Observational cosmology - 30h course

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Contents

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Observational cosmology

Observational cosmology is the study of the structure, the evolution and the origin of the universe through observation, using instruments such as telescopes and cosmic ray detectors.

Early observations

The science of physical cosmology as it is practiced today had its subject material defined in the years following the Shapley-Curtis debate when it was determined that the universe had a larger scale than the Milky Way galaxy. This was precipitated by observations that established the size and the dynamics of the cosmos that could be explained by Einstein's General Theory of Relativity. In its infancy, cosmology was a speculative science based on a very limited number of observations and characterized by a dispute between steady state theorists and promoters of Big Bang cosmology. It was not until the 1990s and beyond that the astronomical observations would be able to eliminate competing theories and drive the science to the "Golden Age of Cosmology" which was heralded by David Schramm at a National Academy of Sciences colloquium in 1992.[1]

Hubble's Law and the cosmic distance ladder

Distance measurements in astronomy have historically been and continue to be confounded by considerable measurement uncertainty. In particular, while stellar parallax can be used to measure the distance to nearby stars, the observational limits imposed by the difficulty in measuring the minuscule parallaxes associated with objects beyond our galaxy meant that astronomers had to look for alternative ways to measure cosmic distances. To this end, a standard candle measurement for Cepheid variables was discovered by Henrietta Swan Leavitt in 1908 which would provide Edwin Hubble with the rung on the cosmic distance ladder he would need to determine the distance to spiral nebula. Hubble used the 100-inch Hooker Telescope at Mount Wilson Observatory to identify individual stars in those galaxies, and determine the distance to the galaxies by isolating individual Cepheids. This firmly established the spiral nebula as being objects well outside the Milky Way galaxy. Determining the distance to "island universes", as they were dubbed in the popular media, established the scale of the universe and settled the Shapley-Curtis debate once and for all.[2]

In 1927, by combining various measurements, including Hubble's distance measurements and Vesto Slipher's determinations of redshifts for these objects, Georges Lemaître was the first to estimate a constant of proportionality between galaxies' distances and what was termed their "recessional velocities", finding a value of about 600 km/s/Mpc. He also showed that this was theoretically expected by using arguments from general relativity. Two years later, Hubble showed that the relation between the distances and velocities appeared to be a positive correlation. This correlation would come to be known as *Hubble's Law* and would serve as the observational foundation for the expanding universe theories on which cosmology is still based. The publication of the observations by Slipher, Wirtz, Hubble and their colleagues and the acceptance by the theorists of their theoretical implications in light of Einstein's General theory of relativity is considered the beginning of the modern science of cosmology.[3]

Nuclide abundances

Determination of the cosmic abundance of elements has a history dating back to early spectroscopic measurements of light from astronomical objects and the identification of emission and absorption lines which corresponded to particular electronic transitions in chemical elements identified on Earth. For example, the element Helium was first identified through its spectroscopic signature in the Sun before it was isolated as a gas on Earth.[4][5]

Computing relative abundances was achieved through corresponding spectroscopic observations to measurements of the elemental composition of meteorites.

Detection of the cosmic microwave background

A cosmic microwave background was predicted in 1948 by George Gamow and Ralph Alpher, and by Alpher and Robert Herman as due to the hot big bang model. Moreover, Alpher and Herman were able to estimate the temperature,[6] but their results were not widely discussed in the community. Their prediction was rediscovered by Robert Dicke and Yakov Zel'dovich in the early 1960s with the first published recognition of the CMB radiation as a detectable phenomenon appeared in a brief paper by Soviet astrophysicists A. G. Doroshkevich and Igor Novikov, in the spring of 1964. In 1964, David Todd Wilkinson and Peter Roll, Dicke's colleagues at Princeton University, began constructing a Dicke radiometer to measure the cosmic microwave background.[7] In 1965, Arno Penzias and Robert Woodrow Wilson at the Crawford Hill location of Bell Telephone Laboratories in nearby Holmdel Township, New Jersey had built a Dicke radiometer that they intended to use for radio astronomy and satellite communication experiments. Their instrument had an excess 3.5 K antenna temperature which they could not account for. After receiving a telephone call from Crawford Hill, Dicke famously quipped: "Boys, we've been scooped."[8] A meeting between the Princeton and Crawford Hill groups determined that the antenna temperature was indeed due to the microwave background. Penzias and Wilson received the 1978 Nobel Prize in Physics for their discovery.

Modern observations

Today, observational cosmology continues to test the predictions of theoretical cosmology and has led to the refinement of cosmological models. For example, the observational evidence for dark matter has heavily influenced theoretical modeling of structure and galaxy formation. When trying to calibrate the Hubble diagram with accurate supernova standard candles, observational evidence for dark energy was obtained in the late 1990s. These observations have been incorporated into a six-parameter framework known as the Lambda-CDM model which explains the evolution of the universe in terms of its constituent material. This model has subsequently been verified by detailed observations of the cosmic microwave background, especially through the WMAP experiment.

Included here are the modern observational efforts that have directly influenced cosmology.

Redshift surveys

With the advent of automated telescopes and improvements in spectroscopes, a number of collaborations have been made to map the universe in redshift space. By combining redshift with angular position data, a redshift survey maps the 3D distribution of matter within a field of the sky. These observations are used to measure properties of the large-scale structure of the universe. The Great Wall, a vast supercluster of galaxies over 500 million light-years wide, provides a dramatic example of a large-scale structure that redshift surveys can detect.[9]

The first redshift survey was the CfA Redshift Survey, started in 1977 with the initial data collection completed in 1982.[10] More recently, the 2dF Galaxy Redshift Survey determined the large-scale structure of one section of the Universe, measuring z-values for over 220,000 galaxies; data collection was completed in 2002, and the final data set was released 30 June 2003.[11] (In addition to mapping large-scale patterns of galaxies, 2dF established an upper limit on neutrino mass.) Another notable investigation, the Sloan Digital Sky Survey (SDSS), is ongoing as of 2011[12] and aims to obtain measurements on around 100 million objects.[13] SDSS has recorded redshifts for galaxies as high as 0.4, and has been involved in the detection of quasars beyond $z = 6$. The DEEP2 Redshift Survey uses the Keck telescopes with the new "DEIMOS" spectrograph; a follow-up to the pilot program DEEP1, DEEP2 is designed to measure faint galaxies with redshifts 0.7 and above, and it is therefore planned to provide a complement to SDSS and 2dF.

Cosmic microwave background experiments

Subsequent to the discovery of the CMB, hundreds of cosmic microwave background experiments had been conducted to measure and characterize the signatures of the radiation. The most famous experiment is probably the NASA Cosmic Background Explorer (COBE) satellite that orbited in 1989–1996 and which detected and quantified the large-scale anisotropies at the limit of its detection capabilities. Inspired by the initial COBE results of an extremely isotropic and homogeneous background, a series of ground-based and balloon-based experiments quantified CMB anisotropies on smaller angular scales over the next decade. The primary goal of those experiments was to measure the angular scale of the first acoustic peak, for which COBE did not have sufficient resolution. The measurements were able to rule out cosmic strings as the leading theory of cosmic structure formation, and suggested cosmic inflation was the right theory. During the 1990s, the first peak was measured with increasing sensitivity and by 2000 the BOOMERanG experiment reported that the highest power fluctuations occur at scales of approximately one degree. Together with other cosmological data, these results implied that the geometry of the Universe is flat. A number of ground-based interferometers provided measurements of the fluctuations with higher accuracy over the next three years, including the Very Small Array, Degree Angular Scale Interferometer (DASI) and the Cosmic Background Imager (CBI). DASI made the first detection of the polarization of the CMB and the CBI provided the first E-mode spectrum with compelling evidence that it is out of phase with the T-mode spectrum.

In June 2001, NASA launched a second CMB space mission, WMAP, to make much more precise measurements of the large-scale anisotropies over the full sky. The first results from this mission, disclosed in 2003, were detailed measurements of the angular power spectrum to below degree scales, tightly constraining various cosmological parameters. The results are broadly consistent with those expected from cosmic inflation as well as various other competing theories, and are available in detail at NASA's data center for Cosmic Microwave Background (CMB) (see links below). Although WMAP provided very accurate measurements of the large angular-scale fluctuations in the CMB (structures about as large in the sky as the moon), it did not have the angular resolution to measure the smaller scale fluctuations which had been observed using previous ground-based interferometers.

A third space mission, Planck, was launched in May 2009. Planck employs both HEMT radiometers and bolometer technology and measures the CMB anisotropies at a higher resolution than WMAP. Unlike the previous two space missions, Planck is a collaboration between NASA and the European Space Agency (ESA). Its detectors got a trial run at the Antarctic Viper telescope as ACBAR (Arcminute Cosmology Bolometer Array Receiver) experiment – which has produced the most precise measurements at small angular scales to date – and at the Archeops balloon telescope.

Additional ground-based instruments such as the South Pole Telescope in Antarctica and the proposed Clover Project, Atacama Cosmology Telescope and the QUIET telescope in Chile will provide additional data not available from satellite observations, possibly including the B-mode polarization.

Telescope observations

Radio

The brightest sources of low-frequency radio emission (10 MHz and 100 GHz) are radio galaxies which can be observed out to extremely high redshifts. These are subsets of the active galaxies that have extended features known as lobes and jets which extend away form the galactic nucleus distances on the order of megaparsecs. Because radio galaxies are so bright, astronomers have used them to probe extreme distances and early times in the evolution of the universe.

Infrared

Far infrared observations including submillimeter astronomy have revealed a number of sources at cosmological distances. With the exception of a few atmospheric windows, most of infrared light is blocked by the atmosphere, the observations generally take place from balloon or space-based instruments. Current observational experiments in the infrared include NICMOS, the Cosmic Origins Spectrograph, the Spitzer Space Telescope, the Keck Interferometer, the Stratospheric Observatory For Infrared Astronomy, and the Herschel Space Observatory. The next large space telescope planned by NASA, the James Webb Space Telescope will also explore in the infrared.

Future observations

Cosmic neutrinos

It is a prediction of the Big Bang model that the universe is filled with a neutrino background radiation, analogous to the cosmic microwave background radiation. The microwave background is a relic from when the universe was about 380,000 years old, but the neutrino background is a relic from when the universe was about two seconds old.

If this neutrino radiation could be observed, it would be a window into very early stages of the universe. Unfortunately, these neutrinos would now be very cold, and so they are effectively impossible to observe directly.

References

[1] Arthur M. Sackler Colloquia of the National Academy of Sciences: Physical Cosmology; Irvine, California: March 27–28, 1992.

[2] "Island universe" is a reference to speculative ideas promoted by a variety of scholastic thinkers in the 18th and 19th centuries. The most famous early proponent of such ideas was philosopher Immanuel Kant who published a number of treatises on astronomy in addition to his more famous philosophical works. See Kant, I., 1755. *Allgemeine Naturgeschichte und Theorie des Himmels*, Part I, J.F. Peterson, Königsberg and Leipzig.

[3] This popular consideration is echoed in *Time Magazine's* listing for Edwin Hubble in their Time 100 list of most influential people of the 20th Century. Michael Lemonick recounts, "He discovered the cosmos, and in doing so founded the science of cosmology." (http://www.time.com/time/time100/scientist/profile/hubble.html)

[4] *The Encyclopedia of the Chemical Elements*, page 256

[5] *Oxford English Dictionary* (1989), s.v. "helium". Retrieved December 16, 2006, from Oxford English Dictionary Online. Also, from quotation there: Thomson, W. (1872). *Rep. Brit. Assoc.* xcix: "Frankland and Lockyer find the yellow prominences to give a very decided bright line not far from D, but hitherto not identified with any terrestrial flame. It seems to indicate a new substance, which they propose to call Helium."

[6] G. Gamow, "The Origin of Elements and the Separation of Galaxies," *Physical Review* **74** (1948), 505. G. Gamow, "The evolution of the universe", *Nature* **162** (1948), 680. R. A. Alpher and R. Herman, "On the Relative Abundance of the Elements," *Physical Review* **74** (1948), 1577.

[7] R. H. Dicke, "The measurement of thermal radiation at microwave frequencies", *Rev. Sci. Instrum.* **17**, 268 (1946). This basic design for a radiometer has been used in most subsequent cosmic microwave background experiments.

[8] A. A. Penzias and R. W. Wilson, "A Measurement of Excess Antenna Temperature at 4080 Mc/s," *Astrophysical Journal* **142** (1965), 419. R. H. Dicke, P. J. E. Peebles, P. G. Roll and D. T. Wilkinson, "Cosmic Black-Body Radiation," *Astrophysical Journal* **142** (1965), 414. The history is given in P. J. E. Peebles, *Principles of physical cosmology* (Princeton Univ. Pr., Princeton 1993).

[9] M. J. Geller & J. P. Huchra, *Science* **246**, 897 (1989). online (http://www.sciencemag.org/cgi/content/abstract/246/4932/897)

[10] See the official CfA website (http://cfa-www.harvard.edu/~huchra/zcat/) for more details.

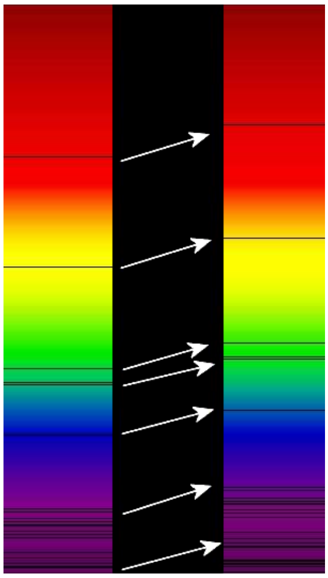
[11] 2dF Galaxy Redshift Survey homepage (http://msowww.anu.edu.au/2dFGRS/)

[12] http://en.wikipedia.org/w/index.php?title=Observational_cosmology&action=edit

[13] SDSS Homepage (http://www.sdss.org/)

Observations: expansion, nucleosynthesis, CMB

Redshift



Absorption lines in the optical spectrum of a supercluster of distant galaxies (right), as compared to absorption lines in the optical spectrum of the Sun (left). Arrows indicate redshift. Wavelength increases up towards the red and beyond (frequency decreases).

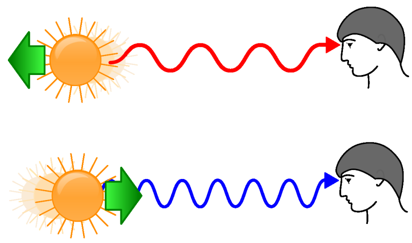
In physics, **redshift** happens when light or other electromagnetic radiation from an object moving away from the observer is increased in wavelength, or shifted to the red end of the spectrum. In general, whether or not the radiation is within the visible spectrum, "redder" means an increase in wavelength – equivalent to a lower frequency and a lower photon energy, in accordance with, respectively, the wave and quantum theories of light.

Redshifts are an example of the Doppler effect, familiar in the change in the apparent pitches of sirens and frequency of the sound waves emitted by speeding vehicles. A redshift occurs whenever a light source moves away from an observer. Cosmological redshift is seen due to the expansion of the universe, and sufficiently distant light sources (generally more than a few million light years away) show redshift corresponding to the rate of increase in their distance from Earth. Finally, gravitational redshifts are a relativistic effect observed in electromagnetic radiation moving out of gravitational fields. Conversely, a *decrease* in wavelength is called blueshift and is generally seen when a light-emitting object moves toward an observer or when electromagnetic radiation moves into a gravitational field.

Although observing redshifts and blueshifts have several terrestrial applications (such as Doppler radar and radar guns),[1] redshifts are most famously seen in the spectroscopic observations of astronomical objects.[2]

A special relativistic redshift formula (and its classical approximation) can be used to calculate the redshift of a nearby object when spacetime is flat. However, many cases such as black holes and Big Bang cosmology require that redshifts be calculated using general relativity.[3] Special relativistic, gravitational, and cosmological redshifts can be understood under the umbrella of frame transformation laws. There exist other physical processes that can lead to a shift in the frequency of electromagnetic radiation, including scattering and optical effects; however, the resulting changes are distinguishable from true redshift and not generally referred to as such (see section on physical optics and radiative transfer).

History


Redshift and blueshift

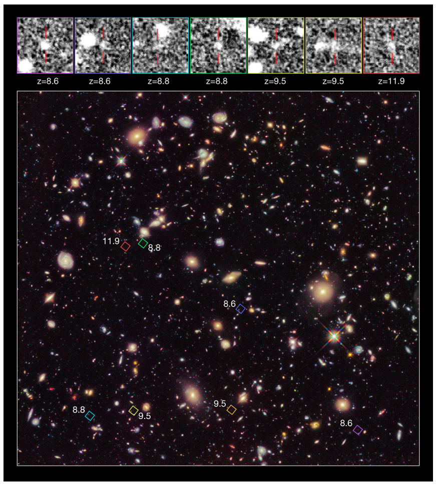
The history of the subject began with the development in the 19th century of wave mechanics and the exploration of phenomena associated with the Doppler effect. The effect is named after Christian Doppler, who offered the first known physical explanation for the phenomenon in 1842. The hypothesis was tested and confirmed for sound waves by the Dutch scientist Christophorus Buys Ballot in 1845. Doppler correctly predicted that the phenomenon should apply to all waves, and in particular suggested that the varying colors of stars could be attributed to their motion with respect to the Earth. Before this was verified, however, it was found that stellar colors were primarily due to a star's temperature, not motion. Only later was Doppler vindicated by verified redshift observations.

The first Doppler redshift was described by French physicist Hippolyte Fizeau in 1848, who pointed to the shift in spectral lines seen in stars as being due to the Doppler effect. The effect is sometimes called the "Doppler–Fizeau effect". In 1868, British astronomer William Huggins was the first to determine the velocity of a star moving away from the Earth by this method. In 1871, optical redshift was confirmed when the phenomenon was observed in Fraunhofer lines using solar rotation, about 0.1 Å in the red. In 1887, Vogel and Scheiner discovered the *annual Doppler effect*, the yearly change in the Doppler shift of stars located near the ecliptic due to the orbital velocity of the Earth. In 1901, Aristarkh Belopolsky verified optical redshift in the laboratory using a system of rotating mirrors.

The earliest occurrence of the term "red-shift" in print (in this hyphenated form), appears to be by American astronomer Walter S. Adams in 1908, where he mentions "Two methods of investigating that nature of the nebular red-shift".[4] The word doesn't appear unhyphenated until about 1934 by Willem de Sitter, perhaps indicating that up to that point its German equivalent, *Rotverschiebung*, was more commonly used.

Beginning with observations in 1912, Vesto Slipher discovered that most spiral nebulae had considerable redshifts. Slipher first reports on his measurement in the inaugural volume of the *Lowell Observatory Bulletin*. Three years later, he wrote a review in the journal *Popular Astronomy*. In it he states, "[...] the early discovery that the great Andromeda spiral had the quite exceptional velocity of –300 km(/s) showed the means then available, capable of investigating not only the spectra of the spirals but their velocities as well." Slipher reported the velocities for 15 spiral nebulae spread across the entire celestial sphere, all but three having observable "positive" (that is recessional) velocities. Subsequently, Edwin Hubble discovered an approximate relationship between the redshifts of such "nebulae" (now known to be galaxies in their own right) and the distances to them with the formulation of his eponymous Hubble's law. These observations corroborated Alexander Friedmann's 1922 work, in which he derived the famous Friedmann equations.[5] They are today considered strong evidence for an expanding universe and the Big Bang theory.[6]

Measurement, characterization, and interpretation


High-redshift galaxy candidates in the Hubble Ultra Deep Field 2012.

The spectrum of light that comes from a single source (see idealized spectrum illustration top-right) can be measured. To determine the redshift, one searches for features in the spectrum such as absorption lines, emission lines, or other variations in light intensity. If found, these features can be compared with known features in the spectrum of various chemical compounds found in experiments where that compound is located on earth. A very common atomic element in space is hydrogen. The spectrum of originally featureless light shone through hydrogen will show a signature spectrum specific to hydrogen that has features at regular intervals. If restricted to absorption lines it would look similar to the illustration (top right). If the same pattern of intervals is seen in an observed spectrum from a distant source but occurring at shifted wavelengths, it can be identified as hydrogen too. If the same spectral line is identified in both spectra but at different wavelengths then the redshift can be calculated using the table below. Determining the redshift of an object in this way requires a frequency- or wavelength-range. In order to calculate the redshift one has to know the wavelength of the emitted light in the rest frame of the source, in other words, the wavelength that would be measured by an observer located adjacent to and comoving with the source. Since in astronomical applications this measurement cannot be done directly, because that would require travelling to the distant star of interest, the method using spectral lines described here is used instead. Redshifts cannot be calculated by looking at unidentified features whose rest-frame frequency is unknown, or with a spectrum that is featureless or white noise (random fluctuations in a spectrum).[7]

Redshift (and blueshift) may be characterized by the relative difference between the observed and emitted wavelengths (or frequency) of an object. In astronomy, it is customary to refer to this change using a dimensionless quantity called z. If λ represents wavelength and f represents frequency (note, $\lambda f = c$ where c is the speed of light), then z is defined by the equations:[8]

Calculation of redshift,

Based on wavelength	Based on frequency
$z = \frac{\lambda_{\mathrm{obsv}} - \lambda_{\mathrm{emit}}}{\lambda_{\mathrm{emit}}}$	$z = \frac{f_{\mathrm{emit}} - f_{\mathrm{obsv}}}{f_{\mathrm{obsv}}}$
$1 + z = \frac{\lambda_{\mathrm{obsv}}}{\lambda_{\mathrm{emit}}}$	$1 + z = \frac{f_{\mathrm{emit}}}{f_{\mathrm{obsv}}}$

After z is measured, the distinction between redshift and blueshift is simply a matter of whether z is positive or negative. See the formula section below for some basic interpretations that follow when either a redshift or blueshift is observed. For example, Doppler effect blueshifts ($z < 0$) are associated with objects approaching (moving closer to) the observer with the light shifting to greater energies. Conversely, Doppler effect redshifts ($z > 0$) are associated with objects receding (moving away) from the observer with the light shifting to lower energies. Likewise, gravitational blueshifts are associated with light emitted from a source residing within a weaker gravitational field as observed from within a stronger gravitational field, while gravitational redshifting implies the opposite conditions.

Redshift formulae

In general relativity one can derive several important special-case formulae for redshift in certain special spacetime geometries, as summarized in the following table. In all cases the magnitude of the shift (the value of z) is independent of the wavelength.

Redshift Summary

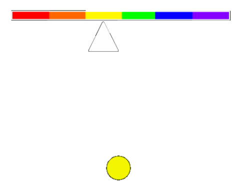
Redshift type	Geometry	Formula[9]
Relativistic Doppler	Minkowski space (flat spacetime)	$1+z=\gamma\left(1+\frac{v_{\parallel}}{c}\right)$ $z\approx\frac{v_{\parallel}}{c}$ for small v $1+z=\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}$ for motion completely in the radial direction. $1+z=\frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$ for motion completely in the transverse direction.
Cosmological redshift	FLRW spacetime (expanding Big Bang universe)	$1+z=\frac{a_{\mathrm{now}}}{a_{\mathrm{then}}}$
Gravitational redshift	any stationary spacetime (e.g. the Schwarzschild geometry)	$1+z=\sqrt{\frac{g_{tt}(\mathrm{receiver})}{g_{tt}(\mathrm{source})}}$ (for the Schwarzschild geometry, $1+z=\sqrt{\frac{1-\frac{2GM}{c^2 r_{\mathrm{receiver}}}}{1-\frac{2GM}{c^2 r_{\mathrm{source}}}}}$

Doppler effect

If a source of the light is moving away from an observer, then redshift ($z > 0$) occurs; if the source moves towards the observer, then blueshift ($z < 0$) occurs. This is true for all electromagnetic waves and is explained by the Doppler effect. Consequently, this type of redshift is called the *Doppler redshift*. If the source moves away from the observer with velocity v, which is much less than the speed of light ($v \ll c$), the redshift is given by

$$z \approx \frac{v}{c} \quad (\text{since } \gamma \approx 1)$$

where c is the speed of light. In the classical Doppler effect, the frequency of the source is not modified, but the recessional motion causes the illusion of a lower frequency.



Doppler effect, yellow (~575 nm wavelength) ball appears greenish (blueshift to ~565 nm wavelength) approaching observer, turns orange (redshift to ~585 nm wavelength) as it passes, and returns to yellow when motion stops. To observe such a change in color, the object would have to be traveling at approximately 5200 km/s, or about 75 times faster than the speed record for the fastest manmade space probe.

A more complete treatment of the Doppler redshift requires considering relativistic effects associated with motion of sources close to the speed of light. A complete derivation of the effect can be found in the article on the relativistic Doppler effect. In brief, objects moving close to the speed of light will experience deviations from the above formula due to the time dilation of special relativity which can be corrected for by introducing the Lorentz factor γ into the classical Doppler formula as follows:

$$1+z=\left(1+\frac{v}{c}\right)\gamma.$$

This phenomenon was first observed in a 1938 experiment performed by Herbert E. Ives and G.R. Stilwell, called the Ives–Stilwell experiment.[10]

Since the Lorentz factor is dependent only on the magnitude of the velocity, this causes the redshift associated with the relativistic correction to be independent of the orientation of the source movement. In contrast, the classical part of the formula is dependent on the projection of the movement of the source into the line-of-sight which yields different results for different orientations. If θ is the angle between the direction of relative motion and the direction of emission in the observer's frame (zero angle is directly away from the observer), the full form for the relativistic Doppler effect becomes:

$$1+z=\frac{1+v\cos(\theta)/c}{\sqrt{1-v^2/c^2}}$$

and for motion solely in the line of sight ($\theta = 0°$), this equation reduces to:

$$1+z=\sqrt{\frac{1+\frac{v}{c}}{1-\frac{v}{c}}}.$$

For the special case that the light is approaching at right angles ($\theta = 90°$) to the direction of relative motion in the observer's frame, the relativistic redshift is known as the transverse redshift, and a redshift:

$$1+z=\frac{1}{\sqrt{1-v^2/c^2}}$$

is measured, even though the object is not moving away from the observer. Even when the source is moving towards the observer, if there is a transverse component to the motion then there is some speed at which the dilation just cancels the expected blueshift and at higher speed the approaching source will be redshifted.[11]

Expansion of space

In the early part of the twentieth century, Slipher, Hubble and others made the first measurements of the redshifts and blueshifts of galaxies beyond the Milky Way. They initially interpreted these redshifts and blueshifts as due solely to the Doppler effect, but later Hubble discovered a rough correlation between the increasing redshifts and the increasing distance of galaxies. Theorists almost immediately realized that these observations could be explained by a different mechanism for producing redshifts. Hubble's law of the correlation between redshifts and distances is required by models of cosmology derived from general relativity that have a metric expansion of space. As a result, photons propagating through the expanding space are stretched, creating the cosmological redshift.

There is a distinction between a redshift in cosmological context as compared to that witnessed when nearby objects exhibit a local Doppler-effect redshift. Rather than cosmological redshifts being a consequence of relative velocities, the photons instead increase in wavelength and redshift because of a feature of the spacetime through which they are traveling that causes space to expand.[12] Due to the expansion increasing as distances increase, the distance between two remote galaxies can increase at more than 3×10^8 m/s, but this does not imply that the galaxies move faster than the speed of light at their present location (which is forbidden by Lorentz covariance).

Mathematical derivation

The observational consequences of this effect can be derived using the equations from general relativity that describe a homogeneous and isotropic universe.

To derive the redshift effect, use the geodesic equation for a light wave, which is

$$ds^2 = 0 = -c^2 dt^2 + \frac{a^2 dr^2}{1 - kr^2}$$

where

- ds^2 is the spacetime interval
- dt^2 is the time interval
- dr^2 is the spatial interval
- c is the speed of light
- a is the time-dependent cosmic scale factor
- k is the curvature per unit area.

For an observer observing the crest of a light wave at a position $r = 0$ and time $t = t_{\text{now}}$, the crest of the light wave was emitted at a time $t = t_{\text{then}}$ in the past and a distant position $r = R$. Integrating over the path in both space and time that the light wave travels yields:

$$c \int_{t_{\text{then}}}^{t_{\text{now}}} \frac{dt}{a} = \int_R^0 \frac{dr}{\sqrt{1 - kr^2}} \,.$$

In general, the wavelength of light is not the same for the two positions and times considered due to the changing properties of the metric. When the wave was emitted, it had a wavelength λ_{then}. The next crest of the light wave was emitted at a time

$$t = t_{\text{then}} + \lambda_{\text{then}}/c \,.$$

The observer sees the next crest of the observed light wave with a wavelength λ_{now} to arrive at a time

$$t = t_{\text{now}} + \lambda_{\text{now}}/c \,.$$

Since the subsequent crest is again emitted from $r = R$ and is observed at $r = 0$, the following equation can be written:

$$c \int_{t_{\text{then}}+\lambda_{\text{then}}/c}^{t_{\text{now}}+\lambda_{\text{now}}/c} \frac{dt}{a} = \int_R^0 \frac{dr}{\sqrt{1 - kr^2}} \,.$$

The right-hand side of the two integral equations above are identical which means

$$c \int_{t_{\text{then}}+\lambda_{\text{then}}/c}^{t_{\text{now}}+\lambda_{\text{now}}/c} \frac{dt}{a} = c \int_{t_{\text{then}}}^{t_{\text{now}}} \frac{dt}{a}$$

or, alternatively,

$$\int_{t_{\text{now}}}^{t_{\text{now}}+\lambda_{\text{now}}/c} \frac{dt}{a} = \int_{t_{\text{then}}}^{t_{\text{then}}+\lambda_{\text{then}}/c} \frac{dt}{a} \,.$$

For very small variations in time (over the period of one cycle of a light wave) the scale factor is essentially a constant ($a = a_{\text{now}}$ today and $a = a_{\text{then}}$ previously). This yields

$$\frac{t_{\text{now}} + \lambda_{\text{now}}/c}{a_{\text{now}}} - \frac{t_{\text{now}}}{a_{\text{now}}} = \frac{t_{\text{then}} + \lambda_{\text{then}}/c}{a_{\text{then}}} - \frac{t_{\text{then}}}{a_{\text{then}}}$$

which can be rewritten as

$$\frac{\lambda_{\text{now}}}{\lambda_{\text{then}}} = \frac{a_{\text{now}}}{a_{\text{then}}} \,.$$

Using the definition of redshift provided above, the equation

$$1+z=\frac{a_{\mathrm{now}}}{a_{\mathrm{then}}}$$

is obtained. In an expanding universe such as the one we inhabit, the scale factor is monotonically increasing as time passes, thus, z is positive and distant galaxies appear redshifted.

Using a model of the expansion of the universe, redshift can be related to the age of an observed object, the so-called *cosmic time–redshift relation*. Denote a density ratio as Ω_0:

$$\Omega_0=\frac{\rho}{\rho_{crit}}\ ,$$

with ρ_{crit} the critical density demarcating a universe that eventually crunches from one that simply expands. This density is about three hydrogen atoms per thousand liters of space. At large redshifts one finds:

$$t(z)=\frac{2}{3H_0{\Omega_0}^{1/2}(1+z)^{3/2}}\ ,$$

where H_0 is the present-day Hubble constant, and z is the redshift.

Distinguishing between cosmological and local effects

For cosmological redshifts of $z < 0.01$ additional Doppler redshifts and blueshifts due to the peculiar motions of the galaxies relative to one another cause a wide scatter from the standard Hubble Law.[13] The resulting situation can be illustrated by the Expanding Rubber Sheet Universe, a common cosmological analogy used to describe the expansion of space. If two objects are represented by ball bearings and spacetime by a stretching rubber sheet, the Doppler effect is caused by rolling the balls across the sheet to create peculiar motion. The cosmological redshift occurs when the ball bearings are stuck to the sheet and the sheet is stretched.[14]

The redshifts of galaxies include both a component related to recessional velocity from expansion of the universe, and a component related to peculiar motion (Doppler shift).[15] The redshift due to expansion of the universe depends upon the recessional velocity in a fashion determined by the cosmological model chosen to describe the expansion of the universe, which is very different from how Doppler redshift depends upon local velocity.[16] Describing the cosmological expansion origin of redshift, cosmologist Edward Robert Harrison said, "Light leaves a galaxy, which is stationary in its local region of space, and is eventually received by observers who are stationary in their own local region of space. Between the galaxy and the observer, light travels through vast regions of expanding space. As a result, all wavelengths of the light are stretched by the expansion of space. It is as simple as that.... Steven Weinberg clarified, "The increase of wavelength from emission to absorption of light does not depend on the rate of change of *a(t)* [here *a(t)* is the Robertson-Walker scale factor] at the times of emission or absorption, but on the increase of *a(t)* in the whole period from emission to absorption."

Popular literature often uses the expression "Doppler redshift" instead of "cosmological redshift" to describe the redshift of galaxies dominated by the expansion of spacetime, but the cosmological redshift is not found using the relativistic Doppler equation[17] which is instead characterized by special relativity; thus $v > c$ is impossible while, in contrast, $v > c$ is possible for cosmological redshifts because the space which separates the objects (for example, a quasar from the Earth) can expand faster than the speed of light.[18] More mathematically, the viewpoint that "distant galaxies are receding" and the viewpoint that "the space between galaxies is expanding" are related by changing coordinate systems. Expressing this precisely requires working with the mathematics of the Friedmann-Robertson-Walker metric.[19]

If the universe were contracting instead of expanding, we would see distant galaxies blueshifted by an amount proportional to their distance instead of redshifted.[20]

Gravitational redshift

In the theory of general relativity, there is time dilation within a gravitational well. This is known as the gravitational redshift or *Einstein Shift*. The theoretical derivation of this effect follows from the Schwarzschild solution of the Einstein equations which yields the following formula for redshift associated with a photon traveling in the gravitational field of an uncharged, nonrotating, spherically symmetric mass:

$$1 + z = \frac{1}{\sqrt{1 - \frac{2GM}{rc^2}}},$$

where

- G is the gravitational constant,
- M is the mass of the object creating the gravitational field,
- r is the radial coordinate of the source (which is analogous to the classical distance from the center of the object, but is actually a Schwarzschild coordinate), and
- c is the speed of light.

This gravitational redshift result can be derived from the assumptions of special relativity and the equivalence principle; the full theory of general relativity is not required.

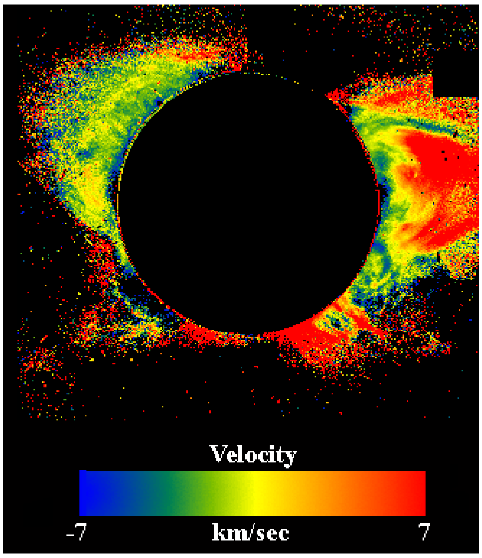
The effect is very small but measurable on Earth using the Mössbauer effect and was first observed in the Pound-Rebka experiment.[21] However, it is significant near a black hole, and as an object approaches the event horizon the red shift becomes infinite. It is also the dominant cause of large angular-scale temperature fluctuations in the cosmic microwave background radiation (see Sachs-Wolfe effect).[22]

Observations in astronomy

The redshift observed in astronomy can be measured because the emission and absorption spectra for atoms are distinctive and well known, calibrated from spectroscopic experiments in laboratories on Earth. When the redshift of various absorption and emission lines from a single astronomical object is measured, z is found to be remarkably constant. Although distant objects may be slightly blurred and lines broadened, it is by no more than can be explained by thermal or mechanical motion of the source. For these reasons and others, the consensus among astronomers is that the redshifts they observe are due to some combination of the three established forms of Doppler-like redshifts. Alternative hypotheses and explanations for redshift such as tired light are not generally considered plausible.[23]

Spectroscopy, as a measurement, is considerably more difficult than simple photometry, which measures the brightness of astronomical objects through certain filters.[24] When photometric data is all that is available (for example, the Hubble Deep Field and the Hubble Ultra Deep Field), astronomers rely on a technique for measuring photometric redshifts.[25] Due to the broad wavelength ranges in photometric filters and the necessary assumptions about the nature of the spectrum at the light-source, errors for these sorts of measurements can range up to $\delta z = 0.5$, and are much less reliable than spectroscopic determinations.[26] However, photometry does at least allow a qualitative characterization of a redshift. For example, if a sun-like spectrum had a redshift of $z = 1$, it would be brightest in the infrared rather than at the yellow-green color associated with the peak of its blackbody spectrum, and the light intensity will be reduced in the filter by a factor of four, $(1+z)^2$. Both the photon count rate and the photon energy are redshifted. (See K correction for more details on the photometric consequences of redshift.)[27]

Local observations



A picture of the solar corona taken with the LASCO C1 coronagraph. The picture is a color-coded image of the doppler shift of the FeXIV 5308 Å line, caused by the coronal plasma velocity towards or away from the satellite.

In nearby objects (within our Milky Way galaxy) observed redshifts are almost always related to the line-of-sight velocities associated with the objects being observed. Observations of such redshifts and blueshifts have enabled astronomers to measure velocities and parametrize the masses of the orbiting stars in spectroscopic binaries, a method first employed in 1868 by British astronomer William Huggins. Similarly, small redshifts and blueshifts detected in the spectroscopic measurements of individual stars are one way astronomers have been able to diagnose and measure the presence and characteristics of planetary systems around other stars and have even made very detailed differential measurements of redshifts during planetary transits to determine precise orbital parameters.[28] Finely detailed measurements of redshifts are used in helioseismology to determine the precise movements of the photosphere of the Sun. Redshifts have also been used to make the first measurements of the rotation rates of planets,[29] velocities of interstellar clouds,[30] the rotation of galaxies, and the dynamics of accretion onto neutron stars and black holes which exhibit both Doppler and gravitational redshifts. Additionally, the temperatures of various emitting and absorbing objects can be obtained by measuring Doppler broadening – effectively redshifts and blueshifts over a single emission or absorption line.[31] By measuring the broadening and shifts of the 21-centimeter hydrogen line in different directions, astronomers have been able to measure the recessional velocities of interstellar gas, which in turn reveals the rotation curve of our Milky Way. Similar measurements have been performed on other galaxies, such as Andromeda. As a diagnostic tool, redshift measurements are one of the most important spectroscopic measurements made in astronomy.

Extragalactic observations

The most distant objects exhibit larger redshifts corresponding to the Hubble flow of the universe. The largest observed redshift, corresponding to the greatest distance and furthest back in time, is that of the cosmic microwave background radiation; the numerical value of its redshift is about $z = 1089$ ($z = 0$ corresponds to present time), and it shows the state of the Universe about 13.8 billion years ago, and 379,000 years after the initial moments of the Big Bang.[32]

The luminous point-like cores of quasars were the first "high-redshift" ($z > 0.1$) objects discovered before the improvement of telescopes allowed for the discovery of other high-redshift galaxies.

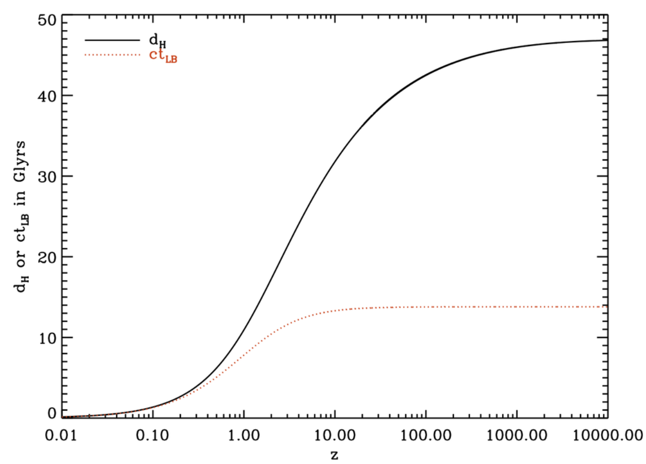
For galaxies more distant than the Local Group and the nearby Virgo Cluster, but within a thousand megaparsecs or so, the redshift is approximately proportional to the galaxy's distance. This correlation was first observed by Edwin Hubble and has come to be known as Hubble's law. Vesto Slipher was the first to discover galactic redshifts, in about the year 1912, while Hubble correlated Slipher's measurements with distances he measured by other means to formulate his Law. In the widely accepted cosmological model based on general relativity, redshift is mainly a result of the expansion of space: this means that the farther away a galaxy is from us, the more the space has expanded in the time since the light left that galaxy, so the more the light has been stretched, the more redshifted the light is, and so the faster it appears to be moving away from us. Hubble's law follows in part from the Copernican principle.[33] Because it is usually not known how luminous objects are, measuring the redshift is easier than more direct distance measurements, so redshift is sometimes in practice converted to a crude distance measurement using Hubble's law.

Gravitational interactions of galaxies with each other and clusters cause a significant scatter in the normal plot of the Hubble diagram. The peculiar velocities associated with galaxies superimpose a rough trace of the mass of virialized objects in the universe. This effect leads to such phenomena as nearby galaxies (such as the Andromeda Galaxy) exhibiting blueshifts as we fall towards a common barycenter, and redshift maps of clusters showing a Fingers of God effect due to the scatter of peculiar velocities in a roughly spherical distribution. This added component gives cosmologists a chance to measure the masses of objects independent of the *mass to light ratio* (the ratio of a galaxy's mass in solar masses to its brightness in solar luminosities), an important tool for measuring dark matter.

The Hubble law's linear relationship between distance and redshift assumes that the rate of expansion of the universe is constant. However, when the universe was much younger, the expansion rate, and thus the Hubble "constant", was larger than it is today. For more distant galaxies, then, whose light has been travelling to us for much longer times, the approximation of constant expansion rate fails, and the Hubble law becomes a non-linear integral relationship and dependent on the history of the expansion rate since the emission of the light from the galaxy in question. Observations of the redshift-distance relationship can be used, then, to determine the expansion history of the universe and thus the matter and energy content.

While it was long believed that the expansion rate has been continuously decreasing since the Big Bang, recent observations of the redshift-distance relationship using Type Ia supernovae have suggested that in comparatively recent times the expansion rate of the universe has begun to accelerate.

Highest redshifts



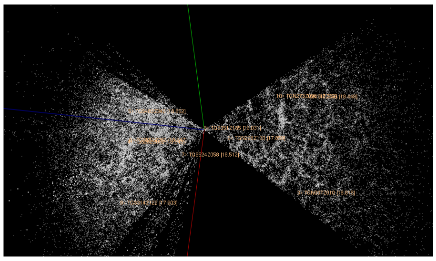
Plot of distance (in giga light-years) vs. redshift according to the Lambda-CDM model. d_H (in solid black) is the comoving distance from Earth to the location with the Hubble redshift *z* while ct_{LB} (in dotted red) is the speed of light multiplied by the lookback time to Hubble redshift *z*. The comoving distance is the physical space-like distance between here and the distant location, asymptoting to the size of the observable universe at some 47 billion light years. The lookback time is the distance a photon traveled from the time it was emitted to now divided by the speed of light, with a maximum distance of 13.8 billion light years corresponding to the age of the universe.

Currently, the objects with the highest known redshifts are galaxies and the objects producing gamma ray bursts. The most reliable redshifts are from spectroscopic data, and the highest confirmed spectroscopic redshift of a galaxy is that of UDFy-38135539 at a redshift of $z = 8.6$, corresponding to just 600 million years after the Big Bang. The previous record was held by IOK-1, at a redshift $z = 6.96$, corresponding to just 750 million years after the Big Bang. Slightly less reliable are Lyman-break redshifts, the highest of which is the lensed galaxy A1689-zD1 at a redshift $z = 7.6$[34] and the next highest being $z = 7.0$.[35] The most distant observed gamma ray burst was GRB 090423, which had a redshift of $z = 8.2$. The most distant known quasar, ULAS J1120+0641, is at $z = 7.1$.[36][37] The highest known redshift radio galaxy (TN J0924-2201) is at a redshift $z = 5.2$ and the highest known redshift molecular material is the detection of emission from the CO molecule from the quasar SDSS J1148+5251 at $z = 6.42$

Extremely red objects (EROs) are astronomical sources of radiation that radiate energy in the red and near infrared part of the electromagnetic spectrum. These may be starburst galaxies that have a high redshift accompanied by reddening from intervening dust, or they could be highly redshifted elliptical galaxies with an older (and therefore redder) stellar population. Objects that are even redder than EROs are termed *hyper extremely red objects* (HEROs).

The cosmic microwave background has a redshift of $z = 1089$, corresponding to an age of approximately 379,000 years after the Big Bang and a comoving distance of more than 46 billion light years. The yet-to-be-observed first light from the oldest Population III stars, not long after atoms first formed and the CMB ceased to be absorbed almost completely, may have redshifts in the range of $20 < z < 100$. Other high-redshift events predicted by physics but not presently observable are the cosmic neutrino background from about two seconds after the Big Bang (and a redshift in excess of $z > 10^{10}$) and the cosmic gravitational wave background emitted directly from inflation at a redshift in excess of $z > 10^{25}$.

Redshift surveys



Rendering of the 2dFGRS data

With advent of automated telescopes and improvements in spectroscopes, a number of collaborations have been made to map the universe in redshift space. By combining redshift with angular position data, a redshift survey maps the 3D distribution of matter within a field of the sky. These observations are used to measure properties of the large-scale structure of the universe. The Great Wall, a vast supercluster of galaxies over 500 million light-years wide, provides a dramatic example of a large-scale structure that redshift surveys can detect.[38]

The first redshift survey was the CfA Redshift Survey, started in 1977 with the initial data collection completed in 1982.[39] More recently, the 2dF Galaxy Redshift Survey determined the large-scale structure of one section of the Universe, measuring redshifts for over 220,000 galaxies; data collection was completed in 2002, and the final data set was released 30 June 2003.[40] The Sloan Digital Sky Survey (SDSS), is ongoing as of 2013 and aims to measure the redshifts of around 3 million objects.[41] SDSS has recorded redshifts for galaxies as high as 0.8, and has been involved in the detection of quasars beyond $z = 6$. The DEEP2 Redshift Survey uses the Keck telescopes with the new "DEIMOS" spectrograph; a follow-up to the pilot program DEEP1, DEEP2 is designed to measure faint galaxies with redshifts 0.7 and above, and it is therefore planned to provide a high redshift complement to SDSS and 2dF.

Effects due to physical optics or radiative transfer

The interactions and phenomena summarized in the subjects of radiative transfer and physical optics can result in shifts in the wavelength and frequency of electromagnetic radiation. In such cases the shifts correspond to a physical energy transfer to matter or other photons rather than being due to a transformation between reference frames. These shifts can be due to such physical phenomena as coherence effects or the scattering of electromagnetic radiation whether from charged elementary particles, from particulates, or from fluctuations of the index of refraction in a dielectric medium as occurs in the radio phenomenon of radio whistlers. While such phenomena are sometimes referred to as "redshifts" and "blueshifts", in astrophysics light-matter interactions that result in energy shifts in the radiation field are generally referred to as "reddening" rather than "redshifting" which, as a term, is normally reserved for the effects discussed above.

In many circumstances scattering causes radiation to redden because entropy results in the predominance of many low-energy photons over few high-energy ones (while conserving total energy). Except possibly under carefully controlled conditions, scattering does not produce the same relative change in wavelength across the whole spectrum; that is, any calculated z is generally a function of wavelength. Furthermore, scattering from random media generally occurs at many angles, and z is a function of the scattering angle. If multiple scattering occurs, or the scattering particles have relative motion, then there is generally distortion of spectral lines as well.

In interstellar astronomy, visible spectra can appear redder due to scattering processes in a phenomenon referred to as interstellar reddening – similarly Rayleigh scattering causes the atmospheric reddening of the Sun seen in the sunrise or sunset and causes the rest of the sky to have a blue color. This phenomenon is distinct from red*shift*ing because the spectroscopic lines are not shifted to other wavelengths in reddened objects and there is an additional dimming and distortion associated with the phenomenon due to photons being scattered in and out of the line-of-sight.

For a list of scattering processes, see Scattering.

References

Notes

[1] See Feynman, Leighton and Sands (1989) or any introductory undergraduate (and many high school) physics textbooks. See Taylor (1992) for a relativistic discussion.

[2] See Binney and Merrifeld (1998), Carroll and Ostlie (1996), Kutner (2003) for applications in astronomy.

[3] See Misner, Thorne and Wheeler (1973) and Weinberg (1971) or any of the physical cosmology textbooks

[4] Reprinted in

[5] English translation in)

[6] This was recognized early on by physicists and astronomers working in cosmology in the 1930s. The earliest layman publication describing the details of this correspondence is (Reprint: ISBN 978-0-521-34976-5)

[7] See, for example, this 25 May 2004 press release (http://heasarc.gsfc.nasa.gov/docs/swift/about_swift/redshift.html) from NASA's Swift space telescope that is researching gamma-ray bursts: "Measurements of the gamma-ray spectra obtained during the main outburst of the GRB have found little value as redshift indicators, due to the lack of well-defined features. However, optical observations of GRB afterglows have produced spectra with identifiable lines, leading to precise redshift measurements."

[8] See (http://ned.ipac.caltech.edu/help/zdef.html) for a tutorial on how to define and interpret large redshift measurements.

[9] Where z = redshift; $v_{||}$ = velocity parallel to line-of-sight (positive if moving away from receiver); c = speed of light; γ = Lorentz factor; a = scale factor; G = gravitational constant; M = object mass; r = radial Schwarzschild coordinate, g_{tt} = t,t component of the metric tensor

[10] H. Ives and G. Stilwell, An Experimental study of the rate of a moving atomic clock, J. Opt. Soc. Am. 28, 215–226 (1938) (http://www.opticsinfobase.org/abstract.cfm?URI=josa-28-7-215)

[11] See " Photons, Relativity, Doppler shift (http://www.physics.uq.edu.au/people/ross/phys2100/doppler.htm)" at the University of Queensland

[12] The distinction is made clear in

[13] Measurements of the peculiar velocities out to 5 Mpc using the Hubble Space Telescope were reported in 2003 by Karachentsev et al. *Local galaxy flows within 5 Mpc*. 02/2003 *Astronomy and Astrophysics*, **398**, 479-491. (http://arxiv.org/abs/astro-ph/0211011)

[14] "It is perfectly valid to interpret the equations of relativity in terms of an expanding space. The mistake is to push analogies too far and imbue space with physical properties that are not consistent with the equations of relativity."

[15] Bedran,M.L.(2002)http://www.df.uba.ar/users/sgil/physics_paper_doc/papers_phys/cosmo/doppler_redshift.pdf "A comparison between the Doppler and cosmological redshifts"; Am.J.Phys.**70**, 406–408 (2002)

[16] . A pdf file can be found here (http://articles.adsabs.harvard.edu/cgi-bin/nph-iarticle_query?1993ApJ...403...28H&data_type=PDF_HIGH&whole_paper=YES&type=PRINTER&filetype=.pdf).

[17] Odenwald & Fienberg 1993

[18] Speed faster than light is allowed because the expansion of the spacetime metric is described by general relativity in terms of sequences of only locally valid inertial frames as opposed to a global Minkowski metric. Expansion faster than light is an integrated effect over many local inertial frames and is allowed because no single inertial frame is involved. The speed-of-light limitation applies only locally. See

[19] M. Weiss, What Causes the Hubble Redshift?, entry in the Physics FAQ (1994), available via John Baez's website (http://math.ucr.edu/home/baez/physics/Relativity/GR/hubble.html)

[20] This is only true in a universe where there are no peculiar velocities. Otherwise, redshifts combine as

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which yields solutions where certain objects that "recede" are blueshifted and other objects that "approach" are redshifted. For more on this bizarre result see Davis, T. M., Lineweaver, C. H., and Webb, J. K. " Solutions to the tethered galaxy problem in an expanding universe and the observation of receding blueshifted objects (http://arxiv.org/abs/astro-ph/0104349/)", *American Journal of Physics* (2003), **71** 358–364.

[21] . This paper was the first measurement.
[22] Dieter Brill, “Black Hole Horizons and How They Begin”, Astronomical Review (2012); Online Article, cited Sept.2012. (http://astroreview.com/issue/2012/article/black-hole-horizons-and-how-they-begin)
[23] When cosmological redshifts were first discovered, Fritz Zwicky proposed an effect known as tired light. While usually considered for historical interests, it is sometimes, along with intrinsic redshift suggestions, utilized by nonstandard cosmologies. In 1981, H. J. Reboul summarised many alternative redshift mechanisms (http://adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=1981A&AS...45..129R&db_key=AST&data_type=HTML&format=&high=42ca922c9c23806) that had been discussed in the literature since the 1930s. In 2001, Geoffrey Burbidge remarked in a review (http://adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=2001PASP..113..899B&db_key=AST&data_type=HTML) that the wider astronomical community has marginalized such discussions since the 1960s. Burbidge and Halton Arp, while investigating the mystery of the nature of quasars, tried to develop alternative redshift mechanisms, and very few of their fellow scientists acknowledged let alone accepted their work. Moreover, Goldhaber *et al.* 2001; "Timescale Stretch Parameterization of Type Ia Supernova B-Band Lightcurves", ApJ, 558:359–386, 2001 September 1 pointed out that alternative theories are unable to account for timescale stretch observed in type Ia supernovae
[24] For a review of the subject of photometry, consider Budding, E., *Introduction to Astronomical Photometry*, Cambridge University Press (September 24, 1993), ISBN 0-521-41867-4
[25] The technique was first described by Baum, W. A.: 1962, in G. C. McVittie (ed.), *Problems of extra-galactic research*, p. 390, IAU Symposium No. 15
[26] Bolzonella, M.; Miralles, J.-M.; Pelló, R., Photometric redshifts based on standard SED fitting procedures (http://arxiv.org/abs/astro-ph/0003380), *Astronomy and Astrophysics*, **363**, p.476–492 (2000).
[27] A pedagogical overview of the K-correction by David Hogg and other members of the SDSS collaboration can be found at astro-ph (http://arxiv.org/abs/astro-ph/0210394).
[28] The Exoplanet Tracker is the newest observing project to use this technique, able to track the redshift variations in multiple objects at once, as reported in
[29] In 1871 Hermann Carl Vogel measured the rotation rate of Venus. Vesto Slipher was working on such measurements when he turned his attention to spiral nebulae.
[30] An early review by Oort, J. H. on the subject:
[31] Rybicki, G. B. and A. R. Lightman, *Radiative Processes in Astrophysics*, John Wiley & Sons, 1979, p. 288 ISBN 0-471-82759-2
[32] An accurate measurement of the cosmic microwave background was achieved by the COBE experiment. The final published temperature of 2.73 K was reported in this paper: Fixsen, D. J.; Cheng, E. S.; Cottingham, D. A.; Eplee, R. E., Jr.; Isaacman, R. B.; Mather, J. C.; Meyer, S. S.; Noerdlinger, P. D.; Shafer, R. A.; Weiss, R.; Wright, E. L.; Bennett, C. L.; Boggess, N. W.; Kelsall, T.; Moseley, S. H.; Silverberg, R. F.; Smoot, G. F.; Wilkinson, D. T.. (1994). "Cosmic microwave background dipole spectrum measured by the COBE FIRAS instrument", *Astrophysical Journal*, 420, 445. The most accurate measurement as of 2006 was achieved by the WMAP experiment.
[33] Peebles (1993).
[34] Bradley, L.., et al., Discovery of a Very Bright Strongly Lensed Galaxy Candidate at z ~ 7.6, *The Astrophysical Journal* (2008), Volume 678, Issue 2, pp. 647-654. [http://adsabs.harvard.edu/abs/2008ApJ...678..647B
[35] Egami, E., et al., Spitzer and Hubble Space Telescope Constraints on the Physical Properties of the z~7 Galaxy Strongly Lensed by A2218, *The Astrophysical Journal* (2005), v. 618, Issue 1, pp. L5–L8 (http://adsabs.harvard.edu/cgi-bin/nph-bib_query?bibcode=2005ApJ...618L...5E&db_key=AST&data_type=HTML&format=&high=43a73989ff16910).
[36] http://www.universetoday.com/87175/most-distant-quasar-opens-window-into-early-universe/
[37] Scientific American, "Brilliant, but Distant: Most Far-Flung Known Quasar Offers Glimpse into Early Universe" (http://www.scientificamerican.com/article.cfm?id=farthest-quasar), **John Matson**, *29 June 2011*
[38] M. J. Geller & J. P. Huchra, *Science* **246**, 897 (1989). online (http://www.sciencemag.org/cgi/content/abstract/246/4932/897)
[39] See the official CfA website (http://cfa-www.harvard.edu/~huchra/zcat/) for more details.
[40] 2dF Galaxy Redshift Survey homepage (http://msowww.anu.edu.au/2dFGRS/)
[41] SDSS Homepage (http://www.sdss3.org/)

Articles

- Odenwald, S. & Fienberg, RT. 1993; "Galaxy Redshifts Reconsidered" in *Sky & Telescope* Feb. 2003; pp31–35 (This article is useful further reading in distinguishing between the 3 types of redshift and their causes.)
- Lineweaver, Charles H. and Tamara M. Davis, " Misconceptions about the Big Bang (http://www.sciam.com/article.cfm?chanID=sa006&colID=1&articleID=0009F0CA-C523-1213-852383414B7F0147)", *Scientific American*, March 2005. (This article is useful for explaining the cosmological redshift mechanism as well as clearing up misconceptions regarding the physics of the expansion of space.)

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- Weinberg, Steven (1971). *Gravitation and Cosmology*. John Wiley. ISBN 0-471-92567-5.
- See also physical cosmology textbooks for applications of the cosmological and gravitational redshifts.

External links

- Ned Wright's Cosmology tutorial (http://www.astro.ucla.edu/~wright/doppler.htm)
- Cosmic reference guide entry on redshift (http://coolcosmos.ipac.caltech.edu/cosmic_classroom/cosmic_reference/redshift.html)
- Mike Luciuk's Astronomical Redshift tutorial (http://www.asterism.org/tutorials/tut29-1.htm)
- Animated GIF of Cosmological Redshift (http://www.astronomy.ohio-state.edu/~pogge/Ast162/Unit5/Images/hu_animexp.gif) by Wayne Hu
- Merrifield, Michael; Hill, Richard (2009). "Z Redshift" (http://www.sixtysymbols.com/videos/redshift.htm). *SIXTψ SYMBΦLS*. Brady Haran for the University of Nottingham.

Hubble's law

Hubble's law is the name for the observation in physical cosmology that: (1) objects observed in deep space (extragalactic space, ~10 megaparsecs or more) are found to have a Doppler shift interpretable as relative velocity away from the Earth; and (2) that this Doppler-shift-measured velocity, of various galaxies receding from the Earth, is approximately proportional to their distance from the Earth for galaxies up to a few hundred megaparsecs away. This is normally interpreted as a direct, physical observation of the expansion of the spatial volume of the observable universe.

The motion of astronomical objects due solely to this expansion is known as the **Hubble flow**. Hubble's law is considered the first observational basis for the expanding space paradigm and today serves as one of the pieces of evidence most often cited in support of the Big Bang model.

Although widely attributed to Edwin Hubble, the law was first derived from the General Relativity equations by Georges Lemaître in a 1927 article where he proposed that the Universe is expanding and suggested an estimated value of the rate of expansion, now called the **Hubble constant**.[1] Two years later Edwin Hubble confirmed the existence of that law and determined a more accurate value for the constant that now bears his name. The recession velocity of the objects was inferred from their redshifts, many measured earlier by Vesto Slipher (1917) and related to velocity by him.

The law is often expressed by the equation $v = H_0 D$, with H_0 the constant of proportionality (the **Hubble constant**) between the "proper distance" D to a galaxy (which can change over time, unlike the comoving distance) and its velocity v (i.e. the derivative of proper distance with respect to cosmological time coordinate; see *Uses of the proper distance* for some discussion of the subtleties of this definition of 'velocity'). The SI unit of H_0 is s^{-1} but it is most frequently quoted in (km/s)/Mpc, thus giving the speed in km/s of a galaxy 1 megaparsec (3.09×10^{19} km) away. The reciprocal of H_0 is the Hubble time.

Observed values

Date published	Hubble constant (km/s)/Mpc	Observer	Citation	Remarks / methodology
2013-03-21	67.80±0.77	Planck Mission		The ESA Planck Surveyor was launched in May 2009. Over a four-year period, it performed a significantly more detailed investigation of cosmic microwave radiation than earlier investigations using HEMT radiometers and bolometer technology to measure the CMB at a smaller scale than WMAP. On 21 March 2013, the European-led research team behind the Planck cosmology probe released the mission's data including a new CMB all-sky map and their determination of the Hubble constant.
2012-12-20	69.32±0.80	WMAP (9-years)		
2010	$70.4^{+1.3}_{-1.4}$	WMAP (7-years), combined with other measurements.		These values arise from fitting a combination of WMAP and other cosmological data to the simplest version of the ΛCDM model. If the data are fit with more general versions, H_0 tends to be smaller and more uncertain: typically around 67±4 (km/s)/Mpc although some models allow values near 63 (km/s)/Mpc.[2]
2010	71.0±2.5	WMAP only (7-years).		

2009-02	70.1±1.3	WMAP (5-years). combined with other measurements.		
2009-02	71.9+2.6 −2.7	WMAP only (5-years)		
2006-08	77.6+14.9 −12.5	Chandra X-ray Observatory		
2007	70.4+1.5 −1.6	WMAP (3-years)		
2001-05	72±8	Hubble Space Telescope		This project established the most precise optical determination, consistent with a measurement of H_0 based upon Sunyaev-Zel'dovich effect observations of many galaxy clusters having a similar accuracy.
prior to 1996	50–90 (est.)			
1958	75 (est.)	Allan Sandage		This was the first good estimate of H_0, but it would be decades before a consensus was achieved.

Discovery

A decade before Hubble made his observations, a number of physicists and mathematicians had established a consistent theory of the relationship between space and time by using Einstein's field equations of general relativity. Applying the most general principles to the nature of the universe yielded a dynamic solution that conflicted with the then-prevailing notion of a static universe.

FLRW equations

In 1922, Alexander Friedmann derived his Friedmann equations from Einstein's field equations, showing that the universe might expand at a rate calculable by the equations.[3] The parameter used by Friedmann is known today as the scale factor which can be considered as a scale invariant form of the proportionality constant of Hubble's law. Georges Lemaître independently found a similar solution in 1927. The Friedmann equations are derived by inserting the metric for a homogeneous and isotropic universe into Einstein's field equations for a fluid with a given density and pressure. This idea of an expanding spacetime would eventually lead to the Big Bang and Steady State theories of cosmology.

Shape of the universe

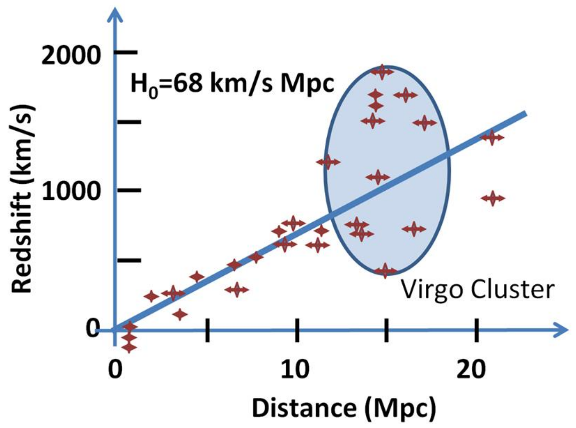
Before the advent of modern cosmology, there was considerable talk about the size and shape of the universe. In 1920, the famous Shapley-Curtis debate took place between Harlow Shapley and Heber D. Curtis over this issue. Shapley argued for a small universe the size of the Milky Way galaxy and Curtis argued that the universe was much larger. The issue was resolved in the coming decade with Hubble's improved observations.

Cepheid variable stars outside of the Milky Way

Edwin Hubble did most of his professional astronomical observing work at Mount Wilson Observatory, the world's most powerful telescope at the time. His observations of Cepheid variable stars in spiral nebulae enabled him to calculate the distances to these objects. Surprisingly, these objects were discovered to be at distances which placed them well outside the Milky Way. They continued to be called "nebulae" and it was only gradually that the term "galaxies" took over.

Combining redshifts with distance measurements

The parameters that appear in Hubble's law: velocities and distances, are not directly measured. In reality we determine, say, a supernova brightness, which provides information about its distance, and the redshift $z = \Delta\lambda/\lambda$ of its spectrum of radiation. Hubble correlated brightness and parameter z.



Fit of redshift velocities to Hubble's law. Various estimates for the Hubble constant exist. The HST Key H_0 Group fitted type Ia supernovae for redshifts between 0.01 and 0.1 to find that $H_0 = 71 \pm 2$ (statistical) $\pm$ 6 (systematic) km s^{-1}Mpc^{-1}, while Sandage *et al.* find $H_0 = 62.3 \pm 1.3$ (statistical) $\pm$ 5 (systematic) km s^{-1}Mpc^{-1}.

Combining his measurements of galaxy distances with Vesto Slipher and Milton Humason's measurements of the redshifts associated with the galaxies, Hubble discovered a rough proportionality between redshift of an object and its distance. Though there was considerable scatter (now known to be caused by peculiar velocities – the 'Hubble flow' is used to refer to the region of space far enough out that the recession velocity is larger than local peculiar velocities), Hubble was able to plot a trend line from the 46 galaxies he studied and obtain a value for the Hubble constant of 500 km/s/Mpc (much higher than the currently accepted value due to errors in his distance calibrations). (See cosmic distance ladder for details.)

At the time of discovery and development of Hubble's law it was acceptable to explain redshift phenomenon as a Doppler shift in the context of special relativity, and use the Doppler formula to associate redshift z with velocity. Today the velocity-distance relationship of Hubble's law is viewed as a theoretical result with velocity to be connected with observed redshift not by the Doppler effect, but by a cosmological model relating recessional velocity to the expansion of the universe. Even for small z the velocity entering the Hubble law is no longer interpreted as a Doppler effect, although at small z the velocity-redshift relation for both interpretations is the same.

Hubble Diagram

Hubble's law can be easily depicted in a "Hubble Diagram" in which the velocity (assumed approximately proportional to the redshift) of an object is plotted with respect to its distance from the observer. A straight line of positive slope on this diagram is the visual depiction of Hubble's law.

Cosmological constant abandoned

After Hubble's discovery was published, Albert Einstein abandoned his work on the cosmological constant, which he had designed to modify his equations of general relativity, to allow them to produce a static solution which, in their simplest form, model either an expanding or contracting universe. After Hubble's discovery that the Universe was, in fact, expanding, Einstein called his faulty assumption that the Universe is static his "biggest mistake". On its own, general relativity could predict the expansion of the universe, which (through observations such as the bending of light by large masses, or the precession of the orbit of Mercury) could be experimentally observed and compared to his theoretical calculations using particular solutions of the equations he had originally formulated.

In 1931, Einstein made a trip to Mount Wilson to thank Hubble for providing the observational basis for modern cosmology.

The cosmological constant has regained attention in recent decades as a hypothesis for dark energy.

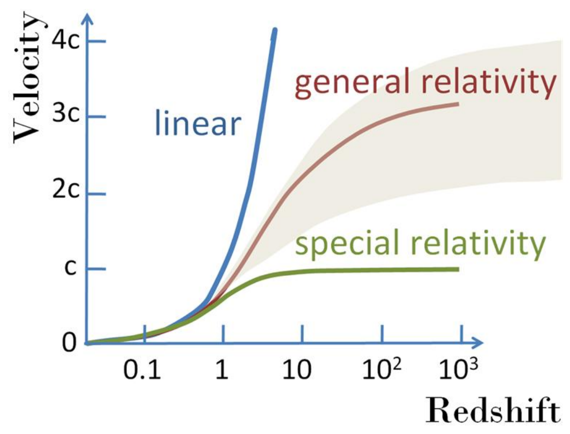
Interpretation

The discovery of the linear relationship between redshift and distance, coupled with a supposed linear relation between recessional velocity and redshift, yields a straightforward mathematical expression for Hubble's Law as follows:

$$v = H_0 D$$

where

- v is the recessional velocity, typically expressed in km/s.
- H_0 is Hubble's constant and corresponds to the value of H (often termed the **Hubble parameter** which is a value that is time dependent and which can be expressed in terms of the scale factor) in the Friedmann equations taken at the time of observation denoted by the subscript *0*. This value is the same throughout the universe for a given comoving time.
- D is the proper distance (which can change over time, unlike the comoving distance which is constant) from the galaxy to the observer, measured in mega parsecs (Mpc), in the 3-space defined by given cosmological time. (Recession velocity is just $v = dD/dt$).



A variety of possible recessional velocity vs. redshift functions including the simple linear relation $v = cz$; a variety of possible shapes from theories related to general relativity; and a curve that does not permit speeds faster than light in accordance with special relativity. All curves are linear at low redshifts. See Davis and Lineweaver.

Hubble's law is considered a fundamental relation between recessional velocity and distance. However, the relation between recessional velocity and redshift depends on the cosmological model adopted, and is not established except for small redshifts.

For distances D larger than the radius of the Hubble sphere r_{HS} , objects recede at a rate faster than the speed of light (*See* Uses of the proper distance for a discussion of the significance of this):

$$r_{HS} = \frac{c}{H_0} \ .$$

Since the Hubble "constant" is a constant only in space, not in time, the radius of the Hubble sphere may increase or decrease over various time intervals. The subscript '0' indicates the value of the Hubble constant today. Current evidence suggests the expansion of the universe is accelerating (*see* Accelerating universe), meaning that for any given galaxy, the recession velocity dD/dt is increasing over time as the galaxy moves to greater and greater distances; however, the Hubble parameter is actually thought to be decreasing with time, meaning that if we were to look at some *fixed* distance D and watch a series of different galaxies pass that distance, later galaxies would pass that distance at a smaller velocity than earlier ones.[4]

Redshift velocity and recessional velocity

Redshift can be measured by determining the wavelength of a known transition, such as hydrogen α-lines for distant quasars, and finding the fractional shift compared to a stationary reference. Thus redshift is a quantity unambiguous for experimental observation. The relation of redshift to recessional velocity is another matter. For an extensive discussion, see Harrison.

Redshift velocity

The redshift z often is described as a *redshift velocity*, which is the recessional velocity that would produce the same redshift *if* it were caused by a linear Doppler effect (which, however, is not the case, as the shift is caused in part by a cosmological expansion of space, and because the velocities involved are too large to use a non-relativistic formula for Doppler shift). This redshift velocity can easily exceed the speed of light. In other words, to determine the redshift velocity v_{rs}, the relation:

$$v_{rs} \equiv cz \ ,$$

is used. That is, there is *no fundamental difference* between redshift velocity and redshift: they are rigidly proportional, and not related by any theoretical reasoning. The motivation behind the "redshift velocity" terminology is that the redshift velocity agrees with the velocity from a low-velocity simplification of the so-called Fizeau-Doppler formula

$$z = \frac{\lambda_o}{\lambda_e} - 1 = \sqrt{\frac{1+v/c}{1-v/c}} - 1 \approx \frac{v}{c} \ .$$

Here, λ_o, λ_e are the observed and emitted wavelengths respectively. The "redshift velocity" v_{rs} is not so simply related to real velocity at larger velocities, however, and this terminology leads to confusion if interpreted as a real velocity. Next, the connection between redshift or redshift velocity and recessional velocity is discussed. This discussion is based on Sartori.

Recessional velocity

[*citation needed*] Suppose *R(t)* is called the *scale factor* of the universe, and increases as the universe expands in a manner that depends upon the cosmological model selected. Its meaning is that all measured distances *D(t)* between co-moving points increase proportionally to *R*. (The co-moving points are not moving relative to each other except as a result of the expansion of space.) In other words:

$$\frac{D(t)}{D(t_0)} = \frac{R(t)}{R(t_0)} \ ,$$

where t_0 is some reference time. If light is emitted from a galaxy at time t_e and received by us at t_0, it is red shifted due to the expansion of space, and this redshift z is simply:

$$z = \frac{R(t_0)}{R(t_e)} - 1 \ .$$

Suppose a galaxy is at distance D, and this distance changes with time at a rate $d_t D$. We call this rate of recession the "recession velocity" v_r:

$$v_r = d_t D = \frac{d_t R}{R} D \ .$$

We now define the Hubble constant as

$$H \equiv \frac{d_t R}{R} \ ,$$

and discover the Hubble law:

$$v_r = HD \ .$$

From this perspective, Hubble's law is a fundamental relation between (i) the recessional velocity contributed by the expansion of space and (ii) the distance to an object; the connection between redshift and distance is a crutch used to connect Hubble's law with observations. This law can be related to redshift z approximately by making a Taylor series expansion:

$$z = \frac{R(t_0)}{R(t_e)} - 1 \approx \frac{R(t_0)}{R(t_0)\left(1 + (t_e - t_0)H(t_0)\right)} - 1 \approx (t_0 - t_e)H(t_0) \ ,$$

If the distance is not too large, all other complications of the model become small corrections and the time interval is simply the distance divided by the speed of light:

$$z \approx (t_0 - t_e)H(t_0) \approx \frac{D}{c}H(t_0) \ , \text{or } cz \approx DH(t_0) = v_r \ .$$

According to this approach, the relation $cz = v_r$ is an approximation valid at low redshifts, to be replaced by a relation at large redshifts that is model-dependent. See velocity-redshift figure.

Observability of parameters

Strictly speaking, neither v nor D in the formula are directly observable, because they are properties *now* of a galaxy, whereas our observations refer to the galaxy in the past, at the time that the light we currently see left it.

For relatively nearby galaxies (redshift z much less than unity), v and D will not have changed much, and v can be estimated using the formula $v = zc$ where c is the speed of light. This gives the empirical relation found by Hubble.

For distant galaxies, v (or D) cannot be calculated from z without specifying a detailed model for how H changes with time. The redshift is not even directly related to the recession velocity at the time the light set out, but it does have a simple interpretation: *(1+z)* is the factor by which the universe has expanded while the photon was travelling towards the observer.

Expansion velocity vs relative velocity

In using Hubble's law to determine distances, only the velocity due to the expansion of the universe can be used. Since gravitationally interacting galaxies move relative to each other independent of the expansion of the universe, these relative velocities, called peculiar velocities, need to be accounted for in the application of Hubble's law.

The Finger of God effect is one result of this phenomenon. In systems that are gravitationally bound, such as galaxies or our planetary system, the expansion of space is a much weaker effect than the attractive force of gravity.

Idealized Hubble's Law

The mathematical derivation of an idealized Hubble's Law for a uniformly expanding universe is a fairly elementary theorem of geometry in 3-dimensional Cartesian/Newtonian coordinate space, which, considered as a metric space, is entirely homogeneous and isotropic (properties do not vary with location or direction). Simply stated the theorem is this:

> *Any two points which are moving away from the origin, each along straight lines and with speed proportional to distance from the origin, will be moving away from each other with a speed proportional to their distance apart.*

In fact this applies to non-Cartesian spaces as long as they are locally homogeneous and isotropic; specifically to the negatively- and positively-curved spaces frequently considered as cosmological models (see shape of the universe).

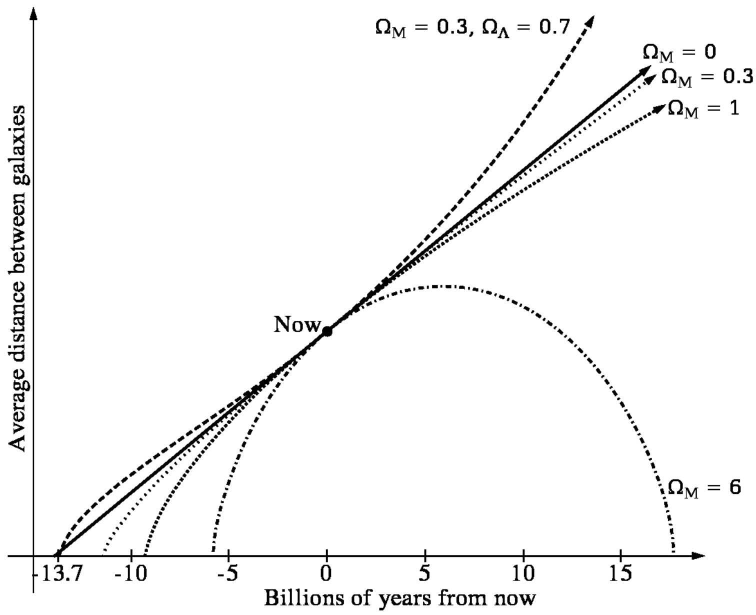
An observation stemming from this theorem is that seeing objects recede from us on Earth is not an indication that Earth is near to a center from which the expansion is occurring, but rather that *every* observer in an expanding universe will see objects receding from them.

Ultimate fate and age of the universe

The value of the Hubble parameter changes over time either increasing or decreasing depending on the sign of the so-called deceleration parameter q which is defined by

$$q = -\left(1 + \frac{\dot{H}}{H^2}\right).$$

In a universe with a deceleration parameter equal to zero, it follows that $H = 1/t$, where t is the time since the Big Bang. A non-zero, time-dependent value of q simply requires integration of the Friedmann equations backwards from the present time to the time when the comoving horizon size was zero.



The age and ultimate fate of the universe can be determined by measuring the Hubble constant today and extrapolating with the observed value of the deceleration parameter, uniquely characterized by values of density parameters (Ω_M for matter and Ω_Λ for dark energy). A "closed universe" with $\Omega_M > 1$ and $\Omega_\Lambda = 0$ comes to an end in a Big Crunch and is considerably younger than its Hubble age. An "open universe" with $\Omega_M \leq 1$ and $\Omega_\Lambda = 0$ expands forever and has an age that is closer to its Hubble age. For the accelerating universe with nonzero Ω_Λ that we inhabit, the age of the universe is coincidentally very close to the Hubble age.

It was long thought that q was positive, indicating that the expansion is slowing down due to gravitational attraction. This would imply an age of the universe less than $1/H$ (which is about 14 billion years). For instance, a value for q of 1/2 (once favoured by most theorists) would give the age of the universe as $2/(3H)$. The discovery in 1998 that q is apparently negative means that the universe could actually be older than $1/H$. However, estimates of the age of the universe are very close to $1/H$.

Olbers' paradox

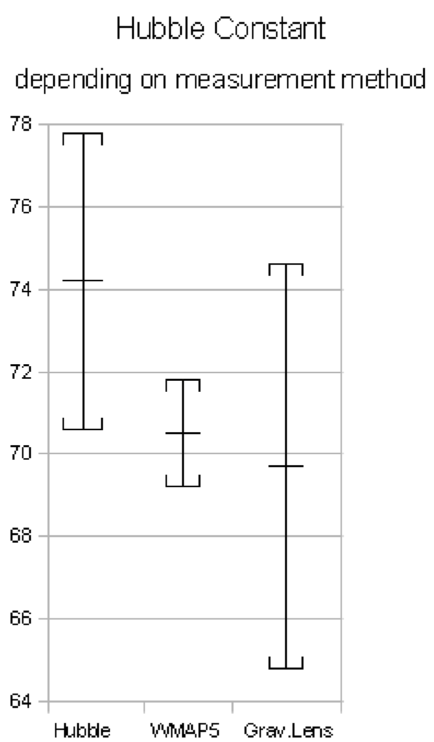
The expansion of space summarized by the Big Bang interpretation of Hubble's Law is relevant to the old conundrum known as Olbers' paradox: if the universe were infinite, static, and filled with a uniform distribution of stars, then every line of sight in the sky would end on a star, and the sky would be as bright as the surface of a star. However, the night sky is largely dark. Since the 17th century, astronomers and other thinkers have proposed many possible ways to resolve this paradox, but the currently accepted resolution depends in part upon the Big Bang theory and in part upon the Hubble expansion. In a universe that exists for a finite amount of time, only the light of finitely many stars has had a chance to reach us yet, and the paradox is resolved. Additionally, in an expanding universe distant objects recede from us, which causes the light emanating from them to be redshifted and diminished in brightness.[5]

Dimensionless Hubble parameter

Instead of working with Hubble's constant, a common practice is to introduce the **dimensionless Hubble parameter**, usually denoted by *h*, and to write the Hubble's parameter H_0 as 100 *h* km s $^{-1}$ Mpc^{-1}, all the uncertainty relative of the value of H_0 being then relegated on *h*.

Determining the Hubble constant

The value of the Hubble constant is estimated by measuring the redshift of distant galaxies and then determining the distances to the same galaxies (by some other method than Hubble's law). Uncertainties in the physical assumptions used to determine these distances have caused varying estimates of the Hubble constant.



Value of the Hubble Constant including measurement uncertainty above measurement method

Earlier measurement and discussion approaches

For most of the second half of the 20th century the value of H_0 was estimated to be between 50 and 90 (km/s)/Mpc.

The value of the Hubble constant was the topic of a long and rather bitter controversy between Gérard de Vaucouleurs who claimed the value was around 100 and Allan Sandage who claimed the value was near 50. In 1996, a debate moderated by John Bahcall between Gustav Tammann and Sidney van den Bergh was held in similar fashion to the earlier Shapley-Curtis debate over these two competing values.

This previously wide variance in estimates was partially resolved with the introduction of the ΛCDM model of the universe in the late 1990s. With the ΛCDM model observations of high-redshift clusters at X-ray and microwave wavelengths using the Sunyaev-Zel'dovich effect, measurements of anisotropies in the cosmic microwave background radiation, and optical surveys all gave a value of around 70 for the constant.[*citation needed*]

The consistency of the measurements from all these methods lends support to both the measured value of H_0 and the ΛCDM model.

See table of measurements above for many recent and older measurements.

Acceleration of the expansion

A value for q measured from standard candle observations of Type Ia supernovae, which was determined in 1998 to be negative, surprised many astronomers with the implication that the expansion of the universe is currently "accelerating" (although the Hubble factor is still decreasing with time, as mentioned above in the Interpretation section; see the articles on dark energy and the ΛCDM model).

Derivation of the Hubble parameter

[*citation needed*] Start with the Friedmann equation:

$$H^2 \equiv \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3},$$

where H is the Hubble parameter, a is the scale factor, G is the gravitational constant, k is the normalised spatial curvature of the universe and equal to −1, 0, or +1, and Λ is the cosmological constant.

Matter-dominated universe (with a cosmological constant)

[*citation needed*] If the universe is matter-dominated, then the mass density of the universe ρ can just be taken to include matter so

$$\rho = \rho_m(a) = \frac{\rho_{m_0}}{a^3},$$

where ρ_{m_0} is the density of matter today. We know for nonrelativistic particles that their mass density decreases proportional to the inverse volume of the universe so the equation above must be true. We can also define (see density parameter for Ω_m)

$$\rho_c = \frac{3H^2}{8\pi G};$$

$$\Omega_m \equiv \frac{\rho_{m_0}}{\rho_c} = \frac{8\pi G}{3H_0^2}\rho_{m_0};$$

so $\rho = \rho_c \Omega_m / a^3$. Also, by definition,

$$\Omega_k \equiv \frac{-kc^2}{(a_0 H_0)^2}$$

and

$$\Omega_\Lambda \equiv \frac{\Lambda c^2}{3H_0^2},$$

where the subscript nought refers to the values today, and $a_0 = 1$. Substituting all of this in into the Friedmann equation at the start of this section and replacing a with $a = 1/(1+z)$ gives

$$H^2(z) = H_0^2 \left(\Omega_M (1+z)^3 + \Omega_k (1+z)^2 + \Omega_\Lambda \right).$$

Matter- and dark energy-dominated universe

[*citation needed*] If the universe is both matter-dominated and dark energy- dominated, then the above equation for the Hubble parameter will also be a function of the equation of state of dark energy. So now:

$$\rho = \rho_m(a) + \rho_{de}(a),$$

where ρ_{de} is the mass density of the dark energy. By definition an equation of state in cosmology is $P = w\rho c^2$, and if we substitute this into the fluid equation, which describes how the mass density of the universe evolves with time,

$$\dot{\rho} + 3\frac{\dot{a}}{a}\left(\rho + \frac{P}{c^2}\right) = 0;$$

$$\frac{d\rho}{\rho} = -3\frac{da}{a}\left(1+w\right).$$

If w is constant,

$$\ln \rho = -3\left(1+w\right)\ln a;$$

$$\rho = a^{-3(1+w)}.$$

Therefore for dark energy with a constant equation of state w, $\rho_{de}(a) = \rho_{de0} a^{-3(1+w)}$. If we substitute this into the Friedman equation in a similar way as before, but this time set $k = 0$ which is assuming we live in a spatially flat universe, (see Shape of the Universe)

$$H^2(z) = H_0^2 \left(\Omega_M (1+z)^3 + \Omega_{de} (1+z)^{3(1+w)} \right).$$

If dark energy does not have a constant equation-of-state w, then

$$\rho_{de}(a) = \rho_{de0} e^{-3\int \frac{da}{a}(1+w(a))},$$

and to solve this we must parametrize $w(a)$, for example if $w(a) = w_0 + w_a(1-a)$, giving

$$H^2(z) = H_0^2 \left(\Omega_M a^{-3} + \Omega_{de} a^{-3(1+w_0+w_a)} e^{-3w_a(1-a)} \right).$$

Other ingredients have been formulated recently. In certain era, where the high energy experiments seem to have a reliable access in analyzing the property of the matter dominating the background geometry, with this era we mean the quark-gluon plasma, the transport properties have been taken into consideration. Therefore, the evolution of the Hubble parameter and of other essential cosmological parameters, in such a background are found to be considerably (non-negligibly) different than their evolution in an ideal, gaseous, non-viscous background.

Units derived from the Hubble constant

Hubble time

The Hubble constant H_0 has units of inverse time, i.e. $H_0 \approx 2.3\times10^{-18}$ s^{-1}. "Hubble time" is defined as $1/H_0$. The value of Hubble time in the standard cosmological model is 4.35×10^{17} s or 13.8 billion years. (Liddle 2003, p. 57) The phrase "expansion timescale" means "Hubble time".[*citation needed*]

The Hubble unit is defined as hH_0, where h is around 1, and denotes the uncertainty in H_0. H_0 is 100 km/s / Mpc = 1 dm/s/pc. The unit of time, then has as many seconds as there are decimetres in a parsec.

As mentioned above, H_0 is the current value of Hubble parameter H. In a model in which speeds are constant, H decreases with time. In the naive model where H is constant the Hubble time would be the time taken for the universe to increase in size by a factor of e (because the solution of $dx/dt = xH_0$ is $x = s_0\exp(H_0 t)$, where s_0 is the size of some feature at some arbitrary initial condition $t = 0$).

Over long periods of time the dynamics are complicated by general relativity, dark energy, inflation, etc., as explained above.

Hubble length

The Hubble length or Hubble distance is a unit of distance in cosmology, defined as cH_0^{-1}—the speed of light multiplied by the Hubble time. It is equivalent to 4,228 million parsecs or 13.8 billion light years. (The numerical value of the Hubble length in light years is, by definition, equal to that of the Hubble time in years.) The Hubble distance would be the distance at which galaxies are *currently* receding from us at the speed of light, as can be seen by substituting $D = c/H_0$ into the equation for Hubble's law, $v = H_0 D$.

Hubble volume

The Hubble volume is sometimes defined as a volume of the universe with a comoving size of cH_0. The exact definition varies: it is sometimes defined as the volume of a sphere with radius cH_0, or alternatively, a cube of side cH_0. Some cosmologists even use the term Hubble volume to refer to the volume of the observable universe, although this has a radius approximately three times larger.

Notes

[1] Partially translated in

[2] Results for H_0 and other cosmological parameters obtained by fitting a variety of models to several combinations of WMAP and other data are available at the NASA's LAMBDA website (http://lambda.gsfc.nasa.gov/product/map/current/parameters.cfm).

[3] Translated in

[4] Is the universe expanding faster than the speed of light? (http://curious.astro.cornell.edu/question.php?number=575) (see final paragraph)

[5] See also

References

- Hubble, E. P. (1937). *The Observational Approach to Cosmology*. Clarendon Press. LCCN 38011865 (http://lccn.loc.gov/38011865).
- Kutner, M. (2003). *Astronomy: A Physical Perspective*. Cambridge University Press. ISBN 0-521-52927-1.
- Liddle, A. R. (2003). *An Introduction to Modern Cosmology* (2nd ed.). John Wiley & Sons. ISBN 0-470-84835-9.

Further reading

- Freedman, W. L.; Madore, B. F. (2010). "The Hubble Constant". *Annual Review of Astronomy and Astrophysics* **48**: 673. arXiv: 1004.1856 (http://arxiv.org/abs/1004.1856). Bibcode: 2010ARA&A..48..673F (http://adsabs.harvard.edu/abs/2010ARA&A..48..673F). doi: 10.1146/annurev-astro-082708-101829 (http://dx.doi.org/10.1146/annurev-astro-082708-101829).

External links

- The Hubble Key Project (http://www.ipac.caltech.edu/H0kp/H0KeyProj.html)
- The Hubble Diagram Project (http://cas.sdss.org/dr3/en/proj/advanced/hubble/)
- Merrifield, Michael (2009). "Hubble Constant" (http://www.sixtysymbols.com/videos/hubble.htm). *Sixty Symbols*. Brady Haran for the University of Nottingham.
- Hubble's quantum law. (http://alemanow.narod.ru/hubbles.htm)

Metric expansion of space

The **metric expansion of space** is the increase of the distance between two distant parts of the universe with time. It is an intrinsic expansion whereby *the scale of space itself is changed*. That is, a metric expansion is defined by an increase in distance between parts of the universe even without those parts "moving" anywhere. This is not the same as any usual concept of motion, or any kind of expansion of objects "outward" into other "preexisting" space, or any kind of explosion of matter which is commonly experienced on earth.

Metric expansion is a key feature of Big Bang cosmology and is modeled mathematically with the FLRW metric. This model is valid in the present era only on large scales (roughly the scale of galaxy clusters and above). At smaller scales matter has become bound together under the influence of gravitational attraction and such bound objects clumps do not expand at the metric expansion rate as the universe ages, though they continue to recede from one another. The expansion is a generic property of the universe we inhabit, though the reason we are expanding is explained by most cosmologists as having its origin in the end of the early universe's inflationary period which set matter and energy in the universe on an inertial trajectory consistent with the equivalence principle and Einstein's theory of general relativity (that is, the matter in the universe is separating because it was separating in the past). Additionally, the expansion rate of the universe has been measured to be accelerating; to explain this, physicists postulate a repulsive force of dark energy, which appears in the theoretical models as a cosmological constant. This acceleration of the universe has only recently become measurable. Due to recent measurements, it is now thought that up until about five billion years ago, the universe's expansion rate was actually *decelerating* due to the gravitational attraction of the matter content of the universe. According to the simplest extrapolation of the currently-favored cosmological model (known as "ΛCDM"), however, the dark energy acceleration will dominate on into the future.

While special relativity constrains objects in the universe from moving faster than the speed of light with respect to each other, it places no theoretical constraint on changes to the scale of space itself. It is thus possible for two objects to be stationary or moving at speeds below that of light, and yet to become separated in space by more than the distance light could have travelled, which can suggest the objects travelled faster than light. For example there are stars which may be expanding away from us (or each other) faster than the speed of light, and this is true for any object that is more than approximately 4.5 gigaparsecs away from us. We can still see such objects because the universe in the past was expanding more slowly than it is today, so the ancient light being received from these objects is still able to reach us, though if the expansion continues unabated there will come a time that we will never see the light from such objects being produced *today* (on a so-called "space-like slice of spacetime") because space itself is expanding between Earth and the source faster than their light can reach us.

Because of the changing rate of expansion, it is also possible for a distance to exceed the value calculated by multiplying the speed of light by the age of the universe. These details are a frequent source of confusion among amateurs and even professional physicists.[1]

Due to the non-intuitive nature of the subject and what has been described by some as "careless" choices of wording, certain descriptions of the metric expansion of space and the misconceptions to which such descriptions can lead are an ongoing subject of discussion in the realm of pedagogy and communication of scientific concepts.

Basic concepts and overview

Metric expansion

The metric expansion of space is a key part of science's current understanding of the universe, whereby space itself is described by a metric tensor which changes over time. It explains how the universe expands in the Big Bang model, a feature of our universe supported by all cosmological experiments, astrophysics calculations, and measurements to date.

This kind of expansion is different from all kinds of expansions and explosions commonly seen in nature. What we see normally as "space" and "distance" are not absolutes, but are determined by a metric that can change. In the metric expansion of space, rather than objects in a fixed "space" moving apart into "emptiness", it is space itself which is changing. It is as if without objects themselves moving, space is somehow growing or shrinking between them: if it were possible to place a tape measure between even stationary objects, one would observe the scale of the tape measure changing to show more distance between them.

Because this expansion is caused by changes in the distance-defining metric, and not by objects themselves moving in space, this expansion (and the resultant movement apart of objects) is not restricted by the speed of light upper bound of special relativity. So objects can be moving at sub-light speed yet appear to be moving apart faster than light.

Theory and observations suggest that very early in the history of the universe, there was an "inflationary" phase where this metric changed very rapidly, and that the remaining time-dependence of this metric is what we observe as the so-called Hubble expansion, the moving apart of all gravitationally unbound objects in the universe. The expanding universe is therefore a fundamental feature of the universe we inhabit - a universe fundamentally different from the static universe Albert Einstein first considered when he developed his gravitational theory.

Measuring distances in expanding spaces

A *metric* defines how a distance can be measured between two points in space. In Euclidean geometry, this distance can be measured by tracking a straight line between two points. However, in non-Euclidean geometry, the notion of a "straight line" or "distance" may not be the same, and the notion of "distance" varies depending upon the actual metric involved. In this sense, a metric is a generalization of the concept of "distance" for other geometries.

In expanding space, proper distances are dynamical quantities which change with time. An easy way to correct for this is to use comoving coordinates which remove this feature and allow for a characterization of the universe as a whole without having to characterize the physics associated with metric expansion. In comoving coordinates, the distances between all objects are fixed and the instantaneous dynamics of matter and light are determined by the normal physics of gravity and electromagnetic radiation. Any time-evolution however must be accounted for by taking into account the Hubble law expansion in the appropriate equations. Cosmological simulations that run through significant fractions of the universe's history therefore must be able to work in physical units which can directly predict observational cosmology.

Understanding the expansion of Universe

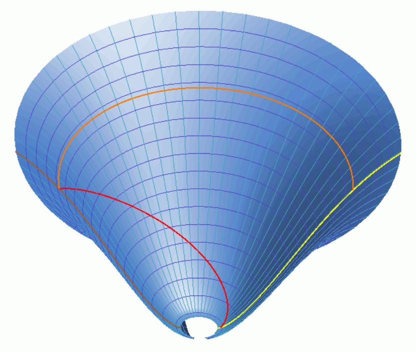
How is the expansion of the universe measured and how does the rate of expansion change?

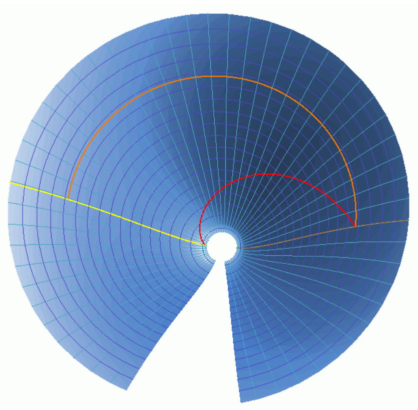
In principle, the expansion of the universe can be measured by taking a standard ruler and measuring the distance between two cosmologically distant points, waiting a certain time, and then measuring the distance again. In practice, standard rulers are not straightforward to find on cosmological scales and the time-scales for waiting to see a measurable expansion of the universe today are too long to be observable by even generations of humans. Instead, the theory of relativity predicts and observations show phenomena associated with the expansion of the universe, notably the redshift-distance relationship known as Hubble's Law, functional forms for cosmological distance measurements that differ from what would be expected if space were not expanding, and an observable change in the matter and energy density of the universe seen at different lookback times.

The first measurement of the expansion of space occurred with the creation of the Hubble diagram. Using standard candles with known intrinsic brightness, the expansion of the universe has been measured using redshift to derive Hubble's Constant: $H_0 = 67.15 \pm 1.2$ (km/s)/Mpc. For every million parsecs of distance from the observer, the rate of expansion increases by about 67 kilometers per second. Since distant objects are observed further back in time, there is a one-to-one correspondence between the distance to a distant galaxy and the amount of time that has passed since the light being observed was emitted from that galaxy. Thus, Hubble's Constant can be thought of as an acceleration which in the local universe is equivalent to approximately 7×10^{-10}meters per second per second, though this value is on large-scales dependent on how one defines the distance between two points and how one measures the elapsed time. Cosmologists often adopt comoving coordinates which remove the expansion altogether.

The acceleration of objects moving away from each other in an expanding universe is not the sort of acceleration which can be associated with a force as in Newton's Second Law because the expansion is an intrinsic property of the way space and time are measured rather than being due to dynamical interactions. Nevertheless, because the dimensional form of Hubble's Constant can yield an acceleration this has caused some confusion associated with the so-called "accelerating universe" which was first discovered and characterized in the late 1990s. In a universe that is undergoing a constant Hubble expansion, the universal Hubble Constant can be conceptualized as a universal acceleration, but Hubble's Constant is not constant through time since there are dynamical forces acting on the particles in the universe which affect the expansion rate. It was expected that the Hubble Constant would be decreasing as time went on due to the influence of gravitational interactions in the universe, and thus there is an additional observable quantity in the universe called the deceleration parameter which cosmologists expected to be directly related to the matter density of the universe. Surprisingly, the deceleration parameter was measured by two different groups to be less than zero (actually, consistent with -1) which implied that today Hubble's Constant is increasing as time goes on. Since Hubble's Constant can be associated with an acceleration, the change in Hubble's Constant over time can be associated with the time derivative of acceleration, and so some cosmologists have whimsically called the effect associated with the "accelerating universe" the "cosmic jerk".[2] The 2011 Nobel Prize in Physics was given for the discovery of this phenomenon.[3]

How are distances between two points measured if space is expanding?





Two views of an isometric embedding of part of the visible universe over most of its history, showing how a light ray (red line) can travel an effective distance of 28 billion light years (orange line) in just 13 billion years of cosmological time. Click the images to zoom. (Mathematical details)

At cosmological scales the present universe is geometrically flat, which is to say that the rules of Euclidean geometry associated with Euclid's fifth postulate hold, though in the past spacetime could have been highly curved. In part to accommodate such different geometries, the expansion of the universe is inherently general relativistic; it cannot be modeled with special relativity alone, though such models can be written down, they are at fundamental odds with the observed interaction between matter and spacetime seen in our universe.

The images to the right show two views of spacetime diagrams that show the large-scale geometry of the universe according to the ΛCDM cosmological model. Two of the dimensions of space are omitted, leaving one dimension of space (the dimension that grows as the cone gets larger) and one of time (the dimension that proceeds "up" the cone's surface). The narrow circular end of the diagram corresponds to a cosmological time of 700 million years after the big bang while the wide end is a cosmological time of 18 billion years, where one can see the beginning of the accelerating expansion as a splaying outward of the spacetime, a feature which eventually dominates in this model. The purple grid lines mark off cosmological time at intervals of one billion years from the big bang. The cyan grid lines mark off comoving distance at intervals of one billion light years. Note that the circular curling of the surface is an artifact of the embedding with no physical significance and is done purely to make the illustration viewable; space does not actually curl around on itself. (A similar effect can be seen in the tubular shape of the pseudosphere.)

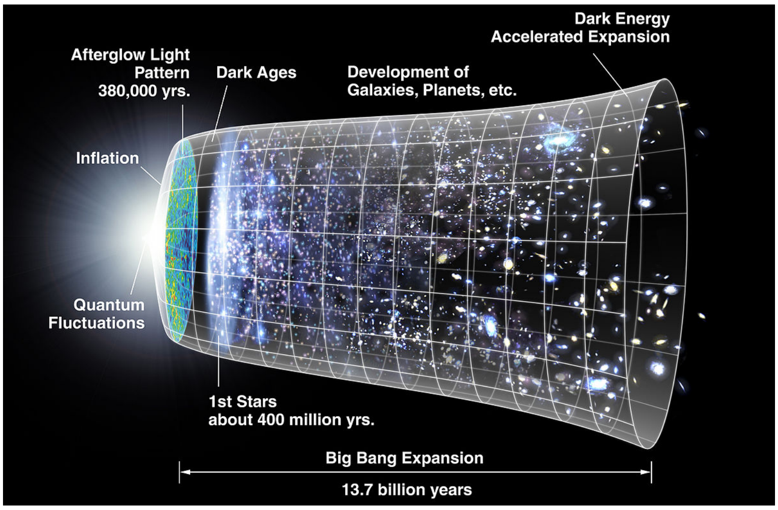
The brown line on the diagram is the worldline of the Earth (or, at earlier times, of the matter which condensed to form the Earth). The yellow line is the worldline of the most distant known quasar. The red line is the path of a light beam emitted by the quasar about 13 billion years ago and reaching the Earth in the present day. The orange line shows the present-day distance between the quasar and the Earth, about 28 billion light years, which is, notably, a larger distance than the age of the universe multiplied by the speed of light: *ct*.

According to the equivalence principle of general relativity, the rules of special relativity are *locally* valid in small regions of spacetime that are approximately flat. In particular, light always travels locally at the speed *c*; in our diagram, this means, according to the convention of constructing spacetime diagrams, that light beams always make an angle of 45° with the local grid lines. It does not follow, however, that light travels a distance *ct* in a time *t*, as the red worldline illustrates. While it always moves locally at *c*, its time in transit (about 13 billion years) is not related to the distance traveled in any simple way since the universe expands as the light beam traverses space and time. In fact the distance traveled is inherently ambiguous because of the changing scale of the universe. Nevertheless, we can single out two distances which appear to be physically meaningful: the distance between the Earth and the quasar when the light was emitted, and the distance between them in the present era (taking a slice of the cone along the dimension that we've declared to be the spatial dimension). The former distance is about 4 billion light years, much smaller than *ct* because the universe expanded as the light traveled the distance, the light had to "run against the treadmill" and therefore went farther than the initial separation between the Earth and the quasar. The latter distance (shown by the orange line) is about 28 billion light years, much larger than *ct*. If expansion could be instantaneously stopped today, it would take 28 billion years for light to travel between the Earth and the quasar while if the expansion had stopped at the earlier time, it would have taken only 4 billion years.

The light took much longer than 4 billion years to reach us though it was emitted from only 4 billion light years away, and, in fact, the light emitted towards the Earth was actually moving *away* from the Earth when it was first emitted, in the sense that the metric distance to the Earth increased with cosmological time for the first few billion years of its travel time, and also indicating that the expansion of space between the Earth and the quasar at the early time was faster than the speed of light. None of this surprising behavior originates from a special property of metric expansion, but simply from local principles of special relativity integrated over a curved surface.

What space is the universe expanding into?

Over time, the space that makes up the universe is expanding. The words 'space' and 'universe', sometimes used interchangeably, have distinct meanings in this context. Here 'space' is a mathematical concept that stands for the three-dimensional manifold into which our respective positions are embedded while 'universe' refers to everything that exists including the matter and energy in space, the extra-dimensions that may be wrapped up in various strings, and the time through which various events take place. The expansion of space is in reference to this 3-D manifold only; that is, the description involves no structures such as extra dimensions or an exterior universe.



A graphical representation of the expansion of the universe with the inflationary epoch represented as the dramatic expansion of the metric seen on the left. This diagram can be confusing because the expansion of space looks like it is happening into an empty "nothingness". However, this is a choice made for convenience of visualization: it is not a part of the physical models which describe the expansion.

The ultimate topology of space is something which in principle must be observed as there are no *a priori* constraints on how the space in which we live is connected or whether it wraps around on itself as a compact space. Though certain cosmological models such as Gödel's universe even permit bizarre worldlines which intersect with themselves, ultimately the question as to whether we are in something like a "pac-man universe" where if traveling far enough in one direction would allow one to simply end up back in the same place like going all the way around the surface of a balloon (or a planet like the Earth) is an observational question which is constrained as measurable or non-measurable by the universe's global geometry. At present, observations are consistent with the universe being infinite in extent and simply connected, though we are limited in distinguishing between simple and more complicated proposals by cosmological horizons. The universe could be infinite in extent or it could be finite; but the evidence that leads to the inflationary model of the early universe also implies that the "total universe" is much larger than the observable universe, and so any edges or exotic geometries or topologies would not be directly observable as light has not reached scales on which such aspects of the universe, if they exist, are still allowed. For all intents and purposes, it is safe to assume that the universe is infinite in spatial extent, without edge or strange connectedness.[4]

Regardless of the overall shape of the universe, the question of what the universe is expanding into is one which does not require an answer according to the theories which describe the expansion; the way we define space in our universe in no way requires additional exterior space into which it can expand since an expansion of an infinite expanse can happen without changing the infinite extent of the expanse. All that is certain is that the manifold of space in which we live simply has the property that the distances between objects are getting larger as time goes on. This only implies the simple observational consequences associated with the metric expansion explored below. No "outside" or embedding in hyperspace is required for an expansion to occur. The visualizations often seen of the universe growing as a bubble into nothingness are misleading in that respect. There is no reason to believe there is anything "outside" of the expanding universe into which the universe expands.

Even if the overall spatial extent is infinite and thus the universe can't get any "larger", we still say that space is expanding because, locally, the characteristic distance between objects is increasing. As an infinite space grows, it remains infinite.

Is the expansion of the universe felt on small scales?

The expansion of space is sometimes described as a force which acts to push objects apart. Though this is an accurate description of the effect of the cosmological constant, it is not an accurate picture of the phenomenon of expansion in general. For much of the universe's history the expansion has been due mainly to inertia. The matter in the very early universe was flying apart for unknown reasons (most likely as a result of cosmic inflation) and has simply continued to do so, though at an ever-decreasing rate due to the attractive effect of gravity.

In addition to slowing the overall expansion, gravity causes local clumping of matter into stars and galaxies. Once objects are formed and bound by gravity, they "drop out" of the expansion and do not subsequently expand under the influence of the cosmological metric, there being no force compelling them to do so.

There is no difference between

- the inertial expansion of the universe and
- the inertial separation of nearby objects in a vacuum;

the former is simply a large-scale extrapolation of the latter.

Once objects are bound by gravity, they no longer recede from each other. Thus, the Andromeda galaxy, which is bound to the Milky Way galaxy, is actually falling *towards* us and is not expanding away. Within our Local Group of galaxies, the gravitational interactions have changed the inertial patterns of objects such that there is no cosmological expansion taking place. Once one goes beyond the local group, the inertial expansion is measurable, though systematic gravitational effects imply that larger and larger parts of space will eventually fall out of the "Hubble Flow" and end up as bound, non-expanding objects up to the scales of superclusters of galaxies. We can predict such future events by knowing the precise way the Hubble Flow is changing as well as the masses of the objects to which we are being gravitationally pulled. Currently, our Local Group is being gravitationally pulled towards either the Shapley Supercluster or the "Great Attractor" with which, if dark energy were not acting, we would eventually merge and no longer see expand away from us after such a time.

An interesting consequence of metric expansion being due to inertial motion is that a uniform local "explosion" of matter into a vacuum can be locally described by the FLRW geometry, the same geometry which describes the expansion of the universe as a whole and was also the basis for the simpler Milne universe which ignores the effects of gravity. In particular, general relativity predicts that light will move at the speed c with respect to the local motion of the exploding matter, a phenomenon analogous to frame dragging.

The situation changes somewhat with the introduction of dark energy or a cosmological constant. A cosmological constant due to a vacuum energy density has the effect of adding a repulsive force between objects which is proportional (not inversely proportional) to distance. Unlike inertia it actively "pulls" on objects which have clumped together under the influence of gravity, and even on individual atoms. However, this does not cause the objects to grow steadily or to disintegrate; unless they are very weakly bound, they will simply settle into an equilibrium state which is slightly (undetectably) larger than it would otherwise have been. As the universe expands and the matter in it thins, the gravitational attraction decreases (since it is proportional to the density), while the cosmological repulsion increases; thus the ultimate fate of the ΛCDM universe is a near vacuum expanding at an ever increasing rate under the influence of the cosmological constant. However, the only locally visible effect of the accelerating expansion is the disappearance (by runaway redshift) of distant galaxies; gravitationally bound objects like the Milky Way do not expand and the Andromeda galaxy is moving fast enough towards us that it will still merge with the Milky Way in 3 billion years time, and it is also likely that the merged supergalaxy that forms will eventually fall in and merge with the nearby Virgo Cluster. However, galaxies lying farther away from this will recede away at ever-increasing rates of speed and be redshifted out of our range of visibility.

Scale factor

At a fundamental level, the expansion of the universe is a property of spatial measurement on the largest measurable scales of our universe. The distances between cosmologically relevant points increases as time passes leading to observable effects outlined below. This feature of the universe can be characterized by a single parameter that is called the scale factor which is a function of time and a single value for all of space at any instant (if the scale factor were a function of space, this would violate the cosmological principle). By convention, the scale factor is set to be unity at the present time and, because the universe is expanding, is smaller in the past and larger in the future. Extrapolating back in time with certain cosmological models will yield a moment when the scale factor was zero, our current understanding of cosmology sets this time at 13.798 ± 0.037 billion years ago. If the universe continues to expand forever, the scale factor will approach infinity in the future. In principle, there is no reason that the expansion of the universe must be monotonic and there are models that exist where at some time in the future the scale factor decreases with an attendant contraction of space rather than an expansion.

Other conceptual models of expansion

The expansion of space is often illustrated with conceptual models which show only the size of space at a particular time, leaving the dimension of time implicit.

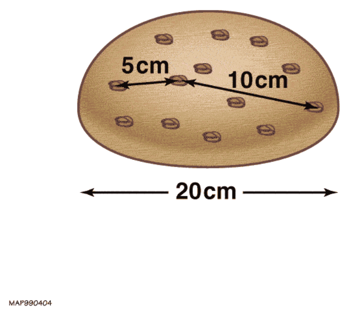
In the "ant on a rubber rope model" one imagines an ant (idealized as pointlike) crawling at a constant speed on a perfectly elastic rope which is constantly stretching. If we stretch the rope in accordance with the ΛCDM scale factor and think of the ant's speed as the speed of light, then this analogy is numerically accurate—the ant's position over time will match the path of the red line on the embedding diagram above.

In the "rubber sheet model" one replaces the rope with a flat two-dimensional rubber sheet which expands uniformly in all directions. The addition of a second spatial dimension raises the possibility of showing local perturbations of the spatial geometry by local curvature in the sheet.

In the "balloon model" the flat sheet is replaced by a spherical balloon which is inflated from an initial size of zero (representing the big bang). A balloon has positive Gaussian curvature while observations suggest that the real universe is spatially flat, but this inconsistency can be eliminated by making the balloon very large so that it is locally flat to within the limits of observation. This analogy is potentially confusing since it wrongly suggests that the big bang took place at the center of the balloon. In fact points off the surface of the balloon have no meaning, even if they were occupied by the balloon at an earlier time.

In the "raisin bread model" one imagines a loaf of raisin bread expanding in the oven. The loaf (space) expands as a whole, but the raisins (gravitationally bound objects) do not expand; they merely grow farther away from each other.

All of these models have the conceptual problem of requiring an outside force acting on the "space" at all times to make it expand. Unlike real cosmological matter, sheets of rubber and loaves of bread are bound together electromagnetically and will not continue to expand on their own after an initial tug.



Animation of an expanding raisin bread model. As the bread doubles in width (depth and length), the distances between raisins also double.

Overview of metrics

Metric expansion is not something that most humans are aware of, on a day to day basis. To understand the expansion of the universe, it is helpful to discuss briefly what a metric is, and how metric expansion works.

Definition of a metric

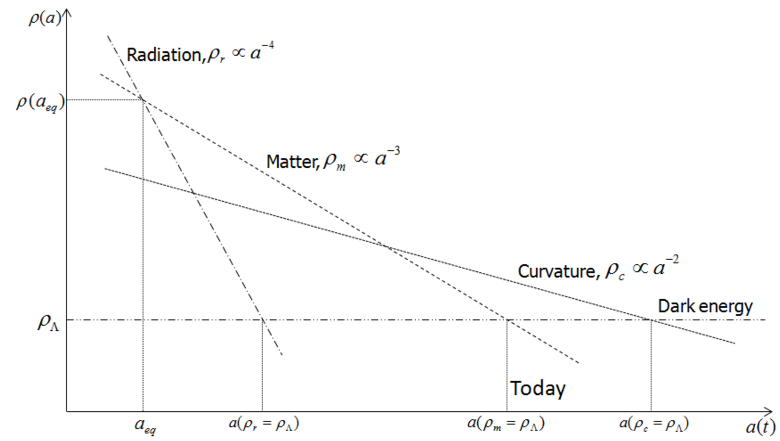
A **metric** defines how a distance can be measured between two *nearby* points in space, in terms of the coordinates of those points. A coordinate system locates points in a space (of whatever number of dimensions) by assigning unique numbers known as coordinates, to each point. The metric is then a formula which converts coordinates of two points into distances.

Metric for Earth's surface

For example, consider the measurement of distance between two places on the surface of the Earth. This is a simple, familiar example of spherical geometry. Because the surface of the Earth is two-dimensional, points on the surface of the earth can be specified by two coordinates—for example, the latitude and longitude. Specification of a metric requires that one first specify the coordinates used. In our simple example of the surface of the Earth, we could choose any kind of coordinate system we wish, for example latitude and longitude, or X-Y-Z Cartesian coordinates. Once we have chosen a specific coordinate system, the numerical values of the coordinates of any two points are uniquely determined, and based upon the properties of the space being discussed, the appropriate metric is mathematically established too. On the curved surface of the Earth, we can see this effect in long-haul airline flights where the distance between two points is measured based upon a Great circle, and not along the straight line that passes through the Earth. While there is always an effect due to this curvature, at short distances the effect is so small as to be unnoticeable.

Theoretical basis and first evidence

Hubble's law



[citation needed]

Technically, the metric expansion of space is a feature of many solutions to the Einstein field equations of general relativity, and distance is measured using the Lorentz interval. This explains observations which indicate that galaxies that are more distant from us are receding faster than galaxies that are closer to us (Hubble's law).

Cosmological constant and the Friedmann equations

The first general relativistic models predicted that a universe which was dynamical and contained ordinary gravitational matter would contract rather than expand. Einstein's first proposal for a solution to this problem involved adding a cosmological constant into his theories to balance out the contraction, in order to obtain a static universe solution. But in 1922 Alexander Friedmann derived a set of equations known as the Friedmann equations, showing that the universe might expand and presenting the expansion speed in this case.[5] The observations of Edwin Hubble in 1929 suggested that distant galaxies were all apparently moving away from us, so that many scientists came to accept that the universe was expanding.

Hubble's concern over the large expansion rate

While the metric expansion of space is implied by Hubble's 1929 observations, Hubble was concerned with the observational implications of the precise value he measured:

> "… if redshift are not primarily due to velocity shift … the velocity-distance relation is linear, the distribution of the nebula is uniform, there is no evidence of expansion, no trace of curvature, no restriction of the time scale … and we find ourselves in the presence of one of the principle of nature that is still unknown to us today … whereas, if redshifts are velocity shifts which measure the rate of expansion, the expanding models are definitely inconsistent with the observations that have been made … expanding models are a forced interpretation of the observational results"
>
> — E. Hubble, *Ap. J., 84, 517, 1936*[6]

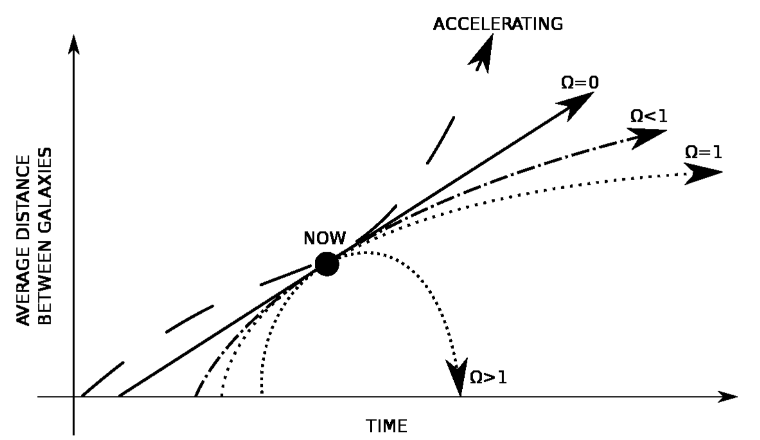
> "[If the redshifts are a Doppler shift] … the observations as they stand lead to the anomaly of a closed universe, curiously small and dense, and, it may be added, suspiciously young. On the other hand, if redshifts are not Doppler effects, these anomalies disappear and the region observed appears as a small, homogeneous, but insignificant portion of a universe extended indefinitely both in space and time."
>
> — E. Hubble, *Monthly Notices of the Royal Astronomical Society, 97, 513, 1937*[7]

In fact, Hubble's skepticism about the universe being too small, dense, and young was justified, though it turned out to be an observational error rather than an error of interpretation. Later investigations showed that Hubble had confused distant HII regions for Cepheid variables and the Cepheid variables themselves had been inappropriately lumped together with low-luminosity RR Lyrae stars causing calibration errors that led to a value of the Hubble Constant of approximately 500 km/s/Mpc instead of the true value of approximately 70 km/s/Mpc. The higher value meant that an expanding universe would have an age of 2 billion years (younger than the Age of the Earth) and extrapolating the observed number density of galaxies to a rapidly expanding universe implied a mass density that was too high by a similar factor, enough to force the universe into a peculiar closed geometry which also implied an impending Big Crunch that would occur on a similar time-scale. After fixing these errors in the 1950s, the new lower values for the Hubble Constant accorded with the expectations of an older universe and the density parameter was found to be fairly close to a geometrically flat universe.[8]

Inflation as an explanation for expansion

While the detailed measurements of the precise rate of expansion were being worked out, the notion of the expansion of the universe became consensus. Until the theoretical developments in the 1980s no one had an explanation for why this seemed to be the case, but with the development of models of cosmic inflation, the expansion of the universe became a general feature resulting from vacuum decay. Accordingly, the question "why is the universe expanding?" is now answered by understanding the details of the inflation decay process which occurred in the first 10^{-32} seconds of the existence of our universe. It is suggested that in this time the metric itself changed exponentially, causing space to change from smaller than an atom to around 100 million light years across.

Measuring distance in a metric space



The expansion of the universe proceeds in all directions as determined by the Hubble constant today. However, the Hubble constant can change in the past and in the future, dependent on the observed value of density parameters (Ω). Before the discovery of dark energy, it was believed that the universe was matter-dominated, and so Ω on this graph corresponds to the ratio of the matter density to the critical density (Ω_m).

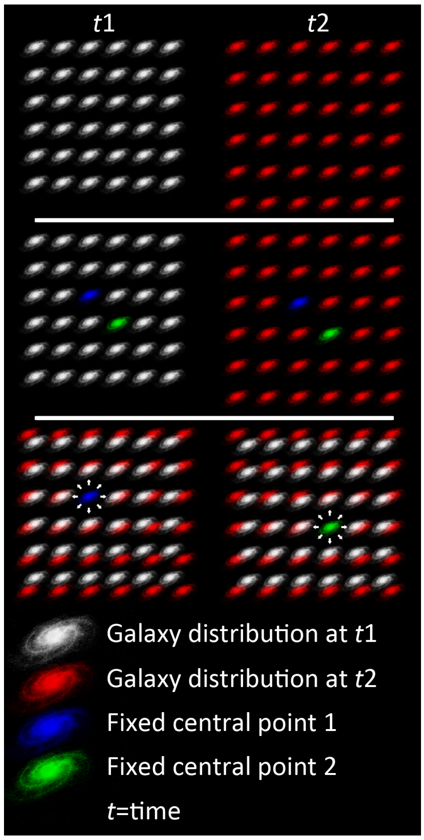
In expanding space, distance is a dynamic quantity which changes with time. There are several different ways of defining distance in cosmology, known as *distance measures*, but the most common is **comoving distance**.

The metric only defines the distance between nearby points. In order to define the distance between arbitrarily distant points, one must specify both the points and a specific curve connecting them. The distance between the points can then be found by finding the length of this connecting curve. Comoving distance defines this connecting curve to be a curve of constant cosmological time. Operationally, comoving distances cannot be directly measured by a single Earth-bound observer. To determine the distance of distant objects, astronomers generally measure luminosity of standard candles, or the redshift factor 'z' of distant galaxies, and then convert these measurements into distances based on some particular model of space-time, such as the Lambda-CDM model. Unfortunately, there is no evidence for any 'slowing down' of the expansion.

Observational evidence

Theoretical cosmologists developing models of the universe have drawn upon a small number of reasonable assumptions in their work. These workings have led to models in which the metric expansion of space is a likely feature of the universe. Chief among the underlying principles that result in models including metric expansion as a feature are:

- the Cosmological Principle which demands that the universe looks the same way in all directions (isotropic) and has roughly the same smooth mixture of material (homogeneous).
- the Copernican Principle which demands that no place in the universe is preferred (that is, the universe has no "starting point").



A diagram depicting the expansion of the universe and the appearance of galaxies moving away from a single galaxy. The phenomenon is relative to the observer. Object *t*1 is a smaller expansion than *t*2. Each section represents the movement of the red galaxies over the white galaxies for comparison. The blue and green galaxies are markers to show which galaxy is the same one (fixed center point) in the subsequent box. *t* = time.

Scientists have tested carefully whether these assumptions are valid and borne out by observation. Observational cosmologists have discovered evidence - very strong in some cases - that supports these assumptions, and as a result, metric expansion of space is considered by cosmologists to be an observed feature on the basis that although we cannot see it directly, scientists have tested the properties of the universe and observation provides compelling confirmation. Sources of this confidence and confirmation include:

- Hubble demonstrated that all galaxies (with the exception of a few very near ones) and distant astronomical objects were moving away from us, as predicted by a universal expansion.[9] Using the redshift of their electromagnetic spectra to determine the distance and speed of remote objects in space, he showed that the speed of such distant objects is roughly proportional to their distance, a feature of metric expansion. Further studies have since shown the expansion to be extremely isotropic and homogeneous, that is, it does not seem to have a special point as a "center", but appears universal and independent of any fixed central point.
- In studies of large-scale structure of the cosmos taken from redshift surveys a so-called "End of Greatness" was discovered at the largest scales of the universe. Until these scales were surveyed, the universe appeared "lumpy" with clumps of galaxy clusters and superclusters and filaments which were anything but isotropic and homogeneous. This lumpiness disappears into a smooth distribution of galaxies at the largest scales.
- The isotropic distribution across the sky of distant gamma-ray bursts and supernovae is another confirmation of the Cosmological Principle.
- The Copernican Principle was not truly tested on a cosmological scale until measurements of the effects of the cosmic microwave background radiation on the dynamics of distant astrophysical systems were made. A group of astronomers at the European Southern Observatory noticed, by measuring the temperature of a distant intergalactic cloud in thermal equilibrium with the cosmic microwave background, that the radiation from the Big Bang was demonstrably warmer at earlier times.[10] Uniform cooling of the cosmic microwave background over billions of years is strong and direct observational evidence for metric expansion.

Taken together, these phenomena overwhelmingly support models that rely on space expanding through a change in metric. Interestingly, it was not until the discovery in the year 2000 of direct observational evidence for the changing temperature of the cosmic microwave background that more bizarre constructions could be ruled out. Until that time, it was based purely on an assumption that the universe did not behave as one with the Milky Way sitting at the middle of a fixed-metric with a universal explosion of galaxies in all directions (as seen in, for example, an early model proposed by Milne). Yet before this evidence, many rejected the Milne viewpoint based on the mediocrity principle.

The spatial and temporal universality of physical laws was until very recently taken as a fundamental philosophical assumption that is now tested to the observational limits of time and space.

Notes

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Big Bang nucleosynthesis

In physical cosmology, **Big Bang nucleosynthesis** (abbreviated BBN, also known as **primordial nucleosynthesis**) refers to the production of nuclei other than those of the lightest isotope of hydrogen during the early phases of the universe. Primordial nucleosynthesis is believed by most cosmologists to have taken place between approximately 10 seconds until 20 minutes after the Big Bang, and is calculated to be responsible for the formation of most of the universe's helium as isotope He-4, along with small amounts of deuterium (H-2 or D), the helium isotope He-3, and a very small amount of the lithium isotope Li-7. In addition to these stable nuclei, two unstable or radioactive isotopes were also produced: tritium or H-3; and beryllium-7 (Be-7); but these unstable isotopes later decayed into He-3 and Li-7, as above.

Essentially all the elements heavier than Lithium were created much later, by stellar nucleosynthesis in evolving and exploding stars.

Characteristics

There are two important characteristics of Big Bang nucleosynthesis (BBN):

- The era began at temperatures of around 10 MeV (116 gigakelvin) and ended at temperatures below 100 keV (1.16 gigakelvin).[1] The corresponding time interval was from a few tenths of a second to up to 10^3 seconds.[2] The temperature/time relation in this era can be given by the equation:

  $$tT^2 = 0.74(10.75/g_*)^{1/2}$$ [3]

  Where t is time in seconds, T is temperature in MeV and g_* is the effective number of particle species. (g_* includes contributions of 2 from photons, 7/2 from electron-positron pairs and 7/4 from each neutrino flavor. In the standard model g_* is 10.75). This expression also shows how a different number of neutrino flavors will change the rate of cooling of the early universe.
- It was widespread, encompassing the entire observable universe.

The key parameter which allows one to calculate the effects of BBN is the number of photons per baryon. This parameter corresponds to the temperature and density of the early universe and allows one to determine the conditions under which nuclear fusion occurs. From this we can derive elemental abundances. Although the baryon per photon ratio is important in determining elemental abundances, the precise value makes little difference to the overall picture. Without major changes to the Big Bang theory itself, BBN will result in mass abundances of about 75% of H-1, about 25% helium-4, about 0.01% of deuterium, trace amounts (on the order of 10^{-10}) of lithium and beryllium, and no other heavy elements. (Traces of boron have been found in some old stars, giving rise to the question whether some boron, not really predicted by the theory, might have been produced in the Big Bang. The question is not presently resolved.) That the observed abundances in the universe are generally consistent with these abundance numbers is considered strong evidence for the Big Bang theory.

In this field it is customary to quote percentages *by mass*, so that 25% helium-4 means that helium-4 atoms account for 25% of the mass, but only about 8% of the atoms would be helium-4 atoms.

Important Parameters

The creation of light elements during BBN was dependent on a number of parameters; among those was the neutron-proton ratio (calculable from Standard Model physics) and the baryon-photon ratio.

Neutron-Proton Ratio

Neutrons can react with positrons or electron neutrinos to create protons and other products in one of the following reactions:

$n + e^+ \leftrightarrow \text{anti-}\nu_e + p$

$n + \nu_e \leftrightarrow p + e^-$

These reactions continue until expansion of the universe outpaces the reactions, which occurs at about T = 0.7 MeV and is called the freeze out temperature. At freeze out, the neutron-proton ratio is about 1/7. Almost all neutrons that exist after the freeze out ended up combined into Helium-4, due to the fact that Helium-4 has the highest binding energy per nucleon among light elements. This predicts that the mass fraction of Helium-4 should be about 25%, which is in line with observations. Some deuterium and Helium-3 remained as there was insufficient time and density for them to react and form Helium-4.

Baryon-Photon Ratio

The baryon-photon ratio η, is a strong indicator of the abundance of light elements present in the early universe. Baryons can react with light elements in the following reactions:

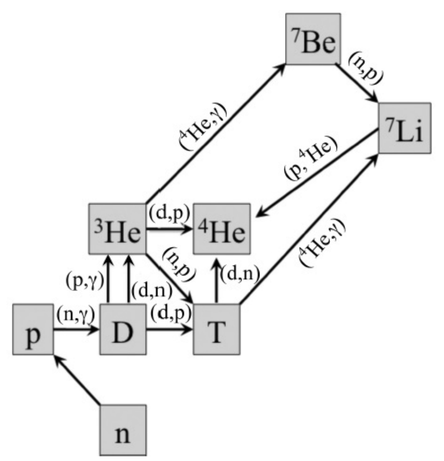
$(p,n) + {}^2H \rightarrow ({}^3He, {}^3H)$

$({}^3He, {}^3H) + (n,p) \rightarrow {}^4He$

It is evident that reactions with baryons during BBN would ultimately result in Helium-4, and also that the abundance of primordial deuterium is indirectly related to the baryon density or baryon-photon ratio. That is, the larger the baryon-photon ratio the more reactions there will be and the more deuterium will be eventually transformed into Helium-4. This result makes deuterium a very useful tool in measuring the baryon-to-photon ratio.

Sequence

Big Bang nucleosynthesis began a few seconds after the big bang, when the universe had cooled sufficiently to allow deuterium nuclei to survive disruption by high-energy photons. This time is essentially independent of dark matter content, since the universe was highly radiation dominated until much later, and this dominant component controls the temperature/time relation. The relative abundances of protons and neutrons follow from simple thermodynamical arguments, combined with the way that the mean temperature of the universe changes over time. If the reactions needed to reach the thermodynamically favoured equilibrium values are too slow compared to the temperature change brought about by the expansion, abundances would have remained at some specific non-equilibrium value. Combining thermodynamics and the changes brought about by cosmic expansion, one can calculate the fraction of protons and neutrons based on the temperature at this point. The answer is that there are about seven protons for every neutron at the beginning of nucleosynthesis. This fraction is in favour of protons, primarily because their lower mass with respect to the neutron favors their production. Free neutrons decay to protons with a



The main nuclear reaction chains for Big Bang nucleosynthesis half-life of about 15 minutes, but this time-scale is longer than the first three minutes of nucleogenesis, during which time a substantial fraction of them were combined with protons into deuterium and then He-4. The sequence of these reaction chains is shown on the image.

One feature of BBN is that the physical laws and constants that govern the behavior of matter at these energies are very well understood, and hence BBN lacks some of the speculative uncertainties that characterize earlier periods in the life of the universe. Another feature is that the process of nucleosynthesis is determined by conditions at the start of this phase of the life of the universe, making what happens before irrelevant.

As the universe expands, it cools. Free neutrons and protons are less stable than helium nuclei, and the protons and neutrons have a strong tendency to form helium-4. However, forming helium-4 requires the intermediate step of forming deuterium. Before nucleosynthesis began, the temperature was high enough for many photons to have energy greater than the binding energy of deuterium; therefore any deuterium that is formed was immediately destroyed (a situation known as the **deuterium bottleneck**). Hence, the formation of helium-4 is delayed until the universe became cool enough for deuterium to survive (at about T = 0.1 MeV); after which there was a sudden burst of element formation. However, very shortly thereafter, at twenty minutes after the Big Bang, the universe became too cool for any further nuclear fusion and nucleosynthesis to occur. At this point, the elemental abundances were nearly fixed, and only change was the result of the radioactive decay of some products of BBN (such as tritium).

History of theory

The history of Big Bang nucleosynthesis began with the calculations of Ralph Alpher and George Gamow in the 1940s. Alpher and Gamow published the seminal Alpher-Bethe-Gamow paper (the addition of Bethe as an author was a joke, see the article on the paper) that outlined the theory of light-element production in the early universe.

During the 1970s, there was a major puzzle in that the density of baryons as calculated by Big Bang nucleosynthesis was much less than the observed mass of the universe based on calculations of the expansion rate. This puzzle was resolved in large part by postulating the existence of dark matter.

Heavy elements

Big Bang nucleosynthesis produced no elements heavier than beryllium, due to a bottleneck: the absence of a stable nucleus with 8 or 5 nucleons. This deficit of larger atoms also limited the amounts of lithium-7 and beryllium-9 produced during BBN. In stars, the bottleneck is passed by triple collisions of helium-4 nuclei, producing carbon (the triple-alpha process). However, this process is very slow, taking tens of thousands of years to convert a significant amount of helium to carbon in stars, and therefore it made a negligible contribution in the minutes following the Big Bang.

Helium-4

Big Bang nucleosynthesis predicts a primordial abundance of about 25% helium-4 by mass, irrespective of the initial conditions of the universe. As long as the universe was hot enough for protons and neutrons to transform into each other easily, their ratio, determined solely by their relative masses, was about 1 neutron to 7 protons (allowing for some decay of neutrons into protons). Once it was cool enough, the neutrons quickly bound with an equal number of protons to form first deuterium, then helium-4. Helium-4 is very stable and is nearly the end of this chain if it runs for only a short time, since helium neither decays nor combines easily to form heavier nuclei (since there are no stable nuclei with mass numbers of 5 or 8, helium does not combine easily with either protons, or with itself). Once temperatures are lowered, out of every 16 nucleons (2 neutrons and 14 protons), 4 of these (25% of the total particles and total mass) combine quickly into one helium-4 nucleus. This produces one helium for every 12 hydrogens, resulting in a universe that is a little over 8% helium by number of atoms, and 25% helium by mass.

One analogy is to think of helium-4 as ash, and the amount of ash that one forms when one completely burns a piece of wood is insensitive to how one burns it. The resort to the BBN theory of the helium-4 abundance is necessary as there is far more helium-4 in the universe than can be explained by stellar nucleosynthesis. In addition, it provides an important test for the Big Bang theory. If the observed helium abundance is much different from 25%, then this would pose a serious challenge to the theory. This would particularly be the case if the early helium-4 abundance was much smaller than 25% because it is hard to destroy helium-4. For a few years during the mid-1990s, observations suggested that this might be the case, causing astrophysicists to talk about a Big Bang nucleosynthetic crisis, but further observations were consistent with the Big Bang theory.

Deuterium

Deuterium is in some ways the opposite of helium-4 in that while helium-4 is very stable and very difficult to destroy, deuterium is only marginally stable and easy to destroy. The temperatures, time, and densities were sufficient to combine a substantial fraction of the deuterium nuclei to form helium-4 but insufficient to carry the process further using helium-4 in the next fusion step. BBN did not convert all of the deuterium in the universe to helium-4 due to the expansion that cooled the universe and reduced the density and so, cut that conversion short before it could proceed any further. One consequence of this is that unlike helium-4, the amount of deuterium is very sensitive to initial conditions. The denser the initial universe was, the more deuterium would be converted to helium-4 before time ran out, and the less deuterium would remain.

There are no known post-Big Bang processes which can produce significant amounts of deuterium. Hence observations about deuterium abundance suggest that the universe is not infinitely old, which is in accordance with the Big Bang theory.

During the 1970s, there were major efforts to find processes that could produce deuterium, but those revealed ways of producing isotopes other than deuterium. The problem was that while the concentration of deuterium in the universe is consistent with the Big Bang model as a whole, it is too high to be consistent with a model that presumes that most of the universe is composed of protons and neutrons. If one assumes that all of the universe consists of protons and neutrons, the density of the universe is such that much of the currently observed deuterium would have been burned into helium-4. The standard explanation now used for the abundance of deuterium is that the universe does not consist mostly of baryons, but that non-baryonic matter (also known as dark matter) makes up most of the mass of the universe. This explanation is also consistent with calculations that show that a universe made mostly of protons and neutrons would be far more *clumpy* than is observed.

It is very hard to come up with another process that would produce deuterium other than by nuclear fusion. Such a process would require that the temperature be hot enough to produce deuterium, but not hot enough to produce helium-4, and that this process should immediately cool to non-nuclear temperatures after no more than a few minutes. It would also be necessary for the deuterium to be swept away before it reoccurs.

Producing deuterium by fission is also difficult. The problem here again is that deuterium is very unlikely due to nuclear processes, and that collisions between atomic nuclei are likely to result either in the fusion of the nuclei, or in the release of free neutrons or alpha particles. During the 1970s, cosmic ray spallation was proposed as a source of deuterium. That theory failed to account for the abundance of deuterium, but led to explanations of the source of other light elements.

Measurements and status of theory

The theory of BBN gives a detailed mathematical description of the production of the light "elements" deuterium, helium-3, helium-4, and lithium-7. Specifically, the theory yields precise quantitative predictions for the mixture of these elements, that is, the primordial abundances at the end of the big-bang.

In order to test these predictions, it is necessary to reconstruct the primordial abundances as faithfully as possible, for instance by observing astronomical objects in which very little stellar nucleosynthesis has taken place (such as certain dwarf galaxies) or by observing objects that are very far away, and thus can be seen in a very early stage of their evolution (such as distant quasars).

As noted above, in the standard picture of BBN, all of the light element abundances depend on the amount of ordinary matter (baryons) relative to radiation (photons). Since the universe is presumed to be homogeneous, it has one unique value of the baryon-to-photon ratio. For a long time, this meant that to test BBN theory against observations one had to ask: can *all* of the light element observations be explained with a *single value* of the baryon-to-photon ratio? Or more precisely, allowing for the finite precision of both the predictions and the observations, one asks: is there some *range* of baryon-to-photon values which can account for all of the observations?

More recently, the question has changed: Precision observations of the cosmic microwave background radiation[4][5] with the Wilkinson Microwave Anisotropy Probe (WMAP) give an independent value for the baryon-to-photon ratio. Using this value, are the BBN predictions for the abundances of light elements in agreement with the observations?

The present measurement of helium-4 indicates good agreement, and yet better agreement for helium-3. But for lithium-7, there is a significant discrepancy between BBN and WMAP, and the abundance derived from Population II stars. The discrepancy is a factor of 2.4—4.3 below the theoretically predicted value and is considered a problem for the original models, that have resulted in revised calculations of the standard BBN based on new nuclear data, and to various reevaluation proposals for primordial proton-proton nuclear reactions, especially the abundances of $^{7}Be(n,p)^{7}Li$ versus $^{7}Be(d,p)^{8}Be$.[6]

Non-standard scenarios

In addition to the standard BBN scenario there are numerous non-standard BBN scenarios. These should not be confused with non-standard cosmology: a non-standard BBN scenario assumes that the Big Bang occurred, but inserts additional physics in order to see how this affects elemental abundances. These pieces of additional physics include relaxing or removing the assumption of homogeneity, or inserting new particles such as massive neutrinos.

There have been, and continue to be, various reasons for researching non-standard BBN. The first, which is largely of historical interest, is to resolve inconsistencies between BBN predictions and observations. This has proved to be of limited usefulness in that the inconsistencies were resolved by better observations, and in most cases trying to change BBN resulted in abundances that were more inconsistent with observations rather than less. The second reason for researching non-standard BBN, and largely the focus of non-standard BBN in the early 21st century, is to use BBN to place limits on unknown or speculative physics. For example, standard BBN assumes that no exotic hypothetical particles were involved in BBN. One can insert a hypothetical particle (such as a massive neutrino) and see what has to happen before BBN predicts abundances which are very different from observations. This has been usefully done to put limits on the mass of a stable tau neutrino.

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[5] David Toback(2009)" Unit 4: The Evolution Of The Universe (http://bigbang.physics.tamu.edu/ChapterText/Ch13text.pdf)"
[6] For a recent calculation of BBN predictions, see
For the observational values, see the following articles:
- Helium-4:
- Helium-3:
- Deuterium:
- Lithium-7:

External links

For a general audience

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- R. A. Alpher, R. Herman, and G. Gamow *Nature* **162** (1948), 774
- Java Big Bang element abundance calculator (http://www.astro.washington.edu/research/bbn/)Wikipedia:Link rot

Cosmic microwave background

The **cosmic microwave background** (**CMB**) is the thermal radiation left over from the "Big Bang" of cosmology. In older literature, the CMB is also variously known as cosmic microwave background radiation (CMBR) or "relic radiation." The CMB is a cosmic background radiation that is fundamental to observational cosmology because it is the oldest light in the universe, dating to the epoch of recombination. With a traditional optical telescope, the space between stars and galaxies (the *background*) is completely dark. However, a sufficiently sensitive radio telescope shows a faint background glow, almost exactly the same in all directions, that is not associated with any star, galaxy, or other object. This glow is strongest in the microwave region of the radio spectrum. The CMB's serendipitous discovery in 1964 by American radio astronomers Arno Penzias and Robert Wilson was the culmination of work initiated in the 1940s, and earned the discoverers the 1978 Nobel Prize.

> *The CMB is a snapshot of the oldest light in our Universe, imprinted on the sky when the Universe was just 380,000 years old. It shows tiny temperature fluctuations that correspond to regions of slightly different densities, representing the seeds of all future structure: the stars and galaxies of today.*

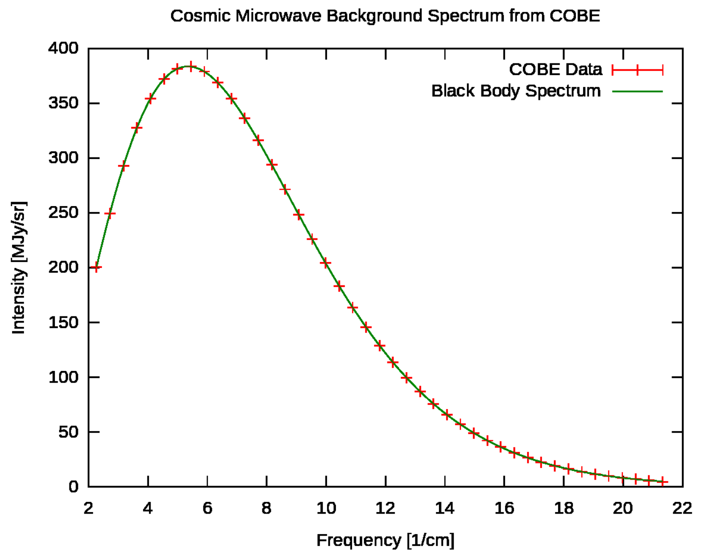
The CMB is well explained as radiation left over from an early stage in the development of the universe, and its discovery is considered a landmark test of the Big Bang model of the universe. When the universe was young, before the formation of stars and planets, it was denser, much hotter, and filled with a uniform glow from a white-hot fog of hydrogen plasma. As the universe expanded, both the plasma and the radiation filling it grew cooler. When the universe cooled enough, protons and electrons combined to form neutral atoms. These atoms could no longer absorb the thermal radiation, and so the universe became transparent instead of being an opaque fog. Cosmologists refer to the time period when neutral atoms first formed as the *recombination epoch*, and the event shortly afterwards when photons started to travel freely through space rather than constantly being scattered by electrons and protons in plasma is referred to as *photon decoupling*. The photons that existed at the time of photon decoupling have been propagating ever since, though growing fainter and less energetic, since the expansion of space causes their wavelength to increase over time (and wavelength is inversely proportional to energy according to Planck's relation). This is the source of the alternative term *relic radiation*. The *surface of last scattering* refers to the set of points in space at the right distance from us so that we are now receiving photons originally emitted from those points at the time of photon decoupling.

Precise measurements of the CMB are critical to cosmology, since any proposed model of the universe must explain this radiation. The CMB has a thermal black body spectrum at a temperature of 2.72548±0.00057 K. The spectral radiance $dE_\nu/d\nu$ peaks at 160.2 GHz, in the microwave range of frequencies. (Alternatively if spectral radiance is defined as $dE_\lambda/d\lambda$ then the peak wavelength is 1.063 mm.)

The glow is very nearly uniform in all directions, but the tiny residual variations show a very specific pattern, the same as that expected of a fairly uniformly distributed hot gas that has expanded to the current size of the universe. In particular, the spectral radiance at different angles of observation in the sky contains small anisotropies, or irregularities, which vary with the size of the region examined. They have been measured in detail, and match what would be expected if small thermal variations, generated by quantum fluctuations of matter in a very tiny space, had expanded to the size of the observable universe we see today. This is a very active field of study, with scientists seeking both better data (for example, the Planck spacecraft) and better interpretations of the initial conditions of expansion. Although many different processes might produce the general form of a black body spectrum, no model other than the Big Bang has yet explained the fluctuations. As a result, most cosmologists consider the Big Bang model of the universe to be the best explanation for the CMB.

The high degree of uniformity throughout the observable universe and its faint but measured anisotropy lend strong support for the Big Bang model in general and the ΛCDM model in particular. Moreover, the WMAP and BICEP experiments have observed coherence of these fluctuations on angular scales that are larger than the apparent cosmological horizon at recombination. Either such coherence is acausally fine-tuned, or cosmic inflation occurred.

Features



Graph of cosmic microwave background spectrum measured by the FIRAS instrument on the COBE, the most-precisely measured black body spectrum in nature, the error bars are too small to be seen even in enlarged image, and it is impossible to distinguish the observed data from the theoretical curve

The cosmic microwave background radiation is an emission of uniform, black body thermal energy coming from all parts of the sky. The radiation is isotropic to roughly one part in 100,000: the root mean square variations are only 18 μK, after subtracting out a dipole anisotropy from the Doppler shift of the background radiation. The latter is caused by the peculiar velocity of the Earth relative to the comoving cosmic rest frame as the planet moves at some 371 km/s towards the constellation Leo. The CMB dipole as well as aberration at higher multipoles have been measured, consistent with galactic motion.

In the Big Bang model for the formation of the universe, Inflationary Cosmology predicts that after about 10^{-37} seconds the nascent universe underwent exponential growth that smoothed out nearly all inhomogeneities. The remaining inhomogeneities were caused by quantum fluctuations in the inflaton field that caused the inflation event. After 10^{-6} seconds, the early universe was made up of a hot, interacting plasma of photons, electrons, and baryons. As the universe expanded, adiabatic cooling caused the energy density of the plasma to decrease until it became favorable for electrons to combine with protons, forming hydrogen atoms. This recombination event happened when the temperature was around 3000 K or when the universe was approximately 379,000 years old. At this point, the photons no longer interacted with the now electrically neutral atoms and began to travel freely through space, resulting in the decoupling of matter and radiation.

The color temperature of the decoupled photons has continued to diminish ever since; now down to 2.7260 ± 0.0013 K, their temperature will continue to drop as the universe expands. According to the Big Bang model, the radiation from the sky we measure today comes from a spherical surface called *the surface of last scattering*. This represents the set of locations in space at which the decoupling event is estimated to have occurred and at a point in time such that the photons from that distance have just reached observers. Most of the radiation energy in the universe is in the cosmic microwave background, making up a fraction of roughly 6×10^{-5} of the total density of the universe.

Two of the greatest successes of the Big Bang theory are its prediction of the almost perfect black body spectrum and its detailed prediction of the anisotropies in the cosmic microwave background. The CMB spectrum has become the most precisely measured black body spectrum in nature.

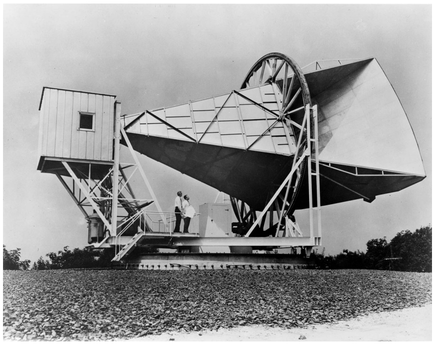
History

Timeline of Observations of the CMB	
Important people and dates	
1941	Andrew McKellar was attempting to measure the average temperature of the interstellar medium, and reported the observation of an average bolometric temperature of 2.3 K based on the study of interstellar absorption lines.
1946	Robert Dicke predicts ".. radiation from cosmic matter" at <20 K but did not refer to background radiation[1]
1948	George Gamow calculates a temperature of 50 K (assuming a 3-billion-year old Universe), commenting it ".. is in reasonable agreement with the actual temperature of interstellar space", but does not mention background radiation.
1948	Ralph Alpher and Robert Herman estimate "the temperature in the Universe" at 5 K. Although they do not specifically mention microwave background radiation, it may be inferred.[2]
1950	Ralph Alpher and Robert Herman re-estimate the temperature at 28 K.
1953	George Gamow estimates 7 K.
1955	Émile Le Roux of the Nançay Radio Observatory, in a sky survey at λ=33 cm, reported a near-isotropic background radiation of 3 kelvins, plus or minus 2.
1956	George Gamow estimates 6 K.
1957	Tigran Shmaonov reports that "the absolute effective temperature of the radioemission background ... is 4±3K". It is noted that the "measurements showed that radiation intensity was independent of either time or direction of observation... it is now clear that Shmaonov did observe the cosmic microwave background at a wavelength of 3.2 cm"
1960s	Robert Dicke re-estimates a MBR (microwave background radiation) temperature of 40 K
1964	A. G. Doroshkevich and Igor Novikov publish a brief paper, where they name the CMB radiation phenomenon as detectable.
1964–65	Arno Penzias and Robert Woodrow Wilson measure the temperature to be approximately 3 K. Robert Dicke, P. J. E. Peebles, P. G. Roll, and D. T. Wilkinson interpret this radiation as a signature of the big bang.
1983	RELIKT-1 Soviet CMB anisotropy experiment was launched.
1990	FIRAS on COBE measures the black body form of the CMB spectrum with exquisite precision.
1992	Scientists who analyzed data from COBE DMR announce the discovery of the primary temperature anisotropy.
1999	First measurements of acoustic oscillations in the CMB anisotropy angular power spectrum from the TOCO, BOOMERANG, and Maxima Experiments.
2002	Polarization discovered by DASI.
2004	E-mode polarization spectrum obtained by the CBI.
2005	Ralph A. Alpher is awarded the National Medal of Science for his groundbreaking work in nucleosynthesis and prediction that the universe expansion leaves behind background radiation, thus providing a model for the Big Bang theory.
2006	Two of COBE's principal investigators, George Smoot and John Mather, received the Nobel Prize in Physics in 2006 for their work on precision measurement of the CMBR.

The cosmic microwave background was first predicted in 1948 by Ralph Alpher, and Robert Herman. Alpher and Herman were able to estimate the temperature of the cosmic microwave background to be 5 K, though two years later they re-estimated it at 28 K. This high estimate was due to a mis-estimate of the Hubble constant by Alfred Behr, which could not be replicated and was later abandoned for the earlier estimate. Although there were several previous estimates of the temperature of space, these suffered from two flaws. First, they were measurements of the *effective* temperature of space and did not suggest that space was filled with a thermal Planck spectrum. Next, they depend on our being at a special spot at the edge of the Milky Way galaxy and they did not suggest the radiation is isotropic. The estimates would yield very different predictions if Earth happened to be located elsewhere in the Universe.[3]

The 1948 results of Alpher and Herman were discussed in many physics settings through about 1955, when both left the Applied Physics Laboratory at Johns Hopkins University. The mainstream astronomical community, however, was not intrigued at the time by cosmology. Alpher and Herman's prediction was rediscovered by Yakov Zel'dovich in the early 1960s, and independently predicted by Robert Dicke at the same time. The first published recognition of the CMB radiation as a detectable phenomenon appeared in a brief paper by Soviet astrophysicists A. G. Doroshkevich and Igor Novikov, in the spring of 1964. In 1964, David Todd Wilkinson and Peter Roll, Dicke's colleagues at Princeton University, began constructing a Dicke radiometer to measure the cosmic microwave background.[4] In 1965, Arno Penzias and Robert Woodrow Wilson at the Crawford Hill location of Bell Telephone Laboratories in nearby Holmdel Township, New Jersey had built a Dicke radiometer that they intended to use for radio astronomy and satellite communication experiments. Their instrument had an excess 3.5 K antenna temperature which they could not account for. After receiving a telephone call from Crawford Hill, Dicke famously quipped: "Boys, we've been scooped."[5] A meeting between the Princeton and Crawford Hill groups determined that the antenna temperature was indeed due to the microwave background. Penzias and Wilson received the 1978 Nobel Prize in Physics for their discovery.

The interpretation of the cosmic microwave background was a controversial issue in the 1960s with some proponents of the steady state theory arguing that the microwave background was the result of scattered starlight from distant galaxies. Using this model, and based on the study of narrow absorption line features in the spectra of stars, the astronomer Andrew McKellar wrote in 1941: "It can be calculated that the 'rotational temperature' of interstellar space is 2 K." However, during the 1970s the consensus was established that the cosmic microwave background is a remnant of the big bang. This was largely because new measurements at a range of frequencies showed that the spectrum was a thermal, black body spectrum, a result that the steady state model was unable to reproduce.



The Holmdel Horn Antenna on which Penzias and Wilson discovered the cosmic microwave background.

Harrison, Peebles, Yu and Zel'dovich realized that the early universe would have to have inhomogeneities at the level of 10^{-4} or 10^{-5}. Rashid Sunyaev later calculated the observable imprint that these inhomogeneities would have on the cosmic microwave background.[6] Increasingly stringent limits on the anisotropy of the cosmic microwave background were set by ground based experiments during the 1980s. RELIKT-1, a Soviet cosmic microwave background anisotropy experiment on board the Prognoz 9 satellite (launched 1 July 1983) gave upper limits on the large-scale anisotropy. The NASA COBE mission clearly confirmed the primary anisotropy with the Differential Microwave Radiometer instrument, publishing their findings in 1992. The team received the Nobel Prize in physics for 2006 for this discovery.

Inspired by the COBE results, a series of ground and balloon-based experiments measured cosmic microwave background anisotropies on smaller angular scales over the next decade. The primary goal of these experiments was to measure the scale of the first acoustic peak, which COBE did not have sufficient resolution to resolve. This peak corresponds to large scale density variations in the early universe that are created by gravitational instabilities, resulting in acoustical oscillations in the plasma. The first peak in the anisotropy was tentatively detected by the Toco experiment and the result was confirmed by the BOOMERanG and MAXIMA experiments. These measurements demonstrated that the geometry of the Universe is approximately flat, rather than curved. They ruled out cosmic strings as a major component of cosmic structure formation and suggested cosmic inflation was the right theory of structure formation.

The second peak was tentatively detected by several experiments before being definitively detected by WMAP, which has also tentatively detected the third peak. As of 2010, several experiments to improve measurements of the polarization and the microwave background on small angular scales are ongoing. These include DASI, WMAP, BOOMERanG, QUaD, Planck spacecraft, Atacama Cosmology Telescope, South Pole Telescope and the QUIET telescope.

Relationship to the Big Bang

The cosmic microwave background radiation and the cosmological redshift-distance relation are together regarded as the best available evidence for the Big Bang theory. Measurements of the CMB have made the inflationary Big Bang theory the Standard Model of Cosmology. The discovery of the CMB in the mid-1960s curtailed interest in alternatives such as the steady state theory.

The CMB essentially confirms the Big Bang theory. In the late 1940s Alpher and Herman reasoned that if there was a big bang, the expansion of the Universe would have stretched and cooled the high-energy radiation of the very early Universe into the microwave region and down to a temperature of about 5 K. They were slightly off with their estimate, but they had exactly the right idea. They predicted the CMB. It took another 15 years for Penzias and Wilson to stumble into discovering that the microwave background was actually there.

The CMB gives a snapshot of the universe when, according to standard cosmology, the temperature dropped enough to allow electrons and protons to form hydrogen atoms, thus making the universe transparent to radiation. When it originated some 380,000 years after the Big Bang—this time is generally known as the "time of last scattering" or the period of recombination or decoupling—the temperature of the universe was about 3000 K. This corresponds to an energy of about 0.25 eV, which is much less than the 13.6 eV ionization energy of hydrogen.

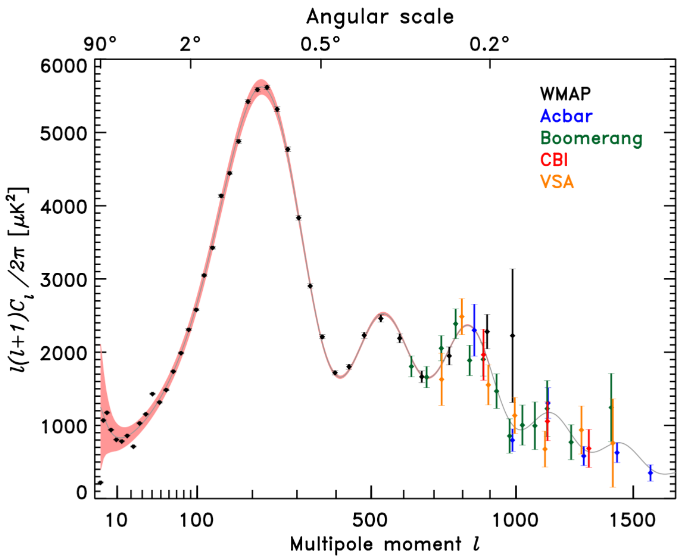
Since decoupling, the temperature of the background radiation has dropped by a factor of roughly 1,100 due to the expansion of the universe. As the universe expands, the CMB photons are redshifted, making the radiation's temperature inversely proportional to a parameter called the universe's scale length. The temperature T_r of the CMB as a function of redshift, z, can be shown to be proportional to the temperature of the CMB as observed in the present day (2.725 K or 0.235 meV):

$$T_r = 2.725(1 + z)$$

For details about the reasoning that the radiation is evidence for the Big Bang, see Cosmic background radiation of the Big Bang.

Primary anisotropy

The anisotropy of the cosmic microwave background is divided into two types: primary anisotropy, due to effects which occur at the last scattering surface and before; and secondary anisotropy, due to effects such as interactions of the background radiation with hot gas or gravitational potentials, which occur between the last scattering surface and the observer.



The power spectrum of the cosmic microwave background radiation temperature anisotropy in terms of the angular scale (or multipole moment). The data shown come from the WMAP (2006), Acbar (2004) Boomerang (2005), CBI (2004), and VSA (2004) instruments. Also shown is a theoretical model (solid line).

The structure of the cosmic microwave background anisotropies is principally determined by two effects: acoustic oscillations and diffusion damping (also called collisionless damping or Silk damping). The acoustic oscillations arise because of a conflict in the photon–baryon plasma in the early universe. The pressure of the photons tends to erase anisotropies, whereas the gravitational attraction of the baryons—moving at speeds much slower than light—makes them tend to collapse to form dense haloes. These two effects compete to create acoustic oscillations which give the microwave background its characteristic peak structure. The peaks correspond, roughly, to resonances in which the photons decouple when a particular mode is at its peak amplitude.

The peaks contain interesting physical signatures. The angular scale of the first peak determines the curvature of the universe (but not the topology of the universe). The next peak—ratio of the odd peaks to the even peaks—determines the reduced baryon density. The third peak can be used to get information about the dark matter density.

The locations of the peaks also give important information about the nature of the primordial density perturbations. There are two fundamental types of density perturbations—called *adiabatic* and *isocurvature*. A general density perturbation is a mixture of both, and different theories that purport to explain the primordial density perturbation spectrum predict different mixtures.

- Adiabatic density perturbations

  the fractional additional density of each type of particle (baryons, photons ...) is the same. That is, if at one place there is 1% more energy in baryons than average, then at that place there is also 1% more energy in photons (and 1% more energy in neutrinos) than average. Cosmic inflation predicts that the primordial perturbations are adiabatic.

- Isocurvature density perturbations

  in each place the sum (over different types of particle) of the fractional additional densities is zero. That is, a perturbation where at some spot there is 1% more energy in baryons than average, 1% more energy in photons than average, and 2% *less* energy in neutrinos than average, would be a pure isocurvature perturbation. Cosmic strings would produce mostly isocurvature primordial perturbations.

The CMB spectrum can distinguish between these two because these two types of perturbations produce different peak locations. Isocurvature density perturbations produce a series of peaks whose angular scales (*l*-values of the peaks) are roughly in the ratio 1:3:5:..., while adiabatic density perturbations produce peaks whose locations are in the ratio 1:2:3:... Observations are consistent with the primordial density perturbations being entirely adiabatic, providing key support for inflation, and ruling out many models of structure formation involving, for example, cosmic strings.

Collisionless damping is caused by two effects, when the treatment of the primordial plasma as fluid begins to break down:

- the increasing mean free path of the photons as the primordial plasma becomes increasingly rarefied in an expanding universe
- the finite depth of the last scattering surface (LSS), which causes the mean free path to increase rapidly during decoupling, even while some Compton scattering is still occurring.

These effects contribute about equally to the suppression of anisotropies at small scales, and give rise to the characteristic exponential damping tail seen in the very small angular scale anisotropies.

The depth of the LSS refers to the fact that the decoupling of the photons and baryons does not happen instantaneously, but instead requires an appreciable fraction of the age of the Universe up to that era. One method of quantifying how long this process took uses the *photon visibility function* (PVF). This function is defined so that, denoting the PVF by P(t), the probability that a CMB photon last scattered between time t and t+dt is given by P(t)dt.

The maximum of the PVF (the time when it is most likely that a given CMB photon last scattered) is known quite precisely. The first-year WMAP results put the time at which P(t) is maximum as 372,000 years. This is often taken as the "time" at which the CMB formed. However, to figure out how *long* it took the photons and baryons to decouple, we need a measure of the width of the PVF. The WMAP team finds that the PVF is greater than half of its maximum value (the "full width at half maximum", or FWHM) over an interval of 115,000 years. By this measure, decoupling took place over roughly 115,000 years, and when it was complete, the universe was roughly 487,000 years old.

Late time anisotropy

Since the CMB came into existence, it has apparently been modified by several subsequent physical processes, which are collectively referred to as late-time anisotropy, or secondary anisotropy. When the CMB photons became free to travel unimpeded, ordinary matter in the universe was mostly in the form of neutral hydrogen and helium atoms. However, observations of galaxies today seem to indicate that most of the volume of the intergalactic medium (IGM) consists of ionized material (since there are few absorption lines due to hydrogen atoms). This implies a period of reionization during which some of the material of the universe was broken into hydrogen ions.

The CMB photons are scattered by free charges such as electrons that are not bound in atoms. In an ionized universe, such charged particles have been liberated from neutral atoms by ionizing (ultraviolet) radiation. Today these free charges are at sufficiently low density in most of the volume of the Universe that they do not measurably affect the CMB. However, if the IGM was ionized at very early times when the universe was still denser, then there are two main effects on the CMB:

1. Small scale anisotropies are erased. (Just as when looking at an object through fog, details of the object appear fuzzy.)
2. The physics of how photons are scattered by free electrons (Thomson scattering) induces polarization anisotropies on large angular scales. This broad angle polarization is correlated with the broad angle temperature perturbation.

Both of these effects have been observed by the WMAP spacecraft, providing evidence that the universe was ionized at very early times, at a redshift more than 17Wikipedia:Please clarify. The detailed provenance of this early ionizing radiation is still a matter of scientific debate. It may have included starlight from the very first population of stars (population III stars), supernovae when these first stars reached the end of their lives, or the ionizing radiation produced by the accretion disks of massive black holes.

The time following the emission of the cosmic microwave background—and before the observation of the first stars—is semi-humorously referred to by cosmologists as the dark age, and is a period which is under intense study by astronomers (See 21 centimeter radiation).

Two other effects which occurred between reionization and our observations of the cosmic microwave background, and which appear to cause anisotropies, are the Sunyaev–Zel'dovich effect, where a cloud of high-energy electrons scatters the radiation, transferring some of its energy to the CMB photons, and the Sachs–Wolfe effect, which causes photons from the Cosmic Microwave Background to be gravitationally redshifted or blueshifted due to changing gravitational fields.

Polarization

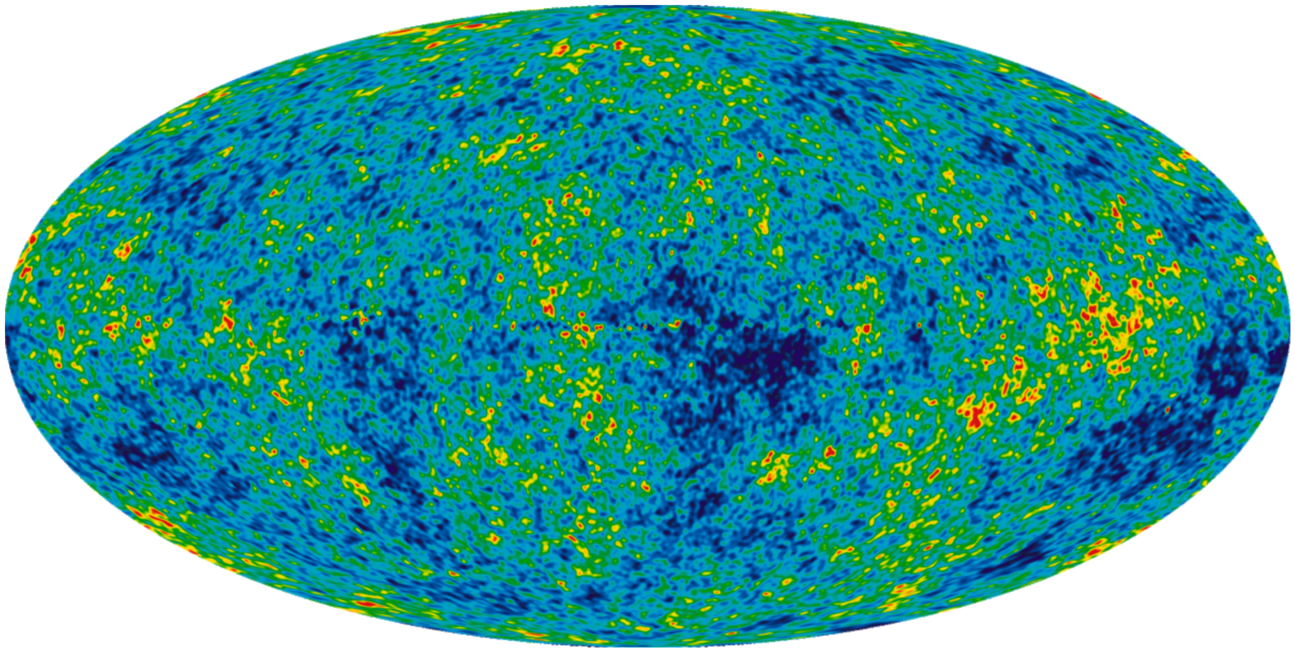
The cosmic microwave background is polarized at the level of a few microkelvin. There are two types of polarization, called *E*-modes and *B*-modes. This is in analogy to electrostatics, in which the electric field (*E*-field) has a vanishing curl and the magnetic field (*B*-field) has a vanishing divergence. The *E*-modes arise naturally from Thomson scattering in a heterogeneous plasma. The *B*-modes, which have not been measured and are thought to have an amplitude of at most 0.1 µK, are not produced from the plasma physics alone. They are a signal from cosmic inflation and are determined by the density of primordial gravitational waves. Detecting the *B*-modes will be extremely difficult, particularly as the degree of foreground contamination is unknown, and the weak gravitational lensing signal mixes the relatively strong *E*-mode signal with the *B*-mode signal.

Microwave background observations

Subsequent to the discovery of the CMB, hundreds of cosmic microwave background experiments have been conducted to measure and characterize the signatures of the radiation. The most famous experiment is probably the NASA Cosmic Background Explorer (COBE) satellite that orbited in 1989–1996 and which detected and quantified the large scale anisotropies at the limit of its detection capabilities. Inspired by the initial COBE results of an extremely isotropic and homogeneous background, a series of ground- and balloon-based experiments quantified CMB anisotropies on smaller angular scales over the next decade. The primary goal of these experiments was to measure the angular scale of the first acoustic peak, for which COBE did not have sufficient resolution. These measurements were able to rule out cosmic strings as the leading theory of cosmic structure formation, and suggested cosmic inflation was the right theory. During the 1990s, the first peak was measured with increasing sensitivity and by 2000 the BOOMERanG experiment reported that the highest power fluctuations occur at scales of approximately one degree. Together with other cosmological data, these results implied that the geometry of the Universe is flat. A number of ground-based interferometers provided measurements of the fluctuations with higher accuracy over the next three years, including the Very Small Array, Degree Angular Scale Interferometer (DASI), and the Cosmic Background Imager (CBI). DASI made the first detection of the polarization of the CMB and the CBI provided the first E-mode polarization spectrum with compelling evidence that it is out of phase with the T-mode spectrum.

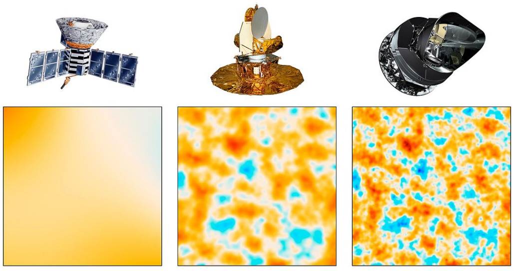
In June 2001, NASA launched a second CMB space mission, WMAP, to make much more precise measurements of the large scale anisotropies over the full sky. WMAP used symmetric, rapid-multi-modulated scanning, rapid switching radiometers to minimize non-sky signal noise. The first results from this mission, disclosed in 2003, were detailed measurements of the angular power spectrum at a scale of less than one degree, tightly constraining various cosmological parameters. The results are broadly consistent with those expected from cosmic inflation as well as various other competing theories, and are available in detail at NASA's data bank for Cosmic Microwave Background (CMB) (see links below). Although WMAP provided very accurate measurements of the large scale angular fluctuations in the CMB (structures about as broad in the sky as the moon), it did not have the angular resolution to measure the smaller scale fluctuations which had been observed by former ground-based interferometers.

All-sky map



All-sky map of the CMB, created from 9 years of WMAP data

A third space mission, the ESA (European Space Agency) Planck Surveyor, was launched in May 2009 and is currently performing an even more detailed investigation. Planck employs both HEMT radiometers and bolometer technology and will measure the CMB at a smaller scale than WMAP. Its detectors were trialled in the Antarctic Viper telescope as ACBAR (Arcminute Cosmology Bolometer Array Receiver) experiment—which has produced the most precise measurements at small angular scales to date—and in the Archeops balloon telescope.



Comparison of CMB results from COBE, WMAP and Planck – March 21, 2013.

On 21 March 2013, the European-led research team behind the Planck cosmology probe released the mission's all-sky map (565x318 jpeg [7], 4000x2020 jpeg [8]) of the cosmic microwave background. The map suggests the universe is slightly older than researchers thought. According to the map, subtle fluctuations in temperature were imprinted on the deep sky when the cosmos was about 370,000 years old. The imprint reflects ripples that arose as early, in the existence of the universe, as the first nonillionth of a second. Apparently, these ripples gave rise to the present vast cosmic web of galaxy clusters and dark matter. According to the team, the universe is 13.798 ± 0.037 billion years old, and contains 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy. Also, the Hubble constant was measured to be 67.15 ± 1.2 (km/s)/Mpc.

Additional ground-based instruments such as the South Pole Telescope in Antarctica and the proposed Clover Project, Atacama Cosmology Telescope and the QUIET telescope in Chile will provide additional data not available from satellite observations, possibly including the B-mode polarization.

Data reduction and analysis

Raw CMBR data from the space vehicle (i.e. WMAP) contain foreground effects that completely obscure the fine-scale structure of the cosmic microwave background. The fine-scale structure is superimposed on the raw CMBR data but is too small to be seen at the scale of the raw data. The most prominent of the foreground effects is the dipole anisotropy caused by the Sun's motion relative to the CMBR background. The dipole anisotropy and others due to Earth's annual motion relative to the Sun and numerous microwave sources in the galactic plane and elsewhere must be subtracted out to reveal the extremely tiny variations characterizing the fine-scale structure of the CMBR background.

The detailed analysis of CMBR data to produce maps, an angular power spectrum, and ultimately cosmological parameters is a complicated, computationally difficult problem. Although computing a power spectrum from a map is in principle a simple Fourier transform, decomposing the map of the sky into spherical harmonics, in practice it is hard to take the effects of noise and foreground sources into account. In particular, these foregrounds are dominated by galactic emissions such as Bremsstrahlung, synchrotron, and dust that emit in the microwave band; in practice, the galaxy has to be removed, resulting in a CMB map that is not a full-sky map. In addition, point sources like galaxies and clusters represent another source of foreground which must be removed so as not to distort the short scale structure of the CMB power spectrum.

Constraints on many cosmological parameters can be obtained from their effects on the power spectrum, and results are often calculated using Markov Chain Monte Carlo sampling techniques.

CMBR dipole anisotropy

From the CMB data it is seen that our local group of galaxies (the galactic cluster that includes the Solar System's Milky Way Galaxy) appears to be moving at 369±0.9 km/s relative to the reference frame of the CMB (also called the CMB rest frame, or the frame of reference in which there is no motion through the CMB) in the direction of galactic longitude l = 263.99±0.14°, b = 48.26±0.03°. This motion results in an anisotropy of the data (CMB appearing slightly warmer in the direction of movement than in the opposite direction).[9] The standard interpretation of this temperature variation is a simple velocity red shift and blue shift due to motion relative to the CMB, but alternative cosmological models can explain some fraction of the observed dipole temperature distribution in the CMB.

Low multipoles and other anomalies

With the increasingly precise data provided by WMAP, there have been a number of claims that the CMB exhibits anomalies, such as very large scale anisotropies, anomalous alignments, and non-Gaussian distributions. The most longstanding of these is the low-l multipole controversy. Even in the COBE map, it was observed that the quadrupole (l =2, spherical harmonic) has a low amplitude compared to the predictions of the Big Bang. In particular, the quadrupole and octupole (l =3) modes appear to have an unexplained alignment with each other and with the ecliptic plane, an alignment sometimes referred to as the *axis of evil*. A number of groups have suggested that this could be the signature of new physics at the greatest observable scales; other groups suspect systematic errors in the data. Ultimately, due to the foregrounds and the cosmic variance problem, the greatest modes will never be as well measured as the small angular scale modes. The analyses were performed on two maps that have had the foregrounds removed as far as possible: the "internal linear combination" map of the WMAP collaboration and a similar map prepared by Max Tegmark and others.[][10] Later analyses have pointed out that these are the modes most susceptible to foreground contamination from synchrotron, dust, and Bremsstrahlung emission, and from experimental uncertainty in the monopole and dipole. A full Bayesian analysis of the WMAP power spectrum demonstrates that the quadrupole prediction of Lambda-CDM cosmology is consistent with the data at the 10% level and that the observed octupole is not remarkable. Carefully accounting for the procedure used to remove the foregrounds from the full sky map further reduces the significance of the alignment by ~5%.

In popular culture

- In the *Stargate Universe* TV series, an Ancient spaceship, *Destiny*, was built to study patterns in the CMBR which indicate that the universe as we know it might have been created by some form of sentient intelligence.[11]
- In *Wheelers*, a novel by Ian Stewart & Jack Cohen, CMBR is explained as the encrypted transmissions of an ancient civilization. This allows the Jovian "blimps" to have a society older than the currently-observed age of the universe.

References

[1] "In 1946, Robert Dicke and coworkers at MIT tested equipment that could test a cosmic microwave background of intensity corresponding to about 20K in the microwave region. However, they did not refer to such a background, but only to 'radiation from cosmic matter'. Also, this work was unrelated to cosmology and is only mentioned because it suggests that by 1950, detection of the background radiation might have been technically possible, and also because of Dicke's later role in the discovery". See also

[2] Kragh, H. (1999:132). "Alpher and Herman first calculated the present temperature of the decoupled primordial radiation in 1948, when they reported a value of 5 K. Although it was not mentioned either then or in later publications that the radiation is in the microwave region, this follows immediately from the temperature... Alpher and Herman made it clear that what they had called "the temperature in the universe" the previous year referred to a blackbody distributed background radiation quite different from sunlight".

[3] but see also

[4] This basic design for a radiometer has been used in most subsequent cosmic microwave background experiments.

[5] The history is given in

[6] While this is the first paper to discuss the detailed observational imprint of density inhomogeneities as anisotropies in the cosmic microwave background, some of the groundwork was laid in Peebles and Yu, above.

[7] http://esacmt.esac.esa.int/science-e-media/img/61/51553_Planck_CMB_Mollweide_565.jpg

[8] http://esacmt.esac.esa.int/science-e-media/img/61/Planck_CMB_orig.jpg

[9] http://antwrp.gsfc.nasa.gov/apod/ap090906.html

[10] This paper states, "Not surprisingly, the two most contaminated multipoles are [the quadrupole and octupole], which most closely trace the galactic plane morphology."

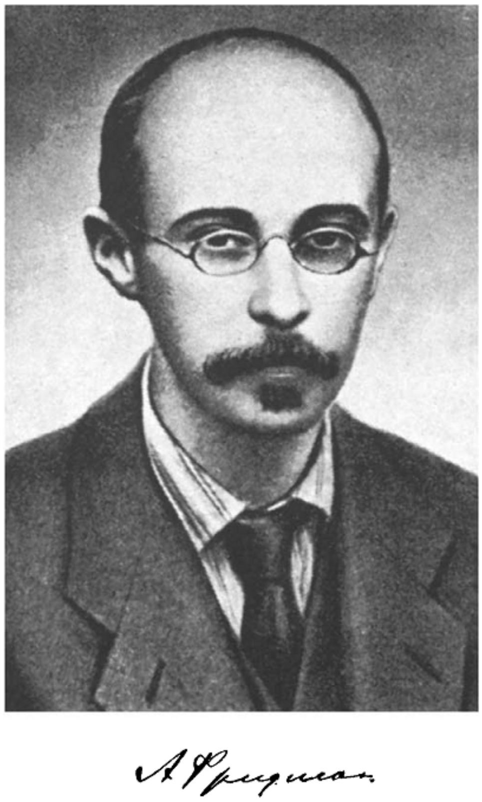
[11] http://news.discovery.com/space/cosmic-rebirth-encoded-in-background-radiation.html

External links

- CMBR Theme on arxiv.org (http://xstructure.inr.ac.ru/x-bin/theme3.py?level=3&index1=87807)
- Audio: Fraser Cain and Dr. Pamela Gay – Astronomy Cast. The Big Bang and Cosmic Microwave Background – October 2006 (http://www.astronomycast.com/cosmology/the-big-bang-and-cosmic-microwave-background/)
- Visualization of the CMB data from the Planck mission (http://thecmb.org)
- Copeland, Ed. "CMBR: Cosmic Microwave Background Radiation" (http://www.sixtysymbols.com/videos/CMBR.htm). *Sixty Symbols*. Brady Haran for the University of Nottingham.

Hot big bang model

Friedmann equations



Alexander Friedmann

The **Friedmann equations** are a set of equations in physical cosmology that govern the expansion of space in homogeneous and isotropic models of the universe within the context of general relativity. They were first derived by Alexander Friedmann in 1922[1] from Einstein's field equations of gravitation for the Friedmann–Lemaître–Robertson–Walker metric and a perfect fluid with a given mass density ρ and pressure p. The equations for negative spatial curvature were given by Friedmann in 1924.[2]

Assumptions

The Friedmann equations start with the simplifying assumption that the universe is spatially homogeneous and isotropic, i.e. the Cosmological Principle; empirically, this is justified on scales larger than ~100 Mpc. The Cosmological Principle implies that the metric of the universe must be of the form:

$$ds^2 = a(t)^2\, ds_3^2 - c^2\, dt^2$$

where ds_3^2 is a three dimensional metric that must be one of **(a)** flat space, **(b)** a sphere of constant positive curvature or **(c)** a hyperbolic space with constant negative curvature. The parameter k discussed below takes the value 0, 1, −1 in these three cases respectively. It is this fact that allows us to sensibly speak of a "scale factor", $a(t)$.

Einstein's equations now relate the evolution of this scale factor to the pressure and energy of the matter in the universe. From FLRW metric we compute Christoffel symbols, then Ricci tensor. With stress-energy tensor for perfect fluid, we plug them into Einstein field equations and the resulting equations are described below.

The equations

There are two independent Friedmann equations for modeling a homogeneous, isotropic universe. The first is:

$$\frac{\dot{a}^2 + kc^2}{a^2} = \frac{8\pi G\rho + \Lambda c^2}{3}$$

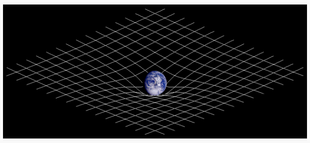
which is derived from the 00 component of Einstein's field equations. And the second is:

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

which is derived from the first together with the trace of Einstein's field equations. $H \equiv \frac{\dot{a}}{a}$ is the Hubble parameter, G, Λ, and c are universal constants (G is Newton's gravitational constant, Λ is the cosmological constant, c is the speed of light in vacuum). k is constant throughout a particular solution, but may vary from one solution to another.

a, H, ρ, and p are functions of time. $\frac{k}{a^2}$ is the spatial curvature in any time-slice of the universe; it is equal to one-sixth of the spatial Ricci curvature scalar R since $R = \frac{6}{c^2 a^2}(\ddot{a}a + \dot{a}^2 + kc^2)$ in the Friedmann model. We see that in the Friedmann depends only on ρ, p, Λ, and intrinsic curvature k. It does not depend on which coordinate system we chose for spatial slices. There are two commonly used choices for a and k which describe the same physics:

General relativity



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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- k = +1, 0 or −1 depending on whether the shape of the universe is a closed 3-sphere, flat (i.e. Euclidean space) or an open 3-hyperboloid, respectively.[3] If k = +1, then a is the radius of curvature of the universe. If k = 0, then a may be fixed to any arbitrary positive number at one particular time. If k = −1, then (loosely speaking) one can say that $i \cdot a$ is the radius of curvature of the universe.
- a is the scale factor which is taken to be 1 at the present time. k is the spatial curvature when $a = 1$ (i.e. today). If the shape of the universe is hyperspherical and R_t is the radius of curvature (R_0 in the present-day), then $a = R_t/R_0$. If k is positive, then the universe is hyperspherical. If k is zero, then the universe is flat. If k is negative, then the universe is hyperbolic.

Using the first equation, the second equation can be re-expressed as

$$\dot{\rho} = -3H\left(\rho + \frac{p}{c^2}\right),$$

which eliminates Λ and expresses the conservation of mass-energy $T^{\alpha\beta}{}_{;\beta} = 0$.

These equations are sometimes simplified by replacing

$$\rho \to \rho - \frac{\Lambda c^2}{8\pi G}$$
$$p \to p + \frac{\Lambda c^4}{8\pi G}$$

to give:

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$
$$\dot{H} + H^2 = \frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right).$$

And the simplified form of the second equation is invariant under this transformation.

The Hubble parameter can change over time if other parts of the equation are time dependent (in particular the mass density, the vacuum energy, or the spatial curvature). Evaluating the Hubble parameter at the present time yields Hubble's constant which is the proportionality constant of Hubble's law. Applied to a fluid with a given equation of state, the Friedmann equations yield the time evolution and geometry of the universe as a function of the fluid density.

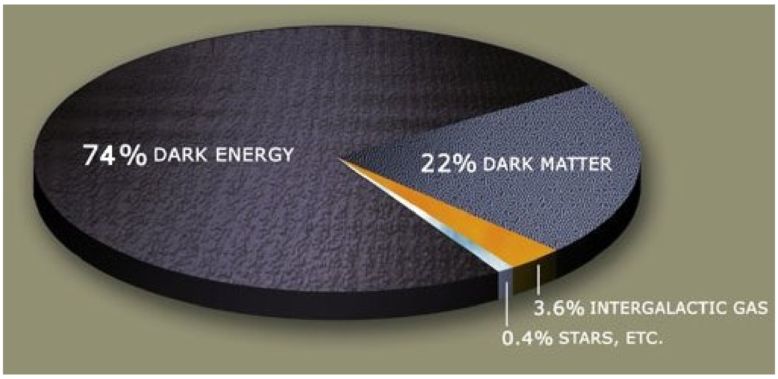
Some cosmologists call the second of these two equations the **Friedmann acceleration equation** and reserve the term *Friedmann equation* for only the first equation.

Density parameter

The density parameter, Ω, is defined as the ratio of the actual (or observed) density ρ to the critical density ρ_c of the Friedmann universe. The relation between the actual density and the critical density determines the overall geometry of the universe. In earlier models, which did not include a cosmological constant term, critical density was regarded also as the watershed between an expanding and a contracting Universe.

To date, the critical density is estimated to be approximately five atoms (of monatomic hydrogen) per cubic metre, whereas the average density of ordinary matter in the Universe is believed to be 0.2 atoms per cubic metre.[4]

A much greater density comes from the unidentified dark matter; both ordinary and dark matter contribute in favor of contraction of the universe. However, the largest part comes from so-called dark energy, which accounts for the cosmological constant term. Although the total density is equal to the critical density (exactly, up to measurement error), the dark energy does not lead to contraction of the universe but rather accelerates its expansion. Therefore, the universe will expand forever.[*citation needed*]



Estimated relative distribution for components of the energy density of the Universe. Dark energy dominates the total energy (74%) while dark matter (22%) constitutes most of the mass. Of the remaining baryonic matter (4%), only one tenth is compact. On 21 March 2013, the European-led research team behind the Planck cosmology probe released new data refining these values to 4.9% ordinary matter, 26.8% dark matter and 68.3% dark energy.

An expression for the critical density is found by assuming Λ to be zero (as it is for all basic Friedmann universes) and setting the normalised spatial curvature, k, equal to zero. When the substitutions are applied to the first of the Friedmann equations we find:

$$\rho_c = \frac{3H^2}{8\pi G}.$$

The density parameter (useful for comparing different cosmological models) is then defined as:

$$\Omega \equiv \frac{\rho}{\rho_c} = \frac{8\pi G\rho}{3H^2}.$$

This term originally was used as a means to determine the spatial geometry of the universe, where ρ_c is the critical density for which the spatial geometry is flat (or Euclidean). Assuming a zero vacuum energy density, if Ω is larger than unity, the space sections of the universe are closed; the universe will eventually stop expanding, then collapse. If Ω is less than unity, they are open; and the universe expands forever. However, one can also subsume the spatial curvature and vacuum energy terms into a more general expression for Ω in which case this density parameter equals exactly unity. Then it is a matter of measuring the different components, usually designated by subscripts. According to the ΛCDM model, there are important components of Ω due to baryons, cold dark matter and dark energy. The spatial geometry of the universe has been measured by the WMAP spacecraft to be nearly flat. This means that the universe can be well approximated by a model where the spatial curvature parameter k is zero; however, this does not necessarily imply that the universe is infinite: it might merely be that the universe is much larger than the part we see. (Similarly, the fact that Earth is approximately flat at the scale of the Netherlands does not imply that the Earth is flat: it only implies that it is much larger than the Netherlands.)

The first Friedmann equation is often seen in terms of the present values of the density parameters, that is[5]

$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda.$$

Here Ω_R is the radiation density today (i.e. when $a = 1$), Ω_M is the matter (dark plus baryonic) density today, $\Omega_k = 1 - \Omega$ is the "spatial curvature density" today, and Ω_Λ is the cosmological constant or vacuum density today.

Useful solutions

The Friedmann equations can be solved exactly in presence of a perfect fluid with equation of state

$$p = w\rho c^2,$$

where p is the pressure, ρ is the mass density of the fluid in the comoving frame and w is some constant.

In spatially flat case (k = 0), the solution for the scale factor is

$$a(t) = a_0 \, t^{\frac{2}{3(w+1)}}$$

where a_0 is some integration constant to be fixed by the choice of initial conditions. This family of solutions labelled by w is extremely important for cosmology. E.g. $w = 0$ describes a matter-dominated universe, where the pressure is negligible with respect to the mass density. From the generic solution one easily sees that in a matter-dominated universe the scale factor goes as

$$a(t) \propto t^{2/3} \text{matter-dominated}$$

Another important example is the case of a radiation-dominated universe, i.e., when $w = 1/3$. This leads to

$$a(t) \propto t^{1/2} \text{radiation dominated}$$

Note that this solution is not valid for domination of the cosmological constant, which corresponds to an $w = -1$. In this case the energy density is constant and the scale factor grows exponentially.

Solutions for other values of k can be found at Tersic, Balsa. "Lecture Notes on Astrophysics" [6]. Retrieved 20 July 2011..

Mixtures

If the matter is a mixture of two or more non-interacting fluids each with such an equation of state, then

$$\dot{\rho}_f = -3H\left(\rho_f + \frac{p_f}{c^2}\right)$$

holds separately for each such fluid f. In each case,

$$\dot{\rho}_f = -3H\left(\rho_f + w_f \rho_f\right)$$

from which we get

$$\rho_f \propto a^{-3(1+w_f)}.$$

For example, one can form a linear combination of such terms

$$\rho = Aa^{-3} + Ba^{-4} + Ca^0$$

where: A is the density of "dust" (ordinary matter, w = 0) when a = 1; B is the density of radiation (w = 1/3) when a = 1; and C is the density of "dark energy" (w=−1). One then substitutes this into

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2}$$

and solves for a as a function of time.

Rescaled Friedmann equation

Set $\tilde{a} = \frac{a}{a_0},\ \rho_c = \frac{3H_0^2}{8\pi G},\ \Omega = \frac{\rho}{\rho_c},\ t = \frac{\tilde{t}}{H_0},\ \Omega_c = -\frac{kc^2}{H_0^2 a_0^2},$ where $a_0$and $H_0$are separately the scale factor and the Hubble parameter today. Then we can have

$$\frac{1}{2}\left(\frac{d\tilde{a}}{d\tilde{t}}\right)^2 + U_{\text{eff}}(\tilde{a}) = \frac{1}{2}\Omega_c$$

where $U_{\text{eff}}(\tilde{a}) = \frac{\Omega\tilde{a}^2}{2}$. For any form of the effective potential $U_{\text{eff}}(\tilde{a})$, there is an equation of state $p = p(\rho)$ that will produce it.

Notes

[1] (English translation in:). The original Russian manuscript of this paper is preserved in the Ehrenfest archive (http://ilorentz.org/history/Friedmann_archive).

[2] (English translation in:)

[3] Ray A d'Inverno, *Introducing Einstein's Relativity*, ISBN 0-19-859686-3.

[4] Rees, M., Just Six Numbers, (2000) Orion Books, London, p. 81, p. 82

[5] http://adsabs.harvard.edu/cgi-bin/bib_query?arXiv:astro-ph/0703739

[6] http://nicadd.niu.edu/~bterzic/PHYS652/PHYS652_notes.pdf

Friedmann–Lemaître–Robertson–Walker metric

The **Friedmann–Lemaître–Robertson–Walker** (**FLRW**) **metric** is an exact solution of Einstein's field equations of general relativity; it describes a homogeneous, isotropic expanding or contracting universe that may be simply connected or multiply connected.[1] (If multiply connected, then each event in spacetime will be represented by more than one tuple of coordinates.) The general form of the metric follows from the geometric properties of homogeneity and isotropy; Einstein's field equations are only needed to derive the scale factor of the universe as a function of time. Depending on geographical or historical preferences, a subset of the four scientists — Alexander Friedmann, Georges Lemaître, Howard Percy Robertson and Arthur Geoffrey Walker — may be named (e.g., **Friedmann–Robertson–Walker** (**FRW**) or **Robertson–Walker** (**RW**) or **Friedmann–Lemaître** (**FL**)). This model is sometimes called the *Standard Model* of modern cosmology. It was developed independently by the named authors in the 1920s and 1930s.

General metric

The FLRW metric starts with the assumption of homogeneity and isotropy of space. It also assumes that the spatial component of the metric can be time-dependent. The generic metric which meets these conditions is

$$-c^2\mathrm{d}\tau^2 = -c^2\mathrm{d}t^2 + a(t)^2\mathrm{d}\mathbf{\Sigma}^2$$

where $\mathbf{\Sigma}$ranges over a 3-dimensional space of uniform curvature, that is, elliptical space, Euclidean space, or hyperbolic space. It is normally written as a function of three spatial coordinates, but there are several conventions for doing so, detailed below. $\mathrm{d}\mathbf{\Sigma}$does not depend on *t* — all of the time dependence is in the function *a*(*t*), known as the "scale factor".

Reduced-circumference polar coordinates

In reduced-circumference polar coordinates the spatial metric has the form

$$\mathrm{d}\mathbf{\Sigma}^2 = \frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\mathbf{\Omega}^2, \quad \text{where } \mathrm{d}\mathbf{\Omega}^2 = \mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2.$$

k is a constant representing the curvature of the space. There are two common unit conventions:

- *k* may be taken to have units of length^{-2}, in which case *r* has units of length and *a*(*t*) is unitless. *k* is then the Gaussian curvature of the space at the time when *a*(*t*) = 1. *r* is sometimes called the reduced circumference because it is equal to the measured circumference of a circle (at that value of *r*), centered at the origin, divided by 2π (like the *r* of Schwarzschild coordinates). Where appropriate, *a*(*t*) is often chosen to equal 1 in the present cosmological era, so that $\mathrm{d}\mathbf{\Sigma}$ measures comoving distance.
- Alternatively, *k* may be taken to belong to the set {−1,0,+1} (for negative, zero, and positive curvature respectively). Then *r* is unitless and *a*(*t*) has units of length. When *k* = ±1, *a*(*t*) is the radius of curvature of the space, and may also be written *R*(*t*).

A disadvantage of reduced circumference coordinates is that they cover only half of the 3-sphere in the case of positive curvature—circumferences beyond that point begin to decrease, leading to degeneracy. (This is not a problem if space is elliptical, i.e. a 3-sphere with opposite points identified.)

Hyperspherical coordinates

In *hyperspherical* or *curvature-normalized* coordinates the coordinate *r* is proportional to radial distance; this gives

$$\mathrm{d}\mathbf{\Sigma}^2 = \mathrm{d}r^2 + S_k(r)^2\,\mathrm{d}\mathbf{\Omega}^2$$

where $\mathrm{d}\mathbf{\Omega}$ is as before and

$$S_k(r) = \begin{cases} \sqrt{k}^{\,-1}\sin(r\sqrt{k}), & k>0 \\ r, & k=0 \\ \sqrt{|k|}^{\,-1}\sinh(r\sqrt{|k|}), & k<0. \end{cases}$$

As before, there are two common unit conventions:

- *k* may be taken to have units of length^{-2}, in which case *r* has units of length and *a*(*t*) is unitless. *k* is then the Gaussian curvature of the space at the time when *a*(*t*) = 1. Where appropriate, *a*(*t*) is often chosen to equal 1 in the present cosmological era, so that $\mathrm{d}\mathbf{\Sigma}$ measures comoving distance.
- Alternatively, as before, *k* may be taken to belong to the set {−1,0,+1} (for negative, zero, and positive curvature respectively). Then *r* is unitless and *a*(*t*) has units of length. When *k* = ±1, *a*(*t*) is the radius of curvature of the space, and may also be written *R*(*t*). Note that, when *k* = +1, *r* is essentially a third angle along with *θ* and *φ*. The letter *χ* may be used instead of *r*.

Though it is usually defined piecewise as above, *S* is an analytic function of both *k* and *r*. It can also be written as a power series

$$S_k(r) = \sum_{n=0}^{\infty} \frac{(-1)^n k^n r^{2n+1}}{(2n+1)!} = r - \frac{kr^3}{6} + \frac{k^2r^5}{120} - \cdots$$

or as

$$S_k(r) = r\ \mathrm{sinc}\,(r\sqrt{k})$$

where sinc is the unnormalized sinc function and $\sqrt{k}$ is one of the imaginary, zero or real square roots of *k*. These definitions are valid for all *k*.

Cartesian coordinates

When $k = 0$ one may write simply

$$\mathrm{d}\mathbf{\Sigma}^2 = \mathrm{d}x^2 + \mathrm{d}y^2 + \mathrm{d}z^2.$$

This can be extended to $k \neq 0$ by defining

$x = r\cos\theta$,

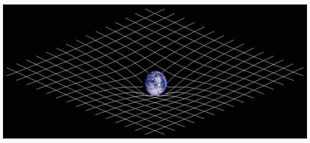
$y = r\sin\theta\cos\phi$, and

$z = r\sin\theta\sin\phi$,

where r is one of the radial coordinates defined above, but this is rare.

Solutions

General relativity



$$G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

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Einstein's field equations are not used in deriving the general form for the metric: it follows from the geometric properties of homogeneity and isotropy. However, determining the time evolution of $a(t)$ does require Einstein's field equations together with a way of calculating the density, $\rho(t)$, such as a cosmological equation of state.

This metric has an analytic solution to Einstein's field equations $G_{\mu\nu} + \Lambda g_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$ giving the Friedmann equations when the energy-momentum tensor is similarly assumed to be isotropic and homogeneous. The resulting equations are:

$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} - \frac{\Lambda c^2}{3} = \frac{8\pi G}{3}\rho$$

$$2\frac{\ddot{a}}{a} + \left(\frac{\dot{a}}{a}\right)^2 + \frac{kc^2}{a^2} - \Lambda c^2 = -\frac{8\pi G}{c^2}p.$$

These equations are the basis of the standard big bang cosmological model including the current ΛCDM model. Because the FLRW model assumes homogeneity, some popular accounts mistakenly assert that the big bang model cannot account for the observed lumpiness of the universe. In a strictly FLRW model, there are no clusters of galaxies, stars or people, since these are objects much denser than a typical part of the universe. Nonetheless, the FLRW model is used as a first approximation for the evolution of the real, lumpy universe because it is simple to calculate, and models which calculate the lumpiness in the universe are added onto the FLRW models as extensions. Most cosmologists agree that the observable universe is well approximated by an *almost FLRW model*, i.e., a model which follows the FLRW metric apart from primordial density fluctuations. As of 2003[2], the theoretical implications of the various extensions to the FLRW model appear to be well understood, and the goal is to make these consistent with observations from COBE and WMAP.

Interpretation

The pair of equations given above is equivalent to the following pair of equations

$$\dot{\rho} = -3\frac{\dot{a}}{a}\left(\rho + \frac{p}{c^2}\right)$$
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3p}{c^2}\right) + \frac{\Lambda c^2}{3}$$

with k , the spatial curvature index, serving as a constant of integration for the second equation.

The first equation can be derived also from thermodynamical considerations and is equivalent to the first law of thermodynamics, assuming the expansion of the universe is an adiabatic process (which is implicitly assumed in the derivation of the Friedmann–Lemaître–Robertson–Walker metric).

The second equation states that both the energy density and the pressure cause the expansion rate of the universe $\dot{a}$ to decrease, i.e., both cause a deceleration in the expansion of the universe. This is a consequence of gravitation, with pressure playing a similar role to that of energy (or mass) density, according to the principles of general relativity. The cosmological constant, on the other hand, causes an acceleration in the expansion of the universe.

The cosmological constant term

The cosmological constant term can be omitted if we make the following replacement

$$\rho \rightarrow \rho + \frac{\Lambda c^2}{8\pi G}$$
$$p \rightarrow p - \frac{\Lambda c^4}{8\pi G}.$$

Therefore the cosmological constant can be interpreted as arising from a form of energy which has negative pressure, equal in magnitude to its (positive) energy density:

$$p = -\rho c^2.$$

Such form of energy—a generalization of the notion of a cosmological constant—is known as dark energy.

In fact, in order to get a term which causes an acceleration of the universe expansion, it is enough to have a scalar field which satisfies

$$p < -\frac{\rho c^2}{3}.$$

Such a field is sometimes called quintessence.

Newtonian interpretation

The Friedmann equations are equivalent to this pair of equations:

$$-a^3\dot{\rho} = 3a^2\dot{a}\rho + \frac{3a^2 p\dot{a}}{c^2}$$
$$\frac{\dot{a}^2}{2} - \frac{G\frac{4\pi a^3}{3}\rho}{a} = -\frac{kc^2}{2}.$$

The first equation says that the decrease in the mass contained in a fixed cube (whose side is momentarily *a*) is the amount which leaves through the sides due to the expansion of the universe plus the mass equivalent of the work done by pressure against the material being expelled. This is the conservation of mass-energy (first law of thermodynamics) contained within a part of the universe.

The second equation says that the kinetic energy (seen from the origin) of a particle of unit mass moving with the expansion plus its (negative) gravitational potential energy (relative to the mass contained in the sphere of matter closer to the origin) is equal to a constant related to the curvature of the universe. In other words, the energy (relative to the origin) of a co-moving particle in free-fall is conserved. General relativity merely adds a connection between the spatial curvature of the universe and the energy of such a particle: positive total energy implies negative curvature and negative total energy implies positive curvature.

The cosmological constant term is assumed to be treated as dark energy and thus merged into the density and pressure terms.

During the Planck epoch, one cannot neglect quantum effects. So they may cause a deviation from the Friedmann equations.

Name and history

The main results of the FLRW model were first derived by the Soviet mathematician Alexander Friedmann in 1922 and 1924. Although his work was published in the prestigious physics journal Zeitschrift für Physik, it remained relatively unnoticed by his contemporaries. Friedmann was in direct communication with Albert Einstein, who, on behalf of Zeitschrift für Physik, acted as the scientific referee of Friedmann's work. Eventually Einstein acknowledged the correctness of Friedmann's calculations, but failed to appreciate the physical significance of Friedmann's predictions.

Friedmann died in 1925. In 1927, Georges Lemaître, a Belgian priest, astronomer and periodic professor of physics at the Catholic University of Leuven, arrived independently at similar results as Friedmann and published them in Annals of the Scientific Society of Brussels. In the face of the observational evidence for the expansion of the universe obtained by Edwin Hubble in the late 1920s, Lemaître's results were noticed in particular by Arthur Eddington, and in 1930–31 his paper was translated into English and published in the Monthly Notices of the Royal Astronomical Society.

Howard Percy Robertson from the US and Arthur Geoffrey Walker from the UK explored the problem further during the 1930s. In 1935 Robertson and Walker rigorously proved that the FLRW metric is the only one on a spacetime that is spatially homogeneous and isotropic (as noted above, this is a geometric result and is not tied specifically to the equations of general relativity, which were always assumed by Friedmann and Lemaître).

Because the dynamics of the FLRW model were derived by Friedmann and Lemaître, the latter two names are often omitted by scientists outside the US. Conversely, US physicists often refer to it as simply "Robertson–Walker". The full four-name title is the most democratic and it is frequently used.[*citation needed*] Often the "Robertson–Walker" *metric*, so-called since they proved its generic properties, is distinguished from the dynamical "Friedmann-Lemaître" *models*, specific solutions for *a(t)* which assume that the only contributions to stress-energy are cold matter ("dust"), radiation, and a cosmological constant.

Einstein's radius of the Universe

Einstein's radius of the universe is the radius of curvature of space of Einstein's universe, a long-abandoned static model that was supposed to represent our universe in idealized form. Putting

$$\dot{a} = \ddot{a} = 0$$

in the Friedmann equation, the radius of curvature of space of this universe (Einstein's radius) is[*citation needed*]

$$R_E = c/\sqrt{4\pi G\rho},$$

where c is the speed of light, G is the Newtonian gravitational constant, and ρ is the density of space of this universe. The numerical value of Einstein's radius is of the order of 10^{10} light years.

References and notes

[1] For an early reference, see Robertson (1935); Robertson *assumes* multiple connectedness in the positive curvature case and says that "we are still free to restore" simple connectedness.
[2] http://en.wikipedia.org/w/index.php?title=Friedmann%E2%80%93Lema%C3%AEtre%E2%80%93Robertson%E2%80%93Walker_metric&action=edit

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Distance measures (cosmology)

Distance measures are used in physical cosmology to give a natural notion of the distance between two objects or events in the universe. They are often used to tie some *observable* quantity (such as the luminosity of a distant quasar, the redshift of a distant galaxy, or the angular size of the acoustic peaks in the CMB power spectrum) to another quantity that is not *directly* observable, but is more convenient for calculations (such as the comoving coordinates of the quasar, galaxy, etc.). The distance measures discussed here all reduce to the common notion of Euclidean distance at low redshift.

In accord with our present understanding of cosmology, these measures are calculated within the context of general relativity, where the Friedmann-Lemaître-Robertson-Walker solution is used to describe the universe.

Overview

There are a few different definitions of "distance" in cosmology which all coincide for sufficiently small redshifts. The expressions for these distances are most practical when written as functions of redshift, since redshift is always the observable. They can easily be written as functions of scale factor $a = 1/(1+z)$, cosmic t or conformal time η as well by performing a simple transformation of variables. By defining the dimensionless Hubble parameter

$$E(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda}$$

and the Hubble distance $d_H = c/H_0$, the relation between the different distances becomes apparent. Here, Ω_m is the total matter density, Ω_Λ is the dark energy density, $\Omega_k = 1 - \Omega_m - \Omega_\Lambda$ represents the curvature, H_0 is the Hubble parameter today and c is the speed of light. The following measures for distances from the observer to an object at redshift z along the line of sight are commonly used in cosmology:

Comoving distance:

$$d_C(z) = d_H \int_0^z \frac{dz'}{E(z')}$$

Transverse comoving distance:

$$d_M(z) = \begin{cases} \frac{d_H}{\sqrt{\Omega_k}} \sinh\left(\sqrt{\Omega_k} d_C(z)/d_H\right) & \text{for } \Omega_k > 0 \\ d_C(z) & \text{for } \Omega_k = 0 \\ \frac{d_H}{\sqrt{|\Omega_k|}} \sin\left(\sqrt{|\Omega_k|} d_C(z)/d_H\right) & \text{for } \Omega_k < 0 \end{cases}$$

Angular diameter distance:

$$d_A(z) = \frac{d_M(z)}{1+z}$$

Luminosity distance:

$$d_L(z) = (1+z) d_M(z)$$

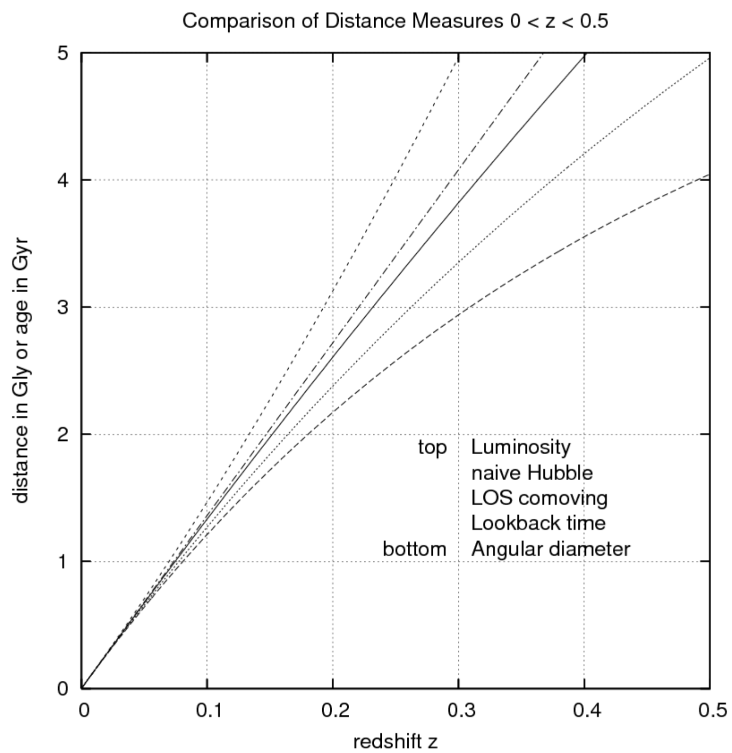
Light-travel distance:

$$d_T(z) = d_H \int_0^z \frac{dz'}{(1+z')E(z')}$$

Note that the comoving distance is recovered from the transverse comoving distance by taking the limit $\Omega_k \to 0$, such that the two distance measures are equivalent in a flat Universe.

Alternative terminology

Peebles (1993, pp 310–320) calls the transverse comoving distance the "angular size distance", which is not to be mistaken for the angular diameter distance [1]. Even though it is not a matter of nomenclature, the comoving distance is equivalent to the proper motion distance, which is defined as the ratio of the transverse velocity and its proper motion in radians per time. Occasionally, the symbols χ or r are used to denote both the comoving and the angular diameter distance. Sometimes, the light-travel distance is also called the "lookback distance".



A comparison of cosmological distance measures, from redshift zero to redshift of 0.5. The background cosmology is Hubble parameter 72 km/s/Mpc, $\Omega_\Lambda = 0.732$, $\Omega_{\mathrm{matter}} = 0.266$, $\Omega_{\mathrm{radiation}} = 0.266/3454$, and Ω_k chosen so that the sum of Omega parameters is 1.

Details

Comoving distance

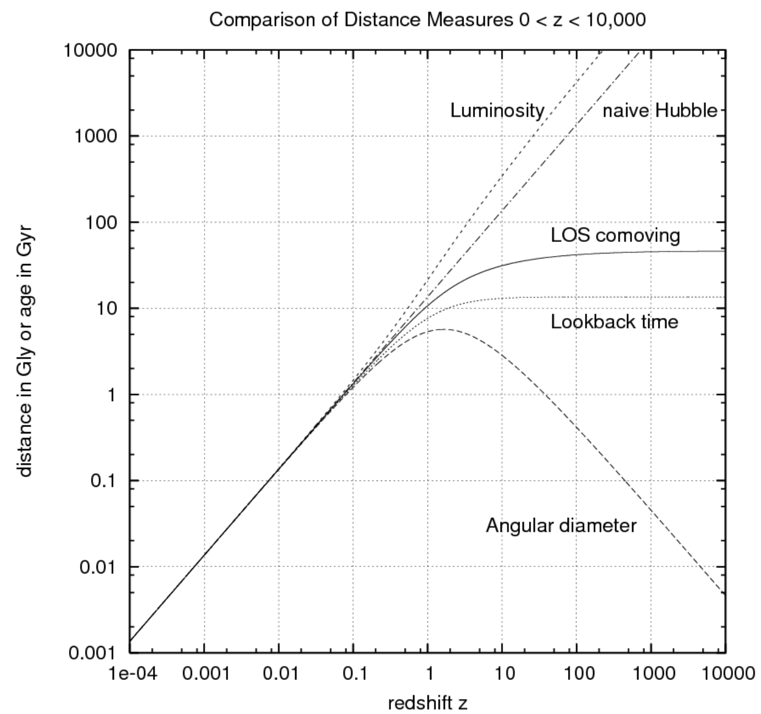
The comoving distance between fundamental observers, i.e. observers that are comoving with the Hubble flow, does not change with time, as it accounts for the expansion of the Universe. It is obtained by integrating up the proper distances of nearby fundamental observers along the line of sight, where the proper distance is what a measurement at constant cosmic time would yield.

Transverse comoving distance

Two comoving objects at constant redshift z that are separated by an angle $\delta\theta$ on the sky are said to have the distance $\delta\theta d_M(z)$, where the transverse comoving distance d_M is defined appropriately.

Angular diameter distance

An object of size x at redshift z that appears to have angular size $\delta\theta$ has the angular diameter distance of $d_A(z) = x/\delta\theta$. This is commonly used to observe so called standard rulers, for example in the context of baryon acoustic oscillations.



A comparison of cosmological distance measures, from redshift zero to redshift of 10,000, corresponding to the epoch of matter/radiation equality. The background cosmology is Hubble parameter 72 km/s/Mpc, $\Omega_\Lambda = 0.732$, $\Omega_{\rm matter} = 0.266$, $\Omega_{\rm radiation} = 0.266/3454$, and Ω_k chosen so that the sum of Omega parameters is one.

Luminosity distance

If the intrinsic luminosity L of a distant object is known, we can calculate its luminosity distance by measuring the flux S and determine $d_L(z) = \sqrt{L/4\pi S}$, which turns out to be equivalent to the expression above for $d_L(z)$. This quantity is important for measurements of standard candles like type Ia supernovae, which were first used to discover the acceleration of the expansion of the Universe.

Light-travel distance

This distance is simply the time that it took light to reach the observer from the object multiplied by the speed of light. For instance, the radius of the observable Universe in this distance measure becomes simply the age of the Universe multiplied by the speed of light (1 light year/year) i.e. 13.8 billion light years. Also see misconceptions about the size of the visible universe.

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[1] http://cdsads.u-strasbg.fr/cgi-bin/nph-bib_query?bibcode=1993ppc..book.....P&db_key=AST&high=3ece3bb64809032

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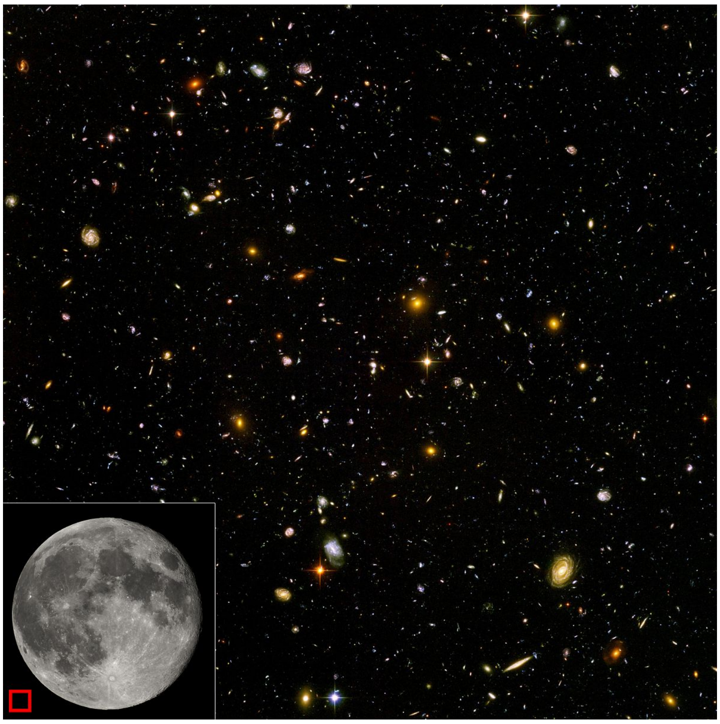
External links

- 'The Distance Scale of the Universe' (http://www.atlasoftheuniverse.com/redshift.html) compares different cosmological distance measures.
- 'Distance measures in cosmology' (http://arxiv.org/abs/astro-ph/9905116) explains in detail how to calculate the different distance measures as a function of world model and redshift.
- iCosmos: Cosmology Calculator (With Graph Generation) (http://icosmos.co.uk/) calculates the different distance measures as a function of cosmological model and redshift, and generates plots for the model from redshift 0 to 20.

Observations: up to 10 Gpc/h

Observable universe



Hubble Ultra-Deep Field image of a region of the observable universe (equivalent sky area size shown in bottom left corner), near the constellation Fornax. Each spot is a galaxy, consisting of billions of stars. The light from the smallest, most red-shifted galaxies originated nearly 14 billion years ago.

The **observable universe** consists of the galaxies and other matter that can, in principle, be observed from Earth in the present day because light (or other signals) from those objects has had time to reach the Earth since the beginning of the cosmological expansion, (see Big Bang cosmology). Assuming the universe is isotropic, the distance to the edge of the observable universe is roughly the same in every direction. That is, the observable universe is a spherical volume (a ball) centered on the observer, regardless of the shape of the universe as a whole. Every location in the universe has its own observable universe, which may or may not overlap with the one centered on Earth.

The word *observable* used in this sense does not depend on whether modern technology actually permits detection of radiation from an object in this region (or indeed on whether there is any radiation to detect). It simply indicates that it is possible *in principle* for light or other signals from the object to reach an observer on Earth. In practice, we can see light only from as far back as the time of photon decoupling in the recombination epoch. That is when particles were first able to emit photons that were not quickly re-absorbed by other particles. Before then, the universe was filled with a plasma that was opaque to photons.

The *surface of last scattering* is the collection of points in space at the exact distance that photons from the time of photon decoupling just reach us today. These are the photons we detect today as cosmic microwave background radiation (CMBR). However, with future technology, it may be possible to observe the still older neutrino background, or even more distant events via gravitational waves (which also should move at the speed of light). Sometimes astrophysicists distinguish between the *visible* universe, which includes only signals emitted since recombination—and the *observable* universe, which includes signals since the beginning of the cosmological expansion (the Big Bang in traditional cosmology, the end of the inflationary epoch in modern cosmology). According to calculations, the *comoving distance* (current proper distance) to particles from the CMBR, which represent the radius of the visible universe, is about 14.0 billion parsecs (about 45.7 billion light years), while the comoving distance to the edge of the observable universe is about 14.3 billion parsecs (about 46.6 billion light years), about 2% larger.

The best estimate of the age of the universe as of 2013 is 13.798 ± 0.037 billion years but due to the expansion of space humans are observing objects that were originally much closer but are now considerably farther away (as defined in terms of cosmological proper distance, which is equal to the comoving distance at the present time) than a static 13.8 billion light-years distance. The diameter of the observable universe is estimated at about 28 billion parsecs (93 billion light-years), putting the edge of the observable universe at about 46–47 billion light-years away.[1]

The universe versus the observable universe

Some parts of the universe may simply be too far away for the light emitted from there at any moment since the Big Bang to have had enough time to reach Earth at present, so these portions of the universe would currently lie outside the observable universe. In the future, light from distant galaxies will have had more time to travel, so some regions not currently observable will become observable. However, due to Hubble's law regions sufficiently distant from us are expanding away from us much faster than the speed of light (special relativity prevents nearby objects in the same local region from moving faster than the speed of light with respect to each other, but there is no such constraint for distant objects when the space between them is expanding; see uses of the proper distance for a discussion), and the expansion rate appears to be accelerating due to dark energy. Assuming dark energy remains constant (an unchanging cosmological constant), so that the expansion rate of the universe continues to accelerate, there is a "future visibility limit" beyond which objects will *never* enter our observable universe at any time in the infinite future, because light emitted by objects outside that limit would never reach us. (A subtlety is that, because the Hubble parameter is decreasing with time, there can be cases where a galaxy that is receding from us just a bit faster than light does emit a signal that reaches us eventually[2]). This future visibility limit is calculated at a comoving distance of 19 billion parsecs (62 billion light years) assuming the universe will keep expanding forever, which implies the number of galaxies that we can ever theoretically observe in the infinite future (leaving aside the issue that some may be impossible to observe in practice due to redshift, as discussed in the following paragraph) is only larger than the number currently observable by a factor of 2.36.[]

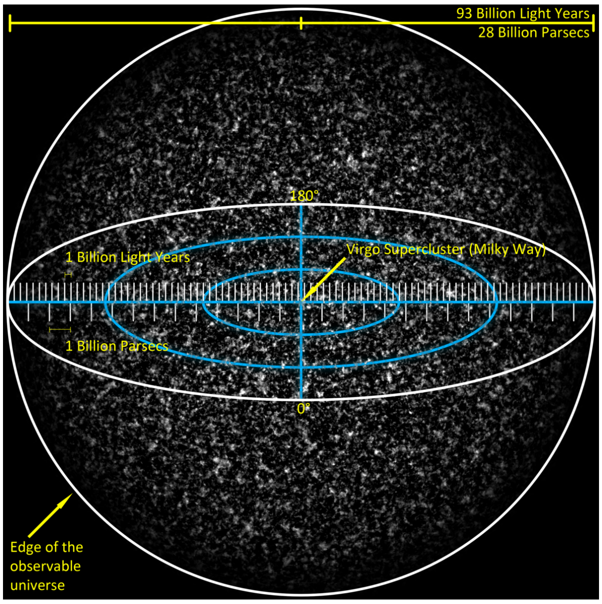
Though in principle more galaxies will become observable in the future, in practice an increasing number of galaxies will become extremely redshifted due to ongoing expansion, so much so that they will seem to disappear from view and become invisible.[3][4] An additional subtlety is that a galaxy at a given comoving distance is defined to lie within the "observable universe" if we can receive signals emitted by the galaxy at any age in its past history (say, a signal sent from the galaxy only 500 million years after the Big Bang), but because of the universe's expansion, there may be some later age at which a signal sent from the same galaxy can *never* reach us at any point in the infinite future (so for example we might never see what the galaxy looked like 10 billion years after the Big Bang), even though it remains at the same comoving distance (comoving distance is defined to be constant with time—unlike proper distance, which is used to define recession velocity due to the expansion of space), which is less than the comoving radius of the observable universe. This fact can be used to define a type of cosmic event horizon whose distance from us changes over time. For example, the current distance to this horizon is about 16 billion light years, meaning that a signal from an event happening *at present* can eventually reach us in the future if the event is less than 16 billion light years away, but the signal will never reach us if the event is more than 16 billion light years away.

Both popular and professional research articles in cosmology often use the term "universe" to mean "observable universe". This can be justified on the grounds that we can never know anything by direct experimentation about any part of the universe that is causally disconnected from us, although many credible theories require a total universe much larger than the observable universe. No evidence exists to suggest that the boundary of the observable universe constitutes a boundary on the universe as a whole, nor do any of the mainstream cosmological models propose that the universe has any physical boundary in the first place, though some models propose it could be finite but unbounded, like a higher-dimensional analogue of the 2D surface of a sphere that is finite in area but has no edge. It is plausible that the galaxies within our observable universe represent only a minuscule fraction of the galaxies in the universe. According to the theory of cosmic inflation and its founder, Alan Guth, if it is assumed that inflation began about 10^{-37} seconds after the Big Bang, then with the plausible assumption that the size of the universe at this time was approximately equal to the speed of light times its age, that would suggest that at present the entire universe's size is at least 10^{23} times larger than the size of the observable universe.

If the universe is finite but unbounded, it is also possible that the universe is *smaller* than the observable universe. In this case, what we take to be very distant galaxies may actually be duplicate images of nearby galaxies, formed by light that has circumnavigated the universe. It is difficult to test this hypothesis experimentally because different images of a galaxy would show different eras in its history, and consequently might appear quite different. Bielewicz et al.:[5] claims to establish a lower bound of 27.9 gigaparsecs (91 billion light-years) on the diameter of the last scattering surface (since this is only a lower bound, the paper leaves open the possibility that the whole universe is much larger, even infinite). This value is based on matching-circle analysis of the WMAP 7 year data. This approach has been disputed.

Size

The comoving distance from Earth to the edge of the observable universe is about 14 gigaparsecs (46 billion light years or 4.3×10^{26} meters) in any direction. The observable universe is thus a sphere with a diameter of about 29 gigaparsecs (93 Gly or 8.8×10^{26} m). Assuming that space is roughly flat, this size corresponds to a comoving volume of about 1.3×10^{4} Gpc^3 (4.1×10^{5} Gly^3 or 3.5×10^{80} m^3).



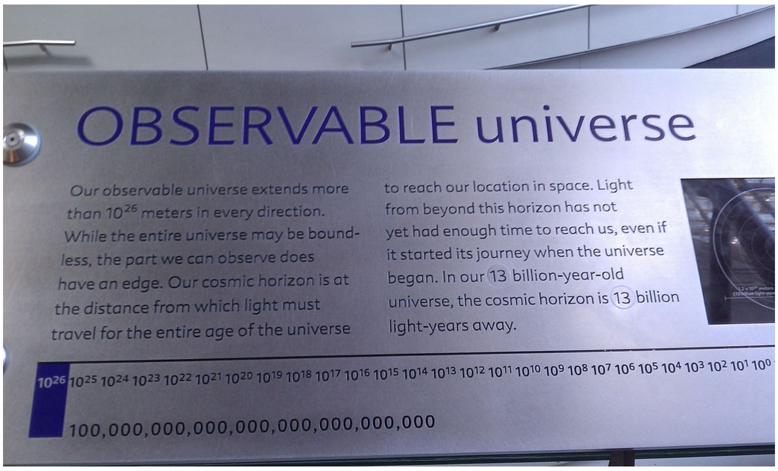
Visualization of the 93 billion light year – or 28 billion parsec – three-dimensional observable universe. The scale is such that the fine grains represent collections of large numbers of superclusters. The Virgo Supercluster – home of Milky Way – is marked at the center, but is too small to be seen in the image.

The figures quoted above are distances *now* (in cosmological time), not distances *at the time the light was emitted*. For example, the cosmic microwave background radiation that we see right now was emitted at the time of photon decoupling, estimated to have occurred about 380,000 years after the Big Bang,[6] which occurred around 13.8 billion years ago. This radiation was emitted by matter that has, in the intervening time, mostly condensed into galaxies, and those galaxies are now calculated to be about 46 billion light-years from us. To estimate the distance to that matter at the time the light was emitted, we may first note that according to the Friedmann–Lemaître–Robertson–Walker metric, which is used to model the expanding universe, if at the present time we receive light with a redshift of z, then the scale factor at the time the light was originally emitted is given by the following equation.

$$a(t) = \frac{1}{1+z}$$

WMAP nine-year results give the redshift of photon decoupling as z=1091.64 $\pm$ 0.47 which implies that the scale factor at the time of photon decoupling would be $^1\!/_{1092.64}$. So if the matter that originally emitted the oldest CMBR photons has a *present* distance of 46 billion light years, then at the time of decoupling when the photons were originally emitted, the distance would have been only about 42 *million* light-years away.

Misconceptions



An example of one of the most common misconceptions about the size of the observable universe. Despite the fact that the universe is 13.8 billion years old, the distance to the edge of the observable universe is **not** 13.8 billion light-years, because the universe is expanding. This plaque appears at the Rose Center for Earth and Space in New York City.

Many secondary sources have reported a wide variety of incorrect figures for the size of the visible universe. Some of these figures are listed below, with brief descriptions of possible reasons for misconceptions about them.

13.8 billion light-years

The age of the universe is estimated to be 13.8 billion years. While it is commonly understood that nothing can accelerate to velocities equal to or greater than that of light, it is a common misconception that the radius of the observable universe must therefore amount to only 13.8 billion light-years. This reasoning would only make sense if the flat, static Minkowski spacetime conception under special relativity were correct. In the real universe, spacetime is curved in a way that corresponds to the expansion of space, as evidenced by Hubble's law. Distances obtained as the speed of light multiplied by a cosmological time interval have no direct physical significance.[7]

15.8 billion light-years

This is obtained in the same way as the 13.8 billion light year figure, but starting from an incorrect age of the universe that the popular press reported in mid-2006.[8][9] For an analysis of this claim and the paper that prompted it, see the following reference at the end of this article.[10]

27.6 billion light-years

This is a diameter obtained from the (incorrect) radius of 13.8 billion light-years.

78 billion light-years

In 2003, Cornish et al. found this lower bound for the diameter of the *whole* universe (not just the observable part), if we postulate that the universe is finite in size due to its having a nontrivial topology,[11] with this lower bound based on the estimated current distance between points that we can see on opposite sides of the cosmic microwave background radiation (CMBR). If the whole universe is smaller than this sphere, then light has had time to circumnavigate it since the big bang, producing multiple images of distant points in the CMBR, which would show up as patterns of repeating circles.[12] Cornish et al. looked for such an effect at scales of up to 24 gigaparsecs (78 Gly or 7.4×10^{26} m) and failed to find it, and suggested that if they could extend their search to all possible orientations, they would then "be able to exclude the possibility that we live in a universe smaller than 24 Gpc in diameter". The authors also estimated that with "lower noise and higher resolution CMB maps (from WMAP's extended mission and from Planck), we will be able to search for smaller circles and extend the limit to ~28 Gpc." This estimate of the maximum lower bound that can be established by future observations corresponds to a radius of 14 gigaparsecs, or around 46 billion light years, about the same as the figure for the radius of the visible universe (whose radius is defined by the CMBR sphere) given in the opening section. A 2012 preprint by most of the same authors as the Cornish et al. paper has extended the current lower bound to a diameter of 98.5% the diameter of the CMBR sphere, or about 26 Gpc.

156 billion light-years

This figure was obtained by doubling 78 billion light-years on the assumption that it is a radius.[13] Since 78 billion light-years is already a diameter (the original paper by Cornish et al. says, "By extending the search to all possible orientations, we will be able to exclude the possibility that we live in a universe smaller than 24 Gpc in diameter," and 24 Gpc is 78 billion light years), the doubled figure is incorrect. This figure was very widely reported.[14] A press release from Montana State University – Bozeman, where Cornish works as an astrophysicist, noted the error when discussing a story that had appeared in *Discover* magazine, saying "*Discover* mistakenly reported that the universe was 156 billion light-years wide, thinking that 78 billion was the radius of the universe instead of its diameter."

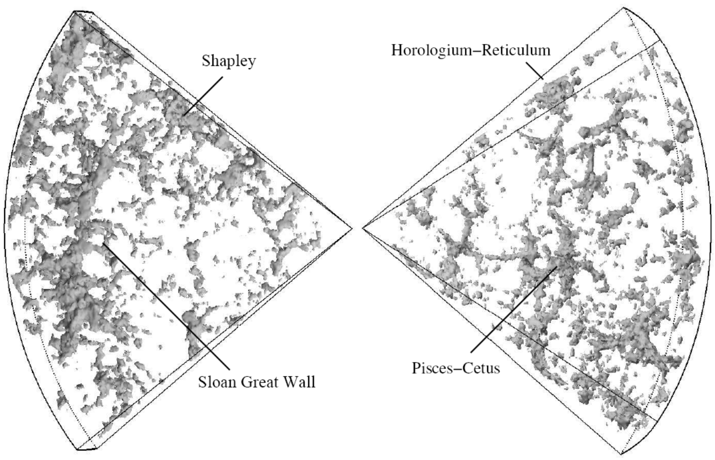
180 billion light-years

This estimate accompanied the age estimate of 15.8 billion years in some sources;[15] it was obtained by adding 15% to the figure of 156 billion light years.

Large-scale structure

Sky surveys and mappings of the various wavelength bands of electromagnetic radiation (in particular 21-cm emission) have yielded much information on the content and character of the universe's structure. The organization of structure appears to follow as a hierarchical model with organization up to the scale of superclusters and filaments. Larger than this, there seems to be no continued structure, a phenomenon that has been referred to as the **End of Greatness**.

Walls, filaments, and voids



DTFE reconstruction of the inner parts of the 2dF Galaxy Redshift Survey

The organization of structure arguably begins at the stellar level, though most cosmologists rarely address astrophysics on that scale. Stars are organized into galaxies, which in turn form galaxy groups, galaxy clusters, superclusters, sheets, walls and filaments, which are separated by immense voids, creating a vast foam-like structure sometimes called the "cosmic web". Prior to 1989, it was commonly assumed that virialized galaxy clusters were the largest structures in existence, and that they were distributed more or less uniformly throughout the universe in every direction. However, based on redshift survey data, in 1989 Margaret Geller and John Huchra discovered the "Great Wall",[16] a sheet of galaxies more than 500 million light-years long and 200 million wide, but only 15 million light-years thick. The existence of this structure escaped notice for so long because it requires locating the position of galaxies in three dimensions, which involves combining location information about the galaxies with distance information from redshifts. In April 2003, another large-scale structure was discovered, the Sloan Great Wall. In August 2007, a possible supervoid was detected in the constellation Eridanus.[17] It coincides with the 'WMAP Cold Spot', a cold region in the microwave sky that is highly improbable under the currently favored cosmological model. This supervoid could cause the cold spot, but to do so it would have to be improbably big, possibly a billion light-years across.

Another large-scale structure is the Newfound Blob, a collection of galaxies and enormous gas bubbles that measures about 200 million light years across.

In recent studies the universe appears as a collection of giant bubble-like voids separated by sheets and filaments of galaxies, with the superclusters appearing as occasional relatively dense nodes. This network is clearly visible in the 2dF Galaxy Redshift Survey. In the figure, a three dimensional reconstruction of the inner parts of the survey is shown, revealing an impressive view of the cosmic structures in the nearby universe. Several superclusters stand out, such as the Sloan Great Wall, the largest wall known to date.

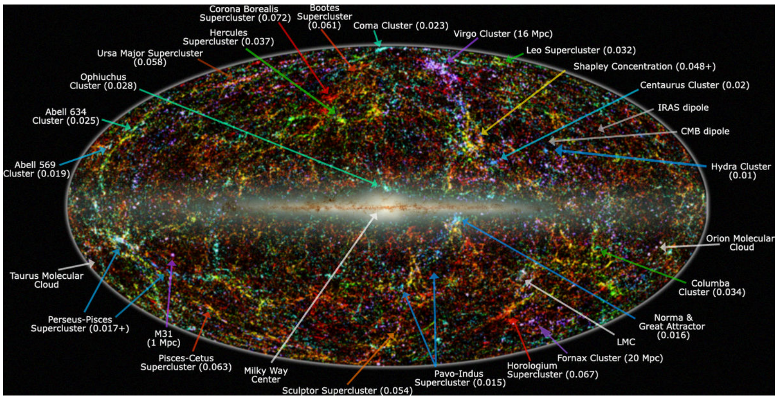
On January 11, 2013, a large quasar group, the Huge-LQG, was discovered, which was measured to be four billion light-years across, the largest known structure in the universe.

End of Greatness

The **End of Greatness** is an observational scale discovered at roughly 100 Mpc (roughly 300 million lightyears) where the lumpiness seen in the large-scale structure of the universe is homogenized and isotropized in accordance with the Cosmological Principle. At this scale, no pseudo-random fractalness is apparent.[18] The superclusters and filaments seen in smaller surveys are randomized to the extent that the smooth distribution of the universe is visually apparent. It was not until the redshift surveys of the 1990s were completed that this scale could accurately be observed.

Observations

Another indicator of large-scale structure is the 'Lyman-alpha forest'. This is a collection of absorption lines that appear in the spectra of light from quasars, which are interpreted as indicating the existence of huge thin sheets of intergalactic (mostly hydrogen) gas. These sheets appear to be associated with the formation of new galaxies.



"Panoramic view of the entire near-infrared sky reveals the distribution of galaxies beyond the Milky Way. The image is derived from the 2MASS Extended Source Catalog (XSC)—more than 1.5 million galaxies, and the Point Source Catalog (PSC)--nearly 0.5 billion Milky Way stars. The galaxies are color-coded by 'redshift' obtained from the UGC, CfA, Tully NBGC, LCRS, 2dF, 6dFGS, and SDSS surveys (and from various observations compiled by the NASA Extragalactic Database), or photo-metrically deduced from the K band (2.2 um). Blue are the nearest sources ($z < 0.01$); green are at moderate distances ($0.01 < z < 0.04$) and red are the most distant sources that 2MASS resolves ($0.04 < z < 0.1$). The map is projected with an equal area Aitoff in the Galactic system (Milky Way at center)." [19]

Caution is required in describing structures on a cosmic scale because things are often different than they appear. Bending of light by gravitation (gravitational lensing) can make images appear to originate in a different direction from their real source. This is caused when foreground objects (such as galaxies) curve surrounding spacetime (as predicted by general relativity), and deflect passing light rays. Rather usefully, strong gravitational lensing can sometimes magnify distant galaxies, making them easier to detect. Weak lensing (gravitational shear) by the intervening universe in general also subtly changes the observed large-scale structure. In 2004, measurements of this subtle shear show considerable promise as a test of cosmological models.

The large-scale structure of the universe also looks different if one only uses redshift to measure distances to galaxies. For example, galaxies behind a galaxy cluster are attracted to it, and so fall towards it, and so are slightly blueshifted (compared to how they would be if there were no cluster) On the near side, things are slightly redshifted.

Thus, the environment of the cluster looks a bit squashed if using redshifts to measure distance. An opposite effect works on the galaxies already within the cluster: the galaxies have some random motion around the cluster centre, and when these random motions are converted to redshifts, the cluster appears elongated. This creates *finger of God*—the illusion of a long chain of galaxies pointed at the Earth.

Cosmography of our cosmic neighborhood

At the centre of the Hydra-Centaurus Supercluster, a gravitational anomaly called the Great Attractor affects the motion of galaxies over a region hundreds of millions of light-years across. These galaxies are all redshifted, in accordance with Hubble's law. This indicates that they are receding from us and from each other, but the variations in their redshift are sufficient to reveal the existence of a concentration of mass equivalent to tens of thousands of galaxies.

The Great Attractor, discovered in 1986, lies at a distance of between 150 million and 250 million light-years (250 million is the most recent estimate), in the direction of the Hydra and Centaurus constellations. In its vicinity there is a preponderance of large old galaxies, many of which are colliding with their neighbours, and/or radiating large amounts of radio waves.

In 1987 Astronomer R. Brent Tully of the University of Hawaii's Institute of Astronomy identified what he called the Pisces-Cetus Supercluster Complex, a structure one billion light years long and 150 million light years across in which, he claimed, the Local Supercluster was embedded.[20][21]

Mass of ordinary matter

The mass of the universe is often quoted as 10^{50} tons or 10^{53} kg. In this context, mass refers to ordinary matter and includes the interstellar medium (ISM) and the intergalactic medium (IGM). However, it excludes dark matter and dark energy. Three calculations substantiate this quoted value for the mass of ordinary matter in the universe: Estimates based on critical density, extrapolations from number of stars, and estimates based on steady-state. The calculations obviously assume a **finite** universe.

Estimates based on critical density

Critical Density is the energy density where the expansion of the universe is poised between continued expansion and collapse. Observations of the cosmic microwave background from the Wilkinson Microwave Anisotropy Probe suggest that the spatial curvature of the universe is very close to zero, which in current cosmological models implies that the value of the density parameter must be very close to a certain critical density value. At this condition, the calculation for ρ_c critical density, is):

$$\rho_c = \frac{3H_0^2}{8\pi G}$$

where G is the gravitational constant. From The European Space Agency's Planck Telescope results: H_0, is 67.15 kilometers per second per mega parsec. This gives a critical density of 0.85×10^{-26} kg/m^3 (commonly quoted as about 5 hydrogen atoms/m^3). This density includes four significant types of energy/mass: ordinary matter (4.8%), neutrinos (0.1%), cold dark matter (26.8%), and dark energy (68.3%). Note that although neutrinos are defined as particles like electrons, they are listed separately because they are difficult to detect and so different from ordinary matter. Thus, the density of ordinary matter is 4.8% times the total critical density calculated or 4.08×10^{-28} kg/m^3. To convert this density to mass we must multiply by volume, a value based on the radius of the "observable universe". Since the universe has been expanding for 13.7 billion years, the comoving distance (radius) is now about 46.6 billion light years. Thus, volume ($4/3\ \pi\ r^3$) equals 3.58×10^{80} m^3 and mass of ordinary matter equals density (4.08×10^{-28} kg/m^3) times volume (3.58×10^{80} m^3) or 1.46×10^{53} kg.

Extrapolation from number of stars

There is currently no way to know exactly the number of stars, but from current literature, the range of 10^{22} to 10^{24} is normally quoted.[22][23] One way to substantiate this range is to estimate the number of galaxies and multiply by the number of stars in an average galaxy. The 2004 Hubble Ultra-Deep Field image contains an estimated 10,000 galaxies.[24] The patch of sky in this area, is 3.4 arc minutes on each side. For a relative comparison, it would require over 50 of these images to cover the full moon. If this area is typical for the entire sky, there are over 100 billion galaxies in the universe. More recently, in 2012, Hubble scientists produced the Hubble Extreme Deep Field image which showed slightly more galaxies for a comparable area.[25] However, in order to compute the number of stars based on these images, we would need additional assumptions: the percent of both large and dwarf galaxies; and, their average number of stars. Thus, a reasonable option is to assume 100 billion average galaxies and 100 billion stars per average galaxy. This results in 10^{22} stars. Next, we need average star mass which can be calculated from the distribution of stars in the Milky Way. Within the Milky Way, if a large number of stars are counted by spectral class, 73% are class M stars which contain only 30% of the Sun's mass. Considering mass and number of stars in each spectral class, the average star is 51.5% of the Sun's mass. The Sun's mass is 2×10^{30} kg. so a reasonable number for the mass of an average star in the universe is 10^{30} kg. Thus, the mass of all stars equals the number of stars (10^{22}) times an average mass of star (10^{30} kg) or 10^{52} kg. The next calculation adjusts for Interstellar Medium (ISM) and Intergalactic Medium (IGM). ISM is material between stars: gas (mostly hydrogen) and dust. IGM is material between galaxies, mostly hydrogen. Ordinary matter (protons, neutrons and electrons) exists in ISM and IGM as well as in stars. In the reference, "The Cosmic Energy Inventory“, the percentage of each part is defined: stars - 5.9%, Interstellar Medium (ISM) - 1.7%, and Intergalactic Medium (IGM) - 92.4%. Thus, to extrapolate the mass of the universe from the star mass, divide the 10^{55} kg mass calculated for stars by 5.9%. The result is 1.7×10^{53} kg for all the ordinary matter.

Estimates based on steady-state universe

Sir Fred Hoyle calculated the mass of an observable steady-state universe using the formula:

$$\frac{4}{3}\pi\rho\left(\frac{c}{H}\right)^3$$

which can also be stated as [26]

$$\frac{c^3}{2GH}$$

Here H = Hubble constant, ρ = Hoyle's value for the density, G = gravitational constant and c = speed of light. This calculation yields approximately 0.92×10^{53} kg; however, this represents **all** energy/matter and is based on the Hubble volume, which is the volume of a sphere with radius equal to the Hubble length or about 13.7 billion light years. The critical density calculation above was based on the comoving distance 46.6 billion light years radius. Thus, the Hoyle equation mass/energy result must be adjusted for increased volume. The comoving distance (radius) gives a volume about 39 times greater (46.7 cubed divided by 13.7 cubed). However, as volume increases, ordinary matter and dark matter would not increase, only dark energy increases with volume. Thus, assuming ordinary matter and dark matter at 27.9% of the total mass/energy and other 72.1% for dark energy, the amount of total mass/energy for the steady-state calculation would be: mass of ordinary matter and dark matter (27.9% times 0.92×10^{53} kg) plus the mass of dark energy ((72.1% times 0.92×10^{53} kg) times increased volume (39)). This equals: 2.61×10^{54} kg . As noted above in the "Estimating based on critical density", ordinary matter is 4.8% of all energy/matter. If the Hoyle result is multiplied by this percent, the result for ordinary matter is 1.25×10^{53} kg.

In summary, the three independent calculations produced reasonably close results: 1.46×10^{53} kg, 1.7×10^{53} kg, and 1.25×10^{53} kg. The average is 1.47×10^{53} kg. The key assumptions using the Extrapolation from Star Mass method were number of stars (10^{22}) and percent of ordinary matter in stars (5.9%). The key assumptions using Critical Density were comoving distance of universe (46.6 billion light years) and percent of ordinary matter in all matter

(4.8%). The Hoyle steady-state method assumed the comoving distance and a percent of dark energy (72.1%). Both Critical Density and the Hoyle steady-state equation also used the Hubble constant (67.15 km/s/Mpc).

Matter content - number of atoms

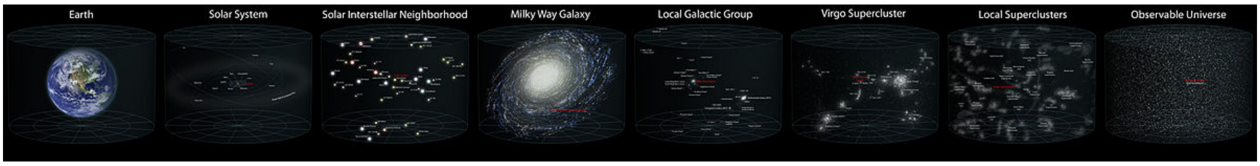
Assuming the mass of ordinary matter is about 1.47×10^{53} kg (reference previous section) and assuming all atoms are hydrogen atoms (which in reality make up about 74% of all atoms in our galaxy by mass, see Abundance of the chemical elements), calculating the total number of atoms in the universe is straight forward. Divide the mass of ordinary matter by the mass of a hydrogen atom (1.47×10^{53} kg divided by 1.67×10^{-27} kg). The result is approximately 10^{80} hydrogen atoms.

Most distant objects

The most distant astronomical object yet announced as of January 2011 is a galaxy candidate classified UDFj-39546284. In 2009, a gamma ray burst, GRB 090423, was found to have a redshift of 8.2, which indicates that the collapsing star that caused it exploded when the universe was only 630 million years old.[27] The burst happened approximately 13 billion years ago,[28] so a distance of about 13 billion light years was widely quoted in the media (or sometimes a more precise figure of 13.035 billion light years), though this would be the "light travel distance" (*see* Distance measures (cosmology)) rather than the "proper distance" used in both Hubble's law and in defining the size of the observable universe (cosmologist Ned Wright argues against the common use of light travel distance in astronomical press releases on this page [29], and at the bottom of the page offers online calculators that can be used to calculate the current proper distance to a distant object in a flat universe based on either the redshift z or the light travel time). The proper distance for a redshift of 8.2 would be about 9.2 Gpc, or about 30 billion light years. Another record-holder for most distant object is a galaxy observed through and located beyond Abell 2218, also with a light travel distance of approximately 13 billion light years from Earth, with observations from the Hubble telescope indicating a redshift between 6.6 and 7.1, and observations from Keck telescopes indicating a redshift towards the upper end of this range, around 7.[30] The galaxy's light now observable on Earth would have begun to emanate from its source about 750 million years after the Big Bang.[31]

Horizons

The limit of observability in our universe is set by a set of cosmological horizons which limit, based on various physical constraints, the extent to which we can obtain information about various events in the universe. The most famous horizon is the particle horizon which sets a limit on the precise distance that can be seen due to the finite age of the Universe. Additional horizons are associated with the possible future extent of observations (larger than the particle horizon owing to the expansion of space), an "optical horizon" at the surface of last scattering, and associated horizons with the surface of last scattering for neutrinos and gravitational waves.



A diagram of our location in the observable universe. (*Click here for an alternate image.*)

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[3] Using Tiny Particles To Answer Giant Questions (http://www.npr.org/templates/story/story.php?storyId=102715275). Science Friday, 3 Apr 2009. According to the transcript (http://www.npr.org/templates/transcript/transcript.php?storyId=102715275), Brian Greene makes the comment "And actually, in the far future, everything we now see, except for our local galaxy and a region of galaxies will have disappeared. The entire universe will disappear before our very eyes, and it's one of my arguments for actually funding cosmology. We've got to do it while we have a chance."

[4] See also Faster than light#Universal expansion and Future of an expanding universe#Galaxies outside the Local Supercluster are no longer detectable.

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External links

- Calculating the total mass of ordinary matter in the universe, what you always wanted to know (http://www.youtube.com/watch?v=K8V8Iy9Tozk)
- "Millennium Simulation" of structure forming (http://www.mpa-garching.mpg.de/galform/millennium/) Max Planck Institute of Astrophysics, Garching, Germany
- Visualisations of large-scale structure: animated spins of groups, clusters, filaments and voids (http://www.physics.usyd.edu.au/sifa/MSPM/An), identified in SDSS data by MSPM (Sydney Institute for Astronomy)
- The Sloan Great Wall: Largest Known Structure? (http://apod.nasa.gov/apod/ap071107.html) on APOD (http://apod.nasa.gov)
- Cosmology FAQ (http://www.astro.ucla.edu/~wright/cosmology_faq.html)
- Forming Galaxies Captured In The Young Universe By Hubble, VLT & Spitzer (http://www.sciencedaily.com/releases/2007/04/070419125240.htm)
- NASA featured Images and Galleries (http://www.nasa.gov/multimedia/imagegallery)
- Star Survey reaches 70 sextillion (http://www.cnn.com/2003/TECH/space/07/22/stars.survey/)
- Animation of the cosmic light horizon (http://www.phys.ksu.edu/personal/gahs/phys191/horizon.html)
- Inflation and the Cosmic Microwave Background by Charles Lineweaver (http://arxiv.org/abs/astro-ph/0305179)
- Logarithmic Maps of the Universe (http://www.astro.princeton.edu/~mjuric/universe/)
- List of publications of the 2dF Galaxy Redshift Survey (http://www.mso.anu.edu.au/2dFGRS/)
- List of publications of the 6dF Galaxy Redshift and peculiar velocity survey (http://www.aao.gov.au/local/www/6df/Publications/index.html)
- The Universe Within 14 Billion Light Years—NASA Atlas of the Universe (note—this map only gives a rough cosmographical estimate of the expected distribution of superclusters within the observable universe; very little actual mapping has been done beyond a distance of one billion light years): (http://www.atlasoftheuniverse.com/universe.html)
- Video: "The Known Universe", from the American Museum of Natural History (http://www.youtube.com/watch?v=17jymDn0W6U)
- NASA/IPAC Extragalactic Database (http://ned.ipac.caltech.edu/)

- Cosmography of the Local Universe (http://irfu.cea.fr/cosmography) at irfu.cea.fr (17:35) (arXiv (http://arxiv.org/abs/1306.0091))

Structure formation

Structure formation refers to a largely unsolved, but extensively researched problem in physical cosmology. The Universe, as is now known from observations of the cosmic microwave background radiation, began in a hot, dense, nearly uniform state approximately 13.8 billion years ago. However, looking in the sky today, we see structures on all scales, from stars and planets to galaxies and, on much larger scales still, galaxy clusters, and enormous voids between galaxies. How did all of this come about from the nearly uniform early Universe?

Overview

Under present models, the structure of the visible universe was formed in the following stages:

- **The very early Universe**
  In this stage, some mechanism, such as cosmic inflation, is responsible for establishing the initial conditions of the Universe: homogeneity, isotropy and flatness. Cosmic inflation also would have amplified minute quantum fluctuations (pre-inflation) into slight overdensities (post-inflation). These acted as seeds around which the dark matter could begin to gravitationally congregate, even as the normal, baryonic matter was still in thermal equilibrium — far too hot to allow gravity to get any purchase on it.
- **The primordial plasma**
  The Universe is dominated by radiation for most of this stage, and due to the intense heat and radiation, the helium nuclei fused in the first few minutes, along with the remaining hydrogen nuclei (essentially protons), cannot capture and hold onto an electron before the radiation blasts it away. The Universe is very hot, dense, but expanding rapidly, and therefore cooling. In this hot, dense situation, the radiation (photons) cannot travel far before interacting with one of these charged particles. Finally, at about 400,000 years after the 'bang', it's cool enough for the nuclei to capture their electrons, forming neutral-charge atoms. As the charged particles pair up, the photons no longer interact with them, they are free to propagate, and we currently detect those photons as the Cosmic Microwave Background Radiation (CMB), because they fill the Universe. After remarkable space-based missions, we have detected very slight variations in the density or temperature in the CMB, otherwise it is nearly the same in every direction. These variations were essentially early "seeds" upon which subsequent structure formed.

From there, the theory is one of hierarchical structure formation: the smaller gravitationally bound structures such as matter peaks containing the first stars and stellar clusters form first, which subsequently merge to form galaxies, followed by groups, clusters and superclusters of galaxies.

Very early Universe

The very early Universe is still a poorly understood epoch, from the viewpoint of fundamental physics. The prevailing theory, cosmic inflation, does a good job explaining the observed flatness, homogeneity and isotropy of the Universe, as well as the absence of exotic relic particles (such as magnetic monopoles). In addition, it has made a crucial prediction that has been borne out by observation: that the primordial Universe would have tiny perturbations which seed the formation of structure in the later Universe. These fluctuations, while they form the foundation for all structure in the Universe, appear most clearly as tiny temperature fluctuations at one part in 100,000. (To put this in perspective, the same level of fluctuations on a topographic map of the United States would show no feature higher than a few centimeters high.) These fluctuations are critical, because they provide the seeds from which the largest structures within the Universe can grow and eventually collapse to form galaxies and stars. COBE (Cosmic

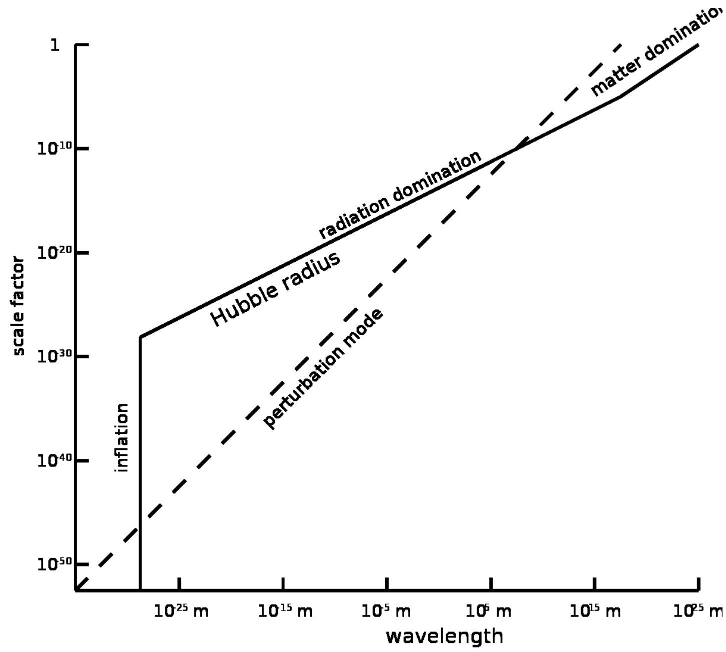
Background Explorer) provided the first detection of the intrinsic fluctuations in the cosmic microwave background radiation in the 1990s.

These perturbations are thought to have a very specific character: they form a Gaussian random field whose covariance function is diagonal and nearly scale-invariant. The observed fluctuations appear to have exactly this form, and in addition the *spectral index* measured by WMAP — the spectral index measures the deviation from a scale-invariant (or Harrison-Zel'dovich) spectrum — is very nearly the value predicted by the simplest and most robust models of inflation. Another important property of the primordial perturbations, that they are adiabatic (or isentropic between the various kinds of matter that compose the Universe), is predicted by cosmic inflation and has been confirmed by observations.

Other theories of the very early Universe, which are claimed to make very similar predictions, have been proposed, such as the brane gas cosmology, cyclic model, pre-big bang model and holographic universe, but they remain in their nascency and are not as widely accepted. Some theories, such as cosmic strings, have largely been refuted by increasingly precise data.

The horizon problem

An extremely important concept in the theory of structure formation is the notion of the Hubble radius, often called simply the *horizon* as it is closely related to the particle horizon. The Hubble radius, which is related to the Hubble parameter H as $R = c/H$, where c is the speed of light, defines, roughly speaking, the volume of the nearby universe that has recently (in the last expansion time) been in causal contact with an observer. Since the Universe is continually expanding, its energy density is continually decreasing (in the absence of truly exotic matter such as phantom energy). The Friedmann equation relates the energy density of the Universe to the Hubble parameter, and shows that the Hubble radius is continually increasing.



The physical size of the Hubble radius (solid line) as a function of the scale factor of the Universe. The physical wavelength of a perturbation mode (dashed line) is shown as well. The plot illustrates how the perturbation mode exits the horizon during cosmic inflation in order to reenter during radiation domination. If cosmic inflation never happened, and radiation domination continued back until a gravitational singularity, then the mode would never have exited the horizon in the very early Universe.

The horizon problem of the big bang cosmology says that, without inflation, perturbations were never in causal contact before they entered the horizon and thus the homogeneity and isotropy of, for example, the large scale galaxy distributions cannot be explained. This is because, in an ordinary Friedmann-Lemaitre-Robertson-Walker cosmology, the Hubble radius increases more rapidly than space expands, so perturbations are only ever entering the Hubble radius, and they are not being pushed out by the expansion of space. This paradox is resolved by cosmic inflation, which suggests that there was a phase of very rapid expansion in the early Universe in which the Hubble radius was very nearly constant. Thus, the large scale isotropy that we see today is due to quantum fluctuations produced during cosmic inflation being pushed outside the horizon.

Primordial plasma

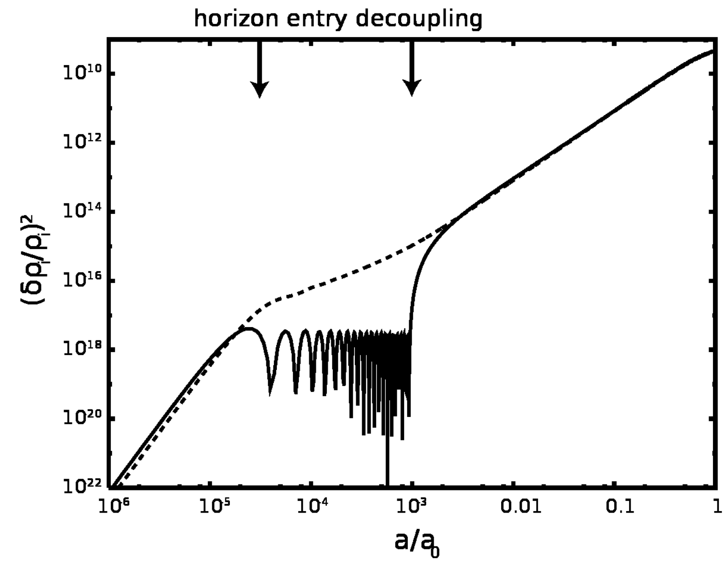
The end of inflation is called reheating, when the inflation particles decay into a hot, thermal plasma of other particles. In this epoch, the energy content of the Universe is entirely radiation, with standard model particles having relativistic velocities. As the plasma cools, baryogenesis and leptogenesis are thought to occur, as the quark-gluon plasma cools, electroweak symmetry breaking occurs and the Universe becomes principally composed of ordinary protons, neutrons and electrons. As the Universe cools further, big bang nucleosynthesis occurs and small quantities of deuterium, helium and lithium nuclei are created. As the Universe cools and expands, the energy in photons begins to redshift away, particles become non-relativistic and ordinary matter begins to dominate the Universe. Eventually, atoms begin to form as free electrons bind to nuclei. This suppresses Thompson scattering of photons. Combined with the rarefaction of the Universe (and consequent increase in the mean free path of photons), this makes the Universe transparent and the cosmic microwave background is emitted at recombination (the *surface of last scattering*).

Acoustic oscillations

The primordial plasma would have had very slight overdensities of matter, thought to have derived from the enlargement of quantum fluctuations during inflation. Whatever the source, these overdensities gravitationally attract matter. But the intense heat of the near constant photon-matter interactions of this epoch rather forcefully seeks thermal equilibrium, which creates a large amount of outward pressure. These counteracting forces of gravity and pressure create oscillations, analogous to sound waves created in air by pressure differences.

These perturbations are important, as they are responsible for the subtle physics that result in the cosmic microwave background anisotropy. In this epoch, the amplitude of perturbations that enter the horizon oscillate sinusoidally, with dense regions becoming more rarefied and then becoming dense again, with a frequency which is related to the size of the perturbation. If the perturbation oscillates an integral or half-integral number of times between coming into the horizon and recombination, it appears as an acoustic peak of the cosmic microwave background anisotropy. (A half-oscillation, in which a dense region becomes a rarefied region or vice-versa, appears as a peak because the anisotropy is displayed as a *power spectrum*, so underdensities contribute to the power just as much as overdensities.) The physics that determines the detailed peak structure of the microwave background is complicated, but these oscillations provide the essence.[1]

Linear structure



Evolution of two perturbations to the ΛCDM homogeneous big bang model. Between entering the horizon and decoupling, the dark matter perturbation (dashed line) grows logarithmically, before the growth accelerates in matter domination. On the other hand, between entering the horizon and decoupling, the perturbation in the baryon-photon fluid (solid line) oscillates rapidly. After decoupling, it grows rapidly to match the dominant matter perturbation, the dark matter mode.

One of the key realizations made by cosmologists in the 1970s and 1980s was that the majority of the matter content of the Universe was composed not of atoms, but rather a mysterious form of matter known as dark matter. Dark matter interacts through the force of gravity, but it is not composed of baryons and it is known with very high accuracy that it does not emit or absorb radiation. It may be composed of particles that interact through the weak interaction, such as neutrinos, but it cannot be composed entirely of the three known kinds of neutrinos (although some have suggested it is a sterile neutrino). Recent evidence suggests that there is about five times as much dark matter as baryonic matter, and thus the dynamics of the Universe in this epoch are dominated by dark matter.

Dark matter plays a key role in structure formation because it feels only the force of gravity: the gravitational Jeans instability which allows compact structures to form is not opposed by any force, such as radiation pressure. As a result, dark matter begins to collapse into a complex network of dark matter halos well before ordinary matter, which is impeded by pressure forces. Without dark matter, the epoch of galaxy formation would occur substantially later in the Universe than is observed.

The physics of structure formation in this epoch is particularly simple, as dark matter perturbations with different wavelengths evolve independently. As the Hubble radius grows in the expanding Universe, it encompasses larger and larger perturbations. During matter domination, all causal dark matter perturbations grow through gravitational clustering. However, the shorter-wavelength perturbations that are encompassed during radiation domination have their growth retarded until matter domination. At this stage, luminous, baryonic matter is expected to simply mirror the evolution of the dark matter, and their distributions should closely trace one another.

It is a simple matter to calculate this "linear power spectrum" and, as a tool for cosmology, it is of comparable importance to the cosmic microwave background. The power spectrum has been measured by galaxy surveys, such as the Sloan Digital Sky Survey, and by surveys of the Lyman-α forest. Since these surveys observe radiation emitted from galaxies and quasars, they do not directly measure the dark matter, but the large scale distribution of galaxies (and of absorption lines in the Lyman-α forest) is expected to closely mirror the distribution of dark matter. This depends on the fact that galaxies will be larger and more numerous in denser parts of the Universe, whereas they will be comparatively scarce in rarefied regions.

Nonlinear structure

When the perturbations have grown sufficiently, a small region might become substantially denser than the mean density of the Universe. At this point, the physics involved becomes substantially more complicated. When the deviations from homogeneity are small, the dark matter may be treated as a pressureless fluid and evolves by very simple equations. In regions which are significantly denser than the background, the full Newtonian theory of gravity must be included. (The Newtonian theory is appropriate because the masses involved are much less than those required to form a black hole, and the speed of gravity may be ignored as the light-crossing time for the structure is still smaller than the characteristic dynamical time.) One sign that the linear and fluid approximations become invalid is that dark matter starts to form caustics in which the trajectories of adjacent particles cross, or particles start to form orbits. These dynamics are generally best understood using *N*-body simulations (although a variety of semi-analytic schemes, such as the Press-Schechter formalism, can be used in some cases). While in principle these simulations are quite simple, in practice they are very difficult to implement, as they require simulating millions or even billions of particles. Moreover, despite the large number of particles, each particle typically weighs 10^9 solar masses and discretization effects may become significant. The largest such simulation as of 2005 is the Millennium simulation.

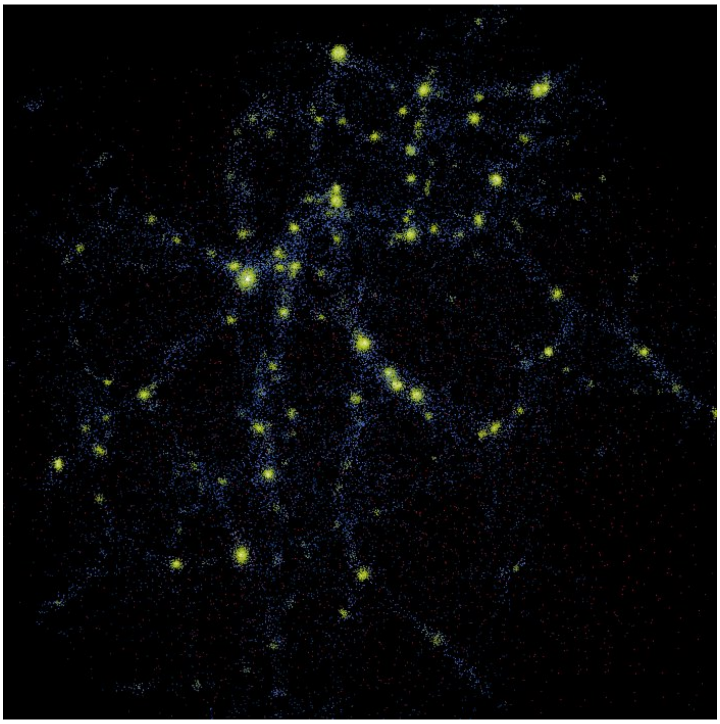
The result of *N*-body simulations suggests that the Universe is composed largely of voids, whose densities might be as low as one tenth the cosmological mean. The matter condenses in large filaments and haloes which have an intricate web-like structure. These form galaxy groups, clusters and superclusters. While the simulations appear to agree broadly with observations, their interpretation is complicated by the understanding of how dense accumulations of dark matter spur galaxy formation. In particular, many more small haloes form than we see in astronomical observations as dwarf galaxies and globular clusters. This is known as the galaxy bias problem, and a variety of explanations have been proposed. Most account for it as an effect in the complicated physics of galaxy formation, but some have suggested that it is a problem with our model of dark matter and that some effect, such as warm dark matter, prevents the formation of the smallest haloes.

Gastrophysical evolution

The final stage in evolution comes when baryons condense in the centres of galaxy haloes to form galaxies, stars and quasars. A paradoxical aspect of structure formation is that while dark matter greatly accelerates the formation of dense haloes, because dark matter does not have radiation pressure, the formation of smaller structures from dark matter is impossible because dark matter cannot dissipate angular momentum, whereas ordinary baryonic matter can collapse to form dense objects by dissipating angular momentum through radiative cooling. Understanding these processes is an enormously difficult computational problem, because they can involve the physics of gravity, magnetohydrodynamics, atomic physics, nuclear reactions, turbulence and even general relativity. In most cases, it is not yet possible to perform simulations that can be compared quantitatively with observations, and the best that can be achieved are approximate simulations that illustrate the main qualitative features of a process such as star formation.

Modelling structure formation

Cosmological perturbations


Snapshot from a computer simulation of large scale structure formation in a Lambda-CDM universe.

Much of the difficulty, and many of the disputes, in understanding the large-scale structure of the Universe can be resolved by better understanding the choice of gauge in general relativity. By the scalar-vector-tensor decomposition, the metric includes four scalar perturbations, two vector perturbations, and one tensor perturbation. Only the scalar perturbations are significant: the vectors are exponentially suppressed in the early Universe, and the tensor mode makes only a small (but important) contribution in the form of primordial gravitational radiation and the B-modes of the cosmic microwave background polarization. Two of the four scalar modes may be removed by a physically meaningless coordinate transformation. Which modes are eliminated determine the infinite number of possible gauge fixings. The most popular gauge is Newtonian gauge (and the closely related conformal Newtonian gauge), in which the retained scalars are the Newtonian potentials Φ and Ψ, which correspond exactly to the Newtonian potential energy from Newtonian gravity. Many other gauges are used, including synchronous gauge, which can be an efficient gauge for numerical computation (it is used by CMBFAST). Each gauge still includes some unphysical degrees of freedom. There is a so-called gauge-invariant formalism, in which only gauge invariant combinations of variables are considered.

Inflation and initial conditions

The initial conditions for the Universe are thought to arise from the scale invariant quantum mechanical fluctuations of cosmic inflation. The perturbation of the background energy density at a given point $\rho(\mathbf{x}, t)$ in space is then given by an isotropic, homogeneous Gaussian random field of mean zero. This means that the spatial Fourier transform of $\rho - \hat{\rho}(\mathbf{k}, t)$ has the following correlation functions

$$\langle \hat{\rho}(\mathbf{k}, t) \hat{\rho}(\mathbf{k}', t) \rangle = f(k) \delta^{(3)}(\mathbf{k} - \mathbf{k}'),$$

where $\delta^{(3)}$ is the three dimensional Dirac delta function and $k = |\mathbf{k}|$ is the length of $\mathbf{k}$. Moreover, the spectrum predicted by inflation is nearly scale invariant, which means

$$\langle \hat{\rho}(\mathbf{k}, t) \hat{\rho}(\mathbf{k}', t) \rangle = k^{n_s - 1} \delta^{(3)}(\mathbf{k} - \mathbf{k}'),$$

where $n_s - 1$ is a small number. Finally, the initial conditions are adiabatic or isentropic, which means that the fractional perturbation in the entropy of each species of particle is equal.

References

[1] R. A. Sunyaev, "Fluctuations of the microwave background radiation," in *Large Scale Structure of the Universe* ed. M. S. Longair and J. Einasto, 393. Dordrecht: Reidel 1978.

Galaxy formation and evolution

The study of **galaxy formation and evolution** is concerned with the processes that formed a heterogeneous universe from a homogeneous beginning, the formation of the first galaxies, the way galaxies change over time, and the processes that have generated the variety of structures observed in nearby galaxies. It is one of the most active research areas in astrophysics.

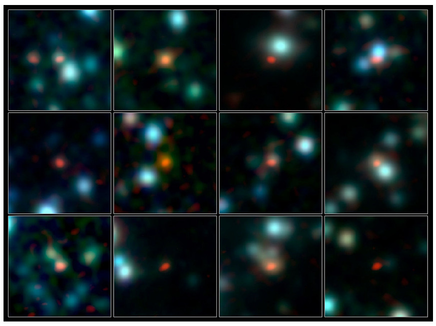
Galaxy formation is hypothesized to occur, from structure formation theories, as a result of tiny quantum fluctuations in the aftermath of the Big Bang. The simplest model for this that is in general agreement with observed phenomena is the ΛCold Dark Matter cosmology; that is to say that clustering and merging is how galaxies gain in mass, and can also determine their shape and structure.

Formation of the first galaxies

After the Big Bang, the universe, for a time, was remarkably homogeneous, as can be observed in the Cosmic Microwave Background or CMB (the fluctuations of which are less than one part in one hundred thousand). There was little-to-no structure in the universe, and thus no galaxies. Therefore we must ask how the smoothly distributed universe of the CMB became the clumpy universe we see today.

The most accepted theory of how these structures came to be is that all the large-scale structure of the cosmos we observe today was formed as a consequence of the growth of the primordial fluctuations, which are small changes in the density of the universe in a confined region. As the universe cooled clumps of dark matter began to condense, and within them gas began to condense. The primordial fluctuations gravitationally attracted gas and dark matter to the denser areas, and thus the seeds that would later become galaxies were formed. These structures constituted the first galaxies. At this point the universe was almost exclusively composed of hydrogen, helium, and dark matter. Soon after the first proto-galaxies formed, the hydrogen and helium gas within them began to condense and make the first stars. Thus the first galaxies were then formed. In 2007, using the Keck telescope, a team from California Institute of Technology found six star forming galaxies about 13.2 billion light years (light travel distance) away and therefore created when the universe was only 500 million years old.[1] The discovery of a galaxy more than 13 billion years old, which existed only 480 million years after the Big Bang, was reported in January 2011.

The universe was very violent in its early epochs, and galaxies grew quickly, evolving by accretion of smaller mass galaxies. The result of this process is left imprinted on the distribution of galaxies in the nearby universe (see image of 2dF Galaxy Redshift Survey). Galaxies are not isolated objects in space; rather, galaxies are distributed in a great cosmic web of filaments throughout the universe. The locations where the filaments meet are dense clusters of galaxies that began as small fluctuations in the early universe. Hence the distribution of galaxies is closely related to the physics of the early universe.



Over 100 of the most fertile star-forming galaxies in the early Universe pinpointed by ALMA.

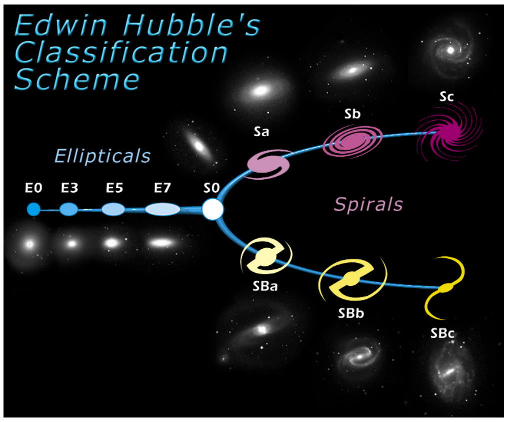
Despite its many successes, this picture is not sufficient to explain the variety of structure we see in galaxies. Galaxies come in a variety of shapes, from round, featureless elliptical galaxies to the pancake-flat spiral galaxies.

Commonly observed properties of galaxies

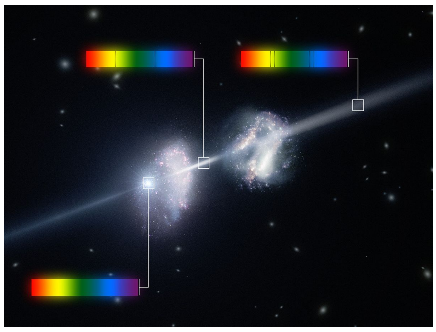
Some notable observed features of galaxy structure (including our own Milky Way) that astronomers wish to explain with galactic formation theories, include (but are certainly not limited to) the following:

- Spiral galaxies and the galactic disk are quite thin, dense, and rotate relatively fast. (Our Milky Way galaxy is believed to be a barred spiral.)
- The majority of mass in galaxies is made up of dark matter, a substance which is not directly observable, and might not interact through any means except gravity.
- Halo stars are typically much older and have much lower metallicities (that is to say, they are almost exclusively composed of hydrogen and helium) than disk stars.
- Many disk galaxies have a puffed up outer disk (often called the "thick disk") that is composed of old stars.
- Globular clusters are typically old and metal-poor as well, but there are a few that are not nearly as metal-poor as most, and/or have some younger stars.
- High velocity clouds, clouds of neutral hydrogen are "raining" down on the galaxy, and presumably have been from the beginning (this would be the necessary source of a gas disk from which the disk stars formed).
- Galaxies come in a great variety of shapes and sizes (see the Hubble Sequence), from giant, featureless blobs of old stars (called elliptical galaxies) to thin disks with gas and stars arranged in highly-ordered spirals.
- The majority of giant galaxies contain a supermassive black hole in their centers, ranging in mass from millions to billions of times the mass of our Sun. The black hole mass is tied to properties of its host galaxy.
- Many of the properties of galaxies (including the galaxy color-magnitude diagram) indicate that there are fundamentally two types of galaxies. These groups divide into blue star-forming galaxies that are more like spiral types, and red nonstar forming galaxies that are more like elliptical galaxies.

NGC 891, a very thin disk galaxy.



Hubble tuning fork diagram of galaxy morphology



This artist's impression shows two galaxies in the early universe. The brilliant explosion on the left is a gamma-ray burst. As the light from the burst passes through the two galaxies on the way to Earth (outside the frame to the right), some colours are absorbed by the cool gas in the galaxies, leaving characteristic dark lines in the spectrum. Careful study of these spectra has allowed astronomers to discover that these two galaxies are remarkably rich in heavier chemical elements.

Formation of disk galaxies


An image of Messier 101 a prototypical spiral galaxy seen face-on.

The key properties of disk galaxies, which are also commonly called spiral galaxies, is that they are very thin, rotate rapidly, and often show spiral structure. One of the main challenges to galaxy formation is the great number of thin disk galaxies in the local universe. The problem is that disks are very fragile, and mergers with other galaxies can quickly destroy thin disks.

Olin Eggen, Donald Lynden-Bell, and Allan Sandage in 1962, proposed a theory that disk galaxies form through a monolithic collapse of a large gas cloud. As the cloud collapses the gas settles into a rapidly rotating disk. Known as a top-down formation scenario, this theory is quite simple yet no longer widely accepted because observations of the early universe strongly suggest that objects grow from bottom-up (i.e. smaller objects merging to form larger ones). It was first proposed by Leonard Searle and Robert Zinn that galaxies form by the coalescence of smaller progenitors.


A spiral galaxy, ESO 510-G13, was warped as a result of colliding with another galaxy. After the other galaxy is completely absorbed, the distortion will disappear. The process typically takes millions if not billions of years.

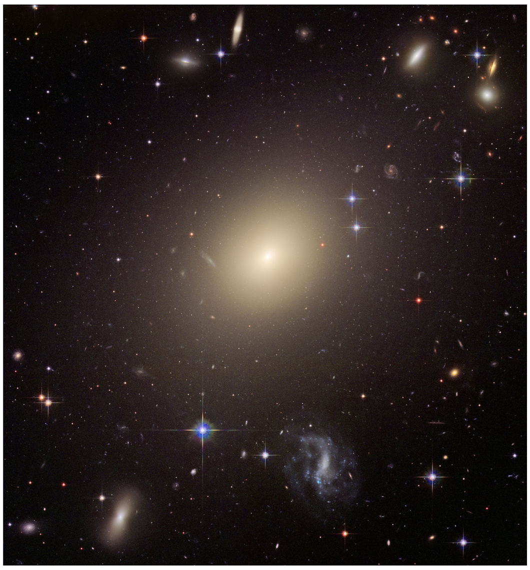
More recent theories include the clustering of dark matter halos in the bottom-up process. Essentially early on in the universe galaxies were composed mostly of gas and dark matter, and thus, there were fewer stars. As a galaxy gained mass (by accreting smaller galaxies) the dark matter stays mostly on the outer parts of the galaxy. This is because the dark matter can only interact gravitationally, and thus will not dissipate. The gas, however, can quickly contract, and as it does so it rotates faster, until the final result is a very thin, very rapidly rotating disk.

Astronomers do not currently know what process stops the contraction. In fact, theories of disk galaxy formation are not successful at producing the rotation speed and size of disk galaxies. It has been suggested that the radiation from bright newly formed stars, or from an active galactic nuclei can slow the contraction of a forming disk. It has also been suggested that the dark matter halo can pull the galaxy, thus stopping disk contraction.

In recent years, a great deal of focus has been put on understanding merger events in the evolution of galaxies. Our own galaxy (the Milky Way) has a tiny satellite galaxy (the Sagittarius Dwarf Elliptical Galaxy) which is currently gradually being ripped up and "eaten" by the Milky Way. It is thought these kinds of events may be quite common in the evolution of large galaxies. The Sagittarius dwarf galaxy is orbiting our galaxy at almost a right angle to the disk. It is currently passing through the disk; stars are being stripped off of it with each pass and joining the halo of our galaxy. There are other examples of these minor accretion events, and it is likely a continual process for many galaxies. Such mergers provide "new" gas, stars, and dark matter to galaxies. Evidence for this process is often observable as warps or streams coming out of galaxies.

The Lambda-CDM model of galaxy formation underestimates the number of thin disk galaxies in the universe. The reason is that these galaxy formation models predict a large number of mergers. If disk galaxies merge with another galaxy of comparable mass (at least 15 percent of its mass) the merger will likely destroy, or at a minimum greatly disrupt the disk, yet the resulting galaxy is not expected to be a disk galaxy. While this remains an unsolved problem for astronomers, it does not necessarily mean that the Lambda-CDM model is completely wrong, but rather that it requires further refinement to accurately reproduce the population of galaxies in the universe.

Galaxy mergers and the formation of elliptical galaxies



ESO 325-G004, a typical elliptical galaxy.

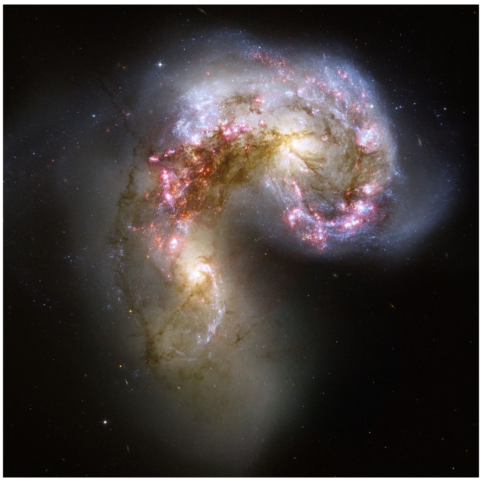
An image of NGC 4676 (also called the Mice Galaxies) is an example of a present merger.

The most massive galaxies in the sky are giant elliptical galaxies. Their stars are on orbits that are randomly oriented within the galaxy (i.e. they are not rotating like disk galaxies). They are composed of old stars and have little to no dust. All elliptical galaxies probed so far have supermassive black holes in their center, and the mass of these black holes is correlated with the mass of the elliptical galaxy. They are also correlated to a property called sigma which is the speed of the stars at the far edge of the elliptical galaxies. Elliptical galaxies do not have disks around them, although some bulges of disk galaxies look similar to elliptical galaxies. One is more likely to find elliptical galaxies in more crowded regions of the universe (such as galaxy clusters).

Astronomers now see elliptical galaxies as some of the most evolved systems in the universe. It is widely accepted that the main driving force for the evolution of elliptical galaxies is mergers of smaller galaxies. These mergers can be extremely violent; galaxies often collide at speeds of 500 kilometers per second.

Many galaxies in the universe are gravitationally bound to other galaxies, that is to say they will never escape the pull of the other galaxy. If the galaxies are of similar size, the resultant galaxy will appear similar to neither of the two galaxies merging,[2] but would instead be an elliptical galaxy. An image of an ongoing merger of equal sized disk galaxies is shown left.

In the Local Group, the Milky Way and M31 (the Andromeda Galaxy) are gravitationally bound, and currently approaching each other at high speed. If the two galaxies do meet they will pass through each other, with gravity distorting both galaxies severely and ejecting some gas, dust and stars into intergalactic space. They will travel apart, slow down, and then again be drawn towards each other, and again collide. Eventually both galaxies will have merged completely, streams of gas and dust will be flying through the space near the newly formed giant elliptical galaxy. M31 is actually already distorted: the edges are warped. This is probably because of interactions with its own galactic companions, as well as possible mergers with dwarf spheroidal galaxies in the recent past - the remnants of which are still visible in the disk populations.



The Antennae Galaxies are a dramatic pair of colliding galaxies. In such a collision, the stars within each galaxy will pass by each other (virtually) without incident. This is due to the relatively large interstellar distances compared to the relatively small size of an individual star. Diffuse gas clouds, however, readily collide to produce shocks which in turn stimulate bursts of star formation. The bright, blue knots indicate the hot, young stars that have recently ignited as a result of the merger.

In our epoch, large concentrations of galaxies (clusters and superclusters) are still assembling.

While scientists have learned a great deal about ours and other galaxies, the most fundamental questions about formation and evolution remain only tentatively answered.

References

[1] "New Scientist" 14th July 2007
[2] Barnes,J. Nature, vol. 338, March 9, 1989, p. 123-126

External links

- NOAO gallery of galaxy images (http://www.noao.edu/image_gallery/galaxies.html)
  - Image of Andromeda galaxy (M31) (http://www.noao.edu/image_gallery/html/im0685.html)
- Javascript passive evolution calculator (http://www.astro.yale.edu/dokkum/evocalc/) for early type (elliptical) galaxies
- Video on the evolution of galaxies by Canadian astrophysicist Doctor P (http://spacegeek.org/ep4_flash.shtml)

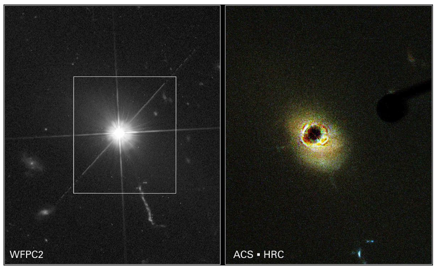
Quasar

Artist's rendering of ULAS J1120+0641, a very distant quasar powered by a black hole with a mass two billion times that of the Sun. Credit: ESO/M. Kornmesser

A **quasi-stellar radio source** (**"quasar"**, /ˈkweɪzɑr/) is a very energetic and distant active galactic nucleus. Quasars are extremely luminous and were first identified as being high redshift sources of electromagnetic energy, including radio waves and visible light, that were point-like, similar to stars, rather than extended sources similar to galaxies.

While the nature of these objects was controversial until the early 1980s, there is now a scientific consensus that a quasar is a compact region in the center of a massive galaxy, that surrounds its central supermassive black hole[*citation needed*]. Its size is 10–10,000 times the Schwarzschild radius of the black hole. The quasar is powered by an accretion disc around the black hole.

Overview



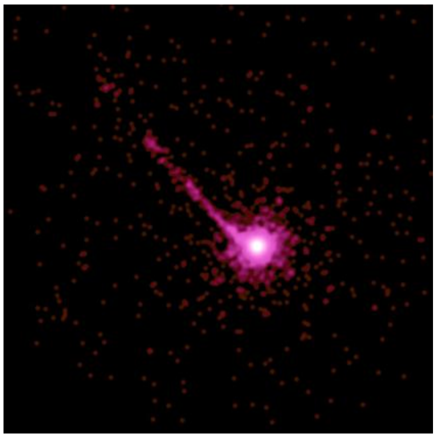
A Hubble picture showing a quasar core

Quasars show a very high redshift, which is an effect of the expansion of the universe between the quasar and the Earth. When combined with Hubble's law, the implication of the redshift is that the quasars are very distant—and thus, it follows, very ancient objects. They tend to inhabit the very centers of active, young galaxies, and are among the most luminous, powerful, and energetic objects known in the universe, emitting up to a thousand times the energy output of the Milky Way, which contains 200–400 billion stars. This radiation is emitted across the spectrum, almost equally, from X-rays to the far-infrared with a peak in the ultraviolet-optical bands, with some quasars also being strong sources of radio emission and of gamma-rays. In early optical images, quasars looked like single points of light (i.e., point sources), indistinguishable from stars, except for their peculiar spectra. With infrared telescopes and the Hubble Space Telescope, the "host galaxies" surrounding the quasars have been identified in some cases.[1] These galaxies are normally too dim to be seen against the glare of the quasar, except with special techniques. Most quasars cannot be seen with small telescopes, but 3C 273, with an average apparent magnitude of 12.9, is an exception. At a distance of 2.44 billion light-years, it is one of the most distant objects directly observable with amateur equipment.

Some quasars display changes in luminosity which are rapid in the optical range and even more rapid in the X-rays. Because these changes occur very rapidly they define an upper limit on the volume of a quasar; quasars are not much larger than the Solar System. This implies an astonishingly high energy density. The mechanism of brightness changes probably involves relativistic beaming of jets pointed nearly directly toward us. The highest redshift quasar known (as of June 2011[2]) is ULAS J1120+0641, with a redshift of 7.085, which corresponds to a proper distance of approximately 29 billion light-years from Earth (see more discussion of how cosmological distances can be greater than the light-travel time at Metric Expansion of Space).

Quasars are believed to be powered by accretion of material into supermassive black holes in the nuclei of distant galaxies, making these luminous versions of the general class of objects known as active galaxies. Since light cannot escape the super massive black holes that are at the center of quasars, the escaping energy is actually generated outside the event horizon by gravitational stresses and immense friction on the incoming material. Large central masses (10^6 to 10^9 Solar masses) have been measured in quasars using reverberation mapping. Several dozen nearby large galaxies, with no sign of a quasar nucleus, have been shown to contain a similar central black hole in their nuclei, so it is thought that all large galaxies have one, but only a small fraction emit powerful radiation and so are seen as quasars. The matter accreting onto the black hole is unlikely to fall directly in, but will have some angular momentum around the black hole that will cause the matter to collect in an accretion disc. Quasars may also be ignited or re-ignited from normal galaxies when they merge and the black hole is infused with a fresh source of matter. In fact, it has been suggested that a quasar could form as the Andromeda Galaxy collides with our own Milky Way galaxy in approximately 3–5 billion years.[3][4]

Properties



The Chandra X-ray image is of the quasar PKS 1127-145, a highly luminous source of X-rays and visible light about 10 billion light years from Earth. An enormous X-ray jet extends at least a million light years from the quasar. Image is 60 arcsec on a side. RA 11h 30m 7.10s Dec -14° 49' 27" in Crater. Observation date: May 28, 2000. Instrument: ACIS.

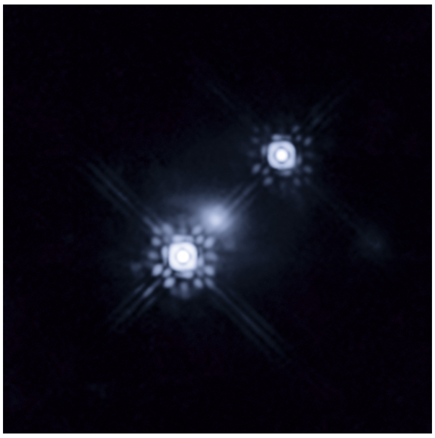
More than 200,000 quasars are known, most from the Sloan Digital Sky Survey. All observed quasar spectra have redshifts between 0.056 and 7.085. Applying Hubble's law to these redshifts, it can be shown that they are between 600 million and 28.85 billion light-years away (in terms of comoving distance). Because of the great distances to the farthest quasars and the finite velocity of light, we see them and their surrounding space as they existed in the very early universe.

Most quasars are more distant than three billion light-years. Although quasars appear faint when viewed from Earth, the fact that they are visible at all from so far is due to quasars being the most luminous objects in the known universe. The quasar that appears brightest in the sky is 3C 273 in the constellation of Virgo. It has an average apparent magnitude of 12.8 (bright enough to be seen through a medium-size amateur telescope), but it has an absolute magnitude of −26.7. From a distance of about 33 light-years, this object would shine in the sky about as brightly as our sun. This quasar's luminosity is, therefore, about 4 trillion (4×10^{12}) times that of our sun, or about 100 times that of the total light of giant galaxies like our Milky Way. However, this assumes the quasar is radiating energy in all directions. An active galactic nucleus can be associated with a powerful jet of matter and energy and is radiating preferentially in the direction of its jet. In a universe containing hundreds of billions of galaxies, most of which had active nuclei billions of years ago but only seen today, it is statistically certain that thousands of energy jets should be pointed toward us, some more directly than others. In many cases it is likely that the brighter the quasar, the more directly its jet is aimed at us.

The hyperluminous quasar APM 08279+5255 was, when discovered in 1998, given an absolute magnitude of −32.2. High resolution imaging with the Hubble Space Telescope and the 10 m Keck Telescope revealed that this system is gravitationally lensed. A study of the gravitational lensing of this system suggests that it has been magnified by a factor of ~10. It is still substantially more luminous than nearby quasars such as 3C 273.

Quasars were much more common in the early universe. This discovery by Maarten Schmidt in 1967 was early strong evidence against the Steady State cosmology of Fred Hoyle, and in favor of the Big Bang cosmology. Quasars show where massive black holes are growing rapidly (via accretion). These black holes grow in step with the mass of stars in their host galaxy in a way not understood at present. One idea is that jets, radiation and winds created by the quasars shut down the formation of new stars in the host galaxy, a process called 'feedback'. The jets that produce strong radio emission in some quasars at the centers of clusters of galaxies are known to have enough power to prevent the hot gas in these clusters from cooling and falling onto the central galaxy.

Quasars' luminosities are variable, with time scales that range from months to hours. This means that quasars generate and emit their energy from a very small region, since each part of the quasar would have to be in contact with other parts on such a time scale to allow the coordination of the luminosity variations. This would mean that a quasar varying on a time scale of a few weeks cannot be larger than a few light-weeks across. The emission of large amounts of power from a small region requires a power source far more efficient than the nuclear fusion that powers stars. The release of gravitational energy by matter falling towards a massive black hole is the only process known that can produce such high power continuously. Stellar explosions – supernovas and gamma-ray bursts – can do likewise, but only for a few weeks. Black holes were considered too exotic by some astronomers in the 1960s. They also suggested that the redshifts arose from some other (unknown) process, so that the quasars were not really so distant as the Hubble law implied. This 'redshift controversy' lasted for many years. Many lines of evidence (optical viewing of host galaxies, finding 'intervening' absorption lines, gravitational lensing) now demonstrate that the quasar redshifts are due to the Hubble expansion, and quasars are as powerful as first thought.



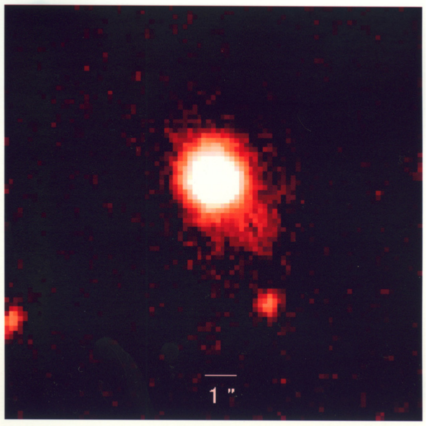
Gravitationally lensed quasar HE 1104-1805.

Quasars have all the properties as active galaxies, but are more powerful: their radiation is partially 'nonthermal' (i.e., not due to black body radiation), and approximately 10 percent are observed to also have jets and lobes like those of radio galaxies that also carry significant (but poorly understood) amounts of energy in the form of particles moving at relativistic speeds. Quasars can be detected over the entire observable electromagnetic spectrum including radio, infrared, visible light, ultraviolet, X-ray and even gamma rays. Most quasars are brightest in their rest-frame near-ultraviolet wavelength of 121.6 nm Lyman-alpha emission line of hydrogen, but due to the tremendous redshifts of these sources, that peak luminosity has been observed as far to the red as 900.0 nm, in the near infrared. A minority of quasars show strong radio emission, which originates from jets of matter moving close to the speed of light. When looked at down the jet, these appear as a blazar and often have regions that appear to move away from the center faster than the speed of light (superluminal expansion). This is an optical illusion due to the properties of special relativity.

Quasar redshifts are measured from the strong spectral lines that dominate their visible and ultraviolet spectra. These lines are brighter than the continuous spectrum, so they are called 'emission' lines. They have widths of several percent of the speed of light. These widths are due to Doppler shifts caused by the high speeds of the gas emitting the lines. Fast motions strongly indicate a large mass. Emission lines of hydrogen (mainly of the Lyman series and Balmer series), helium, carbon, magnesium, iron and oxygen are the brightest lines. The atoms emitting these lines range from neutral to highly ionized, i.e., many of the electrons are stripped off the ion, leaving it highly charged. This wide range of ionization shows that the gas is highly irradiated by the quasar, not merely hot, and not by stars, which cannot produce such a wide range of ionization.

Iron quasars show strong emission lines resulting from low ionization iron (FeII), such as IRAS 18508-7815.

Emission generation



This view, taken with infrared light, is a false-color image of a quasar-starburst tandem with the most luminous starburst ever seen in such a combination.

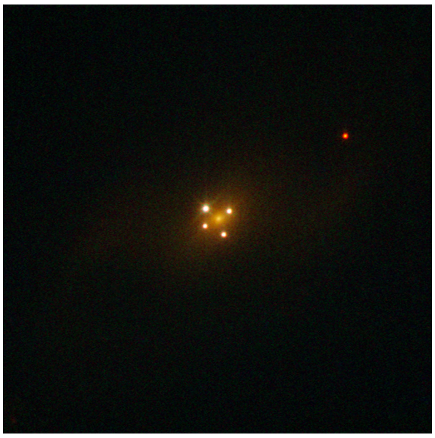
Since quasars exhibit properties common to all active galaxies, the emissions from quasars can be readily compared to those of smaller active galaxies powered by smaller supermassive black holes. To create a luminosity of 10^{40} watts (the typical brightness of a quasar), a super-massive black hole would have to consume the material equivalent of 10 stars per year. The brightest known quasars devour 1000 solar masses of material every year. The largest known is estimated to consume matter equivalent to 600 Earths per minute. Quasars 'turn on and off' depending on their surroundings, and since quasars cannot continue to feed at high rates for 10 billion years, after a quasar finishes accreting the surrounding gas and dust, it becomes an ordinary galaxy.

Quasars also provide some clues as to the end of the Big Bang's reionization. The oldest known quasars (redshift ≥ 6) display a Gunn-Peterson trough and have absorption regions in front of them indicating that the intergalactic medium at that time was neutral gas. More recent quasars show no absorption region but rather their spectra contain a spiky area known as the Lyman-alpha forest. This indicates that the intergalactic medium has undergone reionization into plasma, and that neutral gas exists only in small clouds.

Quasars show evidence of elements heavier than helium, indicating that galaxies underwent a massive phase of star formation, creating population III stars between the time of the Big Bang and the first observed quasars. Light from these stars may have been observed in 2005 using NASA's Spitzer Space Telescope, although this observation remains to be confirmed.

Like all (unobscured) active galaxies, quasars can be strong X-ray sources. Radio-loud quasars can also produce X-rays and gamma rays by inverse Compton scattering of lower-energy photons by the radio-emitting electrons in the jet.

History of observation


Picture shows a famous cosmic mirage known as the Einstein Cross, and is a direct visual confirmation of the theory of general relativity.

The first quasars (3C 48 and 3C 273) were discovered in the early 1960s by Allan Sandage and others. Many were recorded as radio sources with no corresponding visible object. Using small telescopes and the Lovell Telescope as an interferometer, they were shown to have a very small angular size. Hundreds of these objects were recorded by 1960 and published in the Third Cambridge Catalogue as astronomers scanned the skies for their optical counterparts. In 1960, the radio source 3C 48 was finally tied to an optical object. Astronomers detected what appeared to be a faint blue star at the location of the radio source and obtained its spectrum. Containing many unknown broad emission lines, the anomalous spectrum defied interpretation—a claim by John Bolton of a large redshift was not generally accepted.

In 1962 a breakthrough was achieved. Another radio source, 3C 273, was predicted to undergo five occultations by the moon. Measurements taken by Cyril Hazard and John Bolton during one of the occultations using the Parkes Radio Telescope allowed Maarten Schmidt to optically identify the object and obtain an optical spectrum using the 200-inch Hale Telescope on Mount Palomar. This spectrum revealed the same strange emission lines. Schmidt realized that these were actually spectral lines of hydrogen redshifted at the rate of 15.8 percent. This discovery showed that 3C 273 was receding at a rate of 47,000 km/s. This discovery revolutionized quasar observation and allowed other astronomers to find redshifts from the emission lines from other radio sources. As predicted earlier by Bolton, 3C 48 was found to have a redshift of 37% of the speed of light.

The term *quasar* was coined by Chinese-born U.S. astrophysicist Hong-Yee Chiu in May 1964, in *Physics Today*, to describe these puzzling objects:

> So far, the clumsily long name 'quasi-stellar radio sources' is used to describe these objects. Because the nature of these objects is entirely unknown, it is hard to prepare a short, appropriate nomenclature for them so that their essential properties are obvious from their name. For convenience, the abbreviated form 'quasar' will be used throughout this paper.

Later it was found that not all (about 10%) quasars have strong radio emission (are 'radio-loud'). Hence the name 'QSO' (quasi-stellar object) is used (in addition to 'quasar') to refer to these objects, including the 'radio-loud' and the 'radio-quiet' classes.

One great topic of debate during the 1960s was whether quasars were nearby objects or distant objects as implied by their redshift. It was suggested, for example, that the redshift of quasars was not due to the expansion of space but rather to light escaping a deep gravitational well. However a star of sufficient mass to form such a well would be unstable and in excess of the Hayashi limit. Quasars also show 'forbidden' spectral emission lines which were previously only seen in hot gaseous nebulae of low density, which would be too diffuse to both generate the observed power and fit within a deep gravitational well. There were also serious concerns regarding the idea of cosmologically distant quasars. One strong argument against them was that they implied energies that were far in excess of known energy conversion processes, including nuclear fusion. At this time, there were some suggestions that quasars were made of some hitherto unknown form of stable antimatter and that this might account for their brightness. Others speculated that quasars were a white hole end of a wormhole. However, when accretion disc energy-production mechanisms were successfully modeled in the 1970s, the argument that quasars were too luminous became moot and today the cosmological distance of quasars is accepted by almost all researchers.

In 1979 the gravitational lens effect predicted by Einstein's General Theory of Relativity was confirmed observationally for the first time with images of the double quasar 0957+561.

In the 1980s, unified models were developed in which quasars were classified as a particular kind of active galaxy, and a consensus emerged that in many cases it is simply the viewing angle that distinguishes them from other classes, such as blazars and radio galaxies. The huge luminosity of quasars results from the accretion discs of central supermassive black holes, which can convert on the order of 10% of the mass of an object into energy as compared to 0.7% for the p-p chain nuclear fusion process that dominates the energy production in sun-like stars.

This mechanism also explains why quasars were more common in the early universe, as this energy production ends when the supermassive black hole consumes all of the gas and dust near it. This means that it is possible that most galaxies, including our own Milky Way, have gone through an active stage (appearing as a quasar or some other class of active galaxy that depended on the black hole mass and the accretion rate) and are now quiescent because they lack a supply of matter to feed into their central black holes to generate radiation.

Role in celestial reference systems

The energetic radiation of the quasar makes dark galaxies glow, helping astronomers to understand the obscure early stages of galaxy formation.

Because quasars are extremely distant, bright, and small in apparent size, they are useful reference points in establishing a measurement grid on the sky. The International Celestial Reference System (ICRS) is based on hundreds of extra-galactic radio sources, mostly quasars, distributed around the entire sky. Because they are so distant, they are apparently stationary to our current technology, yet their positions can be measured with the utmost accuracy by Very Long Baseline Interferometry (VLBI). The positions of most are known to 0.001 arcsecond or better, which is orders of magnitude more precise than the best optical measurements.

Multiple quasars

A multiply imaged quasar is a quasar that is undergoing gravitational lensing, resulting in double, triple or quadruple images of the same quasar. The first such gravitational lens to be discovered was the double-imaged quasar Q0957+561 (or Twin Quasar) in 1979 A grouping of two or more quasars can result from a chance alignment, physical proximity, actual close physical interaction, or effects of gravity bending the light of a single quasar into two or more images.

As quasars are rare objects, the probability of three or more separate quasars being found near the same location is very low. The first true triple quasar was found in 2007 by observations at the W. M. Keck Observatory Mauna Kea, Hawaii. LBQS 1429-008 (or QQQ J1432−0106) was first observed in 1989 and was found to be a double quasar; itself a rare occurrence. When astronomers discovered the third member, they confirmed that the sources were separate and not the result of gravitational lensing. This triple quasar has a red shift of $z = 2.076$, which is equivalent to 10.5 billion light years. The components are separated by an estimated 30–50 kpc, which is typical of interacting galaxies. Another example of a triple quasar formed by lensing is PG1115 +08.

In 2013, the second true triplet quasars QQQ J1519+0627 was found with redshift $z = 1.51$ (approx 9 billion light years) by an international team of astronomers led by Farina of the University of Insubria, the whole system is well accommodated within 25′′ (i.e., 200 kpc in projected distance). The team accessed data from observations collected at the La Silla Observatory with the New Technology Telescope (NTT) of the European Southern Observatory (ESO) and at the Calar Alto Observatory with the 3.5m telescope of the Centro Astronómico Hispano Alemán (CAHA).

When two quasars are so nearly in the same direction as seen from Earth that they appear to be a single quasar but may be separated by the use of telescopes, they are referred to as a "double quasar", such as the Twin Quasar. These are two different quasars, and not the same quasar that is gravitationally lensed. This configuration is similar to the optical double star. Two quasars, a "quasar pair", may be closely related in time and space, and be gravitationally bound to one another. These may take the form of two quasars in the same galaxy cluster. This configuration is similar to two prominent stars in a star cluster. A "binary quasar", may be closely linked gravitationally and form a pair of interacting galaxies. This configuration is similar to that of a binary star system.

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[2] http://en.wikipedia.org/w/index.php?title=Quasar&action=edit
[3] http://www.galaxydynamics.org/papers/GreatMilkyWayAndromedaCollision.pdf
[4] http://www.cfa.harvard.edu/~tcox/localgroup/lg.pdf

External links

- 3C 273: Variable Star Of The Season (http://www.aavso.org/vstar/vsots/)
- SKY-MAP.ORG SDSS image of quasar 3C 273 (http://www.sky-map.org/?object=3C 273&zoom=12&img_source=SDSS)
- Expanding Gallery of Hires Quasar Images (http://www.perseus.gr/Astro-DSO-Quasars.htm)
- Gallery of Quasar Spectra from SDSS (http://www.sdss.org/gallery/gal_zqso.html)
- SDSS Advanced Student Projects: Quasars (http://cas.sdss.org/dr6/en/proj/advanced/quasars/default.asp)
- Black Holes: Gravity's Relentless Pull (http://www.hubblesite.org/go/blackholes) Award-winning interactive multimedia Web site about the physics and astronomy of black holes from the Space Telescope Science Institute
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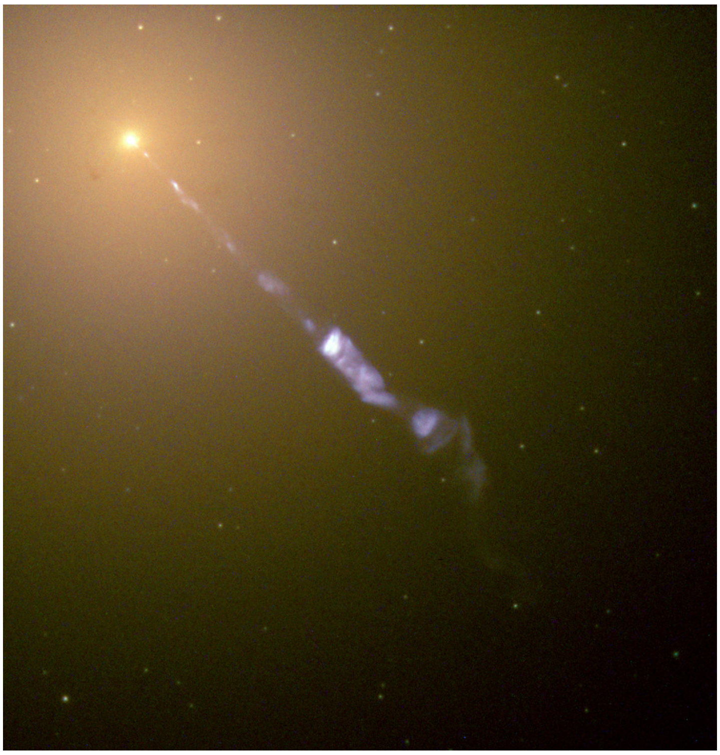
Active galactic nucleus

An **active galactic nucleus** (**AGN**) is a compact region at the centre of a galaxy that has a much higher than normal luminosity over at least some portion, and possibly all, of the electromagnetic spectrum. Such excess emission has been observed in the radio, infrared, optical, ultra-violet, X-ray and gamma ray wavebands. A galaxy hosting an AGN is called an **active galaxy**. The radiation from AGN is believed to be a result of accretion of mass by a supermassive black hole at the centre of its host galaxy. AGN are the most luminous and persistent sources of electromagnetic radiation in the universe, and as such can be used as a means of discovering distant objects; their evolution as a function of cosmic time also puts constraints on models of the cosmos.

Models of the active nucleus



Hubble Space Telescope image of a 5000-light-year-long (1.5-kiloparsec-long) jet being ejected from the active nucleus of the active galaxy M87, a radio galaxy. The blue synchrotron radiation of the jet contrasts with the yellow starlight from the host galaxy.

For a long time it has been argued that an AGN must be powered by accretion of mass onto massive black holes (10^6 to 10^{10} times the Solar mass). AGN are both compact and persistently extremely luminous. Accretion can potentially give very efficient conversion of potential and kinetic energy to radiation, and a massive black hole has a high Eddington luminosity, and as a result, it can provide the observed high persistent luminosity. Supermassive black holes are now believed to exist in the centers of most if not all massive galaxies. Evidence for that is that the mass of the black hole correlates well with the velocity dispersion of the galactic bulge (the M-sigma relation) or with bulge luminosity (e.g.). Thus AGN-like characteristics are expected whenever a supply of material for accretion comes within the sphere of influence of the central black hole.

Accretion disc

In the standard model of AGN, cold material close to a black hole forms an accretion disc. Dissipative processes in the accretion disc transport matter inwards and angular momentum outwards, while causing the accretion disc to heat up. The expected spectrum of an accretion disc peaks in the optical-ultraviolet waveband; in addition, a corona of hot material forms above the accretion disc and can inverse-Compton scatter photons up to X-ray energies. The radiation from the accretion disc excites cold atomic material close to the black hole and this in turn radiates at particular emission lines. A large fraction of the AGN's radiation may be obscured by interstellar gas and dust close to the accretion disc, but (in a steady-state situation) this will be re-radiated at some other waveband, most likely the infrared.

Relativistic jets

Some accretion discs produce jets of twin, highly collimated, and fast outflows that emerge in opposite directions from close to the disc. The direction of the jet ejection is determined either by the angular momentum axis of the accretion disc or the spin axis of the black hole. The jet production mechanism and indeed the jet composition on very small scales are not understood at present due to the low resolution of astronomical instruments, and as a result, observations cannot provide enough evidence to support one of the various theoretical models of jet production over the many that exist. The jets have their most obvious observational effects in the radio waveband, where Very Long Baseline Interferometry can be used to study the synchrotron radiation they emit at resolutions of sub-parsec scales. However, they radiate in all wavebands from the radio through to the gamma-ray range via the synchrotron and the inverse-Compton scattering process, and so AGN jets are a second potential source of any observed continuum radiation.

Radiatively inefficient AGN

There exists a class of 'radiatively inefficient' solutions to the equations that govern accretion. The most widely known of these is the Advection Dominated Accretion Flow (ADAF), but other theories exist. In this type of accretion, which is important for accretion rates well below the Eddington limit, the accreting matter does not form a thin disc and consequently does not efficiently radiate away the energy that it acquired as it moved close to the black hole. Radiatively inefficient accretion has been used to explain the lack of strong AGN-type radiation from massive black holes at the centres of elliptical galaxies in clusters, where otherwise we might expect high accretion rates and correspondingly high luminosities. Radiatively inefficient AGN would be expected to lack many of the characteristic features of standard AGN with an accretion disc.

Observational characteristics

There is no single observational signature of an AGN. The list below covers some of the historically important features that have allowed systems to be identified as AGN.

- Nuclear optical continuum emission. This is visible whenever there is a direct view of the accretion disc. Jets can also contribute to this component of the AGN emission. The optical emission has a roughly power-law dependence on wavelength.
- Nuclear infra-red emission. This is visible whenever the accretion disc and its environment are obscured by gas and dust close to the nucleus and then re-emitted ('reprocessing'). As it is thermal emission, it can be distinguished from any jet or disc-related emission.
- Broad optical emission lines. These come from cold material close to the central black hole. The lines are broad because the emitting material is revolving around the black hole with high speeds causing a range of Doppler shifts of the emitted photons.
- Narrow optical emission lines. These come from more distant cold material, and so are narrower than the broad lines.
- Radio continuum emission. This is always due to a jet. It shows a spectrum characteristic of synchrotron radiation.
- X-ray continuum emission. This can arise both from a jet and from the hot corona of the accretion disc via a scattering process: in both cases it shows a power-law spectrum. In some radio-quiet AGN there is an excess of soft X-ray emission in addition to the power-law component. The origin of the soft X-rays is not clear at present.
- X-ray line emission. This is a result of illumination of cold heavy elements by the X-ray continuum that causes fluorescence of X-ray emission lines, the best-known of which is the iron feature around 6.4 keV. This line may be narrow or broad: relativistically broadened iron lines can be used to study the dynamics of the accretion disc very close to the nucleus and therefore the nature of the central black hole.

Types of active galaxy

It is convenient to divide AGN into two classes, conventionally called radio-quiet and radio-loud. In the radio-loud objects the emission contribution from the jet(s) and the lobes that they inflate dominates the luminosity of the AGN, at least at radio wavelengths but possibly at some or all others. Radio-quiet objects are simpler since jet and jet-related emission can be neglected.

AGN terminology is often confusing, since the distinctions between different types of AGN sometimes reflect historical differences in how the objects were discovered or initially classified, rather than real physical differences.

Radio-quiet AGN

- Low-ionization nuclear emission-line regions (LINERs). As the name suggests, these systems show only weak nuclear emission-line regions, and no other signatures of AGN emission. It is debatable whether all such systems are true AGN (powered by accretion on to a supermassive black hole). If they are, they constitute the lowest-luminosity class of radio-quiet AGN. Some may be radio-quiet analogues of the low-excitation radio galaxies (see below).
- Seyfert galaxies. Seyferts were the earliest distinct class of AGN to be identified. They show optical range nuclear continuum emission, narrow and occasionally broad emission lines, occasionally strong nuclear X-ray emission and sometimes a weak small-scale radio jet. Originally they were divided into two types known as Seyfert 1 and 2: Seyfert 1s show strong broad emission lines while Seyfert 2s do not, and Seyfert 1s are more likely to show strong low-energy X-ray emission. Various forms of elaboration on this scheme exist: for example, Seyfert 1s with relatively narrow broad lines are sometimes referred to as narrow-line Seyfert 1s. The host galaxies of Seyferts are usually spiral or irregular galaxies.
- Radio-quiet quasars/QSOs. These are essentially more luminous versions of Seyfert 1s: the distinction is arbitrary and is usually expressed in terms of a limiting optical magnitude. Quasars were originally 'quasi-stellar' in optical images as they had optical luminosities that were greater than that of their host galaxy. They always show strong optical continuum emission, X-ray continuum emission, and broad and narrow optical emission lines. Some astronomers use the term QSO (Quasi-Stellar Object) for this class of AGN, reserving 'quasar' for radio-loud objects, while others talk about radio-quiet and radio-loud quasars. The host galaxies of quasars can be spirals, irregulars or ellipticals. There is a correlation between the quasar's luminosity and the mass of its host galaxy, in that the most luminous quasars inhabit the most massive galaxies (ellipticals).
- 'Quasar 2s'. By analogy with Seyfert 2s, these are objects with quasar-like luminosities but without strong optical nuclear continuum emission or broad line emission. They are scarce in surveys, though a number of possible candidate quasar 2s have been identified.

Radio-loud AGN

See main article Radio galaxy for a discussion of the large-scale behaviour of the jets. Here, only the active nuclei are discussed.

- Radio-loud quasars behave exactly like radio-quiet quasars with the addition of emission from a jet. Thus they show strong optical continuum emission, broad and narrow emission lines, and strong X-ray emission, together with nuclear and often extended radio emission.
- “Blazars” (BL Lac objects and OVV quasars) classes are distinguished by rapidly variable, polarized optical, radio and X-ray emission. BL Lac objects show no optical emission lines, broad or narrow, so that their redshifts can only be determined from features in the spectra of their host galaxies. The emission-line features may be intrinsically absent or simply swamped by the additional variable component. In the latter case, emission lines may become visible when the variable component is at a low level. OVV quasars behave more like standard radio-loud quasars with the addition of a rapidly variable component. In both classes of source, the variable emission is believed to originate in a relativistic jet oriented close to the line of sight. Relativistic effects amplify both the luminosity of the jet and the amplitude of variability.
- Radio galaxies. These objects show nuclear and extended radio emission. Their other AGN properties are heterogeneous. They can broadly be divided into low-excitation and high-excitation classes. Low-excitation objects show no strong narrow or broad emission lines, and the emission lines they do have may be excited by a different mechanism. Their optical and X-ray nuclear emission is consistent with originating purely in a jet. They may be the best current candidates for AGN with radiatively inefficient accretion. By contrast, high-excitation objects (narrow-line radio galaxies) have emission-line spectra similar to those of Seyfert 2s. The small class of broad-line radio galaxies, which show relatively strong nuclear optical continuum emission probably includes

some objects that are simply low-luminosity radio-loud quasars. The host galaxies of radio galaxies, whatever their emission-line type, are essentially always ellipticals.

Summary

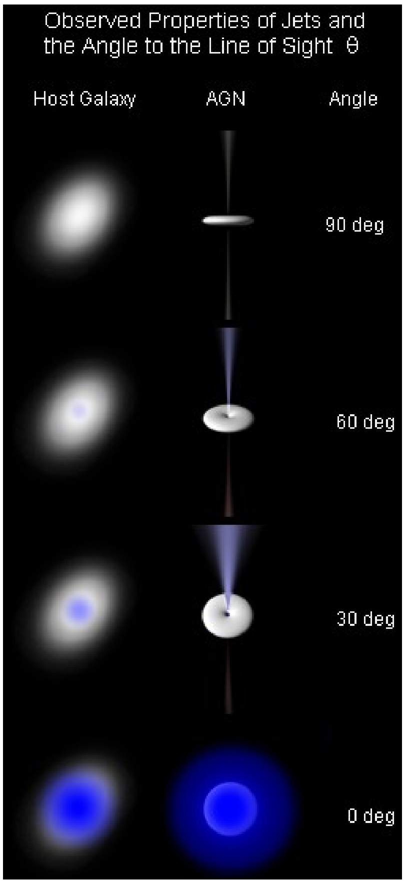
These galaxies can be broadly summarised by the following table:

Differences between active galaxy types and normal galaxies.

Galaxy Type	Active Nuclei	Emission Lines		X-rays	Excess of		Strong Radio	Jets	Variable	Radio loud
		Narrow	Broad		UV	Far-IR				
Normal	no	weak	no	weak	no	no	no	no	no	no
Starburst	no	yes	no	some	no	yes	some	no	no	no
Seyfert I	yes	yes	yes	some	some	yes	few	no	yes	no
Seyfert II	yes	yes	no	some	some	yes	few	yes	yes	no
Quasar	yes	yes	yes	some	yes	yes	some	some	yes	10%
Blazar	yes	no	some	yes	yes	no	yes	yes	yes	yes
BL Lac	yes	no	no/faint	yes	yes	no	yes	yes	yes	yes
OVV	yes	no	stronger than BL Lac	yes	yes	no	yes	yes	yes	yes
Radio galaxy	yes	some	some	some	some	yes	yes	yes	yes	yes

Unification of AGN species

Unified models propose that different observational classes of AGN are really a single type of physical object observed under different conditions. The currently favoured unified models are 'orientation-based unified models' meaning that they propose that the apparent differences between different types of objects arise simply because of their different orientations to the observer.



Unification by viewing angle. From bottom to top: *down the jet* - Blazar, *at an angle to the jet* - Quasar/Seyfert 1 Galaxy, *at 90 degrees from the jet* - Radio galaxy / Seyfert 2 Galaxy[1]

Radio-quiet unification

At low luminosities, the objects to be unified are Seyfert galaxies. The unification models propose that in Seyfert 1s the observer has a direct view of the active nucleus. In Seyfert 2s the nucleus is observed through an obscuring structure which prevents a direct view of the optical continuum, broad-line region or (soft) X-ray emission. The key insight of orientation-dependent accretion models is that the two types of object can be the same if only certain angles to the line of sight are observed. The standard picture is of a torus of obscuring material surrounding the accretion disc. It must be large enough to obscure the broad-line region but not large enough to obscure the narrow-line region, which is seen in both classes of object. Seyfert 2s are seen through the torus. Outside the torus there is material that can scatter some of the nuclear emission into our line of sight, allowing us to see some optical and X-ray continuum and, in some cases, broad emission lines—which are strongly polarized, showing that they have been scattered and proving that some Seyfert 2s really do contain hidden Seyfert 1s. Infrared observations of the nuclei of Seyfert 2s also support this picture.

At higher luminosities, quasars take the place of Seyfert 1s, but, as already mentioned, the corresponding 'quasar 2s' are elusive at present. If they do not have the scattering component of Seyfert 2s they would be hard to detect except through their luminous narrow-line and hard X-ray emission.

Radio-loud unification

Historically, work on radio-loud unification has concentrated on high-luminosity radio-loud quasars. These can be unified with narrow-line radio galaxies in a manner directly analogous to the Seyfert 1/2 unification (but without the complication of much in the way of a reflection component: narrow-line radio galaxies show no nuclear optical continuum or reflected X-ray component, although they do occasionally show polarized broad-line emission). The large-scale radio structures of these objects provide compelling evidence that the orientation-based unified models really are true. X-ray evidence, where available, supports the unified picture: radio galaxies show evidence of obscuration from a torus, while quasars do not, although care must be taken since radio-loud objects also have a soft unabsorbed jet-related component, and high resolution is necessary to separate out thermal emission from the sources' large-scale hot-gas environment. At very small angles to the line of sight, relativistic beaming dominates, and we see a blazar of some variety.

However, the population of radio galaxies is completely dominated by low-luminosity, low-excitation objects. These do not show strong nuclear emission lines — broad or narrow — they have optical continua which appear to be entirely jet-related, and their X-ray emission is also consistent with coming purely from a jet, with no heavily absorbed nuclear component in general. These objects cannot be unified with quasars, even though they include some high-luminosity objects when looking at radio emission, since the torus can never hide the narrow-line region to the required extent, and since infrared studies show that they have no hidden nuclear component: in fact there is no evidence for a torus in these objects at all. Most likely, they form a separate class in which only jet-related emission is important. At small angles to the line of sight, they will appear as BL Lac objects.

Cosmological uses and evolution

For a long time, active galaxies held all the records for the highest-redshift objects known either in the optical or the radio spectrum, because of their high luminosity. They still have a role to play in studies of the early universe, but it is now recognised that an AGN gives a highly biased picture of the 'typical' high-redshift galaxy.

More interesting is the study of the evolution of the AGN population. Most luminous classes of AGN (radio-loud and radio-quiet) seem to have been much more numerous in the early universe. This suggests (1) that massive black holes formed early on and (2) that the conditions for the formation of luminous AGN were more common in the early universe, such as a much higher availability of cold gas near the centre of galaxies than at present. It also implies that many objects that were once luminous quasars are now much less luminous, or entirely quiescent. The evolution of the low-luminosity AGN population is much less well understood due to the difficulty of observing these objects at high redshifts.

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[1] http://www.whatsnextnetwork.com/technology/media/active_galactic_nuclei.jpg

Dusty surprise around giant black hole (http://phys.org/news/2013-06-dusty-giant-black-hole.html)==External links==

- Media related to Active galactic nuclei at Wikimedia Commons

Galaxy filament

In physical cosmology, **galaxy filaments**, also called **supercluster complexes**, **great walls**, or "great attractors",[1][2] are amongst the largest known cosmic structures in the universe. They are massive, thread-like formations, with a typical length of 50 to 80 megaparsecs h^{-1}, that form the boundaries between large voids in the universe.[3] Filaments consist of gravitationally bound galaxies; parts where a large number of galaxies are very close to each other (in cosmic terms) are called superclusters.

Discovery of structures larger than superclusters began in the 1980s. In 1987, astronomer R. Brent Tully of the University of Hawaii's Institute of Astronomy identified what he called the Pisces-Cetus Supercluster Complex. In 1989, the CfA2 Great Wall was discovered,[4] followed by the Sloan Great Wall in 2003.[5] On January 11, 2013, researchers led by Roger Clowes of the University of Central Lancashire announced the discovery of a large quasar group, the Huge-LQG, which dwarfs previously discovered galaxy filaments in size.

In 2006, scientists announced the discovery of three filaments aligned to form one of the largest structures known to humanity,[6] composed of densely packed galaxies and enormous blobs of gas known as Lyman-alpha blobs.

List

Galaxy filaments

Filament subtype of filaments have roughly similar major and minor axes in cross-section, along the lengthwise axis.

Filaments of Galaxies

Filament	Date	Mean Distance	Dimension	Notes
Coma Filament				The Coma Supercluster lies within the Coma Filament.[7] It forms part of the CfA2 Great Wall.[8]
Perseus-Pegasus Filament	1985			Connected to the Pisces-Cetus Supercluster, with the Perseus-Pisces Supercluster being a member of the filament.[9]
Ursa Major Filament				Connected to the CfA Homunculus, a portion of the filament forms a portion of the "leg" of the Homunculus.
Lynx-Ursa Major Filament (LUM Filament)	1999	from 2000 km/s to 8000 km/s in *redshift space*		Connected to and separate from the Lynx-Ursa Major Supercluster.[]
z=2.38 filament around protocluster ClG J2143-4423	2004	z=2.38	110Mpc	A filament the length of the *Great Wall* was discovered in 2004. As of 2008, it was still the largest structure beyond redshift 2.[10][11][12][13]

Galaxy walls

The **Galaxy wall** subtype of filaments have a significantly greater major axis than minor axis in cross-section, along the lengthwise axis.

Walls of Galaxies

Wall	Date	Mean Distance	Dimension	Notes
CfA2 Great Wall (Coma Wall, Great Wall, Northern Great Wall, Great Northern Wall, CfA Great Wall)	1989	z=0.03058	251Mpc long 750 Mly long 250 Mly wide 20 Mly thick	This was the first super-large large-scale structure or pseudo-structure in the universe to be discovered. The CfA Homunculus lies at the heart of the Great Wall, and the Coma Supercluster forms most of the homunculus structure. The Coma Cluster lies at the core.[14]
Sloan Great Wall (SDSS Great Wall)	2005	z=0.07804	433Mpc long	This was the largest known structure or pseudo-structure to be discovered[] until it was eclipsed by the Huge-LQG large quasar group found eight years later.
Sculptor Wall (Southern Great Wall, Great Southern Wall, Southern Wall)			8000 km/s long 5000 km/s wide 1000 km/s deep (in *redshift space* dimensions)	The Sculptor Wall is "parallel" to the Fornax Wall and "perpendicular" to the Grus Wall.[15]
Grus Wall				The Grus Wall is "perpendicular" to the Fornax and Sculptor Walls.[]
Fornax Wall				The Fornax Cluster is part of this wall. The wall is "parallel" to the Sculptor Wall and "perpendicular" to the Grus Wall.

- A "Centaurus Great Wall" (or "Fornax Great Wall" or "Virgo Great Wall") has been proposed, which would include the Fornax Wall as a portion of it (visually created by the Zone of Avoidance) along with the Centaurus Supercluster and the Virgo Supercluster also known as our Local Supercluster within which the Milky Way Galaxy is located (implying this to be the Local Great Wall).
- A wall has been proposed to be the physical embodiment of the Great Attractor, with the Norma Cluster as part of this wall. This wall is also referred to as the Great Attractor Wall or Norma Wall.[16]
- A wall has been proposed, in 2000, to lie at z=1.47 in the vicinity of radio galaxy B3 0003+387.[17]
- A wall has been proposed, in 2000, to lie at z=0.559 in the northern Hubble Deep Field (HDF North).[18][19]

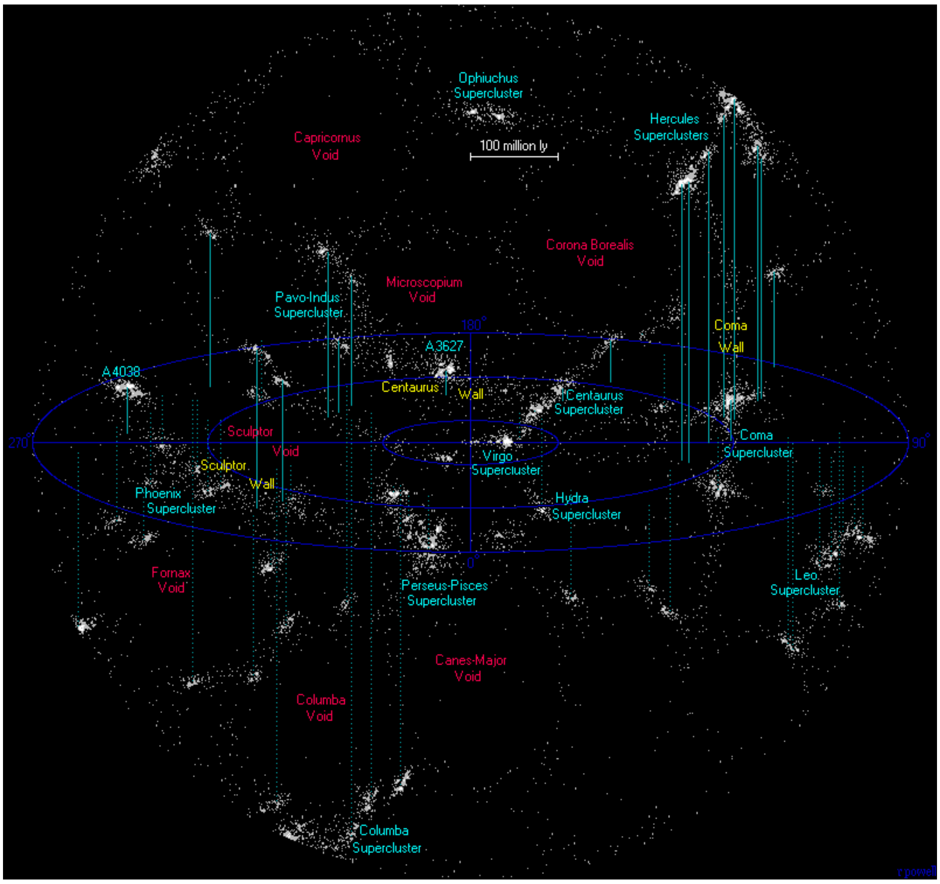
Large Quasar Groups

Large quasar groups (LQGs) are some of the largest structures known. They are theorized to be protohyperclusters/proto-supercluster-complexes/galaxy filament precursors.

Large Quasar Groups

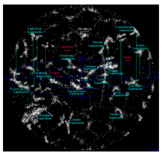
LQG	Date	Mean Distance	Dimension	Notes
Clowes & Campusano LQG (U1.28 , CCLQG)	1991			
Huge-LQG	2012	z=1.27	• characteristic size: 500 Mpc • longest dimension: 1240 Mpc	It is the largest structure known in the universe, as of January 2013. [][]

Map of nearest galaxy walls

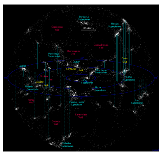


The Universe within 500 million Light Years, showing the nearest galaxy walls

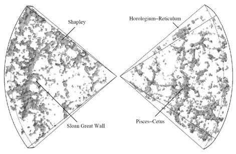
Maps of large-scale distribution



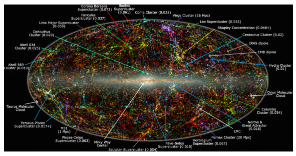
The universe within 1 billion light-years (307 Mpc) of Earth, showing local superclusters forming filaments and voids.



Map of nearest walls, voids and superclusters.



2dF survey map, containing the SDSS Great Wall



2MASS XSC infrared sky map

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Further reading

- arXiv, Pulling out Threads from the Cosmic Tapestry:Defining Filaments of Galaxies (http://www.publish.csiro.au/?act=view_file&file_id=AS05006.pdf) PDF, Kevin A. Pimbblet, 14 March 2005

External links

- Pictures of the filamentary network (http://pil.phys.uniroma1.it/twiki/bin/view/Pil/GalaxyStructures)
- The Universe Within One Billion Light Years with List of Nearby Superclusters (from the Atlas of the Universe): (http://www.atlasoftheuniverse.com/superc.html)

Phenomenological model: LambdaCDM + MOND

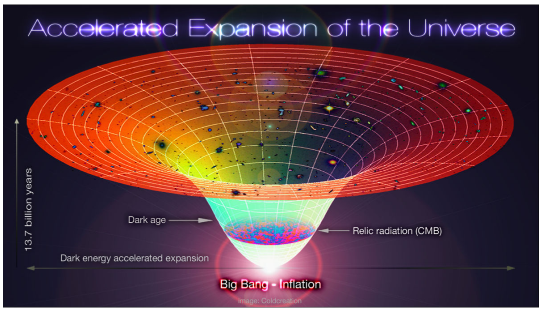
Lambda-CDM model

The **ΛCDM** or **Lambda-CDM** model is a parametrization of the Big Bang cosmological model in which the universe contains a cosmological constant, denoted by Lambda, and cold dark matter. It is frequently referred to as the **standard model** of Big Bang cosmology, since it is the simplest model that provides a reasonably good match to the following observations:

- the existence and structure of the cosmic microwave background
- the large-scale structure in the distribution of galaxies
- the abundances of hydrogen (including deuterium), helium, and lithium
- the accelerating expansion of the universe observed in the light from distant galaxies and supernovae

The model assumes that general relativity is the correct theory of gravity on cosmological scales. It emerged in the late 1990s as a **concordance cosmology**, after a period of time when disparate observed properties of the universe appeared mutually inconsistent, and there was no consensus on the makeup of the energy density of the universe. The ΛCDM model is extended by adding cosmological inflation, quintessence, and other elements that are current areas of research in cosmology. Some alternative models challenge the assumptions of the ΛCDM model, such as modified Newtonian dynamics, modified gravity, and large-scale variations in the matter density of the universe.[1]

Overview



Lambda-CDM, Accelerated Expansion of the Universe. The time-line in this schematic diagram extends from the big bang/inflation era 13.7 Gyr ago to the present cosmological time.

Most modern cosmological models are based on the cosmological principle that our observational location in the universe is not unusual or special; on a large enough scale, the universe looks the same in all directions (isotropy) and from every location (homogeneity).[2]

The model includes an expansion of metric space that is well documented both as the red shift of prominent spectral absorption or emission lines in the light from distant galaxies and as the time dilation in the light decay of supernova luminosity curves. Both effects are attributed to a Doppler shift in electromagnetic radiation as it travels across expanding space. While this expansion increases the distance between objects that are not under shared gravitational influence, it does not increase the size of the objects (e.g. galaxies) in space. It also allows for distant galaxies to recede from each other at speeds greater than the speed of light: local expansion is less than the speed of light, but expansion summed across great distances can collectively exceed the speed of light.

Λ (Lambda) stands for the cosmological constant which is currently associated with a vacuum energy or dark energy inherent in empty space that explains the current accelerating expansion of space against the attractive (collapsing) effects of gravity from matter. A cosmological constant has negative pressure, $p = -\rho c^2$; this contributes to the stress-energy tensor in general relativity and therefore causes accelerating expansion. The cosmological constant is denoted as Ω_Λ, which is interpreted as the fraction of the total mass-energy density of a flat universe that is attributed to dark energy. Currently [2013], about 68.3% of the energy density of the present universe is estimated to be dark energy.

Cold dark matter is a form of matter necessary to account for gravitational effects observed in very large scale structures (anomalies in the rotation of galaxies, the gravitational lensing of light by galaxy clusters, enhanced clustering of galaxies) that cannot be accounted for by the quantity of observed matter. Dark matter is described as being cold (i.e. its velocity is non-relativistic [far below the speed of light] at the epoch of radiation-matter equality), non-baryonic (consisting of matter other than protons and neutrons), dissipationless (cannot cool by radiating photons) and collisionless (i.e., the dark matter particles interact with each other and other particles only through gravity and possibly the weak force). The dark matter component is currently [2013] estimated to constitute about 26.8% of the mass-energy density of the universe.

The remaining 4.9% [2013] comprises all ordinary matter observed as atoms, chemical elements, gas and plasma, the stuff of which visible planets, stars and galaxies are made.

Also, the energy density includes a very small fraction (~ 0.01%) in cosmic microwave background radiation, and not more than 0.5% in relic neutrinos. While very small today, these were much more important in the distant past, dominating the matter at redshift > 3200.

The model includes a single originating event, the "Big Bang" or initial singularity, which was not an explosion but the abrupt appearance of expanding space-time containing radiation at temperatures of around 10^{15} K. This was immediately (within 10^{-29} seconds) followed by an exponential expansion of space by a scale multiplier of 10^{27} or more, known as cosmic inflation. The early universe remained hot (above 10,000 K) for several hundred thousand years, a state that is detectable as a residual cosmic microwave background or CMB, a very low energy radiation emanating from all parts of the sky. The "Big Bang" scenario, with cosmic inflation and standard particle physics, is the only current cosmological model consistent with the observed continuing expansion of space, the observed distribution of lighter elements in the universe (hydrogen, helium, and lithium), and the spatial texture of minute irregularities (anisotropies) in the CMB radiation. Cosmic inflation is also necessary to address the "horizon problem" in the CMB. Indeed, it seems likely that the universe is larger than the observable particle horizon.

The model uses the FLRW metric, the Friedmann equations and the cosmological equations of state to describe the observable universe from right after the inflationary epoch to present and future.

History

The discovery of the Cosmic Microwave Background in 1965 confirmed a key prediction of the Big Bang cosmology. From that point on it was generally accepted that the universe started in a hot, dense early state, and has been expanding over time. The rate of expansion depends on the types of matter and energy present in the universe, and in particular, whether the total density is above or below the so-called critical density. During the 1970s, most attention focused on pure-baryonic models, but there were serious challenges explaining the formation of galaxies given the small anisotropies in the CMB (upper limits at that time). In the early 1980s, it was realised this could be resolved if cold dark matter dominated over the baryons, and the theory of cosmic inflation motivated models with critical density. During the 1980s, most research focused on cold dark matter with critical density in matter, around 95% CDM and 5% baryons: these showed success at forming galaxies and clusters of galaxies, but problems remained: notably the model required a Hubble constant lower than preferred by observations, and the model under-predicted observed large-scale galaxy clustering. These difficulties sharpened with the discovery of CMB anisotropy by COBE in 1992, and several alternatives including LambdaCDM and mixed cold+hot dark matter came under active consideration. The LambdaCDM model then became the standard following the observations of accelerating expansion in 1998, and was quickly supported by other observations: in 2000, the BOOMERanG microwave background experiment measured the total (matter+energy) density to be close to 100% of critical, while in 2001 the 2dFGRS galaxy redshift survey measured the matter density to be near 25%; the large difference between these supports a positive Λ or dark energy. Much more precise measurements of the microwave background from WMAP in 2003 – 2010 have continued to support and refine the model.

There is currently active research into many aspects of the ΛCDM model, both to refine the parameters and possibly detect deviations. In addition, ΛCDM has no explicit physical theory for the origin or physical nature of dark matter or dark energy; the nearly scale-invariant spectrum of the CMB perturbations, and their image across the celestial sphere, are believed to result from very small thermal and acoustic irregularities at the point of recombination. A large majority of astronomers and astrophysicists support the ΛCDM model or close relatives of it, but Milgrom, McGaugh, and Kroupa are leading critics, attacking the dark matter portions of the theory from the perspective of galaxy formation models and supporting the alternative MOND theory which requires a modification of the Einstein Equations and the Friedmann Equations as seen in proposals such as MOG theory or TeVeS theory. Other proposals by theoretical astrophysicists of cosmological alternatives to Einstein's general relativity that attempt to account for dark energy or dark matter include f(R) gravity, scalar-tensor theories, brane cosmologies, the DGP model, and galileon theories.

Successes

In addition to explaining pre-2000 observations, the model has made a number of successful predictions: notably the existence of the baryon acoustic oscillation feature, discovered in 2005 in the predicted location; the polarisation of the CMB; and the statistics of weak gravitational lensing.

Challenges

Extensive searches for dark matter particles have so far shown no well-agreed detection; the dark energy may be almost impossible to detect in a laboratory, and its value is un-naturally small compared to naive theoretical predictions.

Comparison of the model with observations is very successful on large scales (larger than galaxies, up to the observable horizon), but may have some problems on sub-galaxy scales, possibly predicting too many dwarf galaxies and too much dark matter in the innermost regions of galaxies. These small scales are harder to resolve in computer simulations, so it is not yet clear whether the problem is the simulations, non-standard properties of dark matter, or a more radical error in the model.

Parameters

The ΛCDM model is based on six parameters: physical baryon density, physical dark matter density, dark energy density, scalar spectral index, curvature fluctuation amplitude and reionization optical depth. In accordance with Occam's razor, six is the smallest number of parameters needed to give an acceptable fit to current observations; other possible parameters are fixed at "natural" values e.g. total density = 1.00, dark energy equation of state = -1, neutrino masses are small enough to be negligible. (See below for extended models which allow these to vary).

The values of these six parameters are mostly not predicted by current theory (though, ideally, they may be related by a future "Theory of Everything"); except that most versions of cosmic inflation predict the scalar spectral index should be slightly smaller than 1, consistent with the estimated value 0.96. The parameter values, and uncertainties, are estimated using large computer searches to locate the region of parameter space providing an acceptable match to cosmological observations. From these six parameters the other model values, including the Hubble constant and age of the universe, can be readily calculated.

Commonly, the set of observations fitted includes the cosmic microwave background anisotropy, the brightness/redshift relation for supernovae, and large-scale galaxy clustering including the baryon acoustic oscillation feature. Other observations such as the Hubble constant, the abundance of galaxy clusters, weak gravitational lensing, globular cluster ages, are generally consistent with these, providing a check of the model, but are less accurately measured at present.

Parameter values listed below are from the Seven-Year Wilkinson Microwave Anisotropy Probe (WMAP) temperature and polarization observations.[3] These include estimates based on data from Baryon Acoustic Oscillations and Type Ia supernova luminosity/time dilation measurements. Implications of the data for cosmological models are discussed in Komatsu *et al.* [4] and Spergel *et al.* See also Planck (spacecraft).

Parameter	**Value**	**Description**
t_0	$13.75 \pm 0.11 \times 10^9$ years	Age of the universe
H_0	$70.4^{+1.3}_{-1.4}$ km s^{-1} Mpc^{-1}	Hubble constant
$\Omega_b h^2$	0.02260 ± 0.00053	Physical baryon density
$\Omega_c h^2$	0.1123 ± 0.0035	Physical dark matter density
Ω_b	0.0456 ± 0.0016	Baryon density
Ω_c	0.227 ± 0.014	Dark matter density
Ω_Λ	$0.728^{+0.015}_{-0.016}$	Dark energy density
Δ_R^2	$2.441^{+0.088}_{-0.092} \times 10^{-9}$, $k_0 = 0.002 Mpc^{-1}$	Curvature fluctuation amplitude
σ_8	0.809 ± 0.024	Fluctuation amplitude at $8h^{-1}$Mpc
n_s	0.963 ± 0.012	Scalar spectral index
z_*	$1090.89^{+0.68}_{-0.69}$	Redshift at decoupling
t_*	377730^{+3205}_{-3200} years	Age at decoupling
τ	0.087 ± 0.014	Reionization optical depth
z_{reion}	10.4 ± 1.2	Redshift of reionization

The "physical baryon density" $\Omega_b h^2$ differs from the "baryon density" Ω_b in that the baryon density gives the fraction of the critical density made up of baryons (the critical density is the total density of matter/energy needed for the universe to be spatially flat, with measurements indicating that the actual total density Ω_{tot} is very close if not equal to this value, see below), while the physical baryon density is equal to the baryon density multiplied by the square of the reduced Hubble constant h,[5] where h is related to the Hubble constant H_0 by the equation H_0 = 100 h (km/s)/Mpc.[6] Likewise for the difference between "physical dark matter density" and "dark matter density".

Extended models

Possible extensions of the simplest ΛCDM model are to allow quintessence rather than a cosmological constant. In this case, the equation of state of dark energy is allowed to differ from −1. Cosmic inflation predicts tensor fluctuations (gravitational waves). Their amplitude is parameterized by the tensor-to-scalar ratio (denoted r), which is determined by the energy scale of inflation. Other modifications allow for spatial curvature (Ω_{tot} may be different from 1), hot dark matter in the form of neutrinos, or a running spectral index, which are generally viewed as inconsistent with cosmic inflation.

Allowing these parameters will generally *increase* the errors in the parameters quoted above, and may also shift the observed values somewhat.

Parameter	Value	Description
Ω_{tot}	$1.0023^{+0.0056}_{-0.0054}$	Total density
w	-0.980 ± 0.053	Equation of state of dark energy
r	< 0.24, $k_0 = 0.002\mathrm{Mpc}^{-1}$ (2σ)	Tensor-to-scalar ratio
$d\,n_s / d \ln k$	-0.022 ± 0.020, $k_0 = 0.002\mathrm{Mpc}^{-1}$	Running of the spectral index
$\Omega_v h^2$	< 0.0062	Physical neutrino density
Σm_v	< 0.58 eV (2σ)	Sum of three neutrino masses

Some researchers have suggested that there is a running spectral index, but no statistically significant study has revealed one. Theoretical expectations suggest that the tensor-to-scalar ratio r should be between 0 and 0.3, and the latest results are now within those limits.

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External links

- Latest summary of WMAP estimated cosmological parameters (http://lambda.gsfc.nasa.gov/product/map/dr3/parameters_summary.cfm)
- Ned Wright's Cosmology tutorial (http://www.astro.ucla.edu/~wright/cosmolog.htm)
- Millennium Simulation (http://www.mpa-garching.mpg.de/galform/millennium-II/)
- Bolshoi Simulation (http://hipacc.ucsc.edu/Bolshoi/index.html)

Inflation (cosmology)

In physical cosmology, **cosmic inflation**, **cosmological inflation**, or just **inflation** is the extremely rapid exponential expansion of the early universe by a factor of at least 10^{78} in volume, driven by a negative-pressure vacuum energy density.[1] The inflationary epoch comprises the first part of the electroweak epoch following the grand unification epoch. It lasted from 10^{-36} seconds after the Big Bang to sometime between 10^{-33} and 10^{-32} seconds. Following the inflationary period, the universe continued to expand, but at a slower rate.

The term "inflation" is used to refer to the hypothesis that inflation occurred, to the theory of inflation, or to the inflationary epoch. The inflationary hypothesis was originally proposed in 1980 by American physicist Alan Guth, who named it "inflation".[2] It was also proposed by Katsuhiko Sato in 1981.

As a direct consequence of this expansion, all of the observable universe originated in a small causally connected region. Inflation answers the classic conundrum of the Big Bang cosmology: why does the universe appear flat, homogeneous, and isotropic in accordance with the cosmological principle when one would expect, on the basis of the physics of the Big Bang, a highly curved, heterogeneous universe? Inflation also explains the origin of the large-scale structure of the cosmos. Quantum fluctuations in the microscopic inflationary region, magnified to cosmic size, become the seeds for the growth of structure in the universe (see galaxy formation and evolution and structure formation).[3]

While the detailed particle physics mechanism responsible for inflation is not known, the basic picture makes a number of predictions that have been confirmed by observation. The hypothetical particle or field thought to be responsible for inflation is called the inflaton.[*citation needed*]

Overview

An expanding universe generally has a cosmological horizon which, by analogy with the more familiar horizon caused by the curvature of the Earth's surface, marks the boundary of the part of the universe that an observer can see. Light (or other radiation) emitted by objects beyond the cosmological horizon never reaches the observer, because the space in between the observer and the object is expanding too rapidly.

There are two ways to describe a spacetime with a horizon: locally and globally. The local picture includes only what is (potentially) visible from a given point in spacetime, while the global picture includes unobservable regions beyond the horizon. The two perspectives are related by a process of extension: wherever there is a horizon, a particular solution of General Relativity can be extended beyond it by assuming that nothing special happens there (i.e., that it "looks like" the region within the horizon). The local and global points of view have different notions of time. From the local point of view the horizon is infinitely far in the future and nothing ever arrives at it, whereas from the global point of view the horizon is an ordinary surface at finite time, and both space and time extend beyond it. Ignoring quantum mechanics, the two pictures are equivalent: any physical statement can be translated freely back and forth, and both pictures agree on the results of all physical experiments.

For cosmology in the global point of view, the observable universe is one *causal patch* of a much larger unobservable universe; there are parts of the universe which cannot communicate with us yet. These parts of the universe are outside our current cosmological horizon. In the standard hot big bang model, without inflation, the cosmological horizon moves out, bringing new regions into view. As we see these regions for the first time, they look no different from any other region of space we have already seen: they have a background radiation which is at nearly exactly the same temperature as the background radiation of other regions, and their space-time curvature is evolving lock-step with ours. This presents a mystery: how did these new regions know what temperature and curvature they were supposed to have? They couldn't have learned it by getting signals, because they were not in communication with our past light cone before.[4][5]

Inflation answers this question by postulating that all the regions come from an earlier era with a big vacuum energy, or cosmological constant. A space with a cosmological constant is qualitatively different: instead of moving outward, the cosmological horizon stays put. For any one observer, the distance to the cosmological horizon is constant. With exponentially expanding space, two nearby observers are separated very quickly; so much so, that the distance between them quickly exceeds the limits of communications. In the global point of view, the spatial slices are expanding very fast to cover huge volumes. In the local point of view, things are constantly moving beyond the cosmological horizon, which is a fixed distance away, and everything becomes homogeneous very quickly.

In either view, as the inflationary field slowly relaxesWikipedia:Please clarify to the vacuum, the cosmological constant goes to zero, and space begins to expand normally. The new regions which come into view during the normal expansion phase, in the global point of view, are exactly the same regions which were pushed out of the horizon during inflation, and so they are necessarily at nearly the same temperature and curvature, because they come from the same little patch of space. In the local point of view, the cosmological horizon still is at the big bang, and inflation is always going on in a thin skin where time is nearly stopped, and the same process produces new regions as it always did, up to small fluctuations.

Inflation from the global point of view is often called eternal inflation. On a global constant-time slice, regions with inflation have an exponentially growing volume, while regions which are not inflating don't. This means that the volume of the inflating part of the universe in the global picture is always unimaginably larger than the part that has stopped inflating. If the probability of different regions is counted by volume, one should expect that inflation will never end, or applying boundary conditions that we exist to observe it, that inflation will end as late as possible. Weighting by volume is unnatural in the local point of view where inflation is not eternal—it eventually ends as seen by any single observer. This picture gives a meaning to the probability distribution on the anthropic landscape.

The theory of inflation in any picture explains why the temperatures and curvatures of different regions are so nearly equal, and it predicts that the total curvature of a space-slice at constant global time is zero. This prediction means that the total ordinary matter, dark matter, and residual vacuum energy in the universe have to add up to the critical density, a prediction which is very accurately confirmed. More strikingly, inflation allows physicists to calculate the minute differences in temperature of different regions from quantum fluctuations during the inflationary era, and these quantitative predictions have also been confirmed.[*citation needed*]

Space expands

To say that space expands exponentially means that two inertial observers are moving farther apart with accelerating velocity. In stationary coordinates for one observer, a patch of an inflating universe has the following polar metric:[6][7]

$$ds^2 = -(1 - \Lambda r^2)\, dt^2 + \frac{1}{1 - \Lambda r^2}\, dr^2 + r^2\, d\Omega^2.$$

This is just like an inside-out black hole metric—it has a zero in the dt component on a fixed radius sphere called the cosmological horizon. Objects are drawn away from the observer at $r = 0$ towards the cosmological horizon, which they cross in a finite proper time. This means that any inhomogeneities are smoothed out, just as any bumps or matter on the surface of a black hole horizon are swallowed and disappear.

Since the space–time metric has no explicit time dependence, once an observer has crossed the cosmological horizon, observers closer in take its place. This process of falling outward and replacement points closer in are always steadily replacing points further out—an exponential expansion of space–time.

This steady-state exponentially expanding spacetime is called a de Sitter space, and to sustain it there must be a cosmological constant, a vacuum energy proportional to Λ everywhere. In this case, the equation of state is $p = -\rho$. The physical conditions from one moment to the next are stable: the rate of expansion, called the Hubble parameter, is nearly constant, and the scale factor of the universe is proportional to e^{Ht} . Inflation is often called a period of *accelerated expansion* because the distance between two fixed observers is increasing exponentially (i.e. at an accelerating rate as they move apart), while Λ can stay approximately constant (see deceleration parameter).

Few inhomogeneities remain

Cosmological inflation has the important effect of smoothing out inhomogeneities, anisotropies and the curvature of space. This pushes the universe into a very simple state, in which it is completely dominated by the inflaton field, the source of the cosmological constant, and the only significant inhomogeneities are the tiny quantum fluctuations in the inflaton. Inflation also dilutes exotic heavy particles, such as the magnetic monopoles predicted by many extensions to the Standard Model of particle physics. If the universe was only hot enough to form such particles *before* a period of inflation, they would not be observed in nature, as they would be so rare that it is quite likely that there are none in the observable universe. Together, these effects are called the inflationary "no-hair theorem"[8] by analogy with the no hair theorem for black holes.

The "no-hair" theorem works essentially because the cosmological horizon is no different from a black-hole horizon, except for philosophical disagreements about what is on the other side. The interpretation of the no-hair theorem is that the universe (observable and unobservable) expands by an enormous factor during inflation. In an expanding universe, energy densities generally fall, or get diluted, as the volume of the universe increases. For example, the density of ordinary "cold" matter (dust) goes down as the inverse of the volume: when linear dimensions double, the energy density goes down by a factor of eight; the radiation energy density goes down even more rapidly as the universe expands since the wavelength of each photon is stretched (redshifted), in addition to the photons being dispersed by the expansion. When linear dimensions are doubled, the energy density in radiation falls by a factor of sixteen. During inflation, the energy density in the inflaton field is roughly constant. However, the energy density in inhomogeneities, curvature, anisotropies and exotic particles is falling, and through sufficient inflation these become negligible. This leaves an empty, flat, and symmetric universe, which is filled with radiation when inflation ends.

Key requirement

A key requirement is that inflation must continue long enough to produce the present observable universe from a single, small inflationary Hubble volume. This is necessary to ensure that the universe appears flat, homogeneous and isotropic at the largest observable scales. This requirement is generally thought to be satisfied if the universe expanded by a factor of at least 10^{26} during inflation.[9]

Reheating

Inflation is a period of supercooled expansion, when the temperature drops by a factor of 100,000 or so. (The exact drop is model dependent, but in the first models it was typically from 10^{27}K down to 10^{22}K.[10]) This relatively low temperature is maintained during the inflationary phase. When inflation ends the temperature returns to the pre-inflationary temperature; this is called *reheating* or thermalization because the large potential energy of the inflaton field decays into particles and fills the universe with Standard Model particles, including electromagnetic radiation, starting the radiation dominated phase of the Universe. Because the nature of the inflation is not known, this process is still poorly understood, although it is believed to take place through a parametric resonance.[11]

Motivations

Inflation resolves several problems in the Big Bang cosmology that were discovered in the 1970s.[12] Inflation was first discovered by Guth while investigating the problem of why we see no magnetic monopoles today; he found that a positive-energy false vacuum would, according to general relativity, generate an exponential expansion of space. It was very quickly realised that such an expansion would resolve many other long-standing problems. These problems arise from the observation that to look like it does *today*, the universe would have to have started from very finely tuned, or "special" initial conditions at the Big Bang. Inflation attempts to resolve these problems by providing a dynamical mechanism that drives the universe to this special state, thus making a universe like ours much more likely in the context of the Big Bang theory.

Horizon problem

The horizon problem is the problem of determining why the universe appears statistically homogeneous and isotropic in accordance with the cosmological principle. For example, molecules in a canister of gas are distributed homogeneously and isotropically because they are in thermal equilibrium: gas throughout the canister has had enough time to interact to dissipate inhomogeneities and anisotropies. The situation is quite different in the big bang model without inflation, because gravitational expansion does not give the early universe enough time to equilibrate. In a big bang with only the matter and radiation known in the Standard Model, two widely separated regions of the observable universe cannot have equilibrated because they move apart from each other faster than the speed of light—thus have never come into causal contact: in the history of the universe, back to the earliest times, it has not been possible to send a light signal between the two regions. Because they have no interaction, it is difficult to explain why they have the same temperature (are thermally equilibrated). This is because the Hubble radius in a radiation or matter-dominated universe expands much more quickly than physical lengths and so points that are out of communication are coming into communication. Historically, two proposed solutions were the *Phoenix universe* of Georges Lemaître[13] and the related oscillatory universe of Richard Chase Tolman,[14] and the Mixmaster universe of Charles Misner. Lemaître and Tolman proposed that a universe undergoing a number of cycles of contraction and expansion could come into thermal equilibrium. Their models failed, however, because of the buildup of entropy over several cycles. Misner made the (ultimately incorrect) conjecture that the Mixmaster mechanism, which made the universe *more* chaotic, could lead to statistical homogeneity and isotropy.

Flatness problem

Another problem is the flatness problem (which is sometimes called one of the Dicke coincidences, with the other being the cosmological constant problem). It had been known in the 1960s[*citation needed*] that the density of matter in the universe was comparable to the critical density necessary for a flat universe (that is, a universe whose large scale geometry is the usual Euclidean geometry, rather than a non-Euclidean hyperbolic or spherical geometry).

Therefore, regardless of the shape of the universe the contribution of spatial curvature to the expansion of the universe could not be much greater than the contribution of matter. But as the universe expands, the curvature redshifts away more slowly than matter and radiation. Extrapolated into the past, this presents a fine-tuning problem because the contribution of curvature to the universe must be exponentially small (sixteen orders of magnitude less than the density of radiation at big bang nucleosynthesis, for example). This problem is exacerbated by recent observations of the cosmic microwave background that have demonstrated that the universe is flat to the accuracy of a few percent.[15]

Magnetic-monopole problem

The magnetic monopole problem (sometimes called the exotic-relics problem) says that if the early universe were very hot, a large number of very heavyWikipedia:Please clarify, stable magnetic monopoles would be produced. This is a problem with Grand Unified Theories, which proposes that at high temperatures (such as in the early universe) the electromagnetic force, strong, and weak nuclear forces are not actually fundamental forces but arise due to spontaneous symmetry breaking from a single gauge theory.[16] These theories predict a number of heavy, stable particles that have not yet been observed in nature. The most notorious is the magnetic monopole, a kind of stable, heavy "knot" in the magnetic field. Monopoles are expected to be copiously produced in Grand Unified Theories at high temperature, and they should have persisted to the present day, to such an extent that they would become the primary constituent of the universe. Not only is that not the case, but all searches for them have so far turned out fruitless, placing stringent limits on the density of relic magnetic monopoles in the universe.[17] A period of inflation that occurs below the temperature where magnetic monopoles can be produced would offer a possible resolution of this problem: monopoles would be separated from each other as the universe around them expands, potentially lowering their observed density by many orders of magnitude. Though, as cosmologist Martin Rees has written, "Skeptics about exotic physics might not be hugely impressed by a theoretical argument to explain the absence of particles that are themselves only hypothetical. Preventive medicine can readily seem 100 percent effective against a disease that doesn't exist!"[18]

History

Precursors

In the early days of General Relativity, Albert Einstein introduced the cosmological constant to allow a static solution which was a three dimensional sphere with a uniform density of matter. A little later, Willem de Sitter found a highly symmetric inflating universe, which described a universe with a cosmological constant which is otherwise empty. It was discovered that Einstein's solution is unstable, and if there are small fluctuations, it eventually either collapses or turns into de Sitter's.

In the early 1970s Zeldovich noticed the serious flatness and horizon problems of big bang cosmology; before his work, cosmology was presumed to be symmetrical on purely philosophical grounds. In the Soviet Union, this and other considerations led Belinski and Khalatnikov to analyze the chaotic BKL singularity in General Relativity. Misner's Mixmaster universe attempted to use this chaotic behavior to solve the cosmological problems, with limited success.

In the late 1970s, Sidney Coleman applied the instanton techniques developed by Alexander Polyakov and collaborators to study the fate of the false vacuum in quantum field theory. Like a metastable phase in statistical mechanics—water below the freezing temperature or above the boiling point—a quantum field would need to nucleate a large enough bubble of the new vacuum, the new phase, in order to make a transition. Coleman found the most likely decay pathway for vacuum decay and calculated the inverse lifetime per unit volume. He eventually noted that gravitational effects would be significant, but he did not calculate these effects and did not apply the results to cosmology.

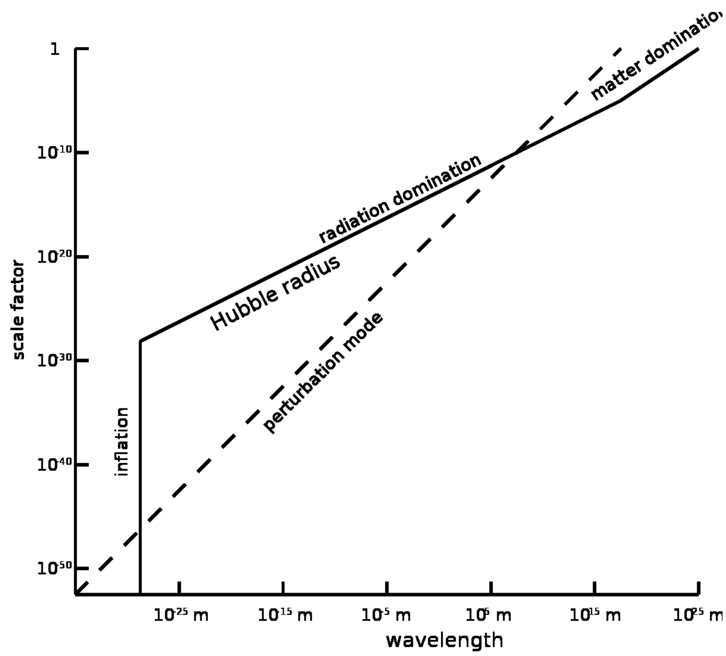
In the Soviet Union, Alexei Starobinsky noted that quantum corrections to general relativity should be important in the early universe, and these generically lead to curvature-squared corrections to the Einstein–Hilbert action. The solution to Einstein's equations in the presence of curvature squared terms, when the curvatures are large, can lead to an effective cosmological constant, so he proposed that the early universe went through a deSitter phase, an inflationary era. This resolved the problems of cosmology, and led to specific predictions for the corrections to the microwave background radiation, corrections which were calculated in detail shortly afterwards.

In 1978, Zeldovich noted the monopole problem, which was an unambiguous quantitative version of the horizon problem, this time in a fashionable subfield of particle physics, which led to several speculative attempts to resolve it. In 1980, working in the west, Alan Guth realized that false vacuum decay in the early universe would solve the problem, leading him to propose scalar driven inflation. Starobinsky's and Guth's scenarios both predicted an initial deSitter phase, differing only in the details of the mechanism.

Early inflationary models

Inflation was proposed in January 1980, by Alan Guth as a mechanism for resolving these problems.[19] At the same time, Starobinsky argued that quantum corrections to gravity would replace the initial singularity of the universe with an exponentially expanding deSitter phase. In October 1980, Demosthenes Kazanas suggested that exponential expansion could eliminate the particle horizon and perhaps solve the horizon problem, while Sato suggested that an exponential expansion could eliminate domain walls (another kind of exotic relic). In 1981 Einhorn and Sato published a model similar to Guth's and showed that it would resolve the puzzle of the magnetic monopole abundance in Grand Unified Theories. Like Guth, they concluded that such a model not only required fine tuning of the cosmological constant, but also would very likely lead to a much too granular universe, i.e., to large density variations resulting from bubble wall collisions.

Guth proposed that as the early universe cooled, it was trapped in a false vacuum with a high energy density, which is much like a cosmological constant. As the very early universe cooled it was trapped in a metastable state (it was supercooled) which it could only decay out of through the process of bubble nucleation via quantum tunneling. Bubbles of true vacuum spontaneously form in the sea of false vacuum and rapidly begin expanding at the speed of light. Guth recognized that this model was problematic because the model did not reheat properly: when the bubbles nucleated, they did not generate any radiation. Radiation could only be generated in collisions between bubble walls. But if inflation lasted long enough to solve the initial conditions problems, collisions between bubbles became exceedingly rare. In any one causal patch it is likely that only one bubble will nucleate.



The physical size of the Hubble radius (solid line) as a function of the linear expansion (scale factor) of the universe. During cosmological inflation, the Hubble radius is constant. The physical wavelength of a perturbation mode (dashed line) is also shown. The plot illustrates how the perturbation mode grows larger than the horizon during cosmological inflation before coming back inside the horizon, which grows rapidly during radiation domination. If cosmological inflation had never happened, and radiation domination continued back until a gravitational singularity, then the mode would never have been outside the horizon in the very early universe, and no causal mechanism could have ensured that the universe was homogeneous on the scale of the perturbation mode.

Slow-roll inflation

The bubble collision problem was solved by Andrei Linde and independently by Andreas Albrecht and Paul Steinhardt in a model named *new inflation* or *slow-roll inflation* (Guth's model then became known as *old inflation*). In this model, instead of tunneling out of a false vacuum state, inflation occurred by a scalar field rolling down a potential energy hill. When the field rolls very slowly compared to the expansion of the universe, inflation occurs. However, when the hill becomes steeper, inflation ends and reheating can occur.

Effects of asymmetries

Eventually, it was shown that new inflation does not produce a perfectly symmetric universe, but that tiny quantum fluctuations in the inflaton are created. These tiny fluctuations form the primordial seeds for all structure created in the later universe. These fluctuations were first calculated by Viatcheslav Mukhanov and G. V. Chibisov in the Soviet Union in analyzing Starobinsky's similar model.[20] In the context of inflation, they were worked out independently of the work of Mukhanov and Chibisov at the three-week 1982 Nuffield Workshop on the Very Early Universe at Cambridge University.[21] The fluctuations were calculated by four groups working separately over the course of the workshop: Stephen Hawking; Starobinsky; Guth and So-Young Pi; and James M. Bardeen, Paul Steinhardt and Michael Turner.

Observational status

Inflation is a mechanism for realizing the cosmological principle which is the basis of the standard model of physical cosmology: it accounts for the homogeneity and isotropy of the observable universe. In addition, it accounts for the observed flatness and absence of magnetic monopoles. Since Guth's early work, each of these observations has received further confirmation, most impressively by the detailed observations of the cosmic microwave background made by the Wilkinson Microwave Anisotropy Probe (WMAP) spacecraft.[22] This analysis shows that the universe is flat to an accuracy of at least a few percent, and that it is homogeneous and isotropic to a part in 10,000.

In addition, inflation predicts that the structures visible in the universe today formed through the gravitational collapse of perturbations which were formed as quantum mechanical fluctuations in the inflationary epoch. The detailed form of the spectrum of perturbations called a nearly-scale-invariant Gaussian random field (or Harrison–Zel'dovich spectrum) is very specific and has only two free parameters, the amplitude of the spectrum and the *spectral index* which measures the slight deviation from scale invariance predicted by inflation (perfect scale invariance corresponds to the idealized de Sitter universe).[23] Inflation predicts that the observed perturbations should be in thermal equilibrium with each other (these are called *adiabatic* or *isentropic* perturbations). This structure for the perturbations has been confirmed by the WMAP spacecraft and other cosmic microwave background experiments, and galaxy surveys, especially the ongoing Sloan Digital Sky Survey. These experiments have shown that the one part in 10,000 inhomogeneities observed have exactly the form predicted by theory. Moreover, there is evidence for a slight deviation from scale invariance. The *spectral index*, n_s is equal to one for a scale-invariant spectrum. The simplest models of inflation predict that this quantity is between 0.92 and 0.98.[24] From the data taken by the WMAP spacecraft it can be inferred that $n_s = 0.963 \pm 0.012$, implying that it differs from one at the level of two standard deviations (2σ). This is considered an important confirmation of the theory of inflation.

A number of theories of inflation have been proposed that make radically different predictions, but they generally have much more fine tuning than is necessary. As a physical model, however, inflation is most valuable in that it robustly predicts the initial conditions of the universe based on only two adjustable parameters: the spectral index (that can only change in a small range) and the amplitude of the perturbations. Except in contrived models, this is true regardless of how inflation is realized in particle physics.

Occasionally, effects are observed that appear to contradict the simplest models of inflation. The first-year WMAP data suggested that the spectrum might not be nearly scale-invariant, but might instead have a slight curvature. However, the third-year data revealed that the effect was a statistical anomaly. Another effect has been remarked upon since the first cosmic microwave background satellite, the Cosmic Background Explorer: the amplitude of the quadrupole moment of the cosmic microwave background is unexpectedly low and the other low multipoles appear to be preferentially aligned with the ecliptic plane. Some have claimed that this is a signature of non-Gaussianity and thus contradicts the simplest models of inflation. Others have suggested that the effect may be due to other new physics, foreground contamination, or even publication bias.[25]

An experimental program is underway to further test inflation with more precise measurements of the cosmic microwave background. In particular, high precision measurements of the so-called "B-modes" of the polarization of the background radiation will be evidence of the gravitational radiation produced by inflation, and they will also show whether the energy scale of inflation predicted by the simplest models (10^{15}–10^{16} GeV) is correct. These measurements are expected to be performed by the Planck spacecraft, although it is unclear if the signal will be visible, or if contamination from foreground sources will interfere with these measurements. Other forthcoming measurements, such as those of 21 centimeter radiation (radiation emitted and absorbed from neutral hydrogen before the first stars turned on), may measure the power spectrum with even greater resolution than the cosmic microwave background and galaxy surveys, although it is not known if these measurements will be possible or if interference with radio sources on earth and in the galaxy will be too great.

Dark energy is broadly similar to inflation, and is thought to be causing the expansion of the present-day universe to accelerate. However, the energy scale of dark energy is much lower, 10^{-12} GeV, roughly 27 orders of magnitude less than the scale of inflation.

Theoretical status

List of unsolved problems in physics

Is the theory of cosmological inflation correct, and if so, what are the details of this epoch? What is the hypothetical inflaton field giving rise to inflation?

In the early proposal of Guth, it was thought that the inflaton was the Higgs field, the field which explains the mass of the elementary particles. It is now believed that the inflaton cannot be the Higgs field although the recent discovery of the Higgs boson has increased the number of works considering the Higgs field as inflaton.[*citation needed*] Other models of inflation relied on the properties of grand unified theories. Since the simplest models of grand unification have failed, it is now thought by many physicists that inflation will be included in a supersymmetric theory like string theory or a supersymmetric grand unified theory. At present, while inflation is understood principally by its detailed predictions of the initial conditions for the hot early universe, the particle physics is largely *ad hoc* modelling. As such, though predictions of inflation have been consistent with the results of observational tests, there are many open questions about the theory.

Fine-tuning problem

One of the most severe challenges for inflation arises from the need for fine tuning in inflationary theories. In new inflation, the *slow-roll conditions* must be satisfied for inflation to occur. The slow-roll conditions say that the inflaton potential must be flat (compared to the large vacuum energy) and that the inflaton particles must have a small mass.[26] In order for the new inflation theory of Linde, Albrecht and Steinhardt to be successful, therefore, it seemed that the universe must have a scalar field with an especially flat potential and special initial conditions.

Andrei Linde

Andrei Linde proposed a theory known as *chaotic inflation* in which he suggested that the conditions for inflation are actually satisfied quite generically and inflation will occur in virtually any universe that begins in a chaotic, high energy state and has a scalar field with unbounded potential energy. However, in his model the inflaton field necessarily takes values larger than one Planck unit: for this reason, these are often called *large field* models and the competing new inflation models are called *small field* models. In this situation, the predictions of effective field theory are thought to be invalid, as renormalization should cause large corrections that could prevent inflation.[27] This problem has not yet been resolved and some cosmologists argue that the small field models, in which inflation can occur at a much lower energy scale, are better models of inflation.[28] While inflation depends on quantum field theory (and the semiclassical approximation to quantum gravity) in an important way, it has not been completely reconciled with these theories.

Robert Brandenberger has commented on fine-tuning in another situation. The amplitude of the primordial inhomogeneities produced in inflation is directly tied to the energy scale of inflation. There are strong suggestions that this scale is around 10^{16} GeV or 10^{-3} times the Planck energy. The natural scale is naïvely the Planck scale so this small value could be seen as another form of fine-tuning (called a hierarchy problem): the energy density given by the scalar potential is down by 10^{-12} compared to the Planck density. This is not usually considered to be a critical problem, however, because the scale of inflation corresponds naturally to the scale of gauge unification.

Eternal inflation

In many models of inflation, the inflationary phase of the universe's expansion lasts forever in at least some regions of the universe. This occurs because inflating regions expand very rapidly, reproducing themselves. Unless the rate of decay to the non-inflating phase is sufficiently fast, new inflating regions are produced more rapidly than non-inflating regions. In such models most of the volume of the universe at any given time is inflating. All models of eternal inflation produce an infinite multiverse, typically a fractal.

Although new inflation is classically rolling down the potential, quantum fluctuations can sometimes bring it back up to previous levels. These regions in which the inflaton fluctuates upwards expand much faster than regions in which the inflaton has a lower potential energy, and tend to dominate in terms of physical volume. This steady state, which first developed by Vilenkin, is called "eternal inflation". It has been shown that any inflationary theory with an unbounded potential is eternal.Wikipedia:Verifiability It is a popular conclusion among physicists that this steady state cannot continue forever into the past. The inflationary spacetime, which is similar to de Sitter space, is incomplete without a contracting region. However, unlike de Sitter space, fluctuations in a contracting inflationary space will collapse to form a gravitational singularity, a point where densities become infinite. Therefore, it is necessary to have a theory for the universe's initial conditions. Linde, however, believes inflation may be past eternal.[29]

Initial conditions

Some physicists have tried to avoid the initial conditions problem by proposing models for an eternally inflating universe with no origin. These models propose that while the universe, on the largest scales, expands exponentially it was, is and always will be, spatially infinite and has existed, and will exist, forever.

Other proposals attempt to describe the ex nihilo creation of the universe based on quantum cosmology and the following inflation. Vilenkin put forth one such scenario. Hartle and Hawking offered the no-boundary proposal for the initial creation of the universe in which inflation comes about naturally.[30]

Alan Guth has described the inflationary universe as the "ultimate free lunch":[31][32] new universes, similar to our own, are continually produced in a vast inflating background. Gravitational interactions, in this case, circumvent (but do not violate) the first law of thermodynamics (energy conservation) and the second law of thermodynamics (entropy and the arrow of time problem). However, while there is consensus that this solves the initial conditions problem, some have disputed this, as it is much more likely that the universe came about by a quantum fluctuation. Donald Page was an outspoken critic of inflation because of this anomaly.[33] He stressed that the thermodynamic arrow of time necessitates low entropy initial conditions, which would be highly unlikely. According to them, rather than solving this problem, the inflation theory further aggravates it – the reheating at the end of the inflation era increases entropy, making it necessary for the initial state of the Universe to be even more orderly than in other Big Bang theories with no inflation phase.

Hawking and Page later found ambiguous results when they attempted to compute the probability of inflation in the Hartle-Hawking initial state. Other authors have argued that, since inflation is eternal, the probability doesn't matter as long as it is not precisely zero: once it starts, inflation perpetuates itself and quickly dominates the universe.[*citation needed*] However, Albrecht and Lorenzo Sorbo have argued that the probability of an inflationary cosmos, consistent with today's observations, emerging by a random fluctuation from some pre-existent state, *compared* with a non-inflationary cosmos overwhelmingly favours the inflationary scenario, simply because the "seed" amount of non-gravitational energy required for the inflationary cosmos is so much less than any required for a non-inflationary alternative, which outweighs any entropic considerations.

Another problem that has occasionally been mentioned is the trans-Planckian problem or trans-Planckian effects. Since the energy scale of inflation and the Planck scale are relatively close, some of the quantum fluctuations which have made up the structure in our universe were smaller than the Planck length before inflation. Therefore, there ought to be corrections from Planck-scale physics, in particular the unknown quantum theory of gravity. There has been some disagreement about the magnitude of this effect: about whether it is just on the threshold of detectability or completely undetectable.

Hybrid inflation

Another kind of inflation, called *hybrid inflation*, is an extension of new inflation. It introduces additional scalar fields, so that while one of the scalar fields is responsible for normal slow roll inflation, another triggers the end of inflation: when inflation has continued for sufficiently long, it becomes favorable to the second field to decay into a much lower energy state.[34]

In hybrid inflation, one of the scalar fields is responsible for most of the energy density (thus determining the rate of expansion), while the other is responsible for the slow roll (thus determining the period of inflation and its termination). Thus fluctuations in the former inflaton would not affect inflation termination, while fluctuations in the latter would not affect the rate of expansion. Therefore hybrid inflation is not eternal.[35][36] When the second (slow-rolling) inflaton reaches the bottom of its potential, it changes the location of the minimum of the first inflaton's potential, which leads to a fast roll of the inflaton down its potential, leading to termination of inflation.

Inflation and string cosmology

The discovery of flux compactifications have opened the way for reconciling inflation and string theory. A new theory, called *brane inflation* suggests that inflation arises from the motion of D-branes[37] in the compactified geometry, usually towards a stack of anti-D-branes. This theory, governed by the *Dirac-Born-Infeld action*, is very different from ordinary inflation. The dynamics are not completely understood. It appears that special conditions are necessary since inflation occurs in tunneling between two vacua in the string landscape. The process of tunneling between two vacua is a form of old inflation, but new inflation must then occur by some other mechanism.

Inflation and loop quantum gravity

When investigating the effects the theory of loop quantum gravity would have on cosmology, a loop quantum cosmology model has evolved that provides a possible mechanism for cosmological inflation. Loop quantum gravity assumes a quantized spacetime. If the energy density is larger than can be held by the quantized spacetime, it is thought to bounce back.

Alternatives to inflation

The flatness and horizon problems are naturally solved in the Einstein-Cartan-Sciama-Kibble theory of gravity, without needing an exotic form of matter and introducing free parameters. This theory extends general relativity by removing a constraint of the symmetry of the affine connection and regarding its antisymmetric part, the torsion tensor, as a dynamical variable. The minimal coupling between torsion and Dirac spinors generates a spin-spin interaction which is significant in fermionic matter at extremely high densities. Such an interaction averts the unphysical Big Bang singularity, replacing it with a cusp-like bounce at a finite minimum scale factor, before which the Universe was contracting. The rapid expansion immediately after the Big Bounce explains why the present Universe at largest scales appears spatially flat, homogeneous and isotropic. As the density of the Universe decreases, the effects of torsion weaken and the Universe smoothly enters the radiation-dominated era.

There are models that explain some of the observations explained by inflation. However none of these "alternatives" has the same breadth of explanation as inflation, and still require inflation for a more complete fit with observation; they should therefore be regarded as adjuncts to inflation, rather than as alternatives.

String theory requires that, in addition to the three spatial dimensions we observe, there exist additional dimensions that are curled up or compactified (see also Kaluza–Klein theory). Extra dimensions appear as a frequent component of supergravity models and other approaches to quantum gravity. This raised the contingent question of why four space-time dimensions became large and the rest became unobservably small. An attempt to address this question, called *string gas cosmology*, was proposed by Robert Brandenberger and Cumrun Vafa. This model focuses on the dynamics of the early universe considered as a hot gas of strings. Brandenberger and Vafa show that a dimension of spacetime can only expand if the strings that wind around it can efficiently annihilate each other. Each string is a one-dimensional object, and the largest number of dimensions in which two strings will generically intersect (and, presumably, annihilate) is three. Therefore, one argues that the most likely number of non-compact (large) spatial dimensions is three. Current work on this model centers on whether it can succeed in stabilizing the size of the compactified dimensions and produce the correct spectrum of primordial density perturbations. For a recent review, see The authors admits that their model "does not solve the entropy and flatness problems of standard cosmology ..... and we can provide no explanation for why the current universe is so close to being spatially flat."

The ekpyrotic and cyclic models are also considered adjuncts to inflation. These models solve the horizon problem through an expanding epoch well *before* the Big Bang, and then generate the required spectrum of primordial density perturbations during a contracting phase leading to a Big Crunch. The universe passes through the Big Crunch and emerges in a hot Big Bang phase. In this sense they are reminiscent of the oscillatory universe proposed by Richard Chace Tolman: however in Tolman's model the total age of the universe is necessarily finite, while in these models this is not necessarily so. Whether the correct spectrum of density fluctuations can be produced, and whether the universe can successfully navigate the Big Bang/Big Crunch transition, remains a topic of controversy and current research. Ekpyrotic models avoid the magnetic monopole problem as long as the temperature at the Big Crunch/Big Bang transition remains below the Grand Unified Scale, as this is the temperature required to produce magnetic monopoles in the first place. As things stand, there is no evidence of any 'slowing down' of the expansion, but this is not surprising as each cycle is expected to last on the order of a trillion years.

Another adjunct, the varying speed of light model has also been theorized by Jean-Pierre Petit in 1988, John Moffat in 1992 as well Andreas Albrecht and João Magueijo in 1999, instead of superluminal expansion the speed of light was 60 orders of magnitude faster than its current value solving the horizon and homogeneity problems in the early universe.

Criticisms

Since its introduction by Alan Guth in 1980, the inflationary paradigm has become widely accepted. Nevertheless, many physicists, mathematicians, and philosophers of science have voiced criticisms, claiming unfulfilled promises and lack of serious empirical support. In 1999, John Earman and Jesús Mosterín published a thorough critical review of inflationary cosmology, concluding that “we do not think that there are, as yet, good grounds for admitting any of the models of inflation into the standard core of cosmology”.

In order to work, and as pointed out by Roger Penrose from 1986 on, inflation requires extremely specific initial conditions of its own, so that the problem (or pseudoproblem) of initial conditions is not solved: “There is something fundamentally misconceived about trying to explain the uniformity of the early universe as resulting from a thermalization process. […] For, if the thermalization is actually doing anything […] then it represents a definite increasing of the entropy. Thus, the universe would have been even more special before the thermalization than after.”[38] The problem of specific or “fine-tuned” initial conditions would not have been solved; it would have gotten worse.

A recurrent criticism of inflation is that the invoked inflation field does not correspond to any known physical field, and that its potential energy curve seems to be an ad hoc contrivance to accommodate almost any data we could get. Paul J. Steinhardt, one of the founding fathers of inflationary cosmology, has recently become one of its sharpest critics. He calls ‘bad inflation’ a period of accelerated expansion whose outcome conflicts with observations, and ‘good inflation’ one compatible with them: “Not only is bad inflation more likely than good inflation, but no inflation is more likely than either. … Roger Penrose considered all the possible configurations of the inflaton and gravitational fields. Some of these configurations lead to inflation … Other configurations lead to a uniform, flat universe directly –without inflation. Obtaining a flat universe is unlikely overall. Penrose's shocking conclusion, though, was that obtaining a flat universe without inflation is much more likely than with inflation –by a factor of 10 to the googol (10 to the 100) power!"[39]

Notes

[1] Liddle and Lyth (2000) and Mukhanov (2005) are recent cosmology text books with extensive discussions of inflation. Kolb and Turner (1988) and Linde (1990) miss some recent developments, but are still widely used. Peebles (1993) provides a technical discussion with historical context. Recent review articles are Lyth and Riotto (1999) and Linde (2012). Guth (1997) and Hawking (1998) give popular introductions to inflation with historical remarks.

[2] Chapter 17 of Peebles (1993).

[3] Tyson, Neil deGrasse and Donald Goldsmith (2004), *Origins: Fourteen Billion Years of Cosmic Evolution*, W. W. Norton & Co., pp. 84–5.

[4] Using Tiny Particles To Answer Giant Questions (http://www.npr.org/templates/story/story.php?storyId=102715275). Science Friday, 3 April 2009.

[5] See also Faster than light#Universal_expansion.

[6] Melia, Fulvio (2007), *The Cosmic Horizon*, MNRAS, **382**, 1917–1921.

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[11] See Kolb and Turner (1988) or Mukhanov (2005).

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[16] Since supersymmetric Grand Unified Theory is built into string theory, it is still a triumph for inflation that it is able to deal with these magnetic relics. See, *e.g.* Kolb and Turner (1988) and

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[20] See Linde (1990) and Mukhanov (2005).

[21] See Guth (1997) for a popular description of the workshop, or *The Very Early Universe*, ISBN 0-521-31677-4 eds Hawking, Gibbon & Siklos for a more detailed report

[22] See, *e.g.*

[23] Perturbations can be represented by Fourier modes of a wavelength. Each Fourier mode is normally distributed (usually called Gaussian) with mean zero. Different Fourier components are uncorrelated. The variance of a mode depends only on its wavelength in such a way that within any given volume each wavelength contributes an equal amount of power to the spectrum of perturbations. Since the Fourier transform is in three dimensions, this means that the variance of a mode goes as k^{-3} to compensate for the fact that within any volume, the number of modes with a given wavenumber k goes as k^3.

[24] This is known as a "red" spectrum, in analogy to redshift, because the spectrum has more power at longer wavelengths.

[25] See cosmic microwave background#Low multipoles for details and references.

[26] Technically, these conditions are that the logarithmic derivative of the potential, UNIQ-math-0-65a9c537dc913223-QINU and second derivative UNIQ-math-1-65a9c537dc913223-QINU are small, where UNIQ-math-2-65a9c537dc913223-QINU is the potential and the equations are written in reduced Planck units. See, *e.g.* Liddle and Lyth (2000).

[27] Technically, this is because the inflaton potential is expressed as a Taylor series in φ/m_{Pl}, where φ is the inflaton and m_{Pl} is the Planck mass. While for a single term, such as the mass term $m_{\varphi}^{4}(\varphi/m_{\text{Pl}})^2$, the slow roll conditions can be satisfied for φ much greater than m_{Pl}, this is precisely the situation in effective field theory in which higher order terms would be expected to contribute and destroy the conditions for inflation. The absence of these higher order corrections can be seen as another sort of fine tuning. See *e.g.*

[28] See, *e.g.*

[29] Linde (2005, §V).

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Modified Newtonian dynamics

In physics, **Modified Newtonian Dynamics** (**MoND**) is a theory that proposes a modification of Newton's law of gravity to explain the galaxy rotation problem. When the uniform velocity of rotation of galaxies was first observed, it was unexpected because Newtonian theory of gravity predicts that objects that are farther out will have lower velocities. For example, planets in the Solar System orbit with velocities that decrease as their distance from the Sun increases.

MoND was proposed by Mordehai Milgrom in 1983 as a way to model this observed uniform velocity data.[1] Milgrom noted that Newton's law for gravitational force has been verified only where gravitational acceleration is large, and suggested that for extremely small accelerations the theory may not hold. MoND theory posits that acceleration is not linearly proportional to gravitational force at small values.

MoND stands in contrast to the more widely accepted theory of dark matter. Dark matter theory suggests that each galaxy contains a halo of an as yet unidentified type of matter that provides an overall mass distribution different from the observed distribution of normal matter. This dark matter accounts for the uniform rotation velocity data without modifying Newton's law of gravity.

Overview: Galaxy dynamics

The original purpose of MoND was to explain the galactic rotation curves for spiral galaxies. A spiral galaxy consists of a bulge of stars at the centre with a vast disc of stars orbiting around the central group. If the orbits of the stars were governed solely by gravitational force and the observed distribution of normal matter (stars, gas clouds, dust, etc.), it was expected that stars at the outer edge of the disc would have a much lower orbital velocity than those near the middle. In the observed galaxies this pattern is not apparent. Stars near the outer edge orbit the centre of the galaxy at the same speed as stars closer to the middle.

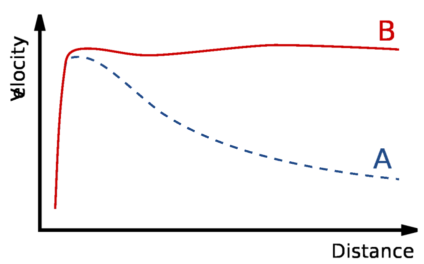

Figure 1 - Expected (A) and observed (B) star velocities as a function of distance from the galactic center.

The dotted curve A in Figure 1 at left shows the predicted orbital velocity as a function of distance from the galactic center assuming neither MoND nor dark matter. The solid curve B shows the observed distribution. Instead of decreasing asymptotically to zero as the effect of gravity wanes, this curve remains flat, showing the same velocity at increasing distances from the bulge. Astronomers call this phenomenon the "flattening of galaxies' rotation curves".

Scientists hypothesized that the flatness of the rotation of galaxies is caused by matter outside the galaxy's visible disc. Since all large galaxies show the same characteristic, large galaxies must, according to this line of reasoning, be embedded in a halo of invisible "dark" matter.

Publication of the MoND theory

In 1983, Mordehai Milgrom, a physicist at the Weizmann Institute in Israel, published three papers in *Astrophysical Journal* to propose a modification of Newton's law of gravity. A pedagogical introduction to MoND can be found in Bekenstein, who characterizes MoND as follows: "Relativistic MoND as here described has developed from the ground up, rather than coming down from the sky: phenomenology, rather than pure theoretical ideas."

Actually, Milgrom provided several interpretations of his proposal, one being a modification of Newton's second law of motion. However, this proposed interpretation is inconsistent with conservation of momentum, requiring some unconventional physical assumptions to regain plausibility. A second interpretation, as a modification of the law of gravity, requires that the acceleration due to gravitational force not depend simply upon the mass *m*, but upon the form $m/\mu(a/a_0)$, where μ is some function approaching the value one for large arguments and a/a_0 for small arguments, and a is the acceleration caused by gravity and a_0 is a natural constant, $a_0 \approx 10^{-10}$ m/s^2. The centripetal accelerations of stars and gas clouds at the outskirts of spiral galaxies tend to be below a_0. This interpretation is also inconsistent with momentum conservation; but this can be repaired by substituting a Lagrangian-based theory known as AQUAL; it reproduces MoND for spherical or disc-like galaxies, and is very similar even for general elliptical galaxies.

A third interpretation views MoND simply as a description of the behavior of the dark matter in a galaxy; this leads to the conclusion that the dark matter must be tightly correlated with the visible matter in accordance with a fixed law, at least for stable galaxies (not engaged in strong interactions with other galaxies). But one would expect instead that the ratio of dark-to-visible matter would depend on the history of the galaxy.

The exact form of μ is unspecified, only its asymptotic behavior when the argument a/a_0 is small or large. As Milgrom proved in his original paper, the form of μ does not change most of the consequences of the theory, such as the flattening of the rotation curve. Empirically, a good description of galaxy rotation curves is given by [2]

$$\mu\left(\frac{a}{a_0}\right) = \left(1 + \frac{a_0}{a}\right)^{-1};$$

a possible physical motivation of this functional form is provided by the assumption that gravity is mediated by gravitons with non-zero mass.[3]

In the everyday world, a is much greater than a_0 for all physical effects, therefore $\mu(a/a_0)=1$ and $F=ma$ as usual. Consequently, the change in Newton's law of gravity is negligible and Newton could not have seen it.

Predicted rotation curve

Far away from the center of a galaxy, the gravitational acceleration, a, that a star undergoes is predicted by MoND to be roughly:

$$\mu\left(\frac{a}{a_0}\right)a = \frac{GM}{r^2}$$

with G the gravitation constant, M the mass of the galaxy, and r the distance between the center and the star.

Assuming that, at this large distance r, a is smaller than a_0, $\mu\left(\frac{a}{a_0}\right) = \frac{a}{a_0}$. This gives:

$$\frac{GM}{r^2} = \frac{a^2}{a_0}$$

Therefore:

$$a = \frac{\sqrt{GMa_0}}{r}$$

Since the equation that relates the velocity to the acceleration for a circular orbit is $a = \frac{v^2}{r}$, one has:

$$a = \frac{v^2}{r} = \frac{\sqrt{GMa_0}}{r}$$

and therefore:

$$v = \sqrt[4]{GMa_0}$$

Consequently, the velocity of stars on a circular orbit far from the center is a constant, and does not depend on the distance *r* : the rotation curve is flat.

The proportion between the "flat" rotation velocity to the observed mass derived here is matching the observed relation between "flat" velocity to luminosity known as the Tully-Fisher relation.

At the same time, there is a clear relationship between the velocity and the constant a_0. The equation $v=(GMa_0)^{1/4}$ allows one to calculate a_0 from the observed v and M. Milgrom found $a_0=1.2\times10^{-10}$ ms^{-2}. As expected, this quantity is far smaller than any acceleration typically found in solar system-scale interactions.

To explain the meaning of this constant, Milgrom said : "... It is roughly the acceleration that will take an object from rest to the speed of light in the lifetime of the universe. It is also of the order of the recently discovered acceleration of the universe."[4][5]

Consistency with the observations

According to the Modified Newtonian Dynamics theory, every physical process that involves small accelerations due to gravity will have an outcome different from that predicted by the simple law *F=ma*. Therefore, astronomers need to look for all such processes and verify that MoND remains compatible with observations, that is, within the limit of the uncertainties on the data. There is, however, a complication overlooked up to this point but that strongly affects the compatibility between MoND and the observed world: in a system considered as isolated, for example a single satellite orbiting a planet, the effect of MoND results in an increased velocity beyond a given range (actually, below a given acceleration, but for circular orbits it is the same thing) that depends on the mass of both the planet and the satellite. However, if the same system is actually orbiting a star, the planet and the satellite will be accelerated in the star's gravitational field. For the satellite, the sum of the two fields could yield acceleration greater than a_0, and the orbit would not be the same as that in an isolated system.

For this reason, the typical acceleration of any physical process is not the only parameter astronomers must consider. Also critical is the process's environment, which is all external forces that are usually neglected. In his paper, Milgrom arranged the typical acceleration of various physical processes in a two-dimensional diagram. One parameter is the acceleration of the process itself, the other parameter is the acceleration induced by the environment.

This affects MoND's application to experimental observation and empirical data because all experiments done on Earth or its neighborhood are subject to the Sun's gravitational field, and this field is so strong that all objects in the Solar system undergo an acceleration greater than a_0. This explains why the flattening of galaxies' rotation curve, or the MoND effect, had not been detected until the early 1980s, when astronomers first gathered empirical data on the rotation of galaxies.

Therefore, only galaxies and other large systems are expected to exhibit the dynamics that will allow astronomers to verify that MoND agrees with observation. Since Milgrom's theory first appeared in 1983, the most accurate data has come from observations of distant galaxies and neighbors of the Milky Way. Within the uncertainties of the data, MoND has remained valid. The Milky Way itself is scattered with clouds of gas and interstellar dust, and until now it has not been possible to draw a rotation curve for the galaxy. Finally, the uncertainties on the velocity of galaxies within clusters and larger systems have been too large to conclude in favor of or against MoND. Indeed, conditions for conducting an experiment that could confirm or disprove MoND may only be possible outside the Solar system. A couple of near-to-Earth tests of MoND have been proposed though: one involves flying the LISA Pathfinder spacecraft through the Earth-Sun saddlepoint;[6] another involves using a precisely controlled spinning disk to cancel out the acceleration effects of Earth's orbit around the Sun, and Sun's orbit around the galaxy;[7] if either of these tests are carried out, and if MoND holds true, then they should feel a slight kick as they approach the very low acceleration levels required by MoND.

In search of observations that would validate his theory, Milgrom noticed that a special class of objects, the low surface brightness galaxies (LSB), is of particular interest: the radius of an LSB is large compared to its mass, and thus almost all stars are within the flat part of the rotation curve. Also, other theories predict that the velocity at the edge depends on the average surface brightness in addition to the LSB mass. Finally, no data on the rotation curve of these galaxies was available at the time. Milgrom thus could make the prediction that LSBs would have a rotation curve which is essentially flat, and with a relation between the flat velocity and the mass of the LSB identical to that of brighter galaxies.

Since then, the majority of LSBs observed has been consistent with the rotational curve predicted by MoND.

An exception to MoND other than LSB is prediction of the speeds of galaxies that gyrate around the center of a galaxy cluster. Our galaxy is part of the Virgo supercluster. MoND predicts a rate of rotation of these galaxies about their center, and temperature distributions, that are contrary to observation.

Computer simulations show that MoND is generally very precise at predicting individual galaxy rotation curves, of all kinds of galaxies: spirals, ellipticals,[8] dwarfs,[9] etc. However, MoND and MoND-like theories are not so good at predicting galactic cluster-scale, or cosmological scale structures.[*citation needed*]

A test that might disprove MoND would be to discover any of the theorized Dark Matter particles, such as the WIMPs.

A recent proposal is that MoND successfully predicts the *local galactic escape speed* of the Milky Way, a measure of the mass beyond the galactocentric radius of the Sun.

Lee Smolin and co-workers have tried unsuccessfully to obtain a theoretical basis for MoND from quantum gravity. His conclusion is "MoND is a tantalizing mystery, but not one that can be resolved now."

In 2011 University of Maryland Astronomy Professor, Stacy McGaugh, examined the rotation of gas rich galaxies, which have relatively fewer stars and a prevalence of mass in the form of interstellar gas. This allowed the mass of the galaxy to be more accurately determined since matter in the form of gas is easier to see and measure than matter in the form of stars or planets. McGaugh studied a sample of 47 galaxies and compared each one's mass and speed of rotation with the ratio expected from MoND predictions. All 47 galaxies fell on or very close to the MoND prediction. No dark matter model performed as well. On the other hand, another 2011 study observing the gravity-induced redshift of galactic clusters found results that strongly supported general relativity, but were inconsistent with MoND.[10] A recent work has found mistakes in the work by Wojtak, Hansen, and Hjorth, and confirmed that MoND can fit the determined redshifts only slightly worse than does general relativity with dark halos.

The mathematics of MoND

In non-relativistic Modified Newtonian Dynamics, Poisson's equation,

$$\nabla^2\Phi_N = 4\pi G\rho$$

(where Φ_N is the gravitational potential and ρ is the density distribution) is modified as

$$\nabla\cdot\left[\mu\left(\frac{\|\nabla\Phi\|}{a_0}\right)\nabla\Phi\right] = 4\pi G\rho$$

where Φ is the MOND potential. The a_0 is a natural constant, approximately equal to $10^{-10}\ m/s^2$. It is a fact that the centripetal accelerations of stars and gas clouds in the outskirts of spiral galaxies tend to be below a_0.
The equation is to be solved with boundary condition $\|\nabla\Phi\| \rightarrow 0$ for $\|\mathbf{r}\| \rightarrow \infty$. The exact form of $\mu(\xi)$ is not constrained by observations, but must have the behaviour $\mu(\xi) \sim 1$ for $\xi \gg 1$ (Newtonian regime), $\mu(\xi) \sim \xi$ for $\xi \ll 1$ (Deep-MoND regime). In the deep-MoND regime, the modified Poisson equation may be

rewritten as

$$\nabla \cdot \left[\frac{\|\nabla\Phi\|}{a_0} \nabla\Phi - \nabla\Phi_N \right] = 0$$

and that simplifies to

$$\frac{\|\nabla\Phi\|}{a_0} \nabla\Phi - \nabla\Phi_N = \nabla \times \mathbf{h}.$$

The vector field $\mathbf{h}$ is unknown, but is null whenever the density distribution is spherical, cylindrical or planar. In that case, MoND acceleration field is given by the simple formula

$$\mathbf{g}_M = \mathbf{g}_N \sqrt{\frac{a_0}{\|\mathbf{g}_N\|}}$$

where $\mathbf{g}_N$ is the normal Newtonian field.

The External Field Effect (EFE)

In MoND it turns out that if a weakly gravitationally bound system *s*, whose inner accelerations are expected to be of the order of 10^{-10} m s^{-2} from a Newtonian calculation, is embedded in an external gravitational field E_g generated by a larger array of masses *S*, then, even if E_g is uniform throughout the spatial extension of *s*, the internal dynamics of the latter is influenced by E_g in such a way that the total acceleration within *s* is, actually, larger than 10^{-10} m s^{-2}. In other words, the Strong Equivalence Principle is violated. Milgrom originally introduced such a concept to explain the fact that the expected phenomenology of dark matter—-to be explained in terms of MoND—-was absent just in some systems (open clusters) in which it should have, instead, been present. It was shown later by R. Scarpa and collaborators that also a number of globular clusters in the neighborhood of the Milky Way behave in the same way, that is MoND effects are seen even though the total (internal+external) field is above MoND acceleration limit.

Discussion and criticisms

An empirical criticism of MoND, released in August 2006, involves the Bullet cluster,[11] a system of two colliding galaxy clusters. In most instances where phenomena associated with either MoND or dark matter are present, they appear to flow from physical locations with similar centers of gravity. But, the dark matter-like effects in this colliding galactic cluster system appears to emanate from different points in space than the center of mass of the visible matter in the system, which is unusually easy to discern due to the high-energy collisions of the gas in the vicinity of the colliding galactic clusters. MoND proponents admit that a purely baryonic MoND is not able to explain this observation. Therefore a “marriage” of MoND with ordinary hot neutrinos of 2eV has been proposed to save the hypothesis.

Beside MoND, three other notable theories that try to explain the mystery of the rotational curves are Nonsymmetric Gravitational Theory proposed by John Moffat, Conformal gravity by Philip Mannheim, and Dynamic Newtonian Advanced gravity (DNAg)[12]

Tensor–vector–scalar gravity

Tensor–Vector–Scalar Gravity (TeVeS) is a proposed relativistic theory that is equivalent to Modified Newtonian Dynamics (MoND) in the non-relativistic limit, which purports to explain the galaxy rotation problem without invoking dark matter. Originated by Jacob Bekenstein in 2004, it incorporates various dynamical and non-dynamical tensor fields, vector fields and scalar fields.

The break-through of TeVeS over MoND is that it can explain the phenomenon of gravitational lensing, a cosmic phenomenon in which nearby matter bends light, which has been confirmed many times.

A recent preliminary finding is that it can explain structure formation without cold dark matter (CDM), but requiring ~2eV massive neutrinos. However, other authors[13] claim that TeVeS can't explain cosmic microwave background anisotropies and structure formation at the same time, i.e. ruling out those models at high significance.

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External links

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Towards a physical model

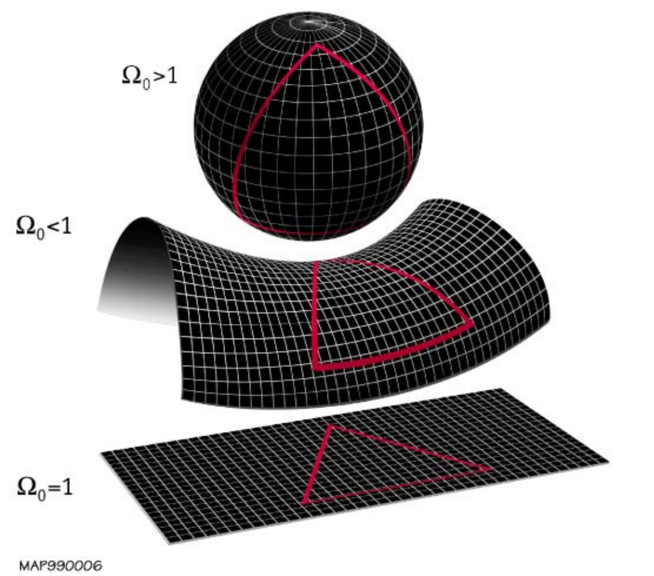
Shape of the universe

The **shape of the universe** is the local and global geometry of the universe, in terms of both curvature and topology (though, strictly speaking, it goes beyond both). Although the shape of the universe is still a matter of debate in physical cosmology, based on the recent Wilkinson Microwave Anisotropy Probe (WMAP) measurements "We now know that the universe is flat with only a 0.4% margin of error", according to NASA scientists. [1] Theorists have been trying to construct a formal mathematical model of the shape of the universe. In formal terms, a 3-manifold model corresponding to the spatial section (in comoving coordinates) of the 4-dimensional space-time of the universe. The model most theorists currently use is the so-called Friedmann–Lemaître–Robertson–Walker (FLRW) model. According to cosmologists, on this model the observational data best fit with the conclusion that the shape of the universe is infinite and flat, [2] but the data are also consistent with other possible shapes, such as the so-called Poincaré dodecahedral spaceand the Picard horn.

Two aspects of shape

Describing the shape of the universe requires a consideration of two aspects:

1. its *local* geometry, which mostly concerns the curvature of the universe, particularly the observable universe, and
2. its *global* geometry, which concerns the topology of the universe as a whole.



The local geometry of the universe is determined by whether the density parameter Ω is greater than, less than, or equal to 1.
From top to bottom: a spherical universe with Ω > 1, a hyperbolic universe with Ω < 1, and a flat universe with Ω = 1. Note that these depictions of two-dimensional surfaces are merely easily visualizable analogs to the 3-dimensional structure of (local) space.

If the observable universe encompasses the entire universe, we may be able to determine the global structure of the entire universe by observation. However, if the observable universe is smaller than the entire universe, our observations will be limited to only a part of the whole, and we may not be able to determine its global geometry through measurement. It is possible to construct different mathematical models of the global geometry of the entire universe all of which are consistent with current observational data. For example, the observable universe may be many orders of magnitude smaller than the entire universe. The universe may be small in some dimensions and not in others (analogous to the way a cylinder is longer in the dimension of length than it is in the dimensions of width and depth). To test whether a given mathematical model describes the universe accurately, scientists look for the model's novel implications—what are some phenomena in the universe that we have not yet observed, but that must exist if the model is correct—and they devise experiments to test whether those phenomena occur or not. For example, if the universe is a small closed loop, one would expect to see multiple images of an object in the sky, although not necessarily images of the same age.

Cosmologists normally work with a given space-like slice of spacetime called the comoving coordinates, the existence of a preferred set of which is possible and widely accepted in present-day physical cosmology. The section of spacetime that can be observed is the backward light cone (all points within the cosmic light horizon, given time to reach a given observer), while the related term Hubble volume can be used to describe either the past light cone or comoving space up to the surface of last scattering. To speak of "the shape of the universe (at a point in time)" is ontologically naive from the point of view of special relativity alone: due to the relativity of simultaneity we cannot speak of different points in space as being "at the same point in time" nor, therefore, of "the shape of the universe at a point in time".

Local geometry (spatial curvature)

The **local geometry** is the curvature describing any arbitrary point in the observable universe (averaged on a sufficiently large scale). Many astronomical observations, such as those from supernovae and the Cosmic Microwave Background (CMB) radiation, show the observable universe to be very close to homogeneous and isotropic and infer it to be accelerating.

FLRW model of the universe

In General Relativity, this is modelled by the Friedmann–Lemaître–Robertson–Walker (FLRW) model. This model, which can be represented by the Friedmann equations, provides a curvature (often referred to as *geometry*) of the universe based on the mathematics of fluid dynamics, i.e. it models the matter within the universe as a perfect fluid. Although stars and structures of mass can be introduced into an "almost FLRW" model, a strictly FLRW model is used to approximate the local geometry of the observable universe.

Another way of saying this is that if all forms of dark energy are ignored, then the curvature of the universe can be determined by measuring the average density of matter within it, assuming that all matter is evenly distributed (rather than the distortions caused by 'dense' objects such as galaxies).

This assumption is justified by the observations that, while the universe is "weakly" inhomogeneous and anisotropic (see the large-scale structure of the cosmos), it is on average homogeneous and isotropic.

The homogeneous and isotropic universe allows for a spatial geometry with a constant curvature. One aspect of local geometry to emerge from General Relativity and the FLRW model is that the density parameter, Omega (Ω), is related to the curvature of space. Omega is the average density of the universe divided by the critical energy density, i.e. that required for the universe to be flat (zero curvature).

The curvature of space is a mathematical description of whether or not the Pythagorean theorem is valid for spatial coordinates. In the latter case, it provides an alternative formula for expressing local relationships between distances:

- If the curvature is zero, then $\Omega = 1$, and the Pythagorean theorem is correct;
- If $\Omega > 1$, there is positive curvature; and
- if $\Omega < 1$ there is negative curvature.

In the last two cases, the Pythagorean theorem is invalid (but discrepancies are only detectable in triangles whose sides' lengths are of cosmological scale).

If you measure the circumferences of circles of steadily larger diameters and divide the former by the latter, all three geometries give a value very close to π for small enough diameters but the ratio departs from π for larger diameters unless $\Omega = 1$:

- For $\Omega > 1$ (the sphere, see diagram) the ratio falls below π: indeed, a great circle on a sphere has circumference only twice its diameter.
- For $\Omega < 1$ the ratio rises above π.

Astronomical measurements of both matter-energy density of the universe and spacetime intervals using supernova events constrain the spatial curvature to be very close to zero, although they do not constrain its sign. This means that although the local geometries of spacetime are generated by the theory of relativity based on spacetime intervals, we can approximate *3-space* by the familiar Euclidean geometry.

Possible local geometries

There are three categories for the possible spatial geometries of constant curvature, depending on the sign of the curvature. If the curvature is exactly zero, then the local geometry is flat; if it is positive, then the local geometry is spherical, and if it is negative then the local geometry is hyperbolic.

The geometry of the universe is usually represented in the system of comoving coordinates, according to which the expansion of the universe can be ignored. Comoving coordinates form a single frame of reference according to which the universe has a static geometry of three spatial dimensions.

Under the assumption that the universe is homogeneous and isotropic, the curvature of the observable universe, or the local geometry, is described by one of the three "primitive" geometries (in mathematics these are called the model geometries):

- 3-dimensional Flat Euclidean geometry, generally notated as E^3
- 3-dimensional spherical geometry with a small curvature, often notated as S^3
- 3-dimensional hyperbolic geometry with a small curvature

Even if the universe is not exactly spatially flat, the spatial curvature is close enough to zero to place the radius at approximately the horizon of the observable universe or beyond.

Global geometry

Global geometry covers the geometry, in particular the topology, of the whole universe—both the observable universe and beyond. While the local geometry does not determine the global geometry completely, it does limit the possibilities, particularly a geometry of a constant curvature. For this discussion, the universe is taken to be a geodesic manifold, free of topological defects; relaxing either of these complicates the analysis considerably.

In general, local to global theorems in Riemannian geometry relate the local geometry to the global geometry. If the local geometry has constant curvature, the global geometry is very constrained, as described in Thurston geometries.

A global geometry is also called a topology, as a global geometry is a local geometry plus a topology, but this terminology is misleading because a topology does not give a global geometry: for instance, Euclidean 3-space and hyperbolic 3-space have the same topology but different global geometries.

Two strongly overlapping investigations within the study of global geometry are whether the universe:

- Is infinite in extent or is a compact space;
- Has a simply or non-simply connected topology.

Detection

For a flat spatial geometry, the scale of any properties of the topology is arbitrary and may or may not be directly detectable. For spherical and hyperbolic spatial geometries, the curvature gives a scale (either by using the radius of curvature or its inverse), a fact noted by Carl Friedrich Gauss in an 1824 letter to Franz Taurinus.[3]

The probability of detection of the topology by direct observation depends on the spatial curvature: a small curvature of the local geometry, with a corresponding radius of curvature greater than the observable horizon, makes the topology difficult or impossible to detect if the curvature is hyperbolic. A spherical geometry with a small curvature (large radius of curvature) does not make detection difficult.

Analysis of data from WMAP implies that on the scale to the surface of last scattering, the density parameter of the Universe is within about 0.5% of the value representing spatial flatness.[4]

Compactness of the global shape

Formally, the question of whether the universe is infinite or finite is whether it is an unbounded or bounded metric space. An infinite universe (unbounded metric space) means that there are points *arbitrarily* far apart: for any distance *d*, there are points that are of a distance at least *d* apart. A finite universe is a bounded metric space, where there is some distance *d* such that all points are within distance *d* of each other. The smallest such *d* is called the **diameter** of the universe, in which case the universe has a well-defined "volume" or "scale."

A **compact space** is a stronger condition: in the context of Riemannian manifolds, it is equivalent to being bounded and geodesically complete. If we assume that the universe is geodesically complete, then boundedness and compactness are equivalent (by the Hopf–Rinow theorem), and they are thus used interchangeably, if completeness is understood.

If the spatial geometry is spherical, the topology is compact. For a flat or a hyperbolic spatial geometry, the topology can be either compact or infinite: for example, Euclidean space is flat and infinite, but the torus is flat and compact.

In cosmological models (geometric 3-manifolds), a compact space is either a spherical geometry, or has infinite fundamental group (and thus is called "multiply connected", or more strictly **non-simply connected**), by general results on geometric 3-manifolds.

Compact geometries can be visualized by means of closed geodesics: on a sphere, a straight line, when extended far enough in the same direction, will reach the starting point.

Note that on a compact geometry, not every straight line comes back to its starting point. For instance, a line of irrational slope on a torus never returns to its origin. Conversely, a non-compact geometry can have closed geodesics: on an infinite cylinder, which is a non-compact flat geometry, a loop around the cylinder is a closed geodesic.

If the geometry of the universe is not compact, then it is infinite in extent with infinite paths of constant direction that, generally do not return, such as in the Euclidean plane.

Open or closed

When cosmologists speak of the universe as being "open" or "closed", they most commonly are referring to whether the curvature is negative or positive. These meanings of open and closed, and the mathematical meanings, give rise to ambiguity because the terms can also refer to a closed manifold i.e. compact without boundary, not to be confused with a closed set. With the former definition, an "open universe" may either be an open manifold, i.e. one that is not compact and without boundary,[5] or a closed manifold, while a "closed universe" is necessarily a closed manifold.

In the Friedmann–Lemaître–Robertson–Walker (FLRW) model the universe is considered to be without boundaries, in which case "compact universe" could describe a universe that is a closed manifold.

The latest research shows that even the most powerful future experiments (like SKA, Planck..) will not be able to distinguish between flat, open and closed universe if the true value of cosmological curvature parameter is smaller than 10^{-4}. If the true value of the cosmological curvature parameter is larger than 10^{-3} we will be able to distinguish between these three models even now.[6]

Flat universe

In a flat universe, all of the local curvature and local geometry is flat. It is generally assumed that it is described by a Euclidean space, although there are some spatial geometries that are flat and bounded in one or more directions (like the surface of a cylinder, for example).

The alternative two-dimensional spaces with a Euclidean metric are the cylinder and the Möbius strip, which are bounded in one direction but not the other, and the torus and Klein bottle, which are compact.

In three dimensions, there are 10 finite closed flat 3-manifolds, of which 6 are orientable and 4 are non-orientable. The most familiar is the 3-Torus. See the doughnut theory of the universe.

In the absence of dark energy, a flat universe expands forever but at a continually decelerating rate, with expansion asymptotically approaching zero. With dark energy, the expansion rate of the universe initially slows down, due to the effect of gravity, but eventually increases. The ultimate fate of the universe is the same as that of an open universe.

A flat universe can have zero total energy. Thus, physicists suggest a flat universe could come from nothing.[7]

Spherical universe

A positively curved universe is described by spherical geometry, and can be thought of as a three-dimensional hypersphere, or some other spherical 3-manifold (such as the Poincaré dodecahedral space), all of which are quotients of the 3-sphere.

Analysis of data from the Wilkinson Microwave Anisotropy Probe (WMAP) looks for multiple "back-to-back" images of the distant universe in the cosmic microwave background radiation. It may be possible to observe multiple images of a given object, if the light it emits has had sufficient time to make one or more complete circuits of a bounded universe. Current results and analysis do not rule out a bounded global geometry (i.e. a closed universe), but they do confirm that the spatial curvature is small, just as the spatial curvature of the surface of the Earth is small compared to a horizon of a thousand kilometers or so. If the universe is bounded, this does not imply anything about the sign[*citation needed*] of its curvature.

In a closed universe lacking the repulsive effect of dark energy, gravity eventually stops the expansion of the universe, after which it starts to contract until all matter in the observable universe collapses to a point, a final singularity termed the Big Crunch, by analogy with Big Bang. However, if the universe has a large amount of dark energy (as suggested by recent findings), then the expansion of the universe could continue forever.

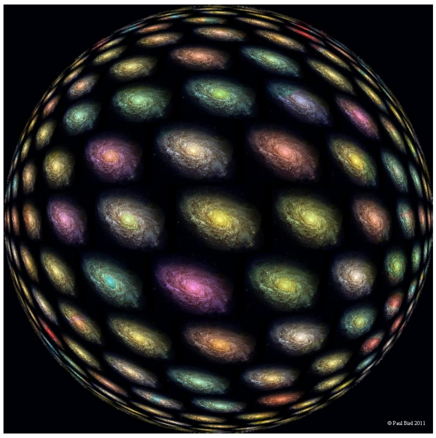
Based on analyses of the WMAP data, cosmologists during 2004–2006 focused on the Poincaré dodecahedral space (PDS), but horn topologies (which are hyperbolic) were also deemed compatible with the data.

Hyperbolic universe

A hyperbolic universe, one of a negative spatial curvature, is described by hyperbolic geometry, and can be thought of locally as a three-dimensional analog of an infinitely extended saddle shape. There are a great variety of hyperbolic 3-manifolds, and their classification is not completely understood. For hyperbolic local geometry, many of the possible three-dimensional spaces are informally called **horn topologies**, so called because of the shape of the pseudosphere, a canonical model of hyperbolic geometry.

Milne model ("spherical" expanding)

If one applies Minkowski space-based Special Relativity to expansion of the universe, without resorting to the concept of a curved spacetime, then one obtains the Milne model. Any spatial section of the universe of a constant age (the proper time elapsed from the Big Bang) will have a negative curvature; this is merely a pseudo-Euclidean geometric fact analogous to one that concentric spheres in the *flat* Euclidean space are nevertheless curved. Spacial geometry of this model is an unbounded hyperbolic space. Entire universe is contained within a light cone, namely the future cone of the Big Bang. For any given moment $t > 0$ of coordinate time (assuming the Big Bang has $t = 0$) entire universe is bounded by a sphere of radius exactly $c\ t$. Apparent paradox of an infinite universe contained within a sphere is explained with length contraction: the galaxies further away, which are travelling away from the observer the fastest, will appear thinner.



Universe in an expanding sphere. The galaxies furthest away are moving fastest and hence experience length contraction and so become smaller to an observer in the centre.

This model is essentially a degenerate FLRW for $\Omega = 0$. It is incompatible with observations that definitely rule out so large negative spatial curvature.

Proposed models

Various models have been proposed for the global geometry of the universe. In addition to the primitive geometries, these proposals include the:

- Poincaré dodecahedral space, a positively curved space, colloquially described as "soccerball-shaped", as it is the quotient of the 3-sphere by the binary icosahedral group, which is very close to icosahedral symmetry, the symmetry of a soccer ball. This was proposed by Jean-Pierre Luminet and colleagues in 2003[8] and an optimal orientation on the sky for the model was estimated in 2008.
- Picard horn, a negatively curved space, colloquially described as "funnel-shaped", for the horn geometry.

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[3] Carl F. Gauss, *Werke 8*, 175–239, cited and translated in John W. Milnor (1982) *Hyperbolic geometry: The first 150 years* (http://projecteuclid.org/euclid.bams/1183548588), *Bull. Amer. Math. Soc*. (N.S.) 6(1), p. 10.

Milnor's translation reads:

> "The assumption that the sum of the three angles [of a triangle] is smaller than 180° leads to a geometry which is quite different from our (euclidean) geometry, but which is in itself completely consistent. I have satisfactorily constructed this geometry for myself so that I can solve every problem, except for the determination of one constant, which cannot be ascertained a priori. The larger one chooses this constant, the closer one approximates euclidean geometry. . . . If non-euclidean geometry were the true geometry, and if this constant were comparable to distances which we can measure on earth or in the heavens, then it could be determined a posteriori. Hence I have sometimes in jest expressed the wish that euclidean geometry is not true. For then we would have an absolute a priori unit of measurement."

[4] Shape of the Universe (http://map.gsfc.nasa.gov/universe/uni_shape.html), WMAP website at NASA.

[5] Since the universe is assumed connected, we do not need to specify the more technical "an open manifold is one without compact component".

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Inhomogeneous cosmology

Inhomogeneous cosmology usually means the study of structure in the universe by means of exact solutions of Einstein's field equations (i.e. *metrics*) or by spatial or spacetime averaging methods. Such models are not homogeneous, but contain enough matter to be possible cosmological models, typically without dark energy, or models of cosmological structures such as voids or galaxy clusters. In contrast, perturbation theory, which deals with small perturbations from e.g. a homogeneous metric, only holds as long as the perturbations are not too large, and N-body simulations use Newtonian gravity which is only a good approximation when speeds are low and gravitational fields are weak.

Exact solutions

The best known examples of such exact solutions are the Lemaître–Tolman metric (or LT model). Some other examples are the Szekeres metric, tSzafron metric, Stephani metric, Kantowski-Sachs metric, Barnes metric, Kustaanheimo-Qvist metric, and Senovilla metric.

Averaging methods

The best-known averaging approach is the scalar averaging approach, often referred to as the set of Buchert equations.

References

Back-reaction

In theoretical physics, **Back-reaction** is often necessary to calculate the behavior of a particle or an object in an external field.

When the particle is considered to be infinitely light or have an infinitesimal charge, it is said that we deal with a **probe** and the **back-reaction** is neglected. However, a real object also carries a mass and charges itself.

They modify the original environment (for example, they help to curve the space in general relativity) and this modification - the **back-reaction** - has to be taken into account when a more accurate calculation is performed.

In Cosmology the term Back-reaction is used for the measure of the non commutativity of the averaging procedure and the dynamical evolution of space-time. The existence of an isotropy scale is determined by the length scale at which the Back-reaction parameter vanishes. The existence of such scale still needs experimental confirmation.

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