuously created and destroyed in collisions . At some point an unknown reaction called baryogenesis violated the conservation of baryon number , leading to a very small excess of quarks and leptons over antiquarks and antileptons ? of the order of one part in 30 million . This resulted in the predominance of matter over antimatter in the present universe .

= = = Cooling = = =

The universe continued to decrease in density and fall in temperature , hence the typical energy of each particle was decreasing . Symmetry breaking phase transitions put the fundamental forces of physics and the parameters of elementary particles into their present form . After about 10 ? 11 seconds , the picture becomes less speculative , since particle energies drop to values that can be attained in particle physics experiments . At about 10 ? 6 seconds , quarks and gluons combined to form baryons such as protons and neutrons . The small excess of quarks over antiquarks led to a small excess of baryons over antibaryons . The temperature was now no longer high enough to create new proton ? antiproton pairs (similarly for neutrons ? antineutrons) , so a mass annihilation immediately followed , leaving just one in 1010 of the original protons and neutrons , and none of their antiparticles . A similar process happened at about 1 second for electrons and positrons . After these annihilations , the remaining protons , neutrons and electrons were no longer moving relativistically and the energy density of the universe was dominated by photons (with a minor contribution from neutrinos) .

A few minutes into the expansion , when the temperature was about a billion (one thousand million ; 109 ; SI prefix giga-) kelvin and the density was about that of air , neutrons combined with protons to form the universe 's deuterium and helium nuclei in a process called Big Bang nucleosynthesis . Most protons remained uncombined as hydrogen nuclei . As the universe cooled , the rest mass energy density of matter came to gravitationally dominate that of the photon radiation . After about 379 @,@ 000 years the electrons and nuclei combined into atoms (mostly hydrogen) ; hence the radiation decoupled from matter and continued through space largely unimpeded . This relic radiation is known as the cosmic microwave background radiation . The chemistry of life may have begun shortly after the Big Bang , 13 @.@ 8 billion years ago , during a habitable epoch when the universe was only 10 ? 17 million years old .

= = = Structure formation = = =

Over a long period of time , the slightly denser regions of the nearly uniformly distributed matter gravitationally attracted nearby matter and thus grew even denser , forming gas clouds , stars , galaxies , and the other astronomical structures observable today . The details of this process depend on the amount and type of matter in the universe . The four possible types of matter are known as cold dark matter , warm dark matter , hot dark matter , and baryonic matter . The best measurements available (from WMAP) show that the data is well @-@ fit by a Lambda @-@ CDM model in which dark matter is assumed to be cold (warm dark matter is ruled out by early reionization) , and is estimated to make up about 23 % of the matter / energy of the universe , while baryonic matter makes up about 4 @.@ 6 % . In an " extended model " which includes hot dark matter in the form of neutrinos , then if the " physical baryon density " ?bh2 is estimated at about 0 @.@ 023 (this is different from the ' baryon density ' ?b expressed as a fraction of the total matter / energy density , which as noted above is about 0 @.@ 046) , and the corresponding cold dark matter density ?ch2 is about 0 @.@ 11 , the corresponding neutrino density ?vh2 is estimated to be less than 0 @.@ 0062 .

= = = Cosmic acceleration = = =

Independent lines of evidence from Type Ia supernovae and the CMB imply that the universe today is dominated by a mysterious form of energy known as dark energy , which apparently permeates all of space . The observations suggest 73 % of the total energy density of today 's universe is in this form . When the universe was very young , it was likely infused with dark energy , but with less space and everything closer together , gravity predominated , and it was slowly braking the expansion . But eventually , after numerous billion years of expansion , the growing abundance of dark energy caused the expansion of the universe to slowly begin to accelerate . Dark energy in its simplest formulation takes the form of the cosmological constant term in Einstein 's field equations of general relativity , but its composition and mechanism are unknown and , more generally , the details of its equation of state and relationship with the Standard Model of particle physics continue to be investigated both through observation and theoretically .

All of this cosmic evolution after the inflationary epoch can be rigorously described and modeled by the ?CDM model of cosmology , which uses the independent frameworks of quantum mechanics and Einstein 's General Relativity . There is no well @-@ supported model describing the action prior to 10 ? 15 seconds or so . Apparently a new unified theory of quantum gravitation is needed to break this barrier . Understanding this earliest of eras in the history of the universe is currently one of the greatest unsolved problems in physics .

= = Underlying assumptions = =

The Big Bang theory depends on two major assumptions : the universality of physical laws and the cosmological principle . The cosmological principle states that on large scales the universe is homogeneous and isotropic .

These ideas were initially taken as postulates , but today there are efforts to test each of them . For example , the first assumption has been tested by observations showing that largest possible deviation of the fine structure constant over much of the age of the universe is of order 10 ? 5 . Also , general relativity has passed stringent tests on the scale of the Solar System and binary stars .

If the large @-@ scale universe appears isotropic as viewed from Earth , the cosmological principle can be derived from the simpler Copernican principle , which states that there is no preferred (or special) observer or vantage point . To this end , the cosmological principle has been confirmed to a level of 10 ? 5 via observations of the CMB . The universe has been measured to be homogeneous on the largest scales at the 10 % level .

= = = Expansion of space = = =

General relativity describes spacetime by a metric , which determines the distances that separate nearby points . The points , which can be galaxies , stars , or other objects , themselves are specified using a coordinate chart or " grid " that is laid down over all spacetime . The cosmological principle implies that the metric should be homogeneous and isotropic on large scales , which uniquely singles out the Friedmann ? Lemaître ? Robertson ? Walker metric (FLRW metric) . This metric contains a scale factor , which describes how the size of the universe changes with time . This enables a convenient choice of a coordinate system to be made , called comoving coordinates . In this coordinate system the grid expands along with the universe , and objects that are moving only because of the expansion of the universe remain at fixed points on the grid . While their coordinate distance (comoving distance) remains constant , the physical distance between two such comoving points expands proportionally with the scale factor of the universe .

The Big Bang is not an explosion of matter moving outward to fill an empty universe . Instead , space itself expands with time everywhere and increases the physical distance between two comoving points . In other words , the Big Bang is not an explosion in space , but rather an expansion of space . Because the FLRW metric assumes a uniform distribution of mass and energy , it applies to our universe only on large scales ? local concentrations of matter such as our galaxy are gravitationally bound and as such do not experience the large @-@ scale expansion of space .

= = = Horizons = = =

An important feature of the Big Bang spacetime is the presence of horizons . Since the universe has a finite age , and light travels at a finite speed , there may be events in the past whose light has not had time to reach us . This places a limit or a past horizon on the most distant objects that can be observed . Conversely , because space is expanding , and more distant objects are receding ever more quickly , light emitted by us today may never " catch up " to very distant objects . This defines a future horizon , which limits the events in the future that we will be able to influence . The presence of either type of horizon depends on the details of the FLRW model that describes our universe . Our understanding of the universe back to very early times suggests that there is a past horizon , though in practice our view is also limited by the opacity of the universe at early times . So our view cannot extend further backward in time , though the horizon recedes in space . If the expansion of the universe continues to accelerate , there is a future horizon as well .

= = History = =

= = = Etymology = = =

English astronomer Fred Hoyle is credited with coining the term " Big Bang " during a 1949 BBC radio broadcast . It is popularly reported that Hoyle , who favored an alternative " steady state " cosmological model , intended this to be pejorative , but Hoyle explicitly denied this and said it was just a striking image meant to highlight the difference between the two models .

= = = Development = = =

The Big Bang theory developed from observations of the structure of the universe and from theoretical considerations . In 1912 Vesto Slipher measured the first Doppler shift of a " spiral nebula " (spiral nebula is the obsolete term for spiral galaxies) , and soon discovered that almost all such nebulae were receding from Earth . He did not grasp the cosmological implications of this fact , and indeed at the time it was highly controversial whether or not these nebulae were " island universes " outside our Milky Way . Ten years later , Alexander Friedmann , a Russian cosmologist and mathematician , derived the Friedmann equations from Albert Einstein 's equations of general relativity , showing that the universe might be expanding in contrast to the static universe model advocated by Einstein at that time . In 1924 Edwin Hubble 's measurement of the great distance to the nearest spiral nebulae showed that these systems were indeed other galaxies . Independently deriving Friedmann 's equations in 1927 , Georges Lemaître , a Belgian physicist and Roman Catholic priest , proposed that the inferred recession of the nebulae was due to the expansion of the universe .

In 1931 Lemaître went further and suggested that the evident expansion of the universe , if projected back in time , meant that the further in the past the smaller the universe was , until at some finite time in the past all the mass of the universe was concentrated into a single point , a " primeval atom " where and when the fabric of time and space came into existence .

Starting in 1924 , Hubble painstakingly developed a series of distance indicators , the forerunner of the cosmic distance ladder , using the 100 @-@ inch (2 @.@ 5 m) Hooker telescope at Mount Wilson Observatory . This allowed him to estimate distances to galaxies whose redshifts had already been measured , mostly by Slipher . In 1929 Hubble discovered a correlation between distance and recession velocity ? now known as Hubble 's law . Lemaître had already shown that this was expected , given the cosmological principle .

In the 1920s and 1930s almost every major cosmologist preferred an eternal steady state universe , and several complained that the beginning of time implied by the Big Bang imported religious concepts into physics ; this objection was later repeated by supporters of the steady state theory . This perception was enhanced by the fact that the originator of the Big Bang theory , Monsignor Georges Lemaître , was a Roman Catholic priest . Arthur Eddington agreed with Aristotle that the universe did not have a beginning in time , viz . , that matter is eternal . A beginning in time was " repugnant " to him . Lemaître , however , thought that

If the world has begun with a single quantum , the notions of space and time would altogether fail to have any meaning at the beginning ; they would only begin to have a sensible meaning when the original quantum had been divided into a sufficient number of quanta . If this suggestion is correct , the beginning of the world happened a little before the beginning of space and time .

During the 1930s other ideas were proposed as non @-@ standard cosmologies to explain Hubble 's observations , including the Milne model , the oscillatory universe (originally suggested by Friedmann , but advocated by Albert Einstein and Richard Tolman) and Fritz Zwicky 's tired light hypothesis .

After World War II , two distinct possibilities emerged . One was Fred Hoyle 's steady state model , whereby new matter would be created as the universe seemed to expand . In this model the universe is roughly the same at any point in time . The other was Lemaître 's Big Bang theory , advocated and developed by George Gamow , who introduced big bang nucleosynthesis (BBN) and whose associates , Ralph Alpher and Robert Herman , predicted the cosmic microwave background radiation (CMB) . Ironically , it was Hoyle who coined the phrase that came to be applied to Lemaître 's theory , referring to it as " this big bang idea " during a BBC Radio broadcast in March 1949 . For a while , support was split between these two theories . Eventually , the observational evidence , most notably from radio source counts , began to favor Big Bang over Steady State . The discovery and confirmation of the cosmic microwave background radiation in 1965 secured the Big Bang as the best theory of the origin and evolution of the universe . Much of the current work in cosmology includes understanding how galaxies form in the context of the Big Bang , understanding the physics of the universe at earlier and earlier times , and reconciling observations with the basic theory .

In 1968 and 1970 Roger Penrose , Stephen Hawking , and George F. R. Ellis published papers where they showed that mathematical singularities were an inevitable initial condition of general relativistic models of the Big Bang . Then , from the 1970s to the 1990s , cosmologists worked on characterizing the features of the Big Bang universe and resolving outstanding problems . In 1981 Alan Guth made a breakthrough in theoretical work on resolving certain outstanding theoretical problems in the Big Bang theory with the introduction of an epoch of rapid expansion in the early universe he called " inflation " . Meanwhile , during these decades , two questions in observational cosmology that generated much discussion and disagreement were over the precise values of the Hubble Constant and the matter @-@ density of the universe (before the discovery of dark energy , thought to be the key predictor for the eventual fate of the universe) . In the mid @-@ 1990s observations of certain globular clusters appeared to indicate that they were about 15 billion years old , which conflicted with most then @-@ current estimates of the age of the universe (and indeed with the age measured today) . This issue was later resolved when new computer simulations , which included the effects of mass loss due to stellar winds , indicated a much younger age for globular clusters . While there still remain some questions as to how accurately the ages of the clusters are measured , globular clusters are of interest to cosmology as some of the oldest objects in the universe .

Significant progress in Big Bang cosmology have been made since the late 1990s as a result of advances in telescope technology as well as the analysis of data from satellites such as COBE , the Hubble Space Telescope and WMAP . Cosmologists now have fairly precise and accurate measurements of many of the parameters of the Big Bang model , and have made the unexpected discovery that the expansion of the universe appears to be accelerating .

= = Observational evidence = =

The earliest and most direct observational evidence of the validity of the theory are the expansion of the universe according to Hubble 's law (as indicated by the redshifts of galaxies) , discovery and measurement of the cosmic microwave background and the relative abundances of light elements produced by Big Bang nucleosynthesis . More recent evidence includes observations of galaxy formation and evolution , and the distribution of large @-@ scale cosmic structures , These are sometimes called the " four pillars " of the Big Bang theory .

Precise modern models of the Big Bang appeal to various exotic physical phenomena that have not been observed in terrestrial laboratory experiments or incorporated into the Standard Model of particle physics . Of these features , dark matter is currently subjected to the most active laboratory investigations . Remaining issues include the cuspy halo problem and the dwarf galaxy problem of cold dark matter . Dark energy is also an area of intense interest for scientists , but it is not clear whether direct detection of dark energy will be possible . Inflation and baryogenesis remain more speculative features of current Big Bang models . Viable , quantitative explanations for such phenomena are still being sought . These are currently unsolved problems in physics .

= = = Hubble 's law and the expansion of space = = =

Observations of distant galaxies and quasars show that these objects are redshifted ? the light emitted from them has been shifted to longer wavelengths . This can be seen by taking a frequency spectrum of an object and matching the spectroscopic pattern of emission lines or absorption lines corresponding to atoms of the chemical elements interacting with the light . These redshifts are uniformly isotropic , distributed evenly among the observed objects in all directions . If the redshift is interpreted as a Doppler shift , the recessional velocity of the object can be calculated . For some galaxies , it is possible to estimate distances via the cosmic distance ladder . When the recessional velocities are plotted against these distances , a linear relationship known as Hubble 's law is observed :