

## Accelerating universe

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**An increased speed of cosmic expansion.** Cosmic expansion is speeding up. In 1998, astronomers published evidence from exploding stars that showed that the expansion of the universe is not slowing down, as would be expected as a result of the gravity of matter in the universe. Instead, the observations show that cosmic expansion is accelerating. Observations of the cosmic microwave background and the clustering of galaxies that have been made since the discovery of cosmic acceleration have made the case for this surprising result more secure. Cosmologists attribute the acceleration to the effect of a mysterious dark energy that does not yet have a secure foundation in fundamental physics. Dark energy makes up about two-thirds of the energy density of the universe. While it may be related to Albert Einstein's controversial cosmological constant, its true nature remains to be discovered by further observation and new ideas. *See also:* COSMOLOGICAL CONSTANT; DARK ENERGY; SUPERNOVA.

Astronomers have known since the 1920s that galaxies are separated by millions of light-years and that the nearest galaxies are moving away from us slowly while distant galaxies are receding more rapidly. This relation was discovered empirically by Edwin Hubble using the Hundred-Inch Telescope at the Mount Wilson Observatory. If our patch of the universe is not unique, the simplest explanation for this observation is that the universe as a whole is expanding in all directions.

Since light travels at a finite speed, a telescope is a no-nonsense time machine that is capable of showing how the expansion of the universe has changed over time by observing distant objects. Einstein's general theory of relativity, applied in the cosmic setting, shows that the presence of matter in the universe should lead to the gradual slowing of cosmic expansion. Since the 1950s, astronomers have sought to measure this deceleration of the universe, hoping to use it as a guide to the density of matter in the universe and as a predictor of the future behavior of cosmic expansion—whether the universe would coast outward indefinitely, or whether it would be drawn back to a dense state like the big bang from which it emerged  $14 \times 10^9$  years ago. *See also:* BIG BANG THEORY; RELATIVITY.

In the 1990s, astronomers learned to use thermonuclear supernova explosions as distance-measuring tools. These supernovae are bright enough to see more than halfway back to the big bang, and the distance to each well-observed explosion can be determined to better than 10%. The effect of cosmic acceleration is to make distant supernovae appear a little fainter than they would otherwise be. The size of this effect is about a 20% reduction in brightness. By assembling sufficiently large samples of supernovae that are nearby and supernovae that are distant, this subtle difference can be firmly established. The present world sample of supernovae for this

purpose has about 1000 well-measured explosions that allow us to establish the acceleration beyond any reasonable doubt, and to begin to test different ideas on the nature of dark energy. Work on the clustering of galaxies and on the faint cosmic background light left over from the big bang itself converges on the same solution: the universe today is dominated by a strange dark energy whose role in fundamental physics is certainly important, but of which our present understanding is very limited. *See also:* COSMIC BACKGROUND RADIATION.

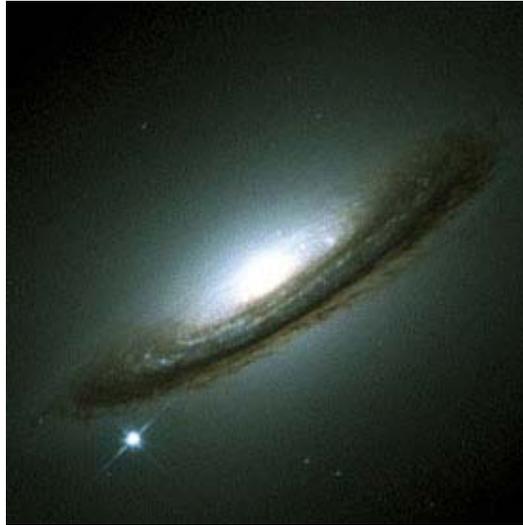
## Expanding universe

Before 1920, astronomers thought that the Milky Way Galaxy, of which the Sun is an inconspicuous member, constituted the entire universe. When Einstein applied his recently developed theory of gravitation, the general theory of relativity, to the universe in 1916, he was guided by astronomical observations to think of it as a static system. Einstein constructed a static solution to his equations by adding in a term that we now call the cosmological constant. This term had the effect of balancing the attractive force of gravity with a kind of cosmic repulsion to produce a static universe.

Hubble, working at the Mount Wilson Observatory, showed that the distances to what he called the spiral nebulae were much larger than the extent of the Milky Way, and that it was more correct to think of these as independent systems, galaxies, each equivalent to the Milky Way. He did this by measuring the apparent brightness of stars whose intrinsic brightness he knew. The fainter such a star appears, the more distant it must be. Hubble was able to show that the distances to even the nearest nebulae were a few million light-years, far larger than the size of the Milky Way. Modern measurements with supernovae use the same principle, except that the stars observed, Type Ia supernovae, are 1,000,000 times brighter and allow us to make similar measurements over a span of distance (and cosmic time) that is 1000 times larger. *See also:* CEPHEIDS; GALAXY, EXTERNAL; MILKY WAY GALAXY.

Hubble also measured the spectra of galaxies to show that their spectrum lines are shifted to the red, the signature that they are receding from us. By combining the measurements of distance and of recession, Hubble discovered that the more distant galaxies are moving away from us more rapidly. The modern interpretation of these observations is cosmic expansion, with the universe stretching out in all directions at a rate of about 1 part in 14,000,000,000 of its size each year. *See also:* HUBBLE CONSTANT; REDSHIFT.

Naturally, Einstein had to adjust to this new picture of the cosmos. He had inserted his cosmological constant to make a static world, but later observations had showed that the world was not static. Einstein was then inclined to banish the cosmological constant, which he knew was not mathematically justified and which he never did like much anyway. Another view, held by Georges Lemaître, was that the cosmological constant was responsible for the expansion observed and had its origin in the energy of the vacuum of space itself. He wrote in 1934, "Everything happens as though the energy *in vacuo* would be different from zero . . . we associate a pressure  $p = -\rho c^2$  to the density of energy  $\rho c^2$  of vacuum. This is essentially the meaning of the cosmological constant  $\lambda$ ." Here  $\rho$  is the matter density and  $c$  is the speed of light.



**Fig. 1** Supernova 1994D. This type Ia supernova, visible at lower left, is in this galaxy at a distance of about  $5 \times 10^7$  light-years in the Virgo cluster of galaxies. For a month, the light from a single exploding white dwarf was as bright as  $4 \times 10^9$  stars like the Sun. (P. Challis, Center for Astrophysics/STScI/NASA)

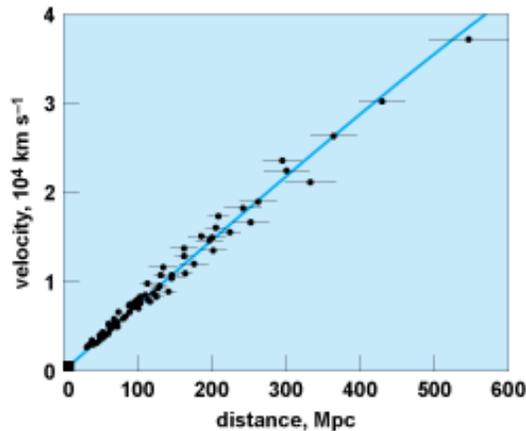
The evidence for cosmic acceleration, adduced 64 years later, lends itself to a picture in which empty space is not without attributes, the most important of which is a negative pressure like the one Lemaître envisioned, that can lead to the observed effects. The ratio of pressure to energy density is characterized as the “equation-of-state parameter,”  $w$ , which would have the value of  $-1$  for the cosmological constant, but could have some other value for a different form of dark energy.

## Type Ia supernovae

The claim that the universe is accelerating is so extraordinary that it is worth examining the evidence on which it is based: the brightness of exploding stars that astronomers call type Ia supernovae (**Fig. 1**).

Type Ia supernovae are a particular type of exploding star that can be recognized by its spectrum. They are found in all types of galaxies and are thought to result from a sudden thermonuclear burning wave that rips through a white-dwarf star as it approaches the maximum mass possible for a white dwarf. This thermonuclear process changes the carbon and oxygen of the star’s interior into radioactive nickel, destroying the star. The nickel’s subsequent radioactive decay into cobalt and iron releases energy gradually as the star flies apart. For about a month, a single type Ia supernova shines  $4 \times 10^9$  as brightly as the Sun. This property makes type Ia supernovae visible over very large distances, large enough to detect halfway across the universe.

But being bright is only half the story. In order to measure cosmic distances from apparent brightness with good precision, the ideal tool would be a “standard candle” for which all the objects had the same intrinsic brightness. Then a measurement of the apparent brightness would give the distance. Type Ia supernovae are pretty good



**Fig. 2** Modern Hubble diagram for 95 type Ia supernovae. Recession velocity is plotted against distance in megaparsecs ( $1 \text{ Mpc} = 3.26 \times 10^6 \text{ light-years} = 3.09 \times 10^{19} \text{ km}$ ). The points represent supernovae up to  $2 \times 10^9$  light-years away, with recession velocities of up to one-tenth the speed of light. The small scatter about the diagonal line shows that type Ia supernovae make excellent standard candles for measuring distances in the universe. This nearby patch does not show the effects of acceleration. (Based on data from Saurabh Jha)

standard candles: the intrinsic light output at their peak luminosity varies by only a factor of 3 or so. This uniform behavior is probably connected to the well-defined upper mass limit for white dwarfs of about 1.4 solar masses, which is set by the quantum-mechanical properties of electrons. However, the merger of two white dwarfs is also a possible path to making type Ia supernova explosions. *See also:* WHITE DWARF STAR.

Better precision comes from empirical approaches to type Ia supernovae. It turns out that the brightest of these supernovae decline more slowly in brightness after they reach their peak, while dimmer type Ia supernovae decline more rapidly. The rise and fall in the brightness of a supernova, which does not depend on its distance, reveals whether it is an extra bright supernova or an extra dim one. When the shape of the light curve is taken into account, the uncertainty in the distance to a single supernova shrinks to less than 10%, making this type of supernova the very best distance-measuring tool for surveying the distant universe (**Fig. 2**). *See also:* LIGHT CURVES.

## Technological advances

The disadvantage of type Ia supernovae is that they are rare. In a typical large galaxy, the rate of type Ia supernova explosions is about one in a century. In our own Milky Way Galaxy, the last event that was probably a type Ia supernova was observed by Tycho Brahe in 1572. So if you want to find and measure a large number of supernovae to survey the history of cosmic expansion, you need either to be very patient or to be able to search many galaxies for the desired events.

This point is where technology has made great strides. The electronic light detectors used in modern telescopes are charge-coupled devices (CCDs), similar to those found in digital cameras. These are more than 100 times

more sensitive to light than the photographic plates used in Hubble's time. As the technology for fabricating computer chips has improved, the CCDs available to astronomers have grown larger as well as more sensitive, so that arrays of 1000 megapixels are now being applied to supernova studies and still larger cameras are in development. These large and sensitive devices allow a modern telescope to image many thousands of galaxies in a single exposure. By coming back night after night to the same part of the sky, supernova searches gather the data needed to find many of these rare events. *See also:* ASTRONOMICAL IMAGING; CHARGE-COUPLED DEVICES.

But gathering the light is only part of the story of finding supernovae to do cosmology. You also need to detect the new starlike events among the many fuzzy galaxies that do not change from night to night. This is the place where advances in computer hardware and software have turned the task of supernova searching from handicraft into something on an industrial scale. By using fast computers to subtract digital images obtained last month (or last year) from the ones obtained tonight, it is relatively straightforward to sift out overnight a handful of new objects from the hundreds of thousands that remain unchanged.

Measuring the apparent brightness of these supernovae and the shape of their rise and fall over a month gives enough information to measure the distance to a supernova. Measuring the spectrum of the supernova establishes that it is of type Ia and measures the redshift. By measuring the redshift at various distances, one can trace the history of cosmic expansion to look for the effects of slowing that results from gravity or acceleration caused by dark energy.

The first attempt at this type of searching was made in 1988 by a Danish group. Because only small CCD chips were available, they published data on only one distant type Ia supernova. But the Supernova Cosmology Project based at Lawrence Berkeley Laboratory developed effective search techniques, and by 1997 they had a preliminary result. Their first indication, based on seven distant supernovae found in 1994 and 1995, was that the universe was slowing down because of the braking effects of dark matter. In 1998, based on 50 supernovae, near and far, the High-Z Supernova Search Team published a result indicating the opposite: that the universe was accelerating. Results from the Supernova Cosmology Project published in 1999 based on 60 type Ia supernovae showed the same thing: we live in a universe in which the rate of cosmic expansion is increasing as the universe grows older.

Well-organized efforts to assemble much larger samples of supernova observations have made this early result more secure. The ESSENCE project carried out at the Cerro Tololo Inter-American Observatory and the Supernova Legacy Survey carried out at the Canada-France-Hawaii Telescope have observed hundreds of distant supernovae. The Carnegie Supernova Program and the CfA Supernova Program have measured hundreds of nearby supernovae, while the Sloan Survey telescope has been harnessed to produce the Sloan Supernova Survey, with hundreds of objects in the gap between the nearby and distant objects. The samples have grown larger, the span of cosmic time probed by the supernova observations has increased, and methods for dealing with the pernicious effects of absorption by dust have been developed by observing the supernovae in infrared light. Type Ia supernovae are more nearly standard candles when they are observed in the infrared, and the effects of dust

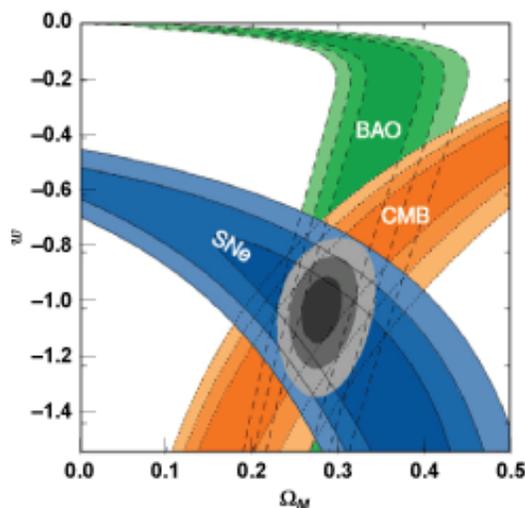
(which can mimic cosmic acceleration) are smaller. One especially interesting result comes from a supernova search and follow-up carried out using the *Hubble Space Telescope* both to find and to get the light curves and spectra of very distant supernovae. This work showed that cosmic acceleration is a comparatively recent phenomenon, acting over only the last  $5 \times 10^9$  years. Supernovae discovered at distances larger than  $5 \times 10^9$  light-years show that the universe was probably slowing down when it was younger. This is evidence that the universe was slowing down when it was young and dense, presumably resulting from the presence of dark matter, but then there came a shift, about  $9 \times 10^9$  years after the big bang (and  $5 \times 10^9$  years before the present), from deceleration to acceleration. In the lexicon of elementary physics, change in position is velocity, change in velocity is acceleration, and change in acceleration is called jerk. This program with the *Hubble Space Telescope* has produced evidence for the cosmic jerk. The ongoing CANDELS (Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey) program with the *Hubble Space Telescope* is expected to increase this sample of distant supernovae and press the range of discovery back to an unexplored era. *See also:* DARK MATTER; HUBBLE SPACE TELESCOPE; SLOAN DIGITAL SKY SURVEY.

## Dark energy?

By combining measurements of supernova distances with results from galaxy clustering and from fluctuations in the cosmic microwave background, consensus has emerged that the universe at present has about 73% of its energy density in dark energy, about 23% in dark matter, and only 4% in the form of atoms made of neutrons, protons, and electrons. While it is satisfying that there is a single solution that matches a wide variety of current data, an honest appraisal is that we do not know what the dark energy is or what the dark matter is.

The dark energy could be a form of Einstein's cosmological constant. The cosmological constant has the right property: a tendency to make the universe expand faster over time. Lemaître thought that the cosmological constant might be responsible for the cosmic expansion observed by Hubble and had the modern view of the cosmological constant: that it has its origin in the quantum properties of the vacuum. But when the quantum principles that work so well for electromagnetism are applied to gravitation, the result is a quantitative disaster of unprecedented proportions: the observed amount of dark energy is about  $10^{120}$  times smaller than the predicted amount. This is a clue that some important theoretical aspect of gravitation is not well understood; whether this understanding will come from advances in string theory or in understanding particle physics through supersymmetry is not yet demonstrated. One approach to this problem is to note that if there really was an inflationary era for our universe, then it is likely that there are many such events in a "multiverse," almost all of which is beyond our ability to observe. People speculate that different realizations of the physical laws in each of these aspects of the landscape might include a wide variety of values for the cosmological constant, only some of which would lead to a universe like the one we inhabit. At the present time, no one knows how to evaluate the probability of this outcome. *See also:* INFLATIONARY UNIVERSE COSMOLOGY; SUPERSTRING THEORY; SUPERSYMMETRY.

Another possibility is that the dark energy is not something that is constant in time, as the cosmological constant would be, but something that has been changing its effects on expansion as the universe unfolds. This property



**Fig. 3** Constraints on  $w$ , the equation-of-state parameter for dark energy, from the combination of supernovae (SNe), galaxy clustering (BAO), and microwave background constraints (CMB). The horizontal axis is the value of  $\Omega_M$ , the fraction of the universe that is gravitating matter. It includes both dark matter and visible matter, and it has a value of about 27%. The gray ellipses show that the combined information is completely consistent with  $w = -1$ , the value for the cosmological constant, but the modest precision of the measurement leaves considerable room for improvement. (From R. Amanullah et al., *Spectra and light curves of six type Ia supernovae at  $0.511 < z < 1.12$  and the Union2 Compilation, *Astrophys. J.*, 716:712–738, 2010*)

could be detected by very precise observations of distant and nearby supernovae. It could show up as a departure from the value of  $-1$  for the ratio of pressure to energy density that Lemaître used to describe the cosmological constant. The numerical value of this number is the “equation-of-state parameter.” At the present time, the combined evidence from supernovae, the cosmic microwave background, and galaxy clustering all points to a value of  $-1$ , the cosmological constant, but the precision of this measurement is not very high (Fig. 3). With little guidance from theory to determine the required goal, the best approach seems to be to make a better measurement, although better ideas would also help. There is a verdant garden of ideas for dark energy; observations will help weed out the ones that are not correct.

Another possibility is that general relativity is not precisely the correct theory of gravity. In that view, some aspects of cosmic acceleration could be attributed to the properties of modified gravity. These theories also make predictions for the growth of structure in the universe; by carefully observing the growth of galaxy clustering, we can find out whether the data do or do not favor any deviation from Einstein’s gravity.

The next round of observational programs for distant supernovae is aimed at observing the history of cosmic expansion with enough precision to tell the difference between a dark energy that does not change (like the cosmological constant) and a dark energy that varies with time. Large samples of supernovae at moderate distances and moderate samples of supernovae at large distances are being constructed. The goal is to pin down the properties of the dark energy well enough to tell if it is different in any way from a cosmological constant

with a very small numerical value. Forthcoming efforts employing the PanSTARRS telescope system operating in Hawaii and the Dark Energy Survey in Chile should provide new constraints. In the National Research Council's Plan for Astrophysics in the 2010–2020 decade in the United States, a satellite to study dark energy called WFIRST was placed at the top of its list of desired space projects for the years ahead. (It will measure  $w$  first.) Dark energy is so new, so important, and so mysterious that it will be the focus of strenuous efforts in observational astronomy for decades to come. *See also:* COSMOLOGY; UNIVERSE.

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## Keywords

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## Bibliography

J. A. Frieman, M. S. Turner, and D. Huterer, Dark energy and the accelerating universe, *Annu. Rev. Astron. Astrophys.*, 46:385–412, 2008 DOI: <http://doi.org/10.1146/annurev.astro.46.060407.145243>

R. P. Kirshner, Foundations of supernova cosmology, in P. Ruiz-Lapuente (ed.), *Dark Energy: Observational and Theoretical Approaches*, Cambridge University Press, 2010

R. P. Kirshner, *The Extravagant Universe: Exploding Stars, Dark Energy, and the Accelerating Cosmos*, Princeton University Press, 2004

R. Panek, *The 4% Universe: Dark Matter, Dark Energy, and the Race to Discover the Rest of Reality*, Houghton Mifflin Harcourt, 2011

## Additional Readings

M. Hicken et al., Improved dark energy constraints from  $\sim 100$  new CfA supernova type Ia light curves, *Astrophys. J.*, 700:1097–1140, 2009 DOI: <http://doi.org/10.1088/0004-637X/700/2/1097>

T. Padmanabhan, Cosmological constant—The weight of the vacuum, *Phys. Rep.*, 380(5–6):235–320, 2003 DOI: [http://doi.org/10.1016/S0370-1573\(03\)00120-0](http://doi.org/10.1016/S0370-1573(03)00120-0)

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The Dark Energy Survey

Ned Wright's Cosmology Tutorial

PanSTARRS (Panoramic Survey Telescope & Rapid Response System)

Sean Carroll: Cosmology Primer

Supernova Legacy Survey (SNLS)