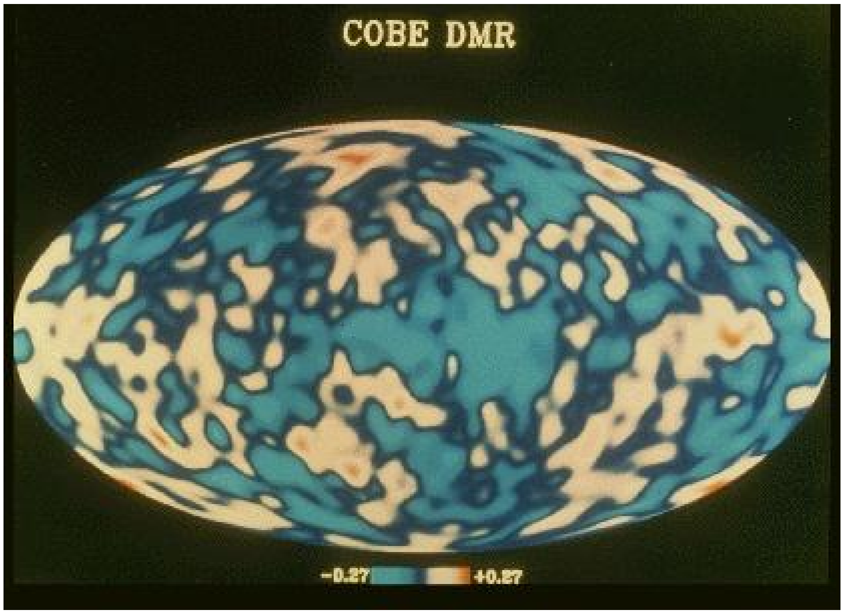
ENCYCLOPEDIA ARTICLE

Cosmology

Microwave map of the whole sky assembled from one year of data taken by the Cosmic Background Explorer (COBE) satellite. Emission from the Milky Way Galaxy has been removed from the view (NASA).



The study of the structure and the origin of the universe, including the origin of galaxies, the elements, and matter itself.

Big bang model

When Albert Einstein proposed his theory of general relativity, the universe was believed to be static. Einstein had to modify his equations so that general relativity would allow a static universe by adding a cosmological constant term. Today, this term is incorporated into the current cosmological model. See also: Cosmological constant; Relativity

At the time of Einstein's work, astronomers were uncertain about the nature of the faint spiral nebulae and the size of the visible universe. Some contended that they were regions of star formation that were part of the Milky Way Galaxy, while others argued that they were distant galaxies much like the Milky Way. This debate was settled in 1923 by E. Hubble's discovery of 12 Cepheid variable stars in M31, the Andromeda Nebula. There is a simple empirical relationship between the period of the Cepheids and their luminosity. Thus, Hubble's observations allowed him to determine that the Andromeda Nebula was at a very large distance and was a galaxy much like the Milky Way. See also: Andromeda Galaxy; Cepheids; Galaxy, external; Milky Way Galaxy

Hubble continued his study of galaxies and found that most were receding from the Earth. Hubble proposed a simple linear relationship between the distance to a galaxy and its recessional velocity Eq. (1),

$$v = Hr \tag{1}$$

where v is the recessional velocity of the galaxy, usually measured in kilometers per second, and r is the distance to the galaxy, usually measured in megaparsecs (1 Mpc = 3.26×10^6 light-years = 3.1×10^{19} km = 1.9×10^{19} mi). Various techniques now yield consistent measurements of the Hubble constant, $H \sim 70$ (km/s)/Mpc. See also: Hubble constant

Hubble's observations of the expanding universe then implied that the addition of a cosmological constant to the equations of general relativity was unnecessary. In the 1920s, G. Lemaître and A. Friedmann independently proposed a general relativistic model of the expanding universe. One of the simplest solutions to Einstein's relativity equation, this model assumes that the universe is homogeneous and expanding. When Lemaître and Friedmann made their proposal, there was no real evidence for their simplifying assumptions. Only since the late 1980s have observations become sensitive enough to confirm them.

The Friedmann-Lemaître model, often called the big bang model, implies that the universe began in an extremely dense state and expanded and cooled. In this model, the Hubble law is predicted as an approximate description of the expansion valid for galaxies within a few hundred megaparsecs of the Milky Way Galaxy. The model implies that radiation is redshifted as the universe expands. Thus, radiation from distant objects should appear at lower frequencies than those at which it was emitted. Observations of atomic lines from distant quasars confirm that radiation is redshifted just as predicted. See also: Quasar; Redshift

The Friedmann-Lemaître model, while fully relativistic, can be described in the language of newtonian physics. The Hubble law implies that a shell of galaxies of radius R and mass m expands with velocity HR. Thus, the kinetic energy of the shell is $m(HR)^2/2$. If M is the mass interior to the shell, then the gravitational binding energy of the shell is GMm/R, where G is the newtonian constant of gravitation. The total energy E of the shell is therefore given by Eq. (2). Since it has

$$E = \frac{m(HR)^2}{2} - \frac{GMm}{R} \tag{2}$$

been assumed that the universe is uniform, the mass M within the shell can be replaced with the quantity $4\pi R^3/3$, where ρ is the density of the universe and $4\pi R^3/3$ is the volume of a shell of radius R. Then Eq. (2) can be rewritten as Eq. (3),

$$\frac{E}{mR^2} = \frac{H^2}{2}\left(1 - \frac{8\pi G\rho}{3H^2}\right) = \frac{H^2}{2}(1 - \Omega) \tag{3}$$

where Ω is the ratio of the density of the universe to the critical density of the universe, $3H^2/(8\pi G)$. If $\Omega < 1$, the total energy of the shell is positive, and the universe will continue to expand forever. If $\Omega > 1$, the total energy of the shell is negative, gravity will eventually stop the expansion, and the universe will eventually collapse. Some physicists speculate that this so-called big crunch will be followed by a future big bang. If $\Omega = 1$, the total energy is zero, and the universe stands on the balance between open and closed and corresponds to a special solution called the Einstein-de Sitter model. See also: Gravitation

This simple newtonian model, while accurately describing the dynamics of the expanding universe, can lead to a conceptual error. The newtonian shell has a center, since newtonian theory cannot deal with a uniform mass density. General relativity, however, allows the universe to be isotropic and to be expanding uniformly without having a special center point. In the Friedmann-Lemaître model, the Milky Way Galaxy is not a special place in the universe.

Geometry of the universe

The density of the universe determines not only the final fate of the universe but also its geometry. If $\Omega > 1$, the universe is closed and its geometry is that of a three-dimensional sphere. (A circle is a one-sphere and the surface of the Earth is a two-sphere.) If two pilots leave New York in opposite directions, one heading east and the other heading west, they will meet somewhere over the Pacific. If the Earth were flat, the two pilots would continue to head directly away from each other. Similarly, if the universe is closed, two light rays sent off in opposite directions will eventually bend toward each other. If $\Omega = 1$, the universe is flat and the two light rays will continue to move away from each other. If $\Omega < 1$, the geometry of the universe is hyperbolic, much like that of a saddle. A common misconception is that if the universe is open it must be spatially infinite. This relationship need not be true, as general relativity does not constrain the topology of the universe. If $\Omega < 1$, the universe could be either infinite or finite and periodic.

Microwave background radiation

One of the most dramatic discoveries of modern physics was the detection of the microwave background radiation by A. Penzias and R. Wilson. Most cosmologists believe that this radiation is the leftover heat from the big bang.

In the hot big bang model, the universe started in an extremely hot dense state. In this state, the universe was composed of electrons, positrons, quarks, neutrinos, and photons. As the universe expanded, most of the matter annihilated with antimatter into photons. These photons then cooled as the universe expanded. Thermal physics predicts that the spectrum of radiation from the big bang would be similar to that emitted by a blackbody, a so-called Planck spectrum. The Friedmann-Lema TeX tre model predicts that this radiation should be uniform since the big bang started in a uniform state. See also: Heat radiation

The observations of the *Cosmic Background Explorer* (*COBE*) satellite, launched in 1989, provided strong confirmation of the hot big bang model. The observed spectrum of the microwave background radiation agrees closely with the predicted Planck spectrum. The *COBE* experiment also confirmed that the microwave background radiation is uniform to nearly 1 part in 50,000, consistent with the homogeneity assumption of the hot big bang model.

Observations of small fluctuations in the temperature of the microwave background have become a powerful tool for studying the basic properties of the universe. Since most of the microwave background photons last interacted with matter when the universe was only 500,000 years old, these tiny fluctuations in temperature are directly probing variations in the density of the universe soon after the big bang. See also: Cosmic background radiation

Nucleosynthesis

Within the context of the hot big bang model, the conditions in the universe now can be extrapolated back to the first moments after the big bang. The temperature of the cosmic background radiation now is 2.73 kelvins above absolute zero. When the universe was half its present size, the background temperature was twice as high. One second after the big bang, the universe was only 3×10^{-11} of its present size and the temperature of the microwave background was roughly 10^{10} K (1.8×10^{10} °F). At this high temperature, the universe consisted of a thermal sea of photons, electrons, positrons, and neutrinos. In addition, there were a handful of protons and neutrons. There was approximately 1 baryon (proton or neutron) for every 10^{10} photons. See also: Baryon; Electron; Neutrino; Neutron; Positron; Proton

As the universe cooled, the protons and neutrons combined to make deuterium. Most of this deuterium then interacted to make helium, while trace amounts combined to make lithium. One of the successes of the big bang model is its ability to account for the observed abundances of light elements. The universe today consists of roughly 28% helium, 70% hydrogen, and 2% other elements, calculated by their masses. Nucleosynthesis in stars produces roughly equal amounts of helium and heavier elements from hydrogen. Thus, it is difficult to understand the helium abundance without big bang nucleosynthesis. See also: Deuterium; Helium; Hydrogen; Lithium

The amounts of deuterium, helium, and lithium produced in the big bang depend sensitively on the number of baryons per photon in the early universe and on the number of neutrino flavors. Based on the observed abundances of this isotope and these elements in old stars, it was predicted that there should be only three flavors of neutrino. Experiments at particle accelerators have confirmed this prediction based on the first moments of the early universe. See also: Flavor

The observed light-element abundances also lead to a prediction for the density of protons and neutrons. The current best estimates suggest that the density in atoms is 5×10^{-31} gram/cm^3. Measurements of the amplitude of microwave background fluctuations also measure the density in atoms as the pattern of fluctuations depends on the atomic density. The best fit value for the density of atoms based on microwave background fluctuations agrees with the estimate based on light-element abundances to better than 10% (and well within the current statistical errors). See also: Big bang theory; Nucleosynthesis

Lambda cold dark-matter model

Over the past few decades, a simple cosmological model called the lambda cold dark-matter (lambda CDM) model has emerged as the best fit to the current observational data. The lambda CDM model is a version of the standard hot big bang model. The big bang model assumes that general relativity is valid on cosmological scales and that the distribution of matter on large scales is homogeneous. This set of assumptions implies that the universe is expanding: the distances between galaxies are constantly growing. Since the universe is expanding, it is constantly getting cooler and less dense. In the standard big bang model, the shape and evolution of the universe depend on its composition.

The lambda CDM model assumes that the universe is composed of atoms, dark matter, and vacuum energy. The total energy density of the universe is very close to the critical density so that the geometry of the universe is flat. See also: Dark energy; Dark matter

This model has five basic parameters: the expansion rate of the universe (the Hubble constant), the density of matter in the universe, the density of atoms in the universe, the amplitude of the primordial density fluctuations, and how the amplitude of fluctuations varies with scale. With these five parameters, the model can fit a host of astronomical data, including measurements of positions of millions of galaxies, observations of microwave background fluctuations, measurements of distances to both nearby galaxies and distant supernovae, as well as a host of other astronomical observations. While simple, the lambda CDM model posits the existence of two novel forms of matter: cold dark matter and vacuum or dark energy.

Evolution of structure

The inflationary universe model is an attractive scenario for simultaneously explaining the homogeneity of the universe on large scales and the fluctuations in density observed on the smaller scales. In this scenario, the universe in its first few moments underwent a period of exponential expansion. This rapid expansion, which took place before nucleosynthesis, stretched out any initial density variations and eliminated any monopoles or other unwanted objects that formed before the inflationary epoch. During this inflationary epoch, quantum fluctuations generated new density fluctuations that are predicted to be the initial source of structure. The inflationary scenarios predict that the density parameter Ω should be extremely close to 1. See also: Inflationary universe cosmology

Since different regions of space underwent different amounts of inflationary expansion, this process generated large-scale variations in the density of the universe. The inflationary universe model predicts that the variations in density should be gaussian random-field fluctuations. This implies that the statistical properties of both fluctuations in the microwave background and the fluctuations in the galaxy density distribution are characterized by its overall amplitude and its dependence on scale.

Observations of the microwave background radiation probe these conditions in the early universe. In most cosmology models, the microwave photons that are detected on Earth last interacted with electrons when the universe was one-thousandth its present size. Thus, fluctuations in the microwave background temperature reflect the density fluctuations in the early universe.

During its first 500,000 years, the early universe was a hot plasma of electrons, protons, electromagnetic and radiation (photons). The density fluctuations generated by inflation set up sound waves that propagated as long as the universe was ionized. When the universe cooled and atoms formed, radiation was able to travel freely to our telescopes and satellites. These density variations and the sound waves that they generated produced a characteristic pattern of fluctuations. Since the early universe was nearly uniform, simple linear physics describes the generation and evolution of these fluctuations. The characteristic size of these fluctuations equals the distance that sound waves can travel in 500,000 years. The amplitude of the fluctuations depends on the amount of matter and the density of atoms in the early universe.

The cosmic microwave background temperature fluctuations are very small: variations of only a few millionths of a degree. Over 25 years of searches for these fluctuations were rewarded in 1992, when the *COBE* satellite detected fluctuations in the microwave background temperature of about 2 parts in 100,000. NASA's *Wilkinson Microwave Anisotropy Probe* (*WMAP*) satellite and several ground and balloon-based measurements have been making ever more accurate measurements of these fluctuations (**Fig. 1**). With the launch of the European Space Agency's *Planck* satellite and a new generation of more sensitive ground-based experiments in development, the accuracy of these measurements will continue to rapidly improve. See also: Wilkinson Microwave Anisotropy Probe

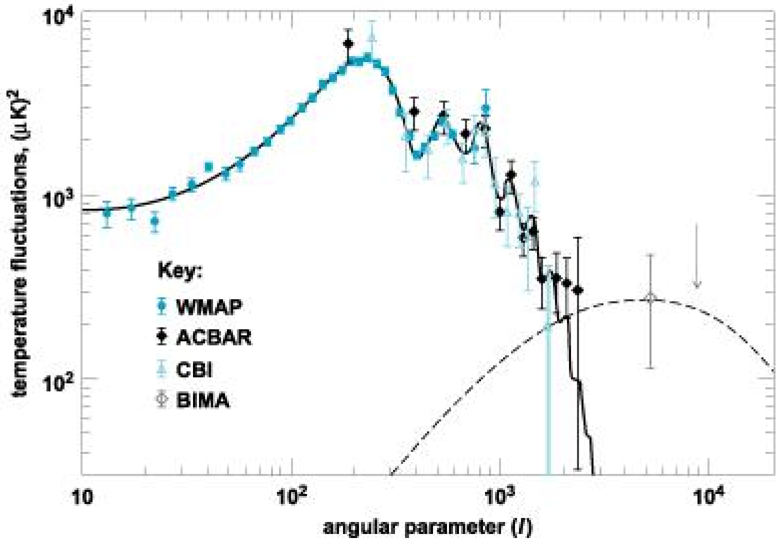


Fig. 1 Measurements of the amplitude of temperature fluctuations as a function of angular scale. The solid line is the predictions of the lambda CDM model. The data points are from the *Wilkinson Microwave Anisotropy Probe* (*WMAP*) and three ground-based experiments. The broken line shows an estimate of the expected level of contamination from hot gas in clusters. The horizontal axis is an angular parameter, l, and the angular scale measured is 180°/l. The vertical axis shows the amplitude of the temperature fluctuations in millionths of a degree (μK). (*A. Readhead; CBI team*)

These inflationary density fluctuations grew to form the observed pattern of galaxies. Regions that were slightly overdense expanded more slowly; thus, these overdense regions collapsed and formed galaxies and clusters. On the other hand, underdense regions expanded more rapidly than the surrounding universe. These underdense regions eventually developed into voids. Astronomers using wide-field surveys such as the Sloan Digital Sky Survey and the 2dF Galaxy Redshift Survey have now measured the positions of several hundred thousand galaxies. They have found that the clustering pattern matches the predictions of the lambda CDM model. See also: Sloan Digital Sky Survey

Cosmologists now use massive computer simulations to model the clustering of matter and the formation of galaxies. These simulations are compared with observations of the large-scale distribution of galaxies and with observations of galaxy and cluster properties. Simulations based on the lambda CDM model match a wide range of astronomical observations. Remarkably, the inflationary model successfully describes the statistical properties of both galaxies and the microwave background and fits astronomical observations over a range of 10^4 in scale and 10^{12} in mass (**Fig. 2**).

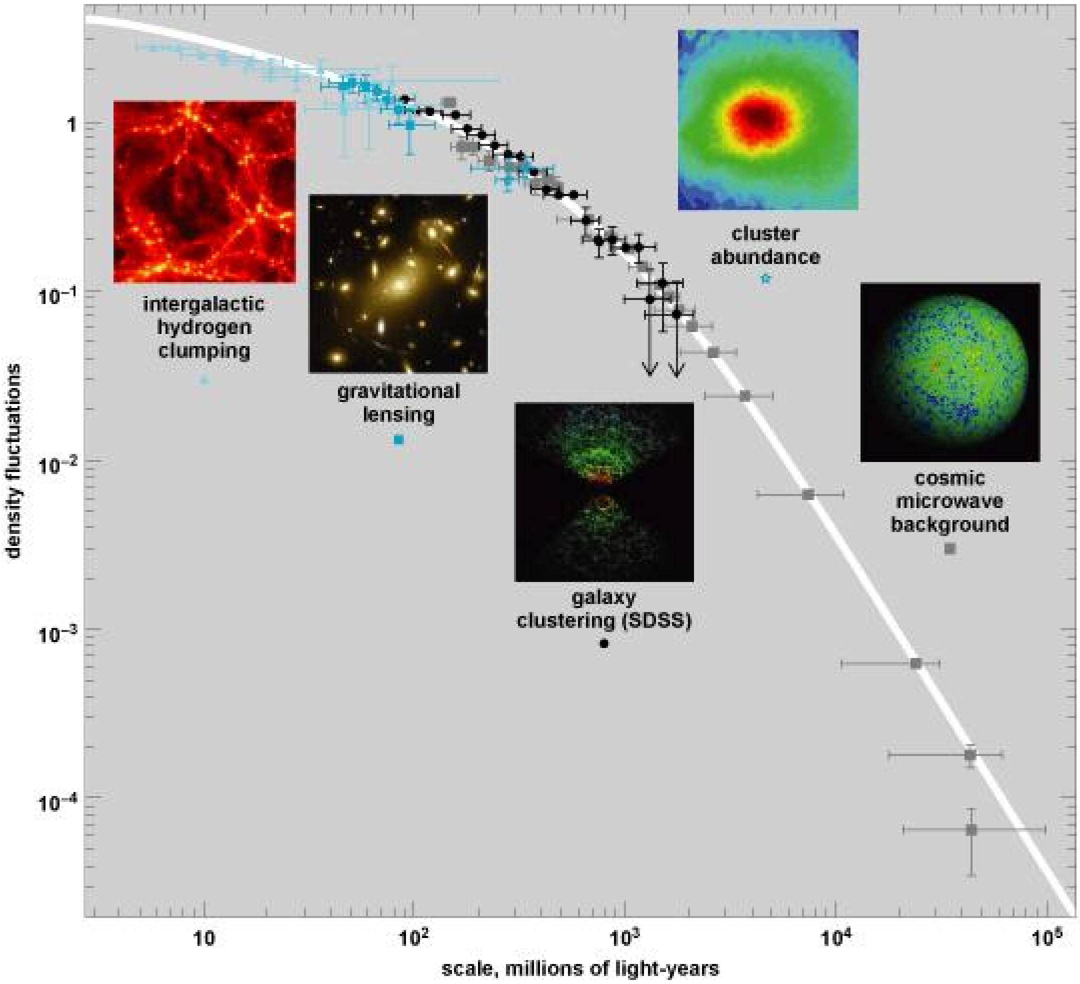


Fig. 2 Amplitude of density fluctuations as a function of scale. The insets indicate the various types of observations that measure the fluctuations and the data points that represent them in this figure. The microwave background observations measure the amplitude of fluctuations 500,000 years after the big bang; the clumping of gas measures the amplitude of fluctuations 2×10^9 years after big bang; and the galaxy and clustering measurements and gravitational lensing observations measure the amplitude of clustering in the nearby universe. The galaxy clustering measurements are based on the Sloan Digital Sky Survey (SDSS). The intergalactic hydrogen abundance is based on measurement of the absorption by its Lyman alpha line of light from distant quasars and galaxies. Cluster abundance is illustrated by an image of x-ray emission from a cluster. The amplitudes have been extrapolated to today using the lambda CDM model. The curve shows the prediction of the model. (*Max Tegmark*)

Measuring the size of the universe

Measuring the distance to astronomical objects remains a great scientific challenge. Astronomers are able to measure the distances to the nearest stars by using parallax. They then must rely on empirical properties of stars to extrapolate to more distant objects. Observations of globular clusters and open clusters in the Milky Way Galaxy are needed to calibrate the luminosity-period relation for Cepheid variable stars. See also: Parallax (astronomy); Star

Primary extragalactic distance indicators are used to measure the distance to nearby galaxies such as the Magellanic Clouds and the Andromeda Galaxy. Variable stars, such as Cepheids and RR Lyrae stars, are still important tools in determining the distances to these objects. Observations of the expansion of the dust shell around Supernova 1987A in the Large Magellanic Cloud have provided an alternative method for measuring distances. All these techniques imply that the Large Magellanic Cloud is at a distance of roughly 50,000 parsecs. See also: Magellanic Clouds; Supernova; Variable star

Secondary distance indicators are then used to determine the relative distance to the Virgo Cluster. For example, the brightest red and blue stars in a distant galaxy in the Virgo Cluster are assumed to have the same luminosity as the brightest stars in Andromeda. Other secondary distance indicators include the brightness of typical globular clusters or planetary nebulae. See also: Virgo Cluster

Tertiary distance indicators are then used to extrapolate from the Virgo Cluster to more distant clusters. Galaxies in the Virgo

Cluster are observed to have a simple relationship, noted by B. Tully and R. Fisher, between their gas velocities and their luminosity. This relation is used to measure the relative distance to distant galaxies. Together with Doppler-shift measurements of recessional velocity, this technique yields estimates of the Hubble constant. See also: Doppler effect

Observations using the *Hubble Space Telescope* have significantly improved our measurements of the Hubble constant. These observations suggest that the Hubble constant is 65–80 (km/s)/Mpc. If the lambda CDM model is assumed, the *Wilkinson Microwave Anisotropy Probe's* measurements of primordial fluctuations imply a Hubble constant of 68–76 (km/s)/Mpc. Estimates of the Hubble constant using other techniques (for example, time delays from multiple imaged quasars) yield consistent results.

Observations of supernovae have become a powerful tool for measuring distances to distant galaxies. Type Ia supernovae, supernovae produced by the explosive burning of a white dwarf star, have nearly the same luminosity. By measuring the time evolution of these supernovae, astronomers can correct for variations in their absolute luminosities and use these standard candles to determine the distances to galaxies. By measuring the distances to supernovae as a function of their redshifts, astronomers have been able to determine the geometry and expansion history of the universe. Current data suggest that the universe is accelerating and is well fit by the basic parameters of the lambda CDM model. See also: Accelerating universe

Ground-based supernova observations have found that supernovae at redshifts of 0.3–0.8 are systematically dimmer than predicted in cosmological models without dark energy (**Fig. 3**). The observations imply that the universe is now accelerating. Hubble telescope observations of supernovae at redshifts greater than 1 (not shown in Fig. 3) find that these more distant supernovae are actually brighter than expected in a universe without dark energy. The observations of these more distant supernovae imply that, earlier in its history, the expansion of the universe was slowing and that dark energy has been dominating the expansion only during the past 5 × 10^9 years. The current supernova data fit the lambda CDM model well and are one of the key pieces of evidence for the existence of dark energy.

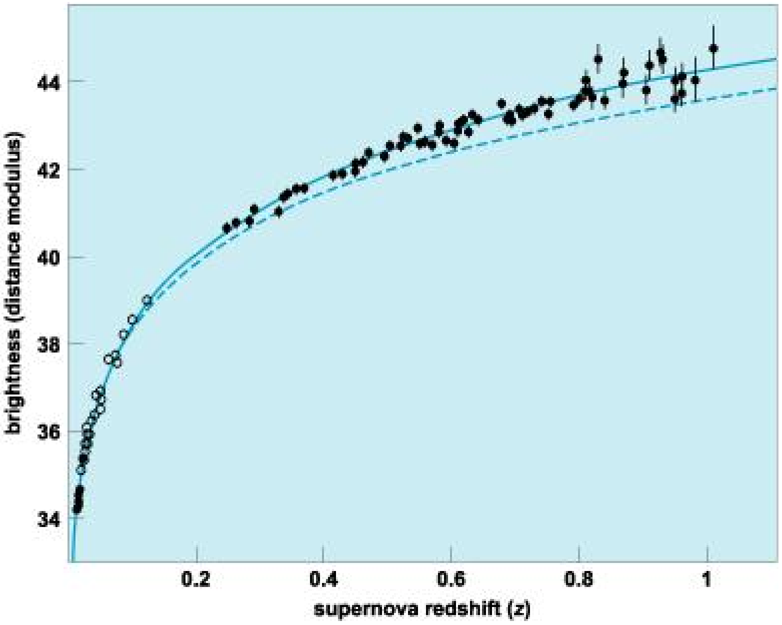


Fig. 3 Brightness of supernovae as a function of their redshift. The supernova brightnesses are measured in terms of the distance modulus, which is related to the magnitude (it is the difference between the apparent and absolute magnitudes), and are corrected for variations in supernova properties. The broken line shows the predictions for a flat universe with no dark energy. The solid line shows the predictions of the lambda CDM model. (*P. Astier; Supernova Legacy Survey*)

Age of the universe

The universe ought to be older than any visible star; thus, the inferred ages of the stars in the Milky Way Galaxy place a lower limit on the age of the universe. The oldest known stars are in globular clusters, dense concentrations of roughly 100,000 stars, believed to be 12–20 × 10^9 years old. These age estimates are based on models of stellar evolution that predict when a star of a given mass becomes a red giant. See also: Star clusters; Stellar evolution

Distant elliptical galaxies are composed almost entirely of old stars. Measurements of their spectra constrain the age of the universe as a function of redshift. Measurements of the age of the universe provided the first strong hints of the existence of dark energy. The current measurements of the Hubble constant imply that a flat universe without dark energy would be only 9 × 10^9 years old, much younger than some of the stars in our galaxy. In a flat universe without dark energy, light from objects with a redshift of 2 was emitted when the universe was only 1.7 × 10^9 years old, which is difficult to reconcile with observations showing the existence of 2.5 × 10^9-year-old stars in galaxies with this redshift. On the other hand, models with dark energy provide a good fit to measurements of stellar and galactic ages (**Fig. 4**).

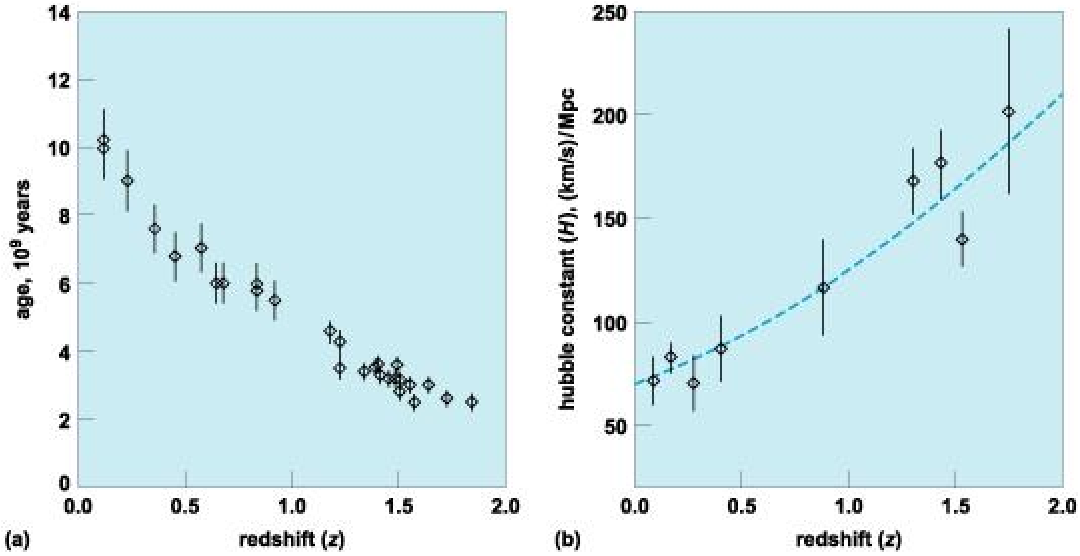


Fig. 4 Comparison of galactic ages with predictions of the lambda CDM model. (*a*) Ages of the oldest galaxies as a function of redshift. (*b*) Data points and bars show the Hubble constant inferred from the galactic ages. The curve shows the predictions of the lambda CDM model. (*J. Simon, L. Verde, R. Jimenez*)

Just as radioactivity lifetimes can be used to date archeological artifacts, nuclear dating provides an alternative independent measure of the age of the Milky Way Galaxy. By using these techniques, the minimum age of the Galaxy has been estimated to be 10 × 10^9 years. The oldest white dwarf stars detected are 9 × 10^9 years old, and the Sun is believed to be 4.5 × 10^9 years old. These age measurements place a firm lower limit on the age of the universe. See also: Solar system; White dwarf star

Observations of the microwave background fluctuations yield a direct geometric measurement of the age of the universe. The fluctuations have a characteristic size set by the distance that sound waves can travel in 500,000 years. By measuring the angular size of the typical fluctuation, cosmologists have determined an age of the universe as 13–14 × 10^9 years.

Dark-matter problem

Astronomers have been in an embarrassing situation for several decades: the amount of mass measured dynamically in galaxies by observing stellar and gas motions is roughly 10 times the mass observed in dust, gas, and known stars. This discrepancy suggests that either there is a basic flaw in newtonian physics or 90% of the mass in galaxies is in some yet unknown form, usually referred to as dark matter.

Evidence for dark matter

Some of the strongest evidence for existence of dark matter comes from radio observations of hydrogen gas and optical observations of star motions in spiral galaxies like the Milky Way Galaxy. The neutral gas and stars in the disks of galaxies are moving in nearly circular orbits. The centrifugal acceleration of the gas (and stars), v^2/r outward (where v is the velocity of motion and r is the orbit radius), must balance the gravitational acceleration of the galaxy, yielding Eq. (4),

$$v^2 = \frac{GM(r)}{r} \tag{4}$$

where $M(r)$ is the mass of the galaxy within radius of the gas or stellar orbit. Thus, observations of the gas or stellar velocity are a direct measure of the mass interior to its orbit. Most of the light in a galaxy like the Milky Way Galaxy is located in the inner 15,000 parsecs. (The Sun is roughly 8000 parsecs from the galactic center.) If mass were distributed as light, the gas rotation velocity should begin to fall off outside the optical edge of the galaxy. In all optical and radio observations of spiral galaxies, the gas rotation velocity is not falling but is either flat or slowly rising. This situation implies that there is mass where there is no light.

Observations of hot x-ray-emitting gas in elliptical galaxies provide a method for measuring their mass distribution. Since the gas pressure gradients must balance the force of gravity, gas density and temperature profiles can be directly related to the elliptical galaxy mass profiles. Data from x-ray satellites suggest that the galactic dark-matter problem is ubiquitous: all galaxies, whether spiral or elliptical, dwarf or normal, seem to have halos of dark matter. See also: X-ray astronomy

Observations of groups and clusters of galaxies provide an alternative method of weighing galaxies. The velocities of galaxies in clusters can be used to determine the mass of the entire cluster. This technique for measuring galactic mass, first applied in the 1930s, also implies a dynamical galactic mass that vastly exceeds the mass in luminous material.

General relativity implies that mass curves space. Thus, the path of light rays moving through a cluster of galaxies is bent by the mass within the cluster (**Fig. 5**). Hence, dense clusters of galaxies can act as gravitational lenses that distort the images of galaxies behind the cluster into arcs. Measurements of these distorted arcs confirm the evidence for enormous amounts of dark matter in clusters. See also: Gravitational lens

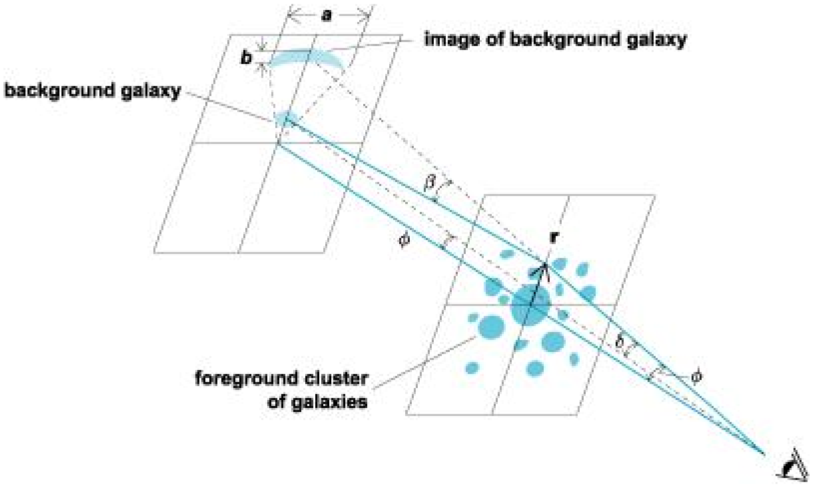


Fig. 5 Gravitational displacement and distortion (lensing) of a distant background galaxy by a compact foreground cluster of galaxies. A light ray passing the cluster plane at an impact parameter vector **r** is gravitationally bent through an angle β. Thus, it is seen displaced (through an angle δ) from φ, its true angular distance from the cluster centroid, to the larger angle φ. Because of its finite width, the image also is distorted into a circular arc (of length *a* and width *b*) concentric with the cluster. (*After A. Tyson, Mapping dark matter with gravitational lenses, Phys. Today, 45(6):24–32, June 1992*)

Candidates for dark matter

Candidates for the dark matter range in mass from microelectronvolt axions to 10^6-solar-mass black holes. Many groups of physicists and astronomers are actively searching for various candidates for the dark matter.

Baryons (such as ordinary protons and neutrons) make up most of the mass of the Earth and the Sun. Baryons are the most obvious dark-matter candidate. These baryons cannot be bound into luminous stars, nor can they be in either hot or cold gas. Cold gas can be detected through hyperfine and molecular lines. Hot gas is detectable by ultraviolet and x-ray satellites. Current observations constrain the gas mass to be much less than the mass needed to account for the dark matter. Within our galaxy, baryons could have escaped direct detection if they were bound together into clumps, either as comets, bound by atomic forces, or as planets or very low mass stars, bound by gravitational forces. However, microwave background observations provide a more direct total accounting of the composition of the universe. These observations imply that the total density in atoms is only one-sixth of the density in matter, so ordinary matter is no longer considered a likely candidate for the dark matter.

Black holes have been proposed as another possible candidate for the dark matter. If the first generation of star formation consisted of very massive stars, these objects would rapidly burn hydrogen to heavier elements and then collapse to black holes. Observational constraints on element abundance require that these massive stars not lose much of the carbon, oxygen, or iron produced during their stellar evolution to the interstellar medium. Models of very massive star evolution suggest that these stars could swallow most of their mass and form a halo of black holes. This scenario is rather tentative, since very little is understood about pregalactic star formation. These black holes could also be detected in the current gravitational lensing searches. See also: Black hole

The currently favored hypothesis is that the dark matter consists of some as yet undetected particle. Particle physicists have suggested several possible candidates for the dark matter. The most popular of these particles is predicted in an extension of standard physics called supersymmetry. This particle, named a WIMP (weakly interacting massive particle), could potentially be detected in deep underground experiments or created in particle accelerators. The upcoming generation of dark-matter experiments at CERN may be able to produce these particles in the laboratory. See also: Elementary particle; Supersymmetry; Weakly interacting massive particle (WIMP)

Dark energy

Measurements of distances to supernovae, galaxies, and the microwave background imply that most of the energy in the universe is not in the form of matter but dark energy. Measurements of the evolution of the clustering of galaxies confirm the existence of this dark energy and imply that it does not cluster gravitationally.

The most popular current idea for the dark energy is that it is energy associated with the vacuum. Einstein first posited the existence of this vacuum energy (or cosmological constant); however, the current model of fundamental physics cannot explain its measured value.

Other possible explanations for the dark energy include extremely weakly interacting ultralight fields or modifications of general relativity. Understanding the dark energy and measuring its properties is one of the most active areas of research not only in cosmology but also in all of physics.

Alternatives to the hot big bang

There have been a variety of models proposed as alternatives to the hot big bang. Historically, the most important alternative model was the steady-state model, which assumes a homogeneous expanding universe that is not evolving because matter is continuously being created out of the vacuum. This model has great difficulty accounting for the observed shape of the microwave background radiation and cannot account for the observed abundance of helium.

Another alternative is the cold big bang model in which the universe began in a big bang that started at absolute zero. It has been suggested that in this model the microwave background radiation could be due to reemitted light from iron needles. This model requires special dust grains and also cannot explain the abundances of light elements.

In H. Alfvén's plasma universe, the Milky Way Galaxy is part of a finite cloud of material expanding into empty flat space. It is very difficult for this model to explain the observed uniformity of the microwave background spectrum or the light-element abundances.

E. Segal has proposed an alternative to cosmology based on general relativity. In this chronometric theory, there is a quadratic rather than a linear relationship between redshift and distance. Modern measurements of the distances to rich clusters find that these objects obey Hubble's linear relationship rather than Segal's quadratic law. Observations of the correlation between jet expansion velocity and redshift are a direct test of the chronometric hypothesis, which it fails.

David N. Spergel

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- Simulations of Galaxy Clustering
- Hubble Constant
- Distant Exploding Stars Foretell Fate of the Universe: It Will Expand Forever
- How Old Is the Universe?
- MACHO Project
- Dark Matter

- Explore the Science of Dark Matter
- Cryogenic Dark Matter Search
- The Cosmological Constant (Introduction to Dark Energy)
- Errors in Some Popular Attacks on the Big Bang

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