KUNGL. VETENSKAPS-AKADEMIEN
THE ROYAL SWEDISH ACADEMY OF SCIENCES

THE NOBEL PRIZE IN PHYSICS 2011
INFORMATION FOR THE PUBLIC

Written in the stars

"Some say the world will end in fire;
Some say in ice..."*

What is the fate of the Universe? Probably it will end in ice if we are to believe this year's Nobel Laureates. They have carefully studied several dozen exploding stars, called supernovae, in faraway galaxies and have concluded that the expansion of the Universe is speeding up.

The discovery came as a complete surprise even to the Nobel Laureates themselves. What they saw would be like throwing a ball up in the air, and instead of having it come back down, watching as it disappears more and more rapidly into the sky, as if gravity could not manage to reverse the ball's trajectory. Something similar seemed to be happening across the entire Universe.

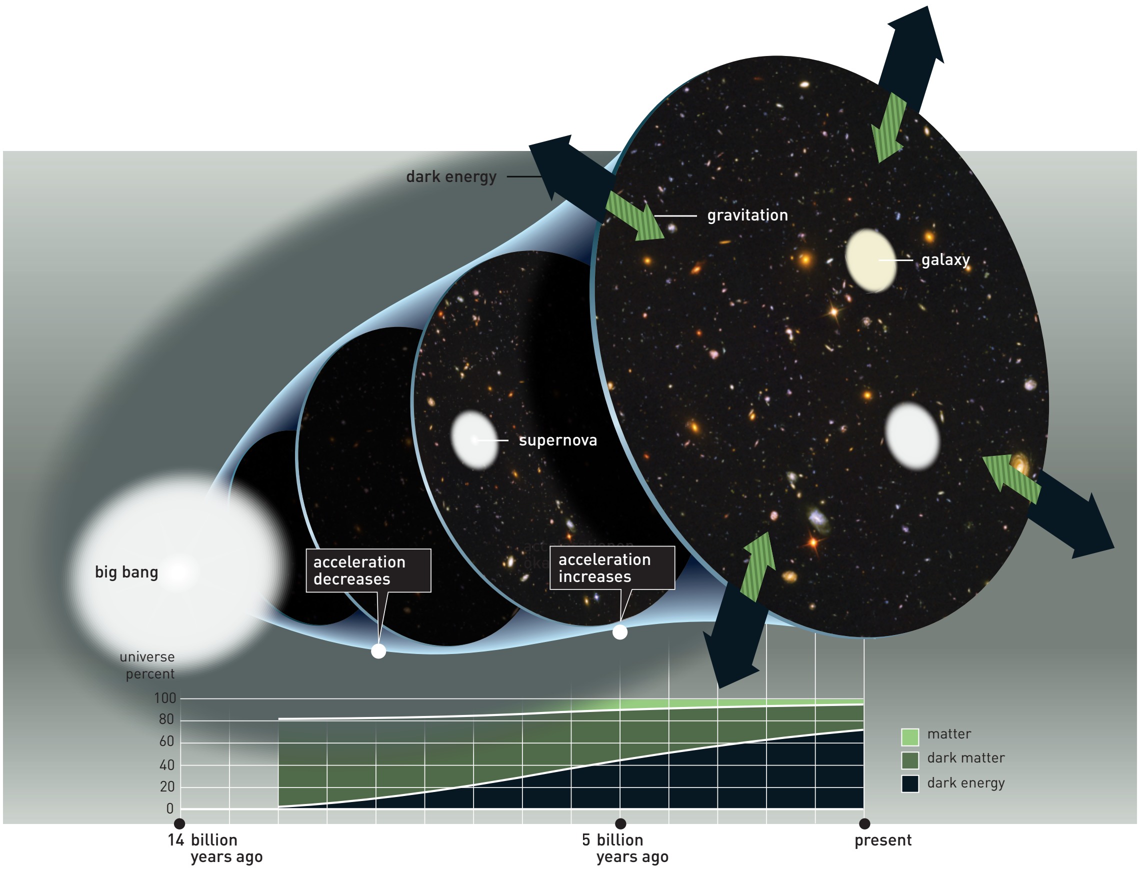


Figure 1. The world is growing. The expansion of the Universe began with the Big Bang 14 billion years ago, but slowed down during the first several billion years. Eventually it started to accelerate. The acceleration is believed to be driven by dark energy, which in the beginning constituted only a small part of the Universe. But as matter got diluted by the expansion, the dark energy became more dominant.

The growing rate of the expansion implies that the Universe is being pushed apart by an unknown form of energy embedded in the fabric of space. This *dark energy* makes up a large part of the Universe, more than 70 %, and it is an enigma, perhaps the greatest in physics today. No wonder, then, that cosmology was shaken at its foundations when two different research groups presented similar results in 1998.

Saul Perlmutter headed one of the two research teams, the Supernova Cosmology Project, initiated a decade earlier in 1988. **Brian Schmidt** headed another team of scientists, which towards the end of 1994 launched a competing project, the High-z Supernova Search Team, in which **Adam Riess** was to play a crucial role.

*Robert Frost, *Fire and Ice*, 1920

The two research teams raced each other to map the Universe by finding the most distant supernovae, star explosions in space. By establishing the distance to the supernovae and the speed at which they are moving away from us, scientists hoped to reveal our cosmic fate. They expected to find signs that the expansion of the Universe was slowing down, which would lead to equilibrium between fire and ice. What they found was the opposite – the expansion was accelerating.

Figure 2a. *Twinkle, twinkle, little star, how I wonder where you are...*

Cosmos is growing

It is not the first time that an astronomical discovery has revolutionized our ideas about the Universe. Only a hundred years ago, the Universe was considered to be a calm and peaceful place, no larger than our own galaxy, the Milky Way. The cosmological clock was ticking reliably and steadily and the Universe was eternal. Soon, however, a radical shift would change this picture.

At the beginning of the 20th century the American astronomer Henrietta Swan Leavitt found a way of measuring distances to faraway stars. At the time, women astronomers were denied access to the large telescopes, but they were frequently employed for the cumbersome task of analyzing photographic plates. Henrietta Leavitt studied thousands of pulsating stars, called *Cepheids*, and found that the brighter ones had longer pulses. Using this information, Leavitt could calculate the intrinsic brightness of Cepheids.

If the distance of just one of the Cepheid stars is known, the distances to other Cepheids can be established – the dimmer its light, the farther away the star. A reliable standard candle was born, a first mark on the cosmic yardstick that is still used today. By making use of Cepheids, astronomers would soon conclude that the Milky Way is just one of many galaxies in the Universe. And in the 1920s, the astronomers got access to the world's then-largest telescope Mount Wilson in California, so they were able to show that almost all galaxies are moving away from us. They were studying the so-called *redshift* that occurs when a source of light is

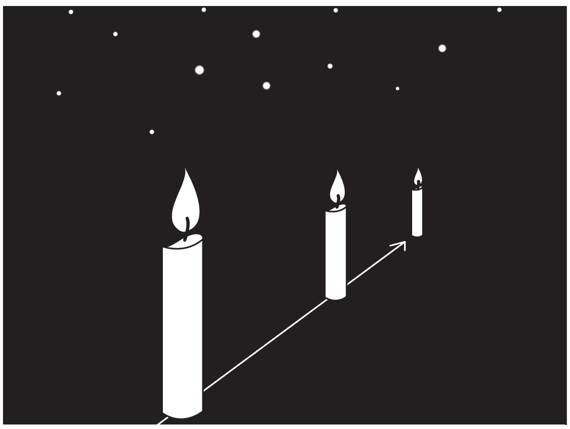


Figure 2b. **Standard light** with steady brightness is needed in order to measure distances to the stars.

receding from us. The light's wavelength gets stretched, and the longer the wave, the redder its colour. The conclusion was that the galaxies are rushing away from us and each other, and the farther away they are, the faster they move – this is known as Hubble's law. The Universe is growing.

The coming and going of the cosmological constant

What was observed in space had already been suggested by theoretical calculations. In 1915, Albert Einstein published his General Theory of Relativity, which has been the foundation of our understanding of the Universe ever since. The theory describes a Universe that has to either shrink or expand.

This disturbing conclusion was reached about a decade before the discovery of the ever-fleeing galaxies. Not even Einstein could reconcile the fact that the Universe was not static. So in order to stop this unwanted cosmic expansion, Einstein added a constant to his equations that he called *the cosmological constant*. Later, Einstein would consider the insertion of the cosmological constant a big mistake. However, with the observations made in 1997–1998 that are awarded this year's Nobel Prize, we can conclude that Einstein's cosmological constant – put in for the wrong reasons – was actually brilliant.

The discovery of the expanding Universe was a groundbreaking first step towards the now standard view that the Universe was created in the Big Bang almost 14 billion years ago. Both time and space began then. Ever since, the Universe has been expanding; like raisins in a raisin cake swelling in the oven, galaxies are moving away from each other due to the cosmological expansion. But where are we heading?

Supernovae – the new measure of the Universe

When Einstein got rid of the cosmological constant and surrendered to the idea of a non-static Universe, he related the geometrical shape of the Universe to its fate. Is it open or closed, or is it something in between – a flat Universe?

An open Universe is one where the gravitational force of matter is not large enough to prevent the expansion of the Universe. All matter is then diluted in an ever larger, ever colder and ever more empty space. In a closed Universe, on the other hand, the gravitational force is strong enough to halt and even reverse the expansion. So the Universe eventually would stop expanding and fall back together in a hot and violent ending, a *Big Crunch*. Most cosmologists, however, would prefer to live in the most simple and mathematically elegant Universe: a flat one, where the expansion is believed to decline. The Universe would thus end neither in fire nor in ice. But there is no choice. If there is a cosmological constant, the expansion will continue to accelerate, even if the Universe is flat.

This year's Nobel Laureates expected to measure the cosmic deceleration, or how the expansion of the Universe is slowing. Their method was in principle the same as the one used by astronomers more than six decades earlier: to locate distant stars and to measure how they move. However, that is easier said than done. Since Henrietta Leavitt's days many other Cepheids have been found that are even farther away. But at the distances that astronomers need to see, billions of light years away, Cepheids are no longer visible. The cosmic yardstick needed to be extended.

Supernovae – star explosions – became the new standard candles. More sophisticated telescopes on the ground and in space, as well as more powerful computers, opened the possibility in the 1990s to add more pieces to the cosmological puzzle. Crucial were the light-sensitive digital imaging sensors – charged-coupled devices or CCD – the invention by Willard Boyle and George Smith who were awarded Nobel Prize in Physics in 2009.

White dwarfs exploding

The newest tool in the astronomer's toolbox is a special kind of star explosion, the *type Ia supernova*. During a few weeks, a single such supernova can emit as much light as an entire galaxy. This type of supernova is the explosion of an extremely compact old star that is as heavy as the Sun but as small as the Earth – a *white dwarf*. The explosion is the final step in the white dwarf's life cycle.

White dwarfs form when a star has no more energy at its core, as all hydrogen and helium have been burned in nuclear reactions. Only carbon and oxygen remain. In the same way, far off in the future, our Sun will fade and cool down as it reaches its end as a white dwarf.

A far more exciting end awaits a white dwarf that is part of a binary star system, which is fairly common. In this case, the white dwarf's strong gravity robs the companion star of its gas. However, when the white dwarf has grown to 1.4 solar masses, it no longer manages to hold together. When this happens, the interior of the dwarf becomes sufficiently hot for runaway fusion reactions to start, and the star gets ripped apart in seconds.

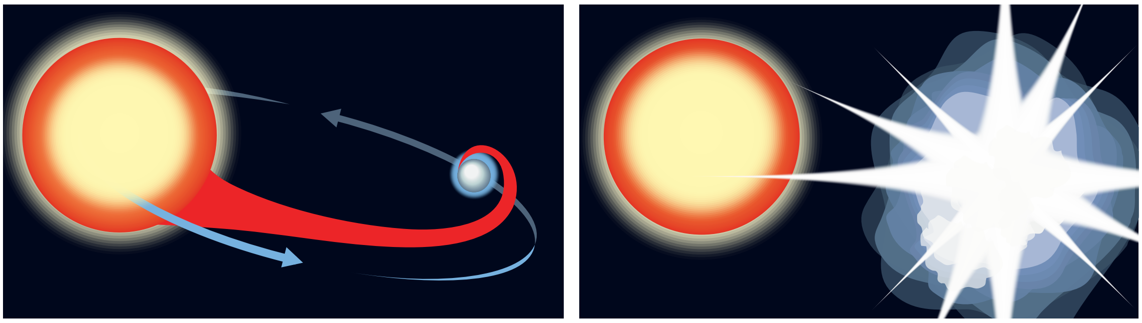


Figure 3. Supernova explosion. A white dwarf steals gas from its neighbour using its gravity. When the white dwarf has grown to 1.4 solar masses, it explodes as a type Ia supernova.

The nuclear fusion products emit strong radiation that increases rapidly during the first weeks after the explosion, only to decrease over the following months. So there is a rush to find supernovae – their violent explosions are brief. Across the visible Universe, about ten type Ia supernovae occur every minute. But the Universe is huge. In a typical galaxy only one or two supernova explosions occur in a thousand years. In September 2011, we were lucky to observe one such supernova in a galaxy close to the Big Dipper, visible just through a pair of regular binoculars. But most supernovae are much farther away and thus dimmer. So where and when would you look in the canopy of the sky?

An astounding conclusion

The two competing teams knew they had to comb the heavens for distant supernovae. The trick was to compare two images of the same small piece of the sky, corresponding to a thumbnail at arm's length. The first image has to be taken just after the new moon and the second three weeks later, before the moonlight swamps out starlight. Then the two images can be compared in the hope of discovering a small dot of light – a pixel among others in the CCD image – that could be a sign of a supernova in a galaxy far away. Only supernovae farther than a third of the way across the visible Universe were used, in order to eliminate local distortions.

The researchers had many other problems to deal with. Type Ia supernovae are not quite as reliable as they initially appeared – the brightest explosions fade more slowly. Furthermore, the light of the supernovae needed to be extracted from the background light of their host galaxies. Another important task was to obtain the correct brightness. The intergalactic dust between us and the stars changes starlight. This affects the results when calculating the maximum brightness of supernovae.

Chasing supernovae challenged not only the limits of science and technology but also those of logistics. First, the right kind of supernova had to be found. Second, its redshift and brightness had to be measured. The light curve had to be analyzed over time in order to be able to compare it to other supernovae of the same type at known distances. This required a network of scientists that could decide quickly whether a particular star was a worthy candidate for observation. They needed to be able to switch between telescopes and have observation time at a telescope granted without delay, a procedure that usually takes months. They needed to act fast because a supernova fades quickly. At times, the two competing research teams discreetly crossed each other's paths.

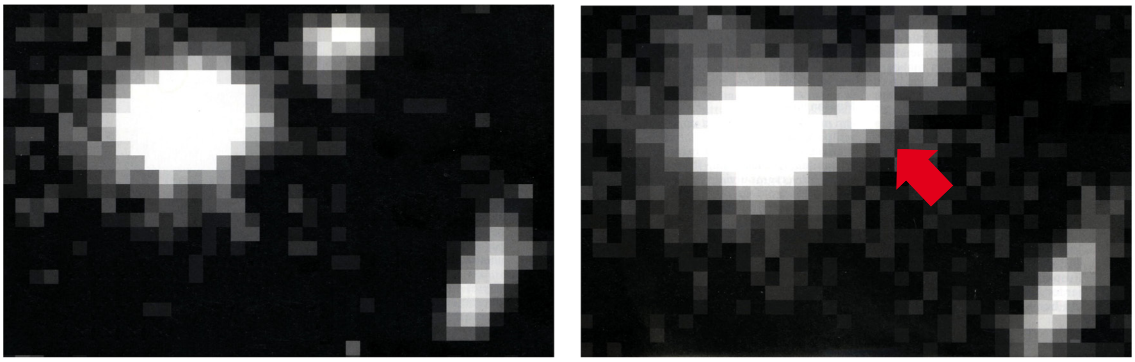
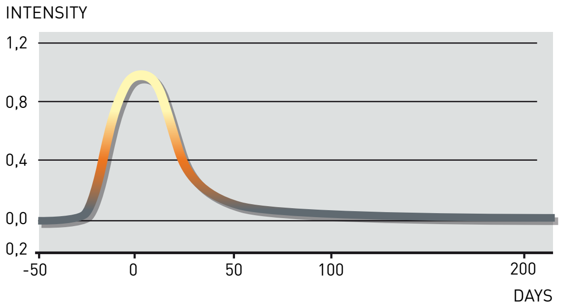


Figure 4. Supernova 1995ar. Two images of the same small piece of the sky taken three weeks apart were compared. Then, on the second image, a small dot of light was discovered! Its status as a type Ia supernova was established after further observations of its light curve. A type Ia supernova can emit as much light as an entire galaxy.The light curve is the same for all type Ia supernovae. Most light is emitted during the first few weeks (see diagram to the right).



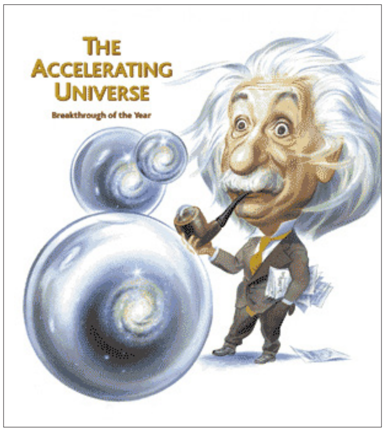
The potential pitfalls had been numerous, and the scientists actually were reassured by the fact that they had reached the same amazing results: all in all, they found some 50 distant supernovae whose light seemed weaker than expected. This was contrary to what they had envisioned. If cosmic expansion had been losing speed, the supernovae should appear brighter. However, the supernovae were fading as they were carried faster and faster away, embedded in their galaxies. The surprising conclusion was that the expansion of the Universe is not slowing down – quite to the contrary, it is accelerating.

From here to eternity

So what is it that is speeding up the Universe? It is called *dark energy* and is a challenge for physics, a riddle that no one has managed to solve yet. Several ideas have been proposed. The simplest is to reintroduce Einstein's cosmological constant, which he once rejected. At that time, he inserted the cosmological constant as an anti-gravitational force to counter the gravitational force of matter and thus create a static Universe. Today, the cosmological constant instead appears to make the expansion of the Universe to accelerate.

The cosmological constant is, of course, constant, and as such does not change over time. So dark energy becomes dominant when matter, and thus its gravity, gets diluted due to expansion of the Universe over billions of years. According to scientists, that would account for why the cosmological constant entered the scene so late in the history of the Universe, only five to six billion years ago. At about that time, the gravitational force of matter had weakened enough in relation to the cosmological constant. Until then, the expansion of the Universe had been decelerating.

The cosmological constant could have its source in the vacuum, empty space that, according to quantum physics, is never completely empty. Instead, the vacuum is a bubbling quantum soup where virtual particles of matter and antimatter pop in and out of existence and give rise to energy. However, the simplest estimation for the amount of dark energy does not correspond at all to the amount that has been measured in space, which is about 10^{120} times larger (1 followed by 120 zeros). This constitutes a gigantic and still unexplained gap between theory and observation – on all the beaches of the world there are no more than 10^{20} (1 followed by 20 zeros) grains of sand.



SOURCE: John Kascht/Science, 18 December 1998, Vol. 282, No. 5397.

Figure 5. The discovery. The accelerating expansion of the Universe was proclaimed "Breakthrough of the Year" in the December 1998 issue of *Science*. On the cover, Albert Einstein gazed upon his cosmological constant, which has returned to the forefront of cosmology.

It may be that the dark energy is not constant after all. Perhaps it changes over time. Perhaps an unknown force field only occasionally generates dark energy. In physics there are many such force fields that collectively go by the name *quintessence*, after the Greek name for the fifth element. Quintessence could speed up the Universe, but only sometimes. That would make it impossible to foresee the fate of the Universe.

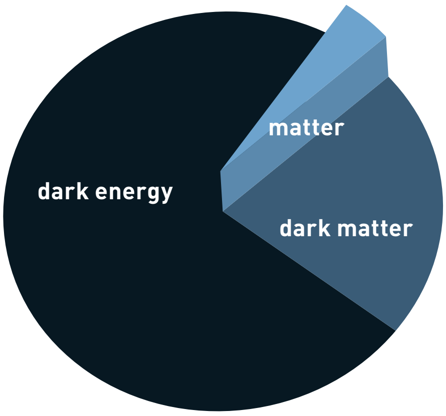


Figure 6. The Universe. The implication of the discovery is that three quarters of the Universe is an unknown form of energy, called dark energy. Together with equally unknown dark matter, the dark energy constitutes 95 % of the Universe. Only the remaining 5 % is regular matter that makes up galaxies, stars, flowers and humans.

Whatever dark energy is, it seems to be here to stay. It fits very well in the cosmological puzzle that physicists and astronomers have been working on for a long time. According to current consensus, about three quarters of the Universe consist of dark energy. The rest is matter. But the regular matter, the stuff that galaxies, stars, humans and flowers are made of, is only five percent of the Universe. The remaining matter is called *dark matter* and is so far hidden from us.

The dark matter is yet another mystery in our largely unknown cosmos. Like dark energy, dark matter is invisible. So we know both only by their effects – one is pushing, the other one is pulling. They only have the adjective "dark" in common.

Therefore the findings of the 2011 Nobel Laureates in Physics have helped to unveil a Universe that is to 95% unknown to science. And everything is possible again.

LINKS AND FURTHER READING

Additional information on this year's Prizes, including a scientific background article in English, may be found at the website of the Royal Swedish Academy of Sciences, *http://kva.se,* and at *http://nobelprize.org*. The latter also includes web-TV versions of the press conferences at which the awards were announced. Information on exhibitions and activities related to the Nobel Prizes and the Prize in Economic Sciences may be found at *www.nobelmuseet.se.*

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THE LAUREATES

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