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Big bang theory

Article by:

Pasachoff, Jay M. Hopkins Observatory, Williams College, Williamstown, Massachusetts.

Last updated: 2014

DOI: https://doi.org/10.1036/1097-8542.080900 (https://doi.org/10.1036/1097-8542.080900)

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Key Concepts

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- Scientists theorize that the original universe was extremely hot and dense, and has since been expanding.
- Three observations support the big bang theory: (1) the universe is expanding uniformly, (2) Earth is bathed in cosmic background radiation, and (3) the expansion of the universe is accelerating.
- As the early universe cooled, temperatures became sufficiently low for elements to begin to form.
- Einstein's theory of general relativity is an important component of the big bang theory.

The theory that the universe began in a state of extremely high density and has been expanding since some particular instant that marked the origin of the universe. The big bang is the generally accepted cosmological theory; the incorporation of developments in elementary particle theory has led to the inflationary universe version. The predictions of the inflationary universe and older big bang theories are the same after the first 10^{-35} s. *See also:* **Inflationary universe cosmology (/content/inflationary-universe-cosmology/343650)**

Two observations are at the base of observational big bang cosmology. First, the universe is expanding uniformly, with objects at greater distances receding at a greater velocity. Second, the Earth is bathed in the cosmic background radiation, an isotropic glow of radiation that has the characteristics expected from the remnant of a hot primeval fireball. Since the last years of the twentieth century, a third observation has come to the fore: The expansion of the universe is accelerating.

Cosmological theory, in general, and the big bang theory, in particular, are based on the theory of gravitation advanced by Albert Einstein in 1916 and known as the general theory of relativity. Although the predictions of this theory have little effect in the limited sphere of the Earth, they dominate on as large a scale as the universe, and have been well tested in such sources as the Hulse-Taylor binary pulsar. *See also:* **Relativity (/content/relativity/580100)**

Expansion of the universe

In the 1920s it became clear that the “spiral nebulae,” clouds of gas with arms spiraling outward from a core, were galaxies on the scale of the Milky Way Galaxy. This was established in 1925, when observations of variable stars in several galaxies by E. Hubble enabled the distance to these galaxies to be determined with some accuracy.

Starting in 1912, the spectra of many of these spiral nebulae were found to have large redshifts. According to the Doppler effect, these large redshifts correspond to large velocities of recession from the Earth. Estimates of distances to these objects by Hubble and colleagues established a direct relation between the distance to a galaxy and its velocity of recession. It was soon interpreted as the result of an expanding universe. *See also:* **Doppler effect (/content/doppler-effect/203400)**; **Redshift (/content/redshift/576450)**

The relation known as Hubble's law is $v = H_0 d$, where v is the velocity of recession, d is the distance to the galaxy, and H_0 is a constant known as Hubble's constant. Determining Hubble's constant requires the independent measurement of the distances to galaxies; the redshift can easily be measured on spectra.

In the Hubble diagram (**Fig. 1**), the horizontal axis is the distance as derived from observations of the periods of Cepheid variable stars in distant galaxies, and the vertical axis is the velocity of recession, calculated from the redshift $z = \Delta\lambda/\lambda$, where $\Delta\lambda$ is the shift in wavelength in radiation of wavelength λ measured on the spectra of those galaxies. The Hubble law is expressed by the fact that the data points in the diagram lie near a straight line. *See also:* **Cepheids (/content/cepheids/120900)**

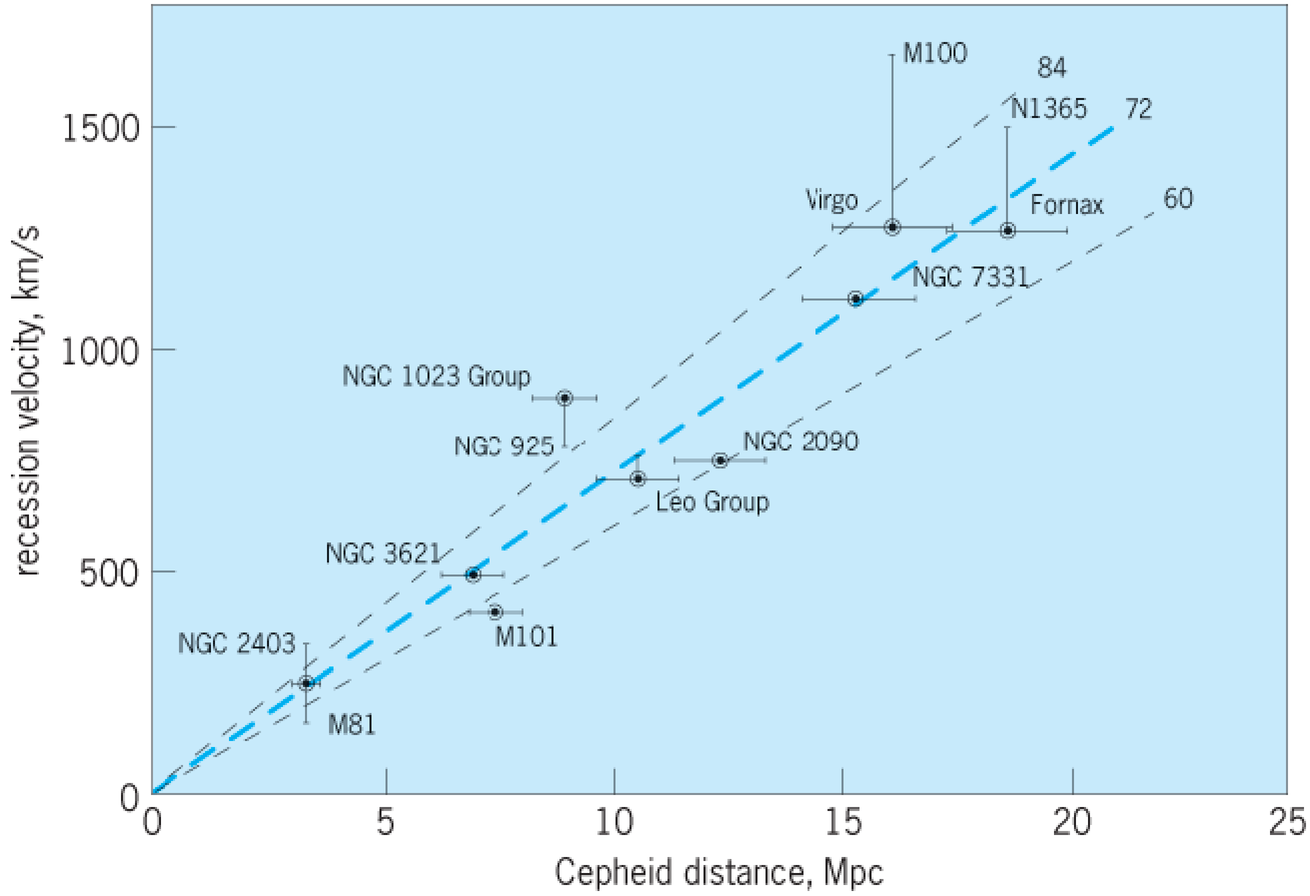

Fig. 1 Hubble diagram. Numbers next to the straight lines passing through the origin indicate corresponding values of Hubble's constant in km · s^{-1} · Mpc^{-1}. Data on this diagram give H_0 = 72 km · s^{-1} · Mpc^{-1}, with an uncertainty of ±4 km · s^{-1} · Mpc^{-1} and a scatter of ±17 k · s^{-1} · Mpc^{-1}. (*Courtesy ofW. L. Freedman, B. Madore, and R. C. Kennicutt; NASA*)

If velocity is expressed in kilometers per second, and distance is expressed in megaparsecs (where 1 parsec is the distance from which the radius of the Earth's orbit would subtend 1 second of arc, and is equivalent to 3.26 light-years or 3.09×10^{13} km or 1.92×10^{13} mi), then Hubble's constant H_0 is given in $\mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$. The determination of Hubble's constant was the aim of one of the three key projects of the *Hubble Space Telescope*, especially through studies of Cepheid variable stars in galaxies sufficiently distant to be beyond internal gravity effects in the Local Group, the cluster of galaxies to which the Milky Way belongs. The result is $72\ \mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$. Tying the *Hubble Space Telescope* results to distances derived from supernovae extends Hubble's constant to still greater distances. Other methods involving planetary nebulae, the spread of rotational velocities of galaxies, the statistical fluctuations of each pixel of galaxy images, and supernovae, for example, also gave values close to $75\ \mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$. The result from the National Aeronautics and Space Administration's (NASA) *Wilkinson Microwave Anisotropy Probe (WMAP)* closely confirms the Hubble Key Project value. *See also:* **Galaxy, external (/content/galaxy-external/277700)**; **Hubble constant (/content/hubble-constant/324300)**; **Hubble Space Telescope (/content/hubble-space-telescope/757724)**; **Local Group (/content/local-group/388575)**; **Supernova (/content/supernova/669600)**; **Wilkinson Microwave Anisotropy Probe (/content/wilkinson-microwave-anisotropy-probe/801110)**

Reversing the expansion rate, tracing the expansion of the universe back in time shows that the universe would have been compressed to infinite density approximately $(8–16) \times 10^9$ years ago (for $H_0 = 72\ \mathrm{km} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$). The *WMAP* pinned this value down more precisely, to 13.7×10^9 years ago. In the big bang theory, the universe began at that time as a so-called big bang began the expansion. The big bang was the origin of space and time.

In 1917, Einstein found a solution to his own set of equations from his general theory of relativity that predicted the nature of the universe. His universe, however, was unstable: It could only be expanding or contracting. This seemed unsatisfactory at the time, for the expansion had not yet been discovered, so Einstein arbitrarily introduced a special term—the cosmological constant—into his equations to make the universe static. The need for the cosmological constant seemed to disappear with Hubble's discovery of the expansion, although the cosmological constant has subsequently reappeared in some models and is a leading explanation for dark energy. *See also:* **Cosmological constant (/content/cosmological-constant/800540)**; **Dark energy (/content/dark-energy/800530)**

Further solutions to Einstein's equations, worked out in the 1920s by Alexander Friedmann and Georges Lemaître, are at the basis of the cosmological models that are now generally accepted. These solutions indicate that the original “cosmic egg” from which the universe was expanding was hot and dense. This reasoning is the origin of the current view that the universe was indeed very hot in its early stages.

Early universe

Modern theoretical work has been able to trace the universe back to the first instants in time. In the big bang theory and in related theories that also propose a hot, dense early universe, the universe may have been filled in the earliest instants with exotic elementary particles of the types now being studied by physicists with large accelerators. Individual quarks may also have been present. By 1 microsecond after the universe's origin, the exotic particles and the quarks had been incorporated in other fundamental particles. *See also:* **Elementary particle (/content/elementary-particle/227700)**; **Quarks (/content/quarks/563300)**

Work in the early 1980s incorporated the effect of elementary particles in cosmological models. The research seems to indicate that the universe underwent a period of extremely rapid expansion in which it inflated by a factor of billions in a very short time. This inflationary universe model provides an explanation for why the universe is so homogeneous: Before the expansion, regions that now seem too separated to have been in contact were close enough to interact. After the inflationary stage, the universe was in a hot stage and was still dense; the models match the big bang models thereafter.

In the inflationary universe models, the universe need not have arisen from a single big bang. Rather, matter could have appeared as fluctuations in the vacuum. Current speculations about multiverses hold that many different universes could exist, perhaps with different physical constants in them.

It is not definitely known why there is an apparent excess of matter over antimatter, although attempts in elementary particle physics to unify the electromagnetic, the weak, and the strong forces show promise in explaining the origin of the matter–antimatter asymmetry. The asymmetry seems to have arisen before the first millisecond. The asymmetry in the decay of certain mesons may provide a clue to resolving this question. If a slight matter–antimatter asymmetry arose, then the paired number of matter and antimatter particles would have annihilated each other, providing the millions of times more photons than matter that we now measure, leaving only the remnant of matter that we see, now calculated and measured to be only about 4% of the contents of the universe. *See also:* **Antimatter (/content/antimatter/041000)**; **Fundamental interactions (/content/fundamental-interactions/275600)**

By 5 s after the origin of the universe, the temperature had cooled to 10^9 K (2×10^9 °F), and only electrons, positrons, neutrinos, antineutrinos, and photons were important. A few protons and neutrons were mixed in, and they grew relatively more important as the temperature continued to drop. The universe was so dense that photons traveled only a short way before being reabsorbed. By the time 1 min had gone by, nuclei of the light elements had started to form.

After about 400,000 years, when the universe cooled to 3000 K (5000°F), and the density dropped sufficiently, the protons and electrons suddenly combined to make hydrogen atoms, a process called recombination. Because hydrogen's spectrum absorbs preferentially at the wavelengths of sets of spectral lines rather than continuously across the spectrum, and because there were no longer free electrons to interact with photons, the universe became transparent at that instant. The average path traveled by a photon—its mean free path—became very large. The blackbody radiation of the gas at the time of recombination was thus released and has been traveling through space ever since. As the universe expands, the spectrum of this radiation retains its blackbody shape although its characteristic temperature drops. *See also:* **Blackbody (/content/blackbody/086400)**; **Heat radiation (/content/heat-radiation/311000)**

Background radiation

Between 1963 and 1965, observations with a well-calibrated horn antenna revealed an isotropic source of radio noise whose strength was independent of time of day and of season, and whose intensity at the observing wavelength of 7 cm (2.8 in.) was equivalent to that which would be emitted by a blackbody—an idealized radiating substance—at a temperature of approximately 3 K (−454°F). Prior calculations that indicated that the remnant radiation from the big bang might be detectable led to the interpretation of the newly discovered radiation in terms of fossil radiation from the big bang. In 1975, final confirmation of the blackbody nature of the radiation was provided by measurements of the spectrum of the background radiation in a frequency range that included the peak of the blackbody curve and extended into the infrared.

The observations of the spectrum from the *Cosmic Background Explorer* (*COBE*) spacecraft during 1989–1993 were in complete agreement with a blackbody curve at 2.728 K (−454.7°F). The *WMAP*'s value, first released in 2003 and later updated, is in close agreement. The European Space Agency's *Planck* mission, launched in 2009, provides even more detailed measurements on a finer spatial scale. The radiation is very isotropic, once the dipole anisotropy caused by the Earth's motion is subtracted. Observations from another experiment on *COBE* discovered temperature fluctuations at the level of 5 parts per million. *WMAP* and now *Planck* observed them in still finer detail. These fluctuations, largely statistical in nature, are revealing the seeds from which galaxies formed. Inflationary big bang models seem best able to explain how widely separated parts of the universe can be as similar as the *COBE*, *WMAP*, and *Planck* observations have revealed them to be. Confirmations and other measurements of these ripples in space have come from cosmic background telescopes on balloons and in Canada, the Canary Islands, and Antarctica. *See also:* **Cosmic background radiation (/content/cosmic-background-radiation/163750)**

Nucleosynthesis

As the early universe cooled, the temperatures became sufficiently low for element formation to begin. By about 100 s, deuterium (comprising one proton plus one neutron) formed. When joined by another neutron to form tritium, the amalgam soon decayed to form an isotope of helium, helium-3. Ordinary helium, helium-4 (with still another neutron), also resulted.

The relative abundances of isotopes of the light elements in the first few minutes have been calculated (**Fig. 2**). The calculations depend on a certain assumed density at some early time. They show that within minutes the temperature drops to 10^9 K (2×10^9°F), too low for most nuclear reactions to continue. Most models give a resulting abundance of about 25% of the mass in the form of helium, regardless of the density of the universe. The helium abundance is hard to determine observationally. Current results are in rough agreement with the theoretical value.

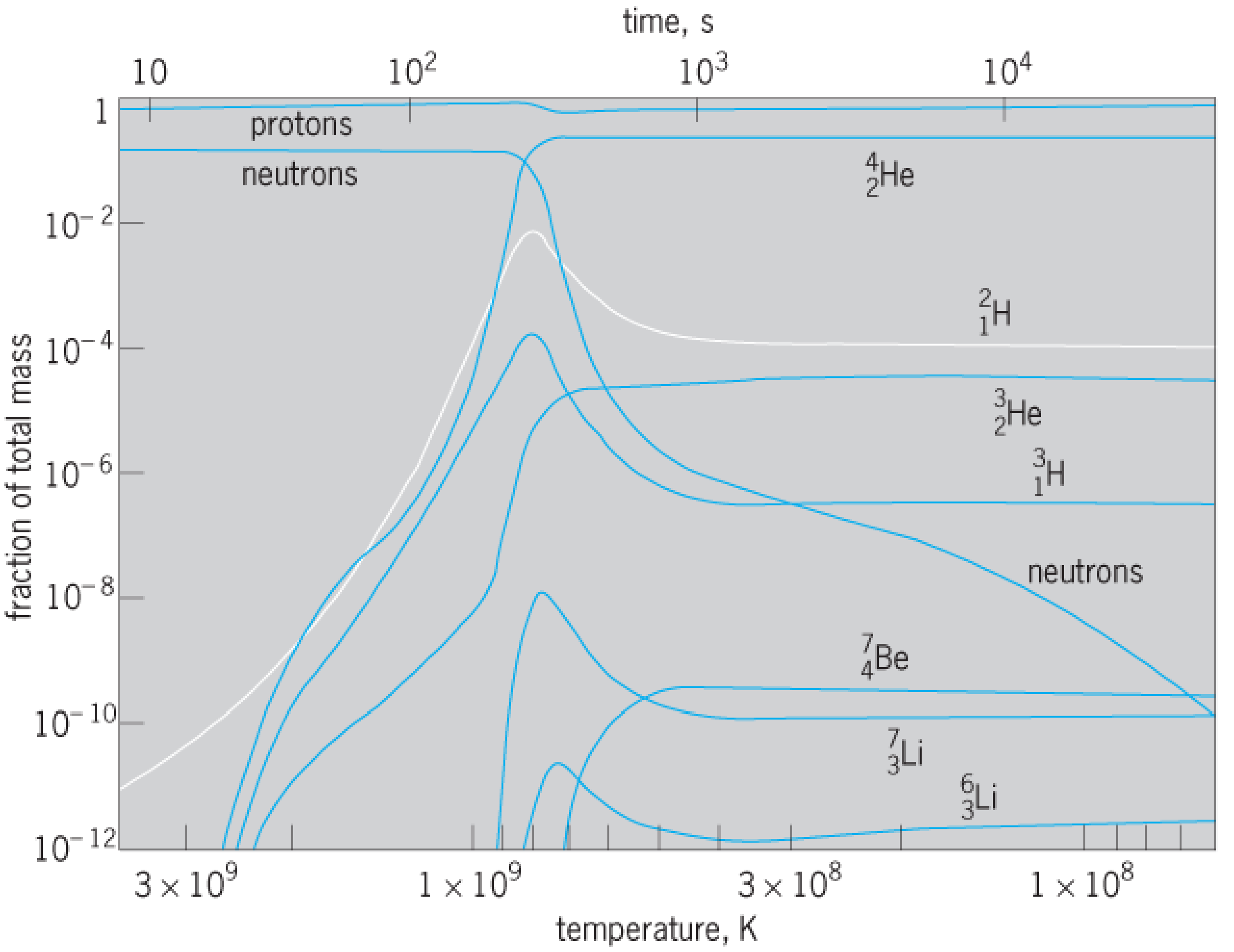

Fig. 2 Relative abundance of isotopes of the light elements in the first few minutes after the big bang according to the model of R. V. Wagoner, for a certain assumed density at some early time. (*After J. M. Pasachoff, Astronomy: From the Earth to the Universe, 6th ed., Brooks/Cole, Belmont, CA, 2002*)

The abundances of other light elements were more sensitive to parameters of matter in the early universe. Such abundances can be calculated as a function of the present-day density of matter (**Fig. 3**). From knowledge of the approximate rate of expansion of the universe, the density of matter in the early universe can be deduced from the current density, and abundances can then be calculated. In particular, the deuterium abundance was especially sensitive to the cosmic density at the time of deuterium formation, because the rate at which deuterium is “cooked” into tritium increases rapidly with increasing density.

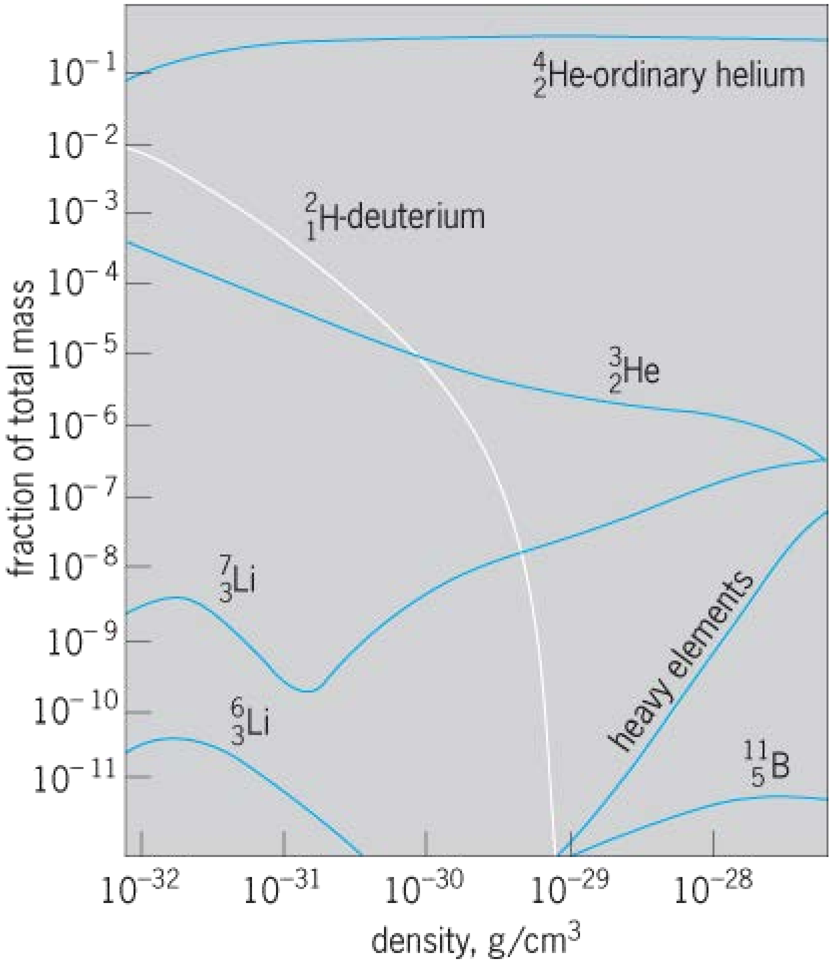

Fig. 3 Relative abundances of isotopes and elements as a function of present-day density of matter, according to the model of R. V. Wagoner. (*After J. M. Pasachoff, Astronomy: From the Earth to the Universe, 6th ed., Brooks/Cole, Belmont, CA, 2002*)

Big bang nucleosynthesis, although at first thought to be a method of forming all the elements, foundered for the heavy elements at mass numbers 5 and 8. Isotopes of these mass numbers are too unstable to form heavier elements quickly enough. The gap is bridged only in stars, through processes worked out in 1957. Thus the lightest elements were formed as a direct result of the big bang (**Fig. 3**), while the heavier elements, as well as additional quantities of most of the lighter elements, were formed later in stars or supernovae. Measurements of the relative abundances of the light isotopes and elements have been used to set a limit of three on the number of neutrino types and thus on the number of quark-lepton families that exist. *See also:* **Lepton (/content/lepton/378200)**; **Neutrino (/content/neutrino/450700)**; **Nucleosynthesis (/content/nucleosynthesis/461110)**

Open versus closed universe

The two extreme possibilities for the future of the universe, until the discovery of the accelerating expansion of the universe, were that the universe would either continue to expand forever, or that it will cease its expansion and begin to contract. It can be shown that the case where the universe will expand forever, in the absence of dark energy or other accelerating mechanisms, corresponds to an infinite universe. The term applied is the open universe. The case where the universe will begin to contract corresponds to a finite universe. The term applied is the closed universe. The inflationary universe scenario has the universe on the boundary between open and closed, as signified by the parameter Ω taking the value of 1. Such a universe would expand forever but at an ever-decreasing rate in the absence of accelerating mechanisms. However, according to more recent conclusions, discussed below, the expansion of the universe is now accelerating, having passed a transition point where dark energy has begun to dominate.

Deceleration parameter

One basic way to test whether the universe is open or closed is to determine the rate at which the expansion of the universe is slowing, that is, the rate at which it is deviating from Hubble's law. The slowing is measured with a term called q_0, the deceleration parameter. The dividing line is marked by, with smaller values corresponding to an open universe and larger values corresponding to a closed universe. The value corresponds to $\Omega = 1$, where Ω is the ratio of the total density of matter in the universe to the critical density that divides open from closed universes.

The most obvious way to measure q_0 is by looking at the most distant galaxies or clusters of galaxies, measuring their distances independently from Hubble's law, and plotting Hubble's law in a search for deviations. But all such observations are subject to the considerable uncertainty introduced by the fact that observations deep into space also see far back into time. The galaxies then were surely different than they are now, so evolutionary effects must be taken into account. It is not even known for certain whether galaxies were brighter or dimmer in the distant past, and thus the method may reveal more about the evolution of galaxies than about cosmology.

Accelerating universe

The deceleration parameter is being studied from very distant supernovae, which are discovered in quantity through automated searches. Astonishingly, evidence from two independent groups of supernova observers showed that the expansion of the universe is accelerating, the opposite of what was expected. These data were carefully scrutinized for systematic errors, but enough independent confirmation has appeared from different kinds of observations that doubt of this astonishing result has vanished. The acceptance of this result led, among other things, to the award of the 2011 Nobel Prize in physics to Saul Perlmutter, Brian Schmidt, and Adam Riess for the discovery.

Observations of extremely distant supernovae have given astronomers views far enough back in time to see the era before the acceleration started. In that era, the universe's expansion was slowing. These discoveries gave confidence to astronomers that the conclusion that the universe is accelerating is correct. Results from observations by NASA's *Chandra X-ray Observatory* of extremely distant clusters of galaxies have confirmed that the universe's expansion is accelerating. *See also:* **Chandra X-ray Observatory (/content/chandra-x-ray-observatory/801990)**

The results from *WMAP*, endorsing earlier results from studying ripples in the cosmic background radiation, have shown that the universe's content is exactly at the critical value between open and closed. At the same time, they show (endorsing nucleosynthesis observations summarized below) that the amount of ordinary matter (composed of atomic particles called baryons, like protons and neutrons) is only 4% of this critical value. Other studies, such as those of the gravitational attractions of objects in clusters of galaxies, show the existence of dark matter—with gravity but without emitting electromagnetic radiation—accounting for another approximately 30% of the critical value.

The remaining two-thirds of the content of the universe remains unknown, and has been given the name “dark energy.” Scientists have no definite idea of what the dark energy is composed, although Einstein's old “cosmological constant"—a seemingly arbitrary term in his equations—is a leading possibility among those being considered. This dark energy now dominates the universe, causing the acceleration of the expansion. When the cosmological constant Λ is taken into account, $q_0 = \Omega_m - \Omega_\Lambda$ (where Ω_m is associated with the matter in the universe and Ω_Λ is associated with the cosmological constant), so it is now negative. *See also:* **Accelerating universe (/content/accelerating-universe/800550)**; **Baryon (/content/baryon/073500)**; **Dark energy (/content/dark-energy/800530)**; **Dark matter (/content/dark-matter/800520)**

Great Attractor

From studies of elliptical and spiral galaxies, a bulk streaming motion has been found toward a region called the Great Attractor. The region would be a concentration in the direction of the constellation Centaurus, 20 times more populous than the Virgo Cluster of galaxies. Its distortion of the Hubble flow may have led to misevaluation of the Hubble constant. An even greater attractor farther out has also been reported. The presence of the Great Attractor and related regions of space mean that the measurements of velocities we made in local areas of the universe can be affected by the Great Attractor's mass, where it gave misleading results about the Hubble flow before the *WMAP* and supernova determinations of Hubble's constant. *See also:* **Virgo Cluster (/content/virgo-cluster/757220)**

Cosmic deuterium abundance

Because deuterium is a sensitive indicator of the cosmic density at the time of its formation soon after the big bang, and because deuterium can only be destroyed and not formed in stars, the study of the cosmic deuterium abundance is one of the best methods for determining the future of the universe. Basically, it involves assessing whether there is enough gravity in the universe to halt the expansion.

Counts can be made of all the stars, galaxies, quasars, interstellar matter, and so forth, and the sum gives a density much too low to close the universe. But this method does not assess the amount of invisible matter, which could be in the form of intergalactic gas, black holes, and so forth. Indeed, studies of the motions of galaxies in clusters of galaxies often indicate that much more mass is present inside galaxy clusters than is visible. The amount of this missing mass (actually the mass is present, and it is the light that is missing) may be 50 times the amount of ordinary mass (known as baryons). As previously noted, it is known as dark matter.

Assessing the density of the universe through studies of the deuterium abundance is independent of whether the ordinary matter is visible or invisible (detectable, for example, from its radio or x-ray emissions). Although deuterium is present even on Earth as a trace isotope, with an abundance 1/6600 that of normal hydrogen in seawater, it is difficult to detect in interstellar space. However, since 1972, a number of determinations of interstellar deuterium abundance have been carried out, through radio observations and studies in the ultraviolet made with telescopes in space, the most precise with the *Hubble Space Telescope*. The fundamental spin-flip line of atomic deuterium was also finally measured, its 92-cm-long wavelength putting it in a part of the radio spectrum that made it particularly difficult to determine. Determinations of deuterium in molecules in the atmospheres of the planets have also been carried out. Although there are some discrepancies remaining between abundances determined in different locations and in different fashions, the deuterium observations indicate clearly that the density of the universe is very low, and hence that the universe is open as far as baryons are concerned. This finding is supported by observations with the 10 m (400 in.) Keck telescopes of deuterium in distant quasars, redshifted into the visible part of the spectrum. This result that the baryon density is low, only about 4% of the critical value that divides open and closed universes, matches the conclusions from observations of the ripples in the cosmic background radiation. *See also:* **Deuterium (/content/deuterium/189100)**; **Quasar (/content/quasar/563800)**

Hot and cold dark matter

Observations of a diffuse background of x-rays had led to the suspicion that a lot of hot material, previously undiscovered, may have been present between the galaxies. However, subsequent observations revealed that at least some of the x-ray background came from faint quasars, which appeared on long exposures of even fields that had been thought to be blank. Continued mapping and pointed observations have detected extensive halos around certain galaxies and even around some sparse clusters of galaxies. These observations indicated the presence of extensive dark matter. *See also:* **X-ray astronomy (/content/x-ray-astronomy/750400)**

Neutrinos are known to be plentiful in the universe; if they each had enough mass they could dominate the universe. Because there are approximately 100 neutrinos in each cubic centimeter (1500 in each cubic inch) of the universe, much mass would be in that form if neutrinos had even a small rest mass. Indeed, observations of neutrinos with the Super-Kamiokande detector show that neutrinos change in type, which can occur only if they have mass, and extensive experiments are ongoing in Italy, at the Fermi National Accelerator Laboratory (Fermilab) near Chicago, and in Japan to study neutrino oscillations directly by sending beams of neutrinos to detectors hundreds of kilometers away. But the mass itself is not determined from these observations. Observations of the neutrinos from Supernova 1987A placed a sensitive limit on the amount of mass that neutrinos could have, as the arrival times of massive neutrinos would have spread out. Because neutrinos move so fast, they are known as hot dark matter. But observations from *WMAP* showed that the total mass of neutrinos does not dominate the universe.

Because hot dark matter would not explain satisfactorily the quickness with which matter clumped to form galaxies, most models include at least some so-called cold dark matter. The cold dark matter could be in the form of elementary particles of types yet unknown, such as axions or weakly interacting massive particles (WIMPs). Or it could be in the form of dim stars, brown dwarfs, or other macroscopic bodies known collectively as massive astrophysical compact halo objects (MACHOs). Supercomputer calculations involving millions of points interacting in a three-dimensional grid have computed the evolution of the universe for models with different values of Ω and for different combinations of cold and hot dark matter. (The 2011 Gruber Prize in Cosmology was awarded to Marc Davis, George Efstathiou, Carlos Frenk, and Simon White for their work on simulating the universe with the assumption of plentiful cold dark matter.) *See also:* **Brown dwarf (/content/brown-dwarf/097150)**; **Weakly interacting massive particle (WIMP) (/content/weakly-interacting-massive-particle-wimp/742250)**

Inflationary scenarios

Although several lines of evidence, including studies of differential velocities of nearby galaxies caused by density perturbations and of the cosmic abundance of deuterium, indicate that the universe is open, it was not clear why the universe was so close to the dividing line between being open or closed that the subject was much in doubt. The inflationary universe model provides a natural explanation for the universe being on this dividing line. After expansion slows down at the close of the inflationary stage (thus causing a phase change, much like supercooled liquid water turning abruptly into ice when perturbed, a more extreme example of a phase change than the household boiling of water into steam), the universe necessarily approaches this line. Thus whether the universe was open or closed was the wrong question to ask. Further work on inflationary scenarios continues to assess certain problems, such as the inflationary model's predictions of the density fluctuations that lead to the coalescence of galaxies, now measured by the *Planck* spacecraft. Although the simplest inflationary scenarios have been ruled out, more complex inflationary theories are viable and are widely accepted by cosmologists. *See also:* **Cosmology (/content/cosmology/164200)**; **Phase transitions (/content/phase-transitions/506100)**; **Universe (/content/universe/722000)**

Jay M. Pasachoff

Test Your Understanding

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1. What is cosmic background radiation, and why is it important to the big bang theory?
2. How did the discovery of the large redshifts of many spiral nebulae indicate that the universe is expanding?
3. Critical Thinking: If the universe is expanding, why isn't Earth moving farther and farther away from the Sun?
4. Critical Thinking: Why is it a misconception to compare the big bang to an explosion?

Links to Primary Literature

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Ned Wright's Cosmology Tutorial (http://www.astro.ucla.edu/~wright/cosmolog.htm)

Nobel Prize site (http://www.nobelprize.org)